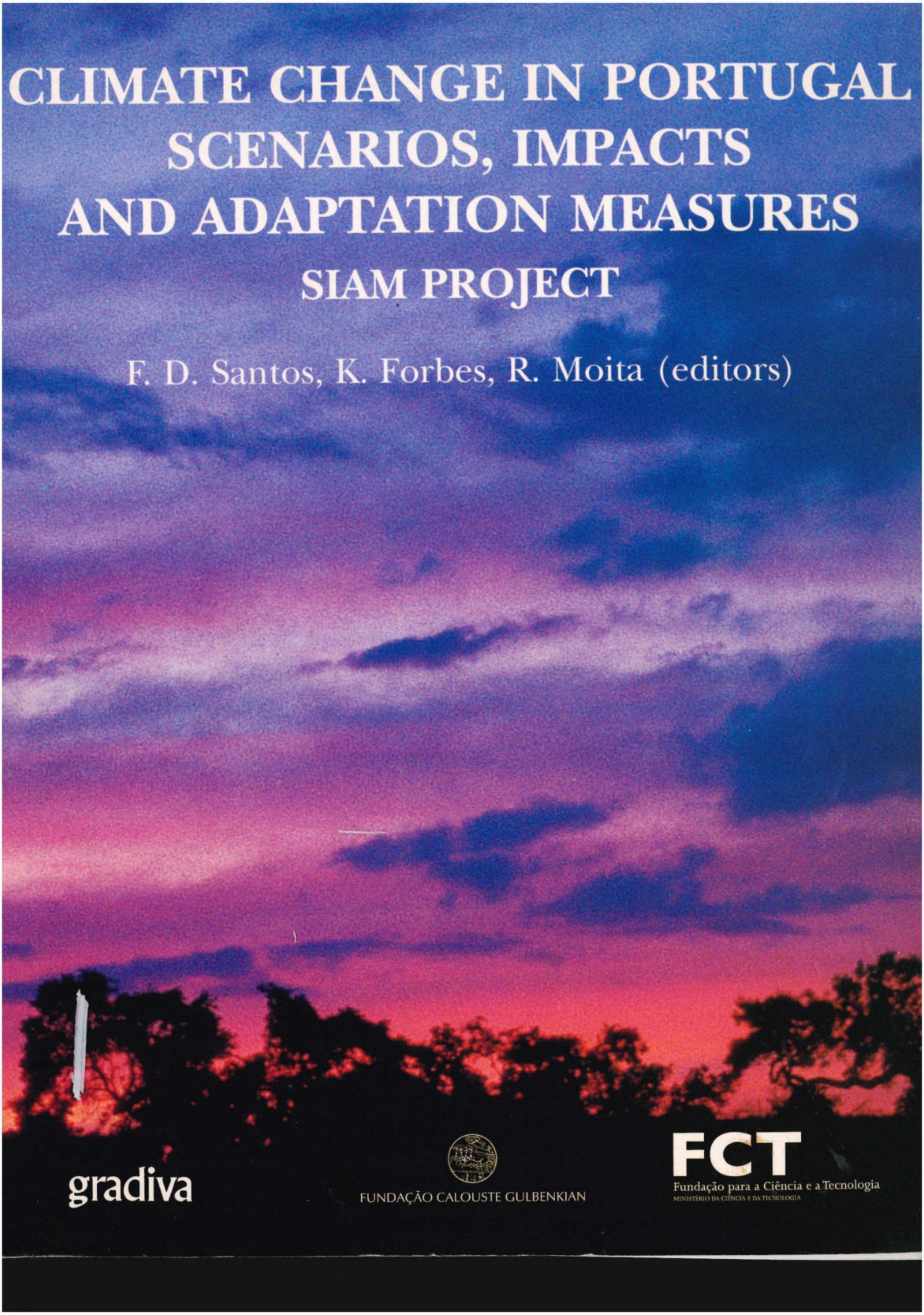

# CLIMATE CHANGE IN PORTUGAL SCENARIOS, IMPACTS AND ADAPTATION MEASURES

## SIAM PROJECT

F. D. Santos, K. Forbes, R. Moita (editors)

gradiva

FUNDAÇÃO CALOUSTE GULBENKIAN

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA E DA TECNOLOGIA

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A "montado" at dusk

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# Foreword

As we approach the 2002 World Summit on Sustainable Development in Johannesburg, 10 years after the United Nations Conference on Environment and Development in Rio de Janeiro and 30 years after the Stockholm Conference on the Human Environment it is important to re-state what are our concerns. The pressure of human claims on some key natural resources, particularly by developed countries, place us at risk of crossing thresholds beyond which lie significant environmental perturbations with very high economic, social and environmental costs. On the other hand it is imperative to attain an equitable standard of living for the developing countries with adequate food, water, energy and a healthy environment. Our major challenge is therefore to meet these basic human needs without crossing dangerous environment thresholds. We know that there are serious risks involved in human-induced climate change, as well as other environmental issues such as the depletion of water resources, land and marine environment degradation and loss of biological diversity.

To protect the climate system against human-induced climate change and to adapt to it will be one of the major challenges in the XXI century. Climate change is an additional new stress on ecological and socio-economic systems already affected by increasing resource demands, non-sustainable management practices and pollution. Human-induced climate change will be inevitable in the next hundred years. To minimize its adverse effects we need to determine the impacts of climate change and identify the most adequate adaptation measures.

This book focuses on the impacts and adaptation measures in continental Portugal. The authors have drawn upon available published material and added their own research and expert judgement. It is a major first step to assess key impacting aspects of climate change and to identify the most vulnerable sectors and regions in Portugal. It provides a solid foundation to initiate a process of adaptation to climate change, complementary and parallel to the implementation of mitigation policies and measures that are required to fulfill our obligations under the Kyoto Protocol.

Jorge Sampaio
President of the Republic of Portugal

# Preface

The influence of humanity on the global climate will grow in the 21st century. Climate is changing as a result of human activities through the emissions of greenhouse gases to the atmosphere and through profound changes in land use. Global climate change represents an unprecedented threat to human and natural systems. A considerable amount of research has either been completed or is under way to determine how important or serious are the impacts of human induced climate change at global, regional and national level. The present report is the result of the first integrated assessment of climate change impacts and adaptation measures in continental Portugal. The integrated assessment was conducted by the SIAM Project from June 1999 until January 2002 and was funded by the Fundação Calouste Gulbenkian and by the Fundação para a Ciência e a Tecnologia.

The report focuses on a core set of socio-economic and biophysical impacts and is based on climate scenarios produced by both General Circulation Models (GCMs) and Regional Climate Models. It is, to our knowledge, the first integrated and comprehensive assessment of climate change impacts using GCM – derived climate scenarios in a southern European country.

SIAM tried to integrate the work of people coming from different areas of research, allowing for a multidisciplinary assessment of Climate Change Impacts in sectors like Water Resources, Coastal Zones, Agriculture, Human Health, Energy, Forests and Biodiversity and Fisheries. For that purpose, the group attempted to gather the best available information on both Climate Change and Socio-Economic Scenarios in the present century, performed a sociological analysis of climate change issues in Portugal and has striven to implement a spirit of strong interaction between dozens of researchers with different backgrounds.

On 3 and 4 November 2000 the SIAM Project organized in Lisbon an International Conference on "Climate Change. Science, Economics and Politics" which was well participated by recognized experts and by the general public. This Conference served as a kick-off meeting for the SIAM Project and was very important for the motivation, planning, and international contacts in the project. At the end of the summer of 2001 the various teams had already reached main conclusions and recommendations on impacts and adaptation measures from the work done during the previous two years. It was therefore decided to make available to the general public and policymakers an Executive Summary and Conclusions of the SIAM Project, which was publicly presented in Lisbon on 21 October 2001.

Acquisition, compilation and validation of data are an essential element in climate impact assessment studies. Data is required to characterize the temporal and spatial patterns of climate and the environmental and socio-economic baselines in the various sectors. Difficulties associated with data availability were often one of the major problems encountered during the course of the Project. Due to unpredictable institutional obligations, the coastal zones team was partially reformulated at a rather critical stage of the research. This naturally limited to a certain degree the impact assessment. Nevertheless, the authors are confident that the final work provides a solid contibution to this area of study in Portugal.

The authors of the sectorial chapters were asked to address a common set of issues which included an overview of the sector in Portugal, its key sensitivities to the weather, the main impacting aspects of climate change in the future, the synergies between impacts, the array of adaptation measures and the uncertainties, unknowns and implications for future research.

Most chapters were reviewed by internationally recognized experts (see list of reviewers) and always by the editors. These reviews were compiled and sent to the lead authors for consideration in an iterative process.

This first integrated assessment – SIAM I – could not attempt to be fully comprehensive. Future assessments should considerer other important sectors such as Tourism, Soil and Land Resources, Urban Areas and Insurance. It was also not possible, during the time available, to extend the assessment to the Autonomous Regions of Açores and Madeira.

In this first assessment, stakeholders such as, for example the central and local administrations, public and private decision makers were not involved. Furthermore, no attempt was made to evaluate the practicality, effectiveness or costs of potential adaptation measures. These and other issues will be addressed in the second phase of Project SIAM – SIAM II – that is presently being funded by the Instituto do Ambiente of the Ministério das Cidades, do Ordenamento do Território e Ambiente.

We strongly believe that mitigation and adaptation are two complementary responses to climate change that must be integrated and developed simultaneously. Adaptation is of fundamental importance to inform the stakeholders and the public in general of the adverse effects of climate change and of the severity of the negative impacts in scenarios of unmitigated climate change. This kind of information is essential to the implementation of policy and measures to mitigate climate change. In Portugal the process of mitigation and adaptation are evolving in a well integrated way. The 2001 version of the Portuguese Programme for Climate Change – Programa Nacional para as Alterações Climáticas – published in March of 2001, involved a close cooperation with the SIAM Project. Furthermore some members of the SIAM team are participating in the negotiations of the United Nations Framework Convention on Climate Change and the Kyoto Protocol.

Many people and many institutions (see acknowledgments) have played an important role in carrying through this assessment with all its scientific, technical and administrative aspects. We are thankful to all for devoting time, effort and resources to this product. We believe it is a significant first step to address the science of climate change and adaptation to climate change in Portugal.

# Introduction

## 1.1 CLIMATE CHANGE

The scientific evidence is now very strong that the anthropogenic emissions of greenhouse gases are having a noticeable effect on the Earth's climate. The globally averaged surface temperatures have increased by 0.6 ± 0.2°C during the 20th century. Part of this warming is now attributed to man-made greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (IPCC 2001a) states that "In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations. Furthermore it is very likely that the 20th century warming has contributed significantly to the observed sea level rise, through thermal expansion of see water and widespread loss of land ice."

Climate change is now affecting important aspects of our society and environment. There is observational evidence that regional changes in climate, particularly increases in temperature, are affecting a great variety of physical and biological systems in many parts of the world. Portugal is likely to experience strong and significant impacts of climate change, although the more dramatic impacts are forecast elsewhere in the world. The main purpose of the present work is to evaluate and report on what we presently know about the potential impacts of climate change in Portugal in the 21st century, and to identify and evaluate potential adaptation measures to climate change.

Climate is the statistical description, in terms of the mean and variability, of the meteorological variables over a period of time ranging from months to thousand or millions of years. The minimum period of time needed to define the climate of a given location, as adopted by the World Meteorological Organization, is 30 years. Hence, climate change implies a statistically significant variation in either the mean climate or in its variability that occurs for an extended period of time, of the order of decades or longer.

Changes in climate may result from natural internal processes or from changes in natural external forcings, but also from anthropogenic changes in the composition of the atmosphere and in land use. The United Nations Framework Convention on Climate Change defines "climate change" as resulting directly or indirectly from human activity and defines "climate variability" as climate change attributable to natural causes. The IPCC (IPCC 2001a) uses a different definition, namely, "Climate Change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer)", without specific identification of the causes of change.

The Earth's environmental history indicates that even small changes in climate can have quite profound consequences for society and environment.

## 1.2 CAUSES OF CLIMATE CHANGE

As previously stated, climate change can have either natural or anthropogenic causes. The most important natural external forcings that induce climate change, by affecting the Earth's energy balance, are changes in solar luminosity and in the parameters that define the Earth's orbit around the sun. Changes in the Earth's orbit occur slowly over periods ranging from about 20,000 to 400,000 years and are thought to be responsible for the alternation of glacial and interglacial periods.

The last major ice age began about 120,000 years ago and came to an end about 20,000 years ago. At that time the global mean temperature was about 5º to 7º C colder than current global temperature and the global mean sea level was about 120 m lower than today. The transition period from the ice age to the current 10,000 years period of relative climate stability – the Holocene Interglacial – lasted for only 5,000 to 1,000 years. During that transition the rate of temperature change was about 1º C for every thousand years. There is clear evidence that such temperature changes are very significant from the point of view of natural ecosystems since they provoked profound alterations to the ecosystems and the extinction of many species. These changes in climate and ecosystems happened naturally, without human influence.

Anthropogenic climate change results mainly from changes in the composition of the atmosphere, especially as regards greenhouse gases (GHGs). The most important GHGs in the atmosphere include water vapour ($H_2O$) (which is the most important), carbon dioxide ($CO_2$) (the most important GHG whose concentration is being increased by human activities), methane ($CH_4$), nitrous oxide ($N_2O$), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluorid ($SF_6$) and ozone ($O_3$). GHGs are those that absorb and reemit infrared radiation.

For the global average temperature in the lower atmosphere (troposphere) to be relatively stable over time there must be a balance of the absorbed solar energy and outgoing energy radiated away in the infrared region of the spectrum. This balance depends crucially on the concentrations of GHGs in the atmosphere and also on cloud cover and surface albedo. Local climate also depends on other energy fluxes, besides radiation, namely on the transport of sensible and latent heat by the atmospheric and ocean circulations.

When the concentration of GHGs is increased, more of the infrared radiation emitted upward from the surface and lower atmosphere is absorbed by the GHGs, increasing the downward atmospheric infrared fluxes arriving to the surface and causing the temperature of the lower troposphere to rise. This phenomenon is referred to as radiative forcing. Equivalent $CO_2$ concentration is the concentration of $CO_2$ that would cause the same amount of radiative forcing as a given mixture of $CO_2$ and other GHGs.The blanketing effect that results from the presence of GHGs in the Earth's atmosphere (natural greenhouse effect) raises the average surface temperature of the Earth by about 32ºC from –18ºC to 14ºC.

Since 1750, the atmospheric concentration of $CO_2$ has increased by more than 31% to a present value of 370 ppmv (parts per million by volume) and many independent studies confirm that this rise is due to the combustion of fossil fuels (coal, oil and natural gas) and to land-use change, especially deforestation. According to paleoclimatic data the present $CO_2$ concentration has not been exceeded in the past 420,000 years and likely not in the past 20 million years.

Combustion of fossil fuels is currently adding more than 6 GtC/year ($10^{12}$ Kg of carbon) to the atmosphere. About 75% of the anthropogenic emissions of $CO_2$ to the atmosphere during the past 20 years resulted from fossil fuel burning, while the rest was mainly due to land-use change. The increase in atmospheric $CO_2$ concentration from 1750 to 2000 is responsible for about 60% of the radiative forcing in the atmosphere caused by all the anthropogenic emissions of GHGs during the same period of time. In other words the increase in $CO_2$ emissions since the start of the industrial revolution is the main cause (but not the only cause) of the anthropogenic greenhouse effect. Human activities also produce aerosols (mainly from fossil fuel and biomass burning) in the atmosphere, which are short-lived and mostly tend to reduce the global warming effects produced by the anthropogenic GHGs.

## 1.3 SCENARIOS OF CLIMATE CHANGE

Based on the scientific understanding of the greenhouse effect, increasing the atmospheric composition of GHGs should cause climate change and especially global temperature to rise. In order to have physically consistent projections of future climate it is necessary to develop models of the earth's climate system that incorporate the most important physical principles and processes that determine climatic conditions. Presently the most comprehensive climate models, called General Circulation Models (GCMs), involve the coupling between the atmosphere, ocean, sea-ice, soil and an interactive biosphere. They provide a comprehensive representation of the climate system and simulate the evolution of wind, temperature, rainfall, snow cover, soil moisture, sea ice, ocean circulation and other variables for the entire globe over periods of decades to centuries.

It is well known that numerical weather prediction models are unable to predict the weather details much beyond ten days. This inherent unpredictability, which has been one of the foundation stones of the modern theory of chaotic systems, results, mainly, from the fact that atmospheric evolution is highly sensitive to its initial conditions, which can not be known with sufficient accuracy. However, long-term climate projections are possible since they involve averages of the meteorological variables over periods of decades to centuries, much larger than the lifetime of individual weather systems.

The Earth's climate response to an increasing concentration of GHGs can be characterized by the equilibrium climate sensitivity, defined as the equilibrium change in global mean surface temperature following a doubling of the atmospheric equivalent $CO_2$ concentration. The equilibrium climate sensitivity obtained from various GCMs over the past twenty years has remained fairly constant in the range between 1.5º and 4.5º C. This range arises from uncertainties in the climate models, particularly those related to clouds (IPCC 2001a). GCM's ability to simulate the Earth's climate has been extensively tested against both observational data in the recent past and paleoclimatic data. Current climate GCMs simulations for the 20th century that take into account both GHGs and sulphate aerosols are consistent with the observed trends in the temperature, and indicate that most of the warming over the last 50 years is likely to have been caused by the anthropogenic increase in GHGs concentrations. It is also very likely (Douglas and Peltier, 2002) that the warming of the troposphere has contributed significantly to the global mean sea level rise in the range of 10 to 20 cm, observed during the 20th century.

In order to make projections of future climate, GCMs must incorporate past and future emissions of GHGs and aerosols. In 1992 the IPCC developed six projections of future global emissions to the year 2100 which were called the IS92 scenarios (Leggett 1992). These scenarios represent six possible paths for future emissions based upon a coherent and internally consistent set of assumptions about world population growth, economic activity and energy use. They range from a low emissions scenario (IS92c) to a high emissions scenario (IS92e) that assumes high economic growth and fossil fuel availability. The emissions scenario most used for analysis throughout the 1990s has been the IS92a scenario, where the equivalent $CO_2$ concentration duplicates in 95 years. The net radiative forcing for the 21st century in the IS92a scenario is near the mid-range of the radiative forcing scenarios based on the new set of 35 SRES (Special Report on Emission Scenarios), prepared by the IPCC (IPCC 2000). In the present work it was decided to consider climate scenarios that used emission scenarios close to the IPCC IS92a scenario in order to facilitate the comparison with other national and international assessments. For instance the HadCM2 and HadCM3 GCMs (Hulme *et al.*, 1999), which are extensively used in the present work were obtained with an approximation to the IS92a emissions scenario.

It should be emphasized that a very complicated and nonlinear system, such as the climate system, when forced to change rapidly by external forcings, such as strong GHGs and aerosols concentration increases is likely to have unanticipated responses. This unexpected behaviour is particularly difficult to simulate and predict with climate models. We should therefore be aware that the future climate change may involve "surprises".

The atmospheric $CO_2$ concentration is very likely to continue to increase during the 21st century due to fossil fuel burning. Carbon cycle models based on the SRES scenarios, project, for 2100, atmospheric concentrations between 520 and 970 ppmv (IPCC 2001a). In any case, it is important to realize that the stabilisation of atmospheric $CO_2$ concentrations can only be achieved through a reduction of the global anthropogenic $CO_2$ emissions below the present levels, and a sustained decrease thereafter. Stabilisation at 450, 650 or 1,000 ppmv would require emissions to drop below 1990 levels, within a few decades, for about a century, or two centuries, respectively (IPCC 2001a). Climate scenarios obtained from climate models clearly indicate that the higher the stabilisation target the larger and faster is the climate change particularly the rises in global mean surface temperature and global mean sea-level. These larger and faster increases imply much more profound and extensive adverse climate impacts in society and in the environment.

It is worthwhile to consider the potential climate impact of anthropogenic GHGs emissions on much larger time scales. Currently it is assumed that the $CO_2$ concentration will increase to a value in the range of 550 to 750 ppmv over the next 200 years, decreasing thereafter to reach the concentration of the natural scenario within 1,000 years. Recent climate models (Berger and Loutre, 2002; Loutre and Berger, 2000) indicate that under this projection the climate system requires at least 40,000 years to be no longer sensitive to what may happen over the next few centuries. The enhanced anthropogenic greenhouse warming may weaken the positive feedback mechanisms, that transform the relatively weak orbital forcing into global interglacial-glacial cycles. In other words the present anthropogenic climate change is likely to have an influence on the timing and magnitude of the next interglacial-glacial transition.

## 1.4 ADAPTATION AND MITIGATION

Responses to climate change can be of two broad and complementary types: adaptation and mitigation. Adaptation is the adjustment in human or natural systems to the effects of climate change. It may be autonomous or spontaneous when it is triggered naturally, or planned, when it is the result of a deliberate policy decision. We can also consider proactive adaptation, when it takes place before the impacts of climate change are observed, and reactive adaptation, when it takes place after the impacts of climate change have been observed. In order to initiate and develop a process of planned adaptation, designed to minimize the adverse effects of climate change, it is essential to first identify the potential impacts of climate change.

The second type of broad response – mitigation – deals with the causes of anthropogenic climate change by reducing the sources and enhancing the sinks of GHGs. The United Nations Framework Convention on Climate Change, which came into force on 21 March 1994, is a very important international agreement for the mitigation of climate change. The signatories to the Convention recognize the reality of global warming and have agreed on an agenda for action to slow and stabilize climate change. The Kyoto Protocol was adopted in 1997 and contains legally binding commitments to reduce anthropogenic GHGs emissions in the countries listed in its Annex B (developed nations). It is expected to enter into force by the end of 2002.

An integrated climate impact assessment (IPCC 2001b) is an interdisciplinary process that investigates the effects of climate change in society and the environment and combines knowledge from diverse scientific disciplines from the natural and social sciences. Beyond the one-way impact of climate on human activity, attention should also be focused on the interactive nature of the relation between climate and human activity, which necessarily includes spontaneous adaptation. The integrated approach to climate impact assessment also requires the study of the interactions and the feedback effects between different sectors and biophysical systems.

An essential component of impact assessment is the identification and evaluation of adaptation options. Adaptation has the potential to reduce substantially the adverse impacts of climate change and to enhance its beneficial impacts. However it should be realized that adaptation always involves a cost and some residual damage will remain from the effects of climate change. The capacity to adapt to climate change varies among regions, countries, socioeconomic groups, biophysical systems and also with time. Another important specific objective in climate impact assessment is the identification of vulnerability, which is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including variability and extremes (IPCC 2001b).

It is desirable that climate impact assessments are performed in a transparent manner using compatible methods and comparable and consistent assumptions. These procedures ensure that there is comparability between assessments, which is important for the evaluation of adequate response actions at the international, regional and national level. Guidelines and methodologies for assessing the impacts of climate change and for evaluating appropriate adaptation measures were prepared by Carter *et al.* (1994) and by Feenstra *et al.* (1998).

The first multi-country climate impact assessment using climate scenarios derived from GCMs was made for Western Europe in 1984 (Meinl and Bach, 1984). More recent studies for Europe include the ACACIA Project (Parry, 2000) and the IPCC Working Group II Third Assessment Report (IPCC, 2001 b). Most European countries have now conducted climate impact assessments. The present work reports on the first integrated climate impact assessment for continental Portugal.

In a world that tends to be dominated by economic arguments it is very important to estimate the costs involved in combating climate change and to compare them with the expenditure in other issues and sectors of the human activity.

Our current environment is being degraded in many ways due to human activities, which are unrelated to climate change. Global warming will tend to exacerbate these degradations and to generate specific and serious adverse impacts on natural ecosystems.

To respond to the adverse impacts of climate change it will be necessary to adapt, which involves costs. For instance, it will be necessary to build new infrastructures to defend against sea level rise and to obtain new water supplies. There will also be costs resulting from losses in the agriculture and forestry sectors, increased morbidity and increased energy consumption for air conditioning.

Economists (Nordhaus 1992, Nordhaus, 1994, Pearce *et al* 1996) have attempted to estimate the average annual cost of the impacts of climate change for the IPCC business as usual scenario of GHGs emissions (Leggett 1992). The estimates are typically around 1 – 1.5 per cent of gross domestic product (GDP) for developed countries. Because of their greater vulnerability to climate change the estimates of the cost of damage in developing countries is larger in the range of 2 to 9 per cent of GDP. It should be noted that there is still little agreement as regards estimating the costs of non-market damages such as the loss of human life, biodiversity, or ecosystem services. However, damages estimates should include monetary loss, loss of life, loss of quality of life (including coercion to mitigate, conflict over resources, loss of cultural diversity, loss of cultural heritage sites) and biodiversity loss (Schneider and Thomson, 2000). Another relevant issue is that there are significant differences, on average, between the opinions of economists and natural scientists, as regards the assessment of climate change damages and related costs. The economists, who, of course, know more about the economy, are comparatively unconcerned and the natural scientists, who know the more about nature, are comparatively very concerned (Roughgarden and Schneider, 1999).

A complementary alternative to adapt to climate change is to mitigate its effects by reducing GHGs emissions, in particular $CO_2$ emissions. Mitigation clearly involves costs, which are strongly dependent on the amount of reduction required in GHGs emissions and the timescale of reduction. Large reductions of emissions in the very near term would involve significant disruption to the economy and therefore large cost. Small and gradually increasing reductions can be made with relatively small cost, especially with planned efficiency gains in the use of energy and a growing use of renewable energy sources, which are not dependent on fossil fuels. It is important to notice that the costs of adaptation have an opposite dependence on the amount of GHGs emissions reductions. Large reductions imply smaller adaptation costs in the future.

The overall cost of mitigation depends strongly on the level of stabilization of the atmospheric $CO_2$ concentration. For a stabilization level of 450 ppmv, the cost is estimated to be of the order of 1 per cent of the globally aggregated GDP or gross world product (Richels and Edmonds, 1995).

To address the scientific and economic aspects of climate change, including the question of costs, in order to assess policy options for the future, more elaborate models called integrated assessment models (IAMs), are currently being built. IAMs are models that represent within one integrated numerical model, the climate system, including the oceans and the biosphere, the physical and human impacts of climate change and the socio-economics of adaptation to and mitigation of climate change (Weyant *et al.*, 1996). They are designed to deal simultaneously with the questions of adaptation and mitigation and the interactions between these two responses to climate change. Hence, they are very useful for decision-making based on a cost-benefit evaluation of adaptative and mitigative capacities of societies over time at the national and international level.

## 1.5 UNCERTAINTIES

A very important part of an integrated climate impact assessment concerns the presentation of the uncertainty associated with all segments of the scientific description, including GHGs emission scenarios, the future climate scenarios, the assessment of the impact of climate change and of adaptation measures. Climate models are already capable of giving useful simulations of climate, past and future, which can be validated against present and paleoclimatic data. Limitations persist and, clearly, more research is needed to improve the modelling of the climatic system and thereby produce higher confidence in the projections of future climate. There is still considerable uncertainty in the simulation of clouds, oceans and their interaction with the atmosphere and anthropogenic radiative forcing from aerosols and changes in land use. Furthermore, the climate scenarios result from simplified model simulations of the climate system that cannot capture its full complexity, especially at regional and smaller scales. However, enough is already known to warrant climate impact assessments of projected climate changes from climate models.

There are also uncertainties in our assessment of the impacts of climate change. Nevertheless, some conclusions can be reached with reasonable confidence. Under a business-as-usual GHGs emissions scenario, the rate of climate change is likely to be large and probably greater than the Earth has experienced over many thousands of years. This climate change will have a noticeable impact on many ecosystems and some may not be able to adapt. Strong impacts are expected on water resources, on the distribution of global food production and on low-lying areas of the world threatened by sea level rise. The confidence placed on the results of an impact assessment decreases as we move to smaller spatial scales as needed for regional assessments, due to the present difficulties of projecting regional climate change.

Another important source of uncertainty, as regards impacts and adaptation measures, is the wide difference of assumptions on the present and future baselines of socio-economic conditions and environmental systems. These assumptions include information on population density, migration, economic trends, income and education levels, culture, changes in land cover use, availability and use of natural resources, especially water.

Uncertainty implies anything from high confidence, just short of certainty, to informed guesses or speculation. Uncertainty results mainly from lack of information, lack of knowledge of the scientific processes, statistical variation, measurement error, variability, approximation and subjective judgement. Some categories of uncertainties can be expressed in terms of probabilities but others cannot. At present, there is no widely accepted and documented method of assigning probabilities to projections of human-induced global warming in the 21st century. Recent studies (Wigley and Raper, 2001) address this question and conclude that the probabilities of global temperature changes at the high and low ends of the IPCC (IPCC 2001a) range are very low.

In the present work we have tried to assess and report a confidence level for a conclusion using the Bayesian probability framework adopted by the IPCC (IPCC, 2001a): virtually certain (99 % or more), very likely (90 to 99 %), likely (66 to 90 %), medium likelihood (33 to 66 %), unlikely (10 to 33 %), very unlikely (1 to 10 %) and exceptionally unlikely (1% or less). In this scale of confidence levels, the probability of an event is the degree of belief that exists among the authors that an event will occur given the observations, the model output and the theories presently available.

What is the interplay between the uncertainties necessarily associated with a climate impact assessment and the political decision-making concerning adaptation and mitigation responses? The essential foundation for this discussion is the precautionary principle, which was one of the basic principles included in the Rio Declaration at the Earth Summit in 1992. The same principle, applied to climate change, is also contained in the Article 3.3 of the United Nations Framework Convention on Climate Change. It states that "The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty, should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost". Most of the issues politicians must take into account represent acute problems in the short term. Climate change is a long term problem but with potentially irreversible effects. That is why it is so important to reduce the uncertainties associated with climate change impact assessments through more research.

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# 2

# 20th Century Portuguese Climate and Climate Scenarios

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## CONTENTS

## EXECUTIVE SUMMARY

An assessment of the evolution of the 20th century Portuguese climate, as given by the network of surface climatological stations, is presented. The analysis of climate observations indicates:

- The existence of three periods of change in the mean temperature, with warming in 1910-1945, followed by cooling in 1946-1975 and by faster warming in 1976-2000.
- In the last decades, because minimum temperatures have increased at a faster rate than maximum temperatures, most stations also show a significant reduction in the diurnal temperature range.
- Precipitation changes have been irregular. However, in the last decades there has been a very significant reduction in the mean March precipitation, all over the country, accompanied in the last decade by a smaller, but important reduction in February. These changes had significant negative correlations with the North Atlantic Oscillation index.

Climate change scenarios for Portugal were analysed, using simulations from different models. The control simulation of the highest resolution model, the Hadley Centre Regional Climate Model, was compared against observations, indicating a remarkable degree of agreement in the mean temperature and precipitation fields. Together with results from other models, output from that regional model in the period 2080-2100 suggest the following climate change scenario:

- A substantial increase in mean air temperature all over the country, but specially in summer and away from the coast. This warming is stronger for maximum than for minimum temperatures, implying an increase in the diurnal temperature range. The land-sea thermal gradient is also significantly increased.
- All temperature related climate indices show dramatic increases in the climate change scenario. Increases are very large in some indices, like the number of hot days (maximum temperature above 35°C) and tropical nights (minimum temperature above 20°C), while large decreases are found for indices related with cold weather (e.g. frost days, with minimum temperature below 0°C).
- Almost all models project reductions in mean precipitation and in the duration of the rainy season. The regional model projects an increase in winter precipitation, due to events of heavy daily precipitation (above 10mm/day), accompanied by a larger decrease in precipitation in the other seasons.
- The Hadley Centre Global Circulation Model control simulation presents a significant negative correlation, comparable with observations, between the NAO index and Portuguese precipitation, in winter. In the 2070-2100 climate change scenario that correlation experiences a significant change and an increase in the mean winter NAO index is accompanied by a slight increase in winter precipitation.

# 2. 20th Century Portuguese Climate and Climate Scenarios

## 2.1 INTRODUCTION

Climate change scenarios have been produced for decades, at the global scale, almost as soon as global circulation models (GCMs) became available. In the early days of climate change research, those scenarios were obtained by comparisons between a control run, representing present day climate, and a climate change run where greenhouse gas concentrations was abruptly changed to a higher value (e.g. a double $CO_2$ experiment). In recent years, climate models have grown in sophistication and are now producing credible simulations of current climate, which can be validated against observations. At the same time, the analysis of an ever growing set of direct and indirect climate observations, including instrumental data, satellite data and many climate indicators (e.g. tree-rings, isotope ratios in air bubbles imprisoned in polar ice caps), have built up strong indications that climate change is occurring at a fast pace.

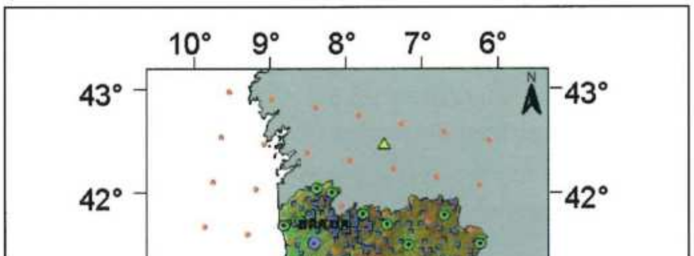


Fig. 2.1 – Map of mainland Portugal, with the location of weather stations (Instituto de Meteorologia - IM), and HadCM3 and HadRM gridpoints. Shading represents topographic contours.

In the last decade of the 20th century, the successive breaking of high temperature records at the global scale, together with the publication of a large set of climate change scenarios pointing in the same direction, has definitively put the climate change problem at the top of the world's priorities. At the same time, it has become clear that there is a need for the definition of climate change scenarios at a scale of the different countries and regions, where many of the relevant decisions have to be made. In the following sections we will try to define such a scenario. First, we will look at climate observations in Portugal, searching for clues of climate change, its relation with established global trends and its spatial patterns. Afterward, we will make use of output from two regional climate models to establish the main features of a climate change scenario. Finally, we will discuss some aspects of the circulation patterns in the Iberian region, which may explain the observed and predicted changes.

## 2.2 PORTUGUESE CLIMATE IN THE 20TH CENTURY

### 2.2.1. 1961-1990 CLIMATE

Mainland Portugal, between latitudes 37° and 42°N (Fig. 2.1), is located in the transitional region between the sub-tropical anticyclone and the sub-polar depression zones. The most conditioning climate factors in mainland Portugal are, in addition to latitude, its orography and the effect of the Atlantic Ocean. As regards altitude, the highest values are between 1000 m and 1500 m, with the exception of the Serra da Estrela range, which peaks just below 2000 m. As regards continentality, the regions furthest from the Atlantic Ocean are around 220 km away.

In spite of the fact that the variation in climate factors is rather small, it is still sufficient to justify significant variations in air temperature and, most of all, in precipitation. While the northwest region of Portugal is one of the wettest spots in Europe, with mean annual accumulated precipitation in excess of 3000 mm, ave-

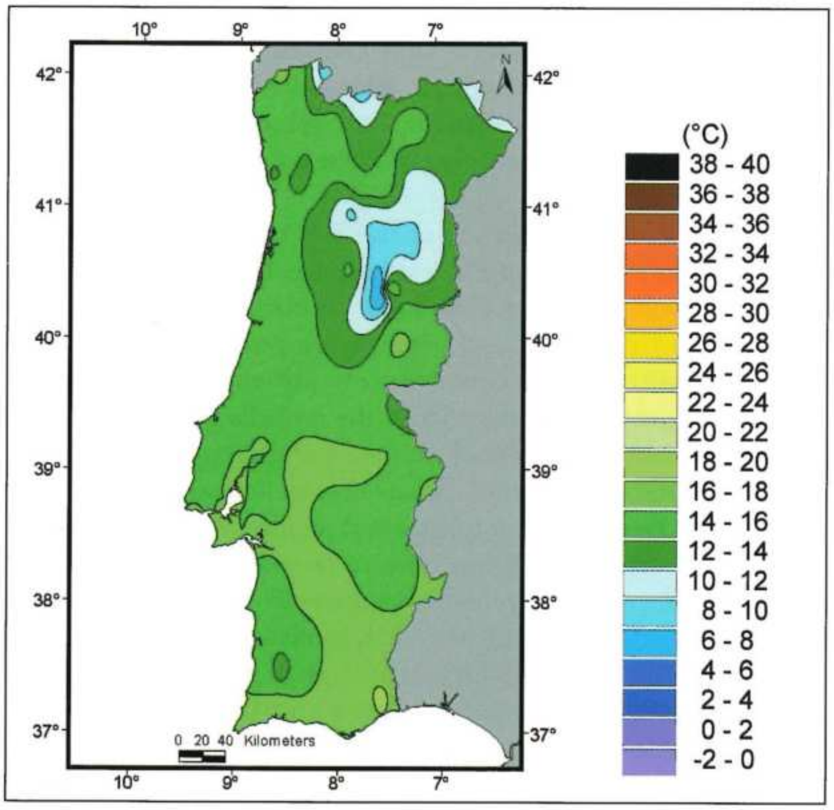


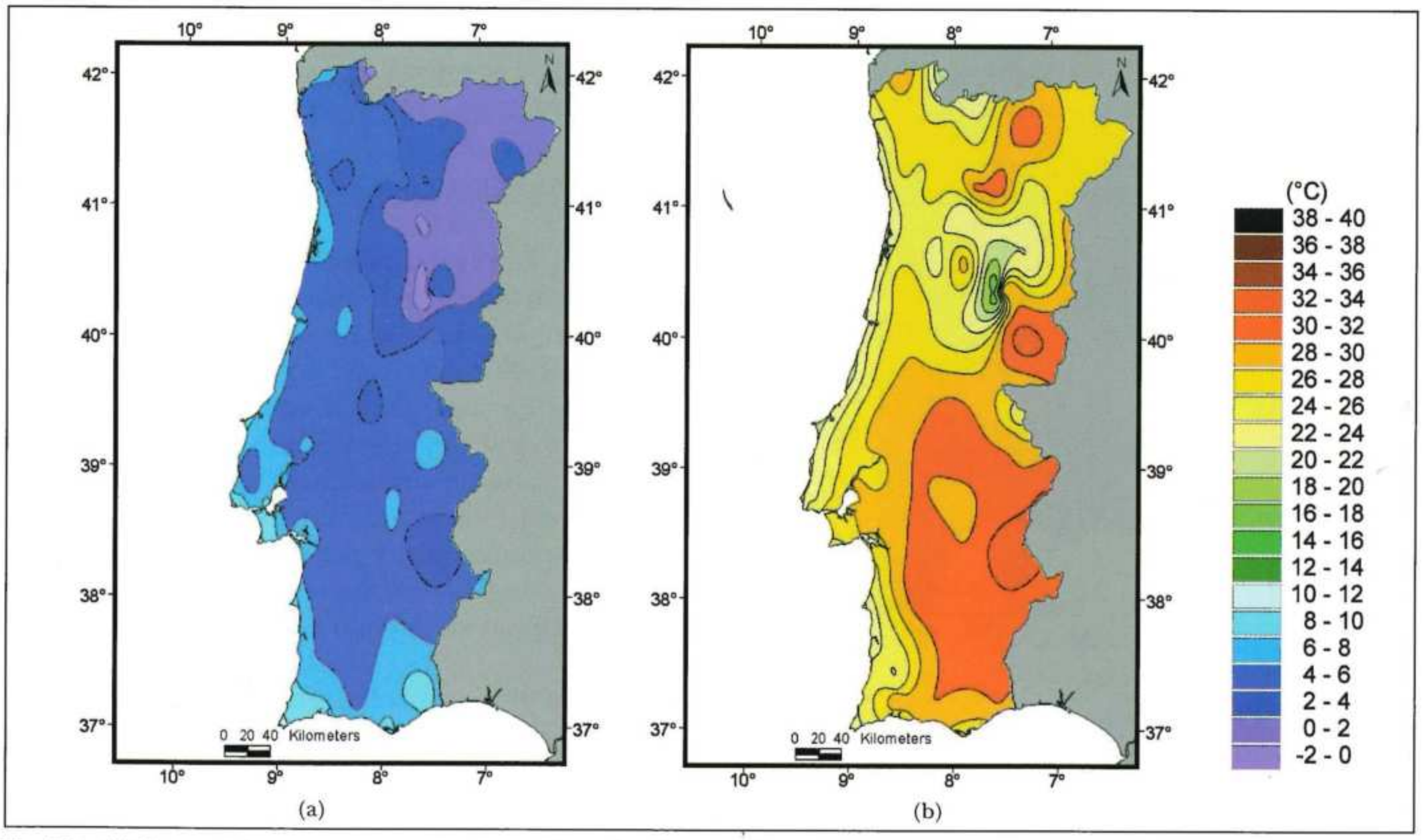
Fig. 2.2 – Mean annual air temperature values. Data from 1961-1990 observations.

rage rain amounts in the interior of the Alentejo are of the order of 500 mm and show large interannual variability. As other southern European regions, Portugal is a place of mild Mediterranean climate, but with well known vulnerability to climate variability, namely to droughts and desertification in the southern sector.

Climate is a complex mixture of many elements, such as temperature, humidity, wind, precipitation, pressure, cloudiness and so on, that contribute to define the physical and chemical environment at the surface of the Earth. In these pages we will describe and discuss some of those elements, concentrating on the two main climate elements – air temperature and precipitation – that are not only the most relevant to our daily life, but also easier to understand in the context of climate change scenarios.

## Air Temperature

The spatial distribution of the mean annual air temperature, based on observations made during the



(a)

(b)

Fig. 2.3 – (a) Mean minimum temperature in winter (December, January, February) and (b) Mean maximum temperature in summer (June, July, August). Data from 1961-1990 observations.

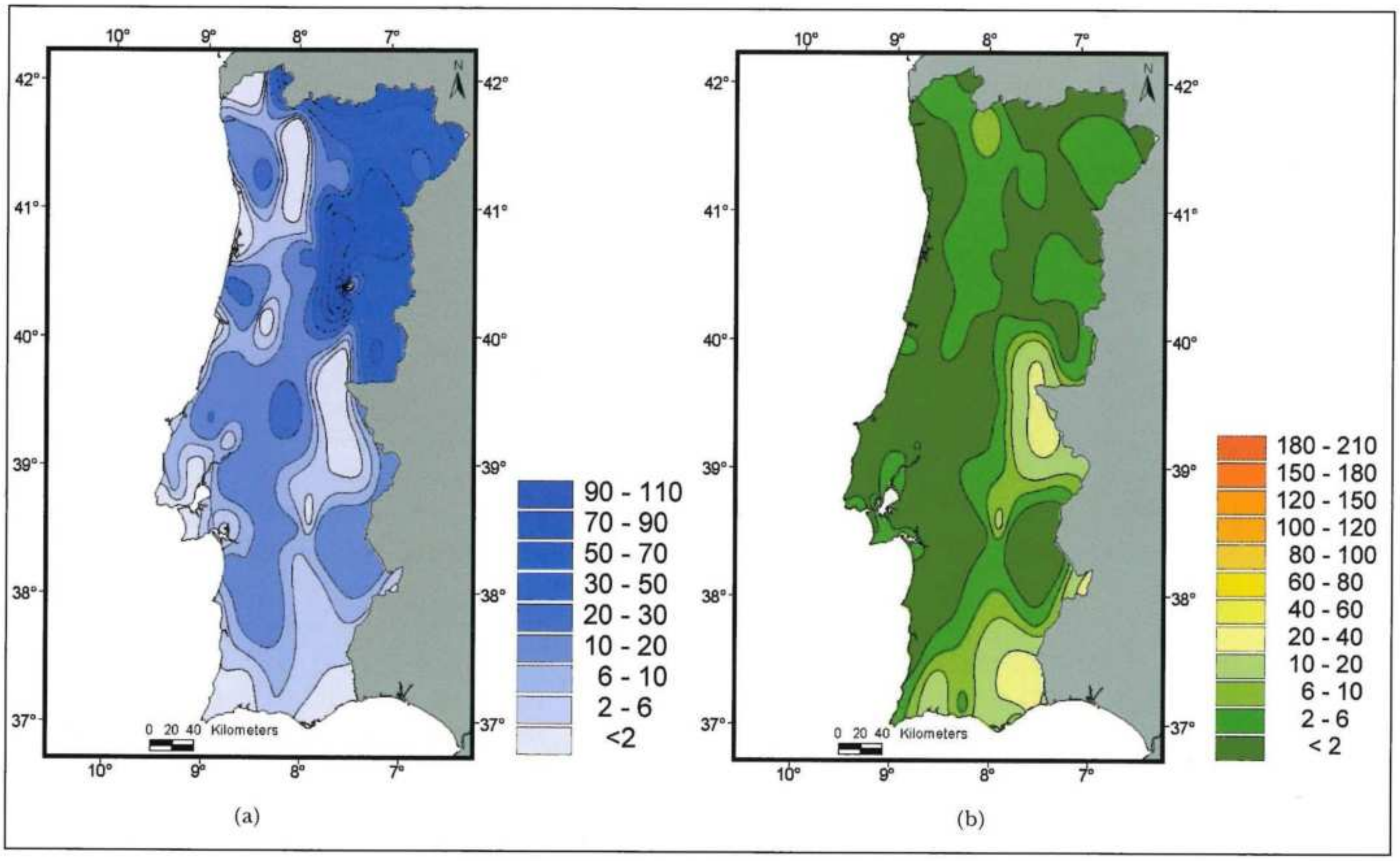
1961-1990 period, is shown in Fig. 2.2. The mean annual air temperature values vary between 7°C in the inner highlands of central Portugal and 18°C in the southern coastal area. The mean monthly air temperature values vary regularly during the year, reaching their maximum in August and minimum in January.

The average minimum temperature in winter varies between 2°C in the mountainous interior zone and 12°C in the Algarve (Fig. 2.3a).In summer, the mean values of maximum temperature vary between 16°C in Serra da Estrela and 32-34°C in the inner central region and eastern Alentejo (Fig. 2.3b).

The number of days of the year with minimum temperature below 0°C ("frost days") reaches a peak in the highlands of the northern and central interior, with more than 100 days/year, and is nil in the western coastal and southern zones (Fig 2.4a). The number of days with minimum temperature above 20°C ("tropical nights", Fig 2.4b) and maximum temperature above 25°C ("summer days", Fig 2.5a) and above 35°C ("hot days", Fig 2.5b) is higher in the inner centre of the country, the eastern part of Alentejo and the seaside Algarve. These statistics are indicators of cold and warm spells in the Portuguese climate, with very significant impacts on agriculture and other human activities. The first three statistics ("frost days", "tropical nights" and "summer days") are standard climate indices, whereas the last one ("hot days") was added because it is a good indicator of very hot spells, which are rather rare in present day climate in most of the country, but may become important in global warming scenarios. Together, these statistics are good indicators of the potential impact of climate change scenarios.

## Precipitation

Mean annual precipitation in mainland Portugal is around 900 mm, with a major degree of spatial variation. The highest values, above 3000 mm, are to be found in the highlands of the northwest region (Minho) and the lowest in the southern coast and in the eastern part of the territory, below or around 500 mm (Fig. 2.6).



(a)

(b)

Fig. 2.4 – Average annual number of days with: (a) minimum temperatures below 0°C ("frost days"); (b) minimum temperature exceeding 20°C ("tropical nights"). Data from 1961-1990 observations.

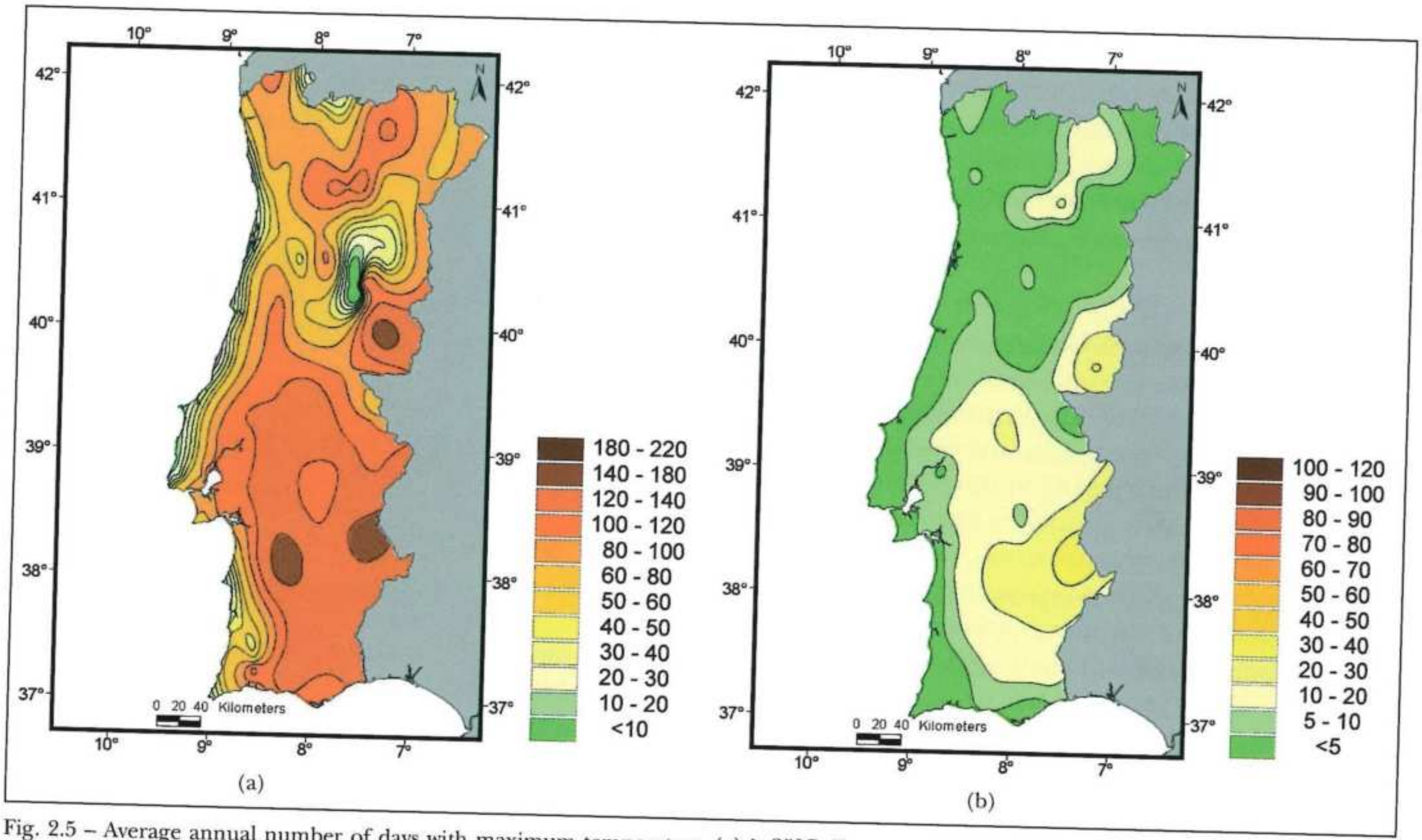


Fig. 2.5 – Average annual number of days with maximum temperature (a) ≥ 25°C ("summer days") and (b) ≥ 35°C ("hot days"). Data from 1961-1990 observations.

On average, about 42% of the annual precipitation falls during the 3-month winter season (December to February). The lowest values of precipitation occur during summer (June to August, Fig. 2.7), corresponding to only 6% of the annual precipitation. During the transition months (March to May, October to November) the amount of precipitation is highly variable. Details are shown in Fig. 2.7. The annual average number of days with precipitation equal or above 10 mm varies between 15 to 25 days in the southern half of country and the northeast and 50 to 65 days in the northwest and the highlands (Fig. 2.8).

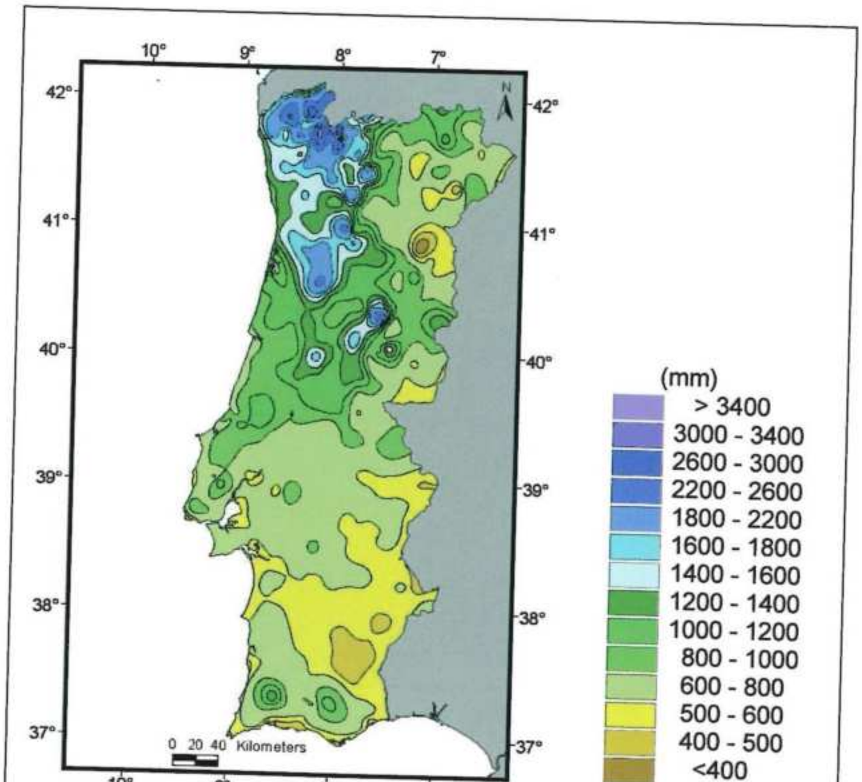


Fig. 2.6 – Mean annual accumulated precipitation. Data from 1961-1990 observations.

The average cloud cover distribution at 9:00 UTC, for the period 1961-1990, shown in Fig. 2.9, shows a region of maximum cloudiness in the coastal area north of Lisbon. Cloud cover is a semi-qualitative parameter, resulting from the visual observation of the sky by skilled meteorologists, and it is well known that it may have a strong diurnal cycle. For those reasons, the interpretation of the details of Fig. 2.9 must be done with some caution. On the other hand, cloud cover is an essential parameter in climate change, because it

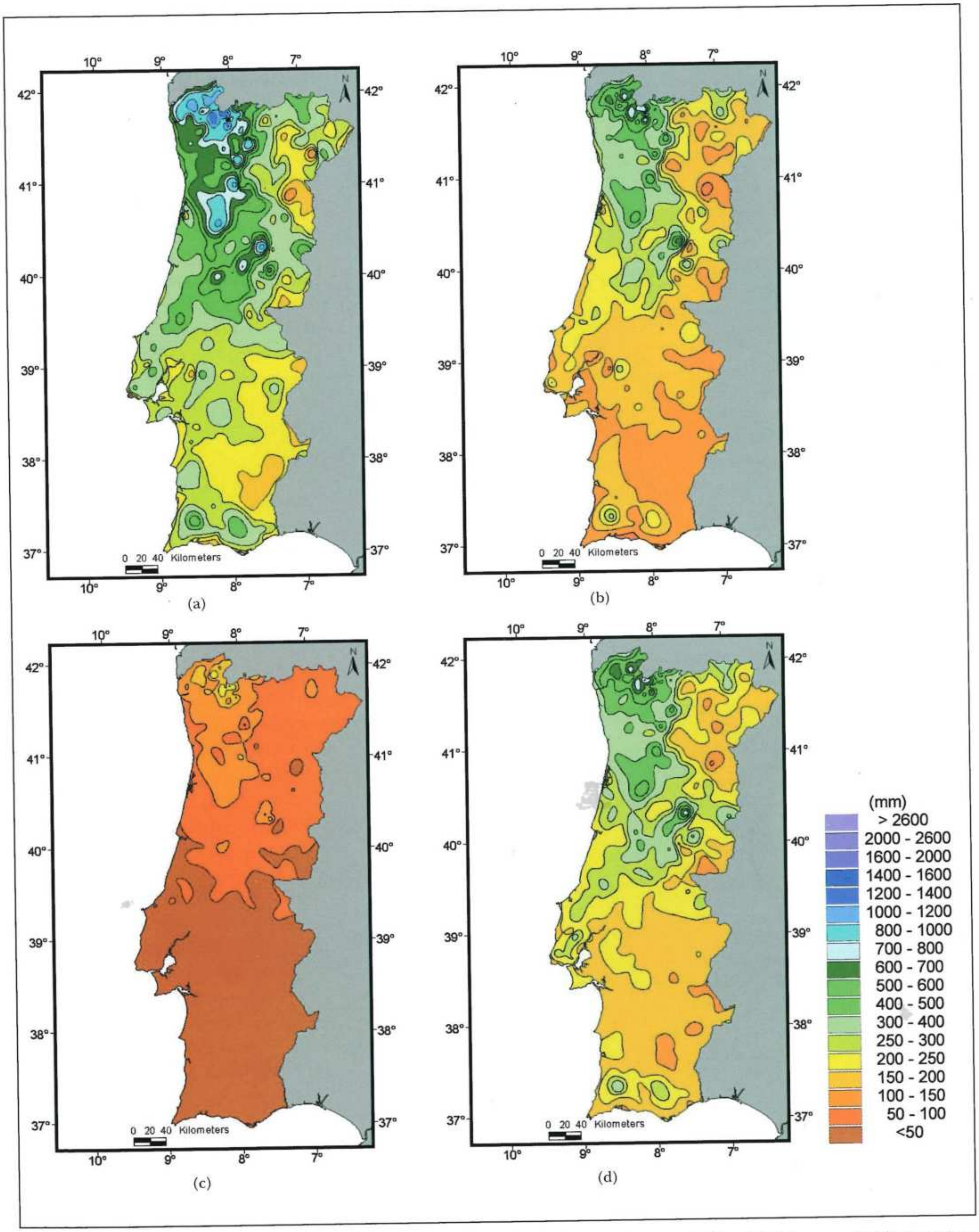


Fig. 2.7 – Mean seasonal precipitation values: (a) Winter (DJF), (b) Spring (MAM), (c) Summer (JJA) and (d) Autumn (SON). Data from 1961-1990 observations.

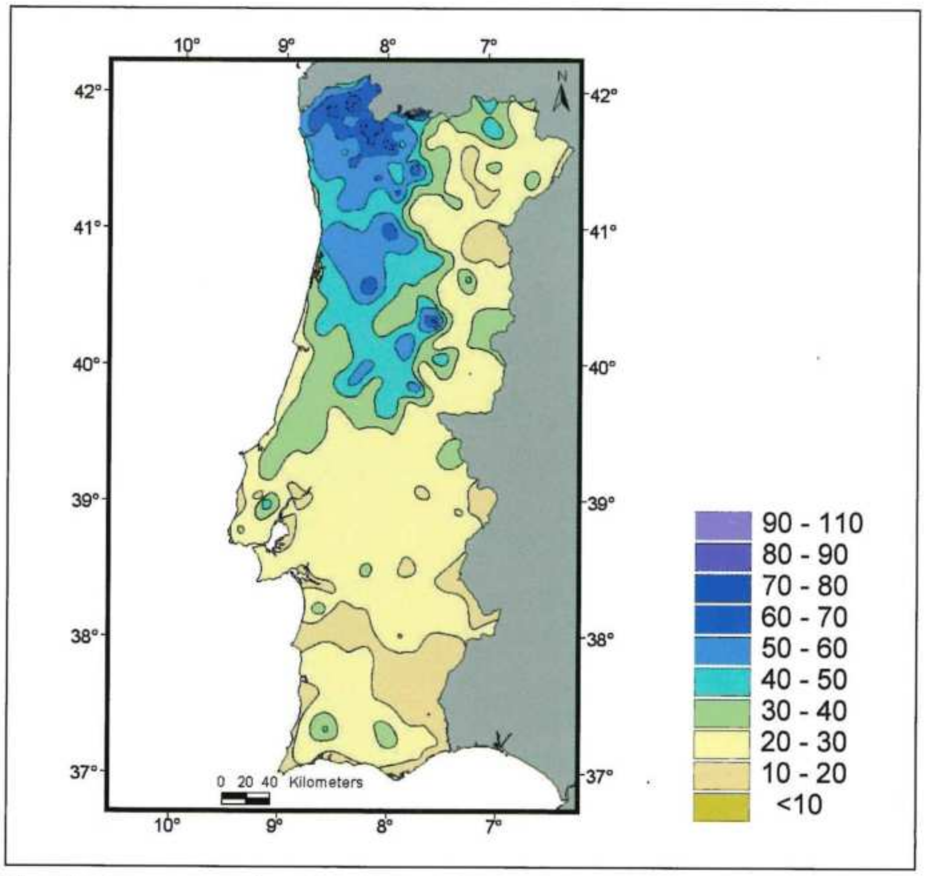


Fig. 2.8 – Average annual number of days with precipitation ≥ 10mm. Data from 1961-1990 observations.

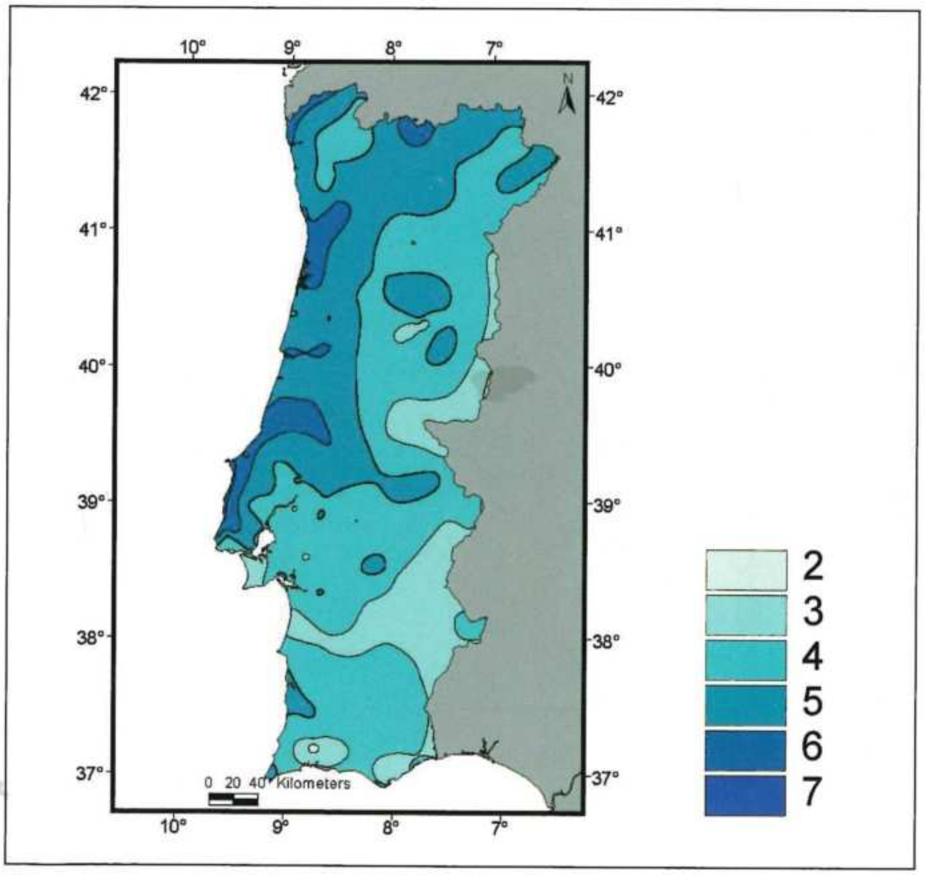


Fig. 2.9 – Average cloud cover at 9:00UTC in oktas. Data from 1961-1990 observations.

interferes strongly with the diurnal temperature cycle and any changes in cloudiness are of great relevance, and must be kept in mind in any analysis. Finally, the annual cycles of both precipitation (monthly mean) and temperature (mean monthly minimum and maximum) in the main synoptic stations are shown in Fig. 2.10, revealing the existence of a warm and dry summer period in all the stations selected, a characteristic of Mediterranean climate. These graphics will be useful for the analysis of temperature and precipitation anomalies in climate change scenarios.

## 2.2.2 OBSERVED CLIMATE TRENDS

### 2.2.2.1 Introduction

Observed climate trends in Portugal have to be assessed in the context of global climate change. The existence of an observable warming trend in the world climate has become a well-established fact in the last decade of the 20th century, where a significant number of the warmest years were observed. Average global surface temperatures have increased by approximately 0.6°C since the late 19th century (IPCC, 2001), with 95% confidence limits of near 0.4 and 0.8°C.

Global near surface air temperatures have increased since the late 19th century. Jones *et al.* (1999) and Karl *et al.* (2000) identified two periods of warming, in the global mean temperature record, around 1910--1945 and since 1976. In Europe, the greatest warming coincides with the two periods of global warming (Klein Tank *et al.*, 2002). Minimum temperatures have also increased and there has been a reduction in the frequency of extreme low temperatures, without an equivalent increase in the frequency of extreme high temperatures.

There is a general agreement with the idea that changes in the frequency or intensity of extreme weather and climate events are likely to have profound impacts on society and environment (Karl *et al.*, 2000). There is also a growing concern that increases in extreme weather events like floods, droughts, severe heat and cold spells may come as a result of global warming (Easterling *et al.*, 2000a, b; IPCC, 2001). So, when considering observed climate trends and future climate scenarios it is important to look, not only at changes in the mean climate, but also to the corresponding modifications in climate variability in different time scales.

### 2.2.2.2 The homogeneity problem of climate series

Climatological time series typically exhibit spurious (non-climatic) jumps and/or gradual shifts due to changes in station location, instrumentation, environment or observing practices. In daily resolution time series, there are also some missing observation days. Because the degree of homogeneity and completeness of a daily resolution series strongly determines the type of analysis of extremes that can be undertaken (see e.g. Moberg *et al.*, 2000; Tuomenvirta *et al.*, 2000), data quality control is a key aspect. When one analyses composite time series representative of a broad region, like average regional (or world) temperatures, it is also necessary to guarantee that the same stations are used throughout the series, in order to avoid spurious trends associated with changes in station location. Local effects, in particular those associated to urbanization (e.g. urban "heat island" effects), have been frequently blamed for a fraction of the observed temperature trends in composite climate series.

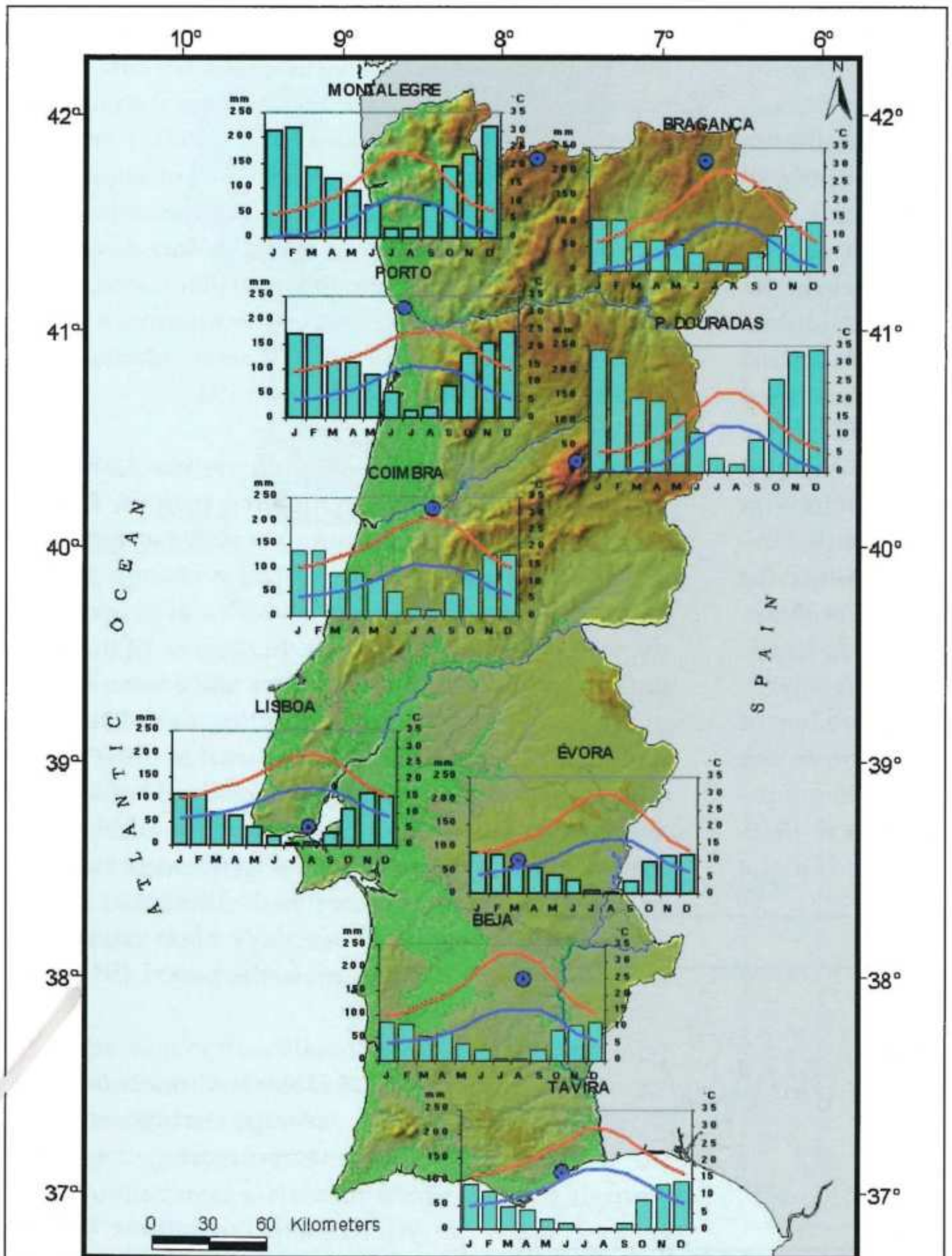


Fig. 2.10 – Mean annual cycles of monthly temperature (min and max) and precipitation in selected Portuguese stations, in the period 1961-1990. Shading represents orography.

In order to use time series for climate analysis it is important to have reliable data without artificial irregularities because such heterogeneities may mask natural trends and variability. In practice, although there are objective statistical tests for time-

-series homogeneity (e.g. Alexandersson, 1986; Buishand, 1982), it is not always easy to identify and correct all artificial jumps in the series. First, it is necessary to have a written station history, reporting all relevant changes in the station settings. Second, different climate variables respond in a different way to a given change. In some cases their behaviour is far from linear and introducing complex corrections to observed series is out of question, as it would change many of its statistical properties. Finally, the different corrections generally used may only work for monthly mean values, leaving out studies of climatic extremes. As a consequence, homogenisation of time series must only be used in small doses and for specific purposes.

In the case of the Portuguese time series, homogeneity tests were applied to the annual series of maximum, minimum, mean temperatures and diurnal temperature range (DTR) of the stations with records from the end of the 19th century. These series were tested without reference series, i.e. for absolute homogeneity. Three methods were chosen for testing the homogeneity of the annual series: the often used Standard Normal Homogeneity Test (SNHT) for a single shift (Alexandersson, 1986), the Range-test (Buishand, 1982) and the classical von Neumann Ratio (von Neumann, 1941). These different techniques for homogeneity testing have been developed for testing and correcting monthly or annual resolution data series, rather than daily series (Szalai *et al.*, 1999).

The homogeneity tests have identified a number of suspect jumps in the time series at all stations. In the case of Lisbon, a large jump in the maximum temperature and in the DTR was located in the year 1940-1941, corresponding to a reported change in the station height by 22 m, from the top of the Geophysical Institute to the nearby garden. Fig. 2.11 shows the DTR annual series, where the jump is clearly identified. The SNHT test gives an extreme in 1941; the maximum value causes a rejection of the null hypothesis significant at the 1% level. As a result, the alternative hypothesis that assumes a shift becomes likely. The same conclusion is drawn from the Range-test with a minimum around 1941. The simple application of these tests to the Lisbon mean annual maximum temperature identified a jump in the series in the 1940 to 1941 transition of 1.4°C, and no identifiable jump in the corresponding minimum temperature. It was found, though, that that would lead to an overcorrection of the series, because a significant fraction of the proposed jump was accompanied by other Portuguese stations, which didn't have any reported change in its operation. As a consequence, a joint technique for the adjustment of piecewise linear trends and instrumentation jumps was developed (Tomé *et al.*, 2002), leading to a smaller correction of 0.9°C in the Lisbon maximum temperature series. Fig 2.11 shows the corrected DTR series, obtained by a constant shift of the series prior to 1941.

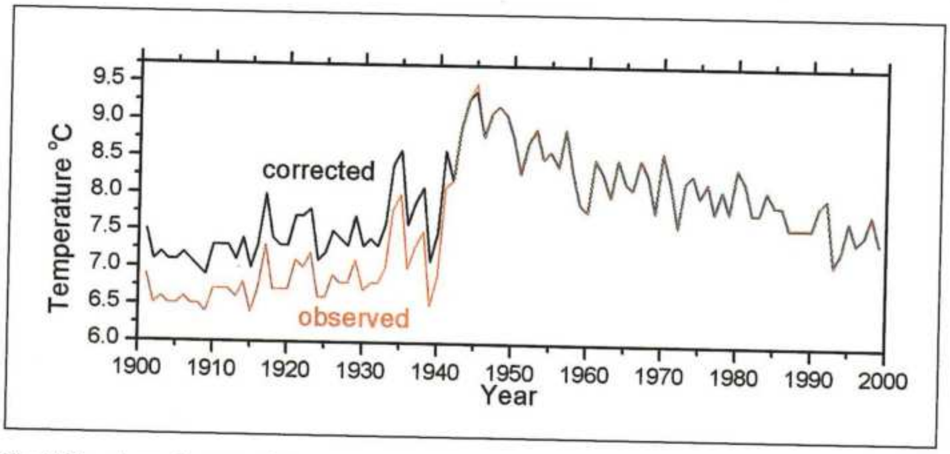


Fig. 2.11 – Annual mean of diurnal temperature range at Lisbon/Geofisico.

An analysis similar to the one presented for Lisbon was performed for all other centennial stations. Only in the case of Beja a significant data shift was identified in association with a reported station change, leading to a correction of the data (by 0.5°C, as proposed by the joint adjustment method). In the case of the other stations, although some (smaller) shifts were located in the tests, there was no supporting metadata about station changes and the data was used as observed. In all cases, because the main shifts occurred before 1940 and corrections were only applied to monthly mean temperature data, the analysis of frequency of weather regimes and climate extremes based on daily observations was restricted to the period 1941-2000.

### 2.2.2.3 Observed trends of average Portuguese temperature

While some Portuguese climate stations were established before the end of the 19th century, starting with the station at the Geophysical Institute in Lisbon in

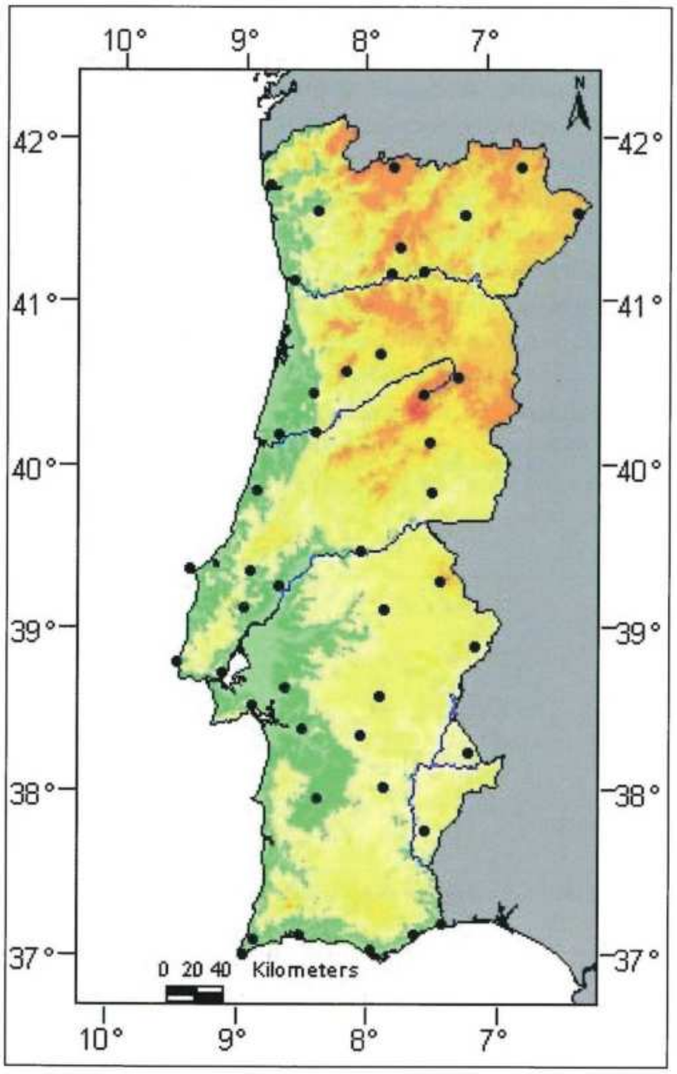


Fig. 2.12 - The 45 climate stations (black circles) used to compute the average Portuguese temperature.

1857, we only have good country coverage after 1930. Figure 2.12 shows the set of 45 stations chosen to compute the average Portuguese temperature, in the period 1931-2000. Not all stations are available for the full period, but, in general, they provide a reasonably regular observational network.

An inspection of the climatological series of air temperatures in mainland Portugal (Fig. 2.13) in the period between 1931 and 2000 shows that, starting in 1972, there is a general trend towards an increase in the mean annual near surface air temperature. This trend is very consistent, appearing both in the average country temperature and in the time series of individual stations. It also agrees remarkably well with findings at the global scale. In the case of Portugal, 1997 was the hottest of the last 70 years, while the 6 warmest years occurred in the last 12 years, and 2000 was the 14th consecutive year with an above normal (i.e. above the 1961-1990 mean) minimum air temperature. In this regional average, both minimum and maximum temperatures show similar trends, although the recent increase of minimum temperature seems to be occurring at a faster pace. More details on those trends will be left to the analysis of individual stations, presented in the following section.

### 2.2.2.4 Temperature trends at individual stations

Studies of the hemispheric and global temperature evolution in the past century have suggested the occurrence of two periods of global warming (1910-1945 and 1976-2000) separated by a period of cooling (1946-1975). This is also apparent in the time series of average Portuguese temperature (Fig. 2.13). This fact has led some authors (Karl *et al.*, 2000) to compute, instead of the average trend of the 20th century temperature, the individual trends of the warming/cooling periods. Individual trends are, of course, much larger, and the overall fitting to the data is clear. In this study, we have developed this approach and applied it to some centennial time series of mean annual minimum and maximum temperatures. For each of the analysed time series, we compute the best piecewise linear fit, in the least square sense (details are in Tomé *et al.*, 2002). Breakpoints in the fitting function are imposed, using the estimate of Karl *et al.* (2000) for the limits of warming and cooling periods,

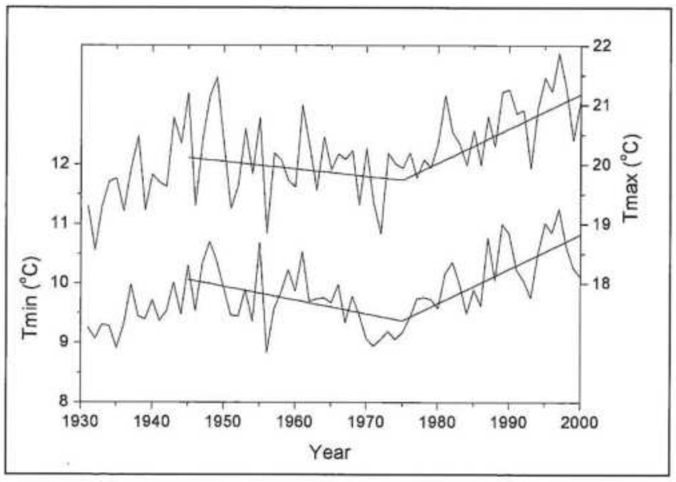


Fig. 2.13 - Evolution of mean minimum (bottom curve, left axis) and maximum (top curve, right axis) temperatures - mainland Portugal average. Superimposed are the piecewise trends (straight lines) calculated for the cooling and warming periods proposed by Karl *et al.* (2000)

whereas ordinates (temperatures) at those breakpoints are computed by minimization of the mean square fitting error in the corresponding period.

Fig. 2.14 shows the observed trends in 6 stations from 1901 to 2000. Inspection of the curves indicates that the data is in good agreement with the existence of the proposed warming and cooling periods in the 20th century. Although details are somewhat different between stations, they all show a warming tendency in the period 1910-1945, but only in the mean maximum temperature. Because the mean minimum temperature changes very little in that period, warming is accompanied by an increase in the DTR (diurnal temperature range). In the 1946-1975 global cooling period, cooling is observed at all stations, especially in the maximum temperature, except in the case of Beja where cooling mostly affected the minimum tempe-

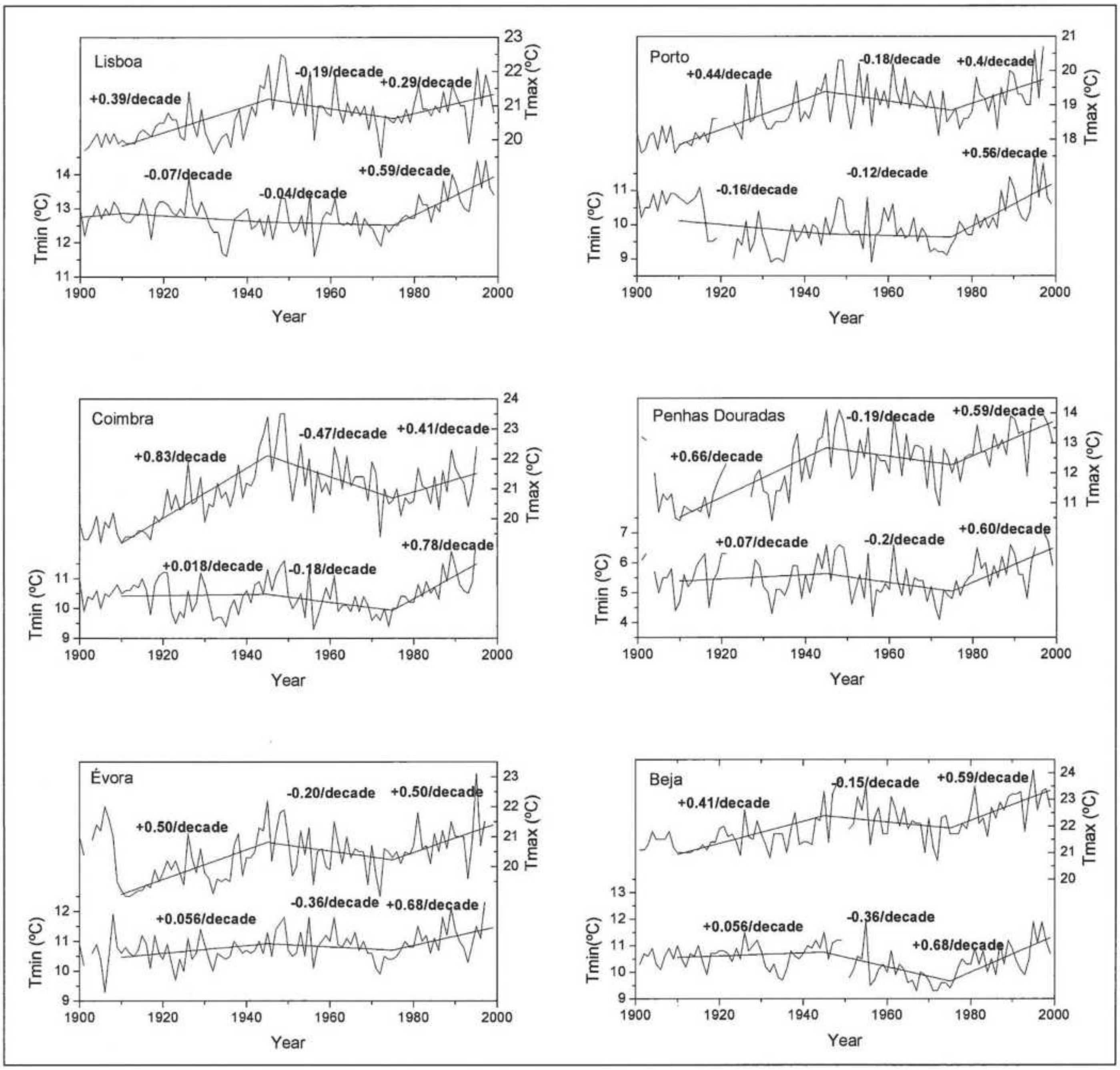


Fig. 2.14 – Annual mean minimum (bottom curve, left axis) and maximum temperatures (top curve, right axis) in: Lisbon (Geophysical Institute), Porto (Geoph. Inst.), Coimbra (Geoph. Inst.), Penhas Douradas, Évora and Beja. Straight segments indicate the trends in the warming (positive trend) and cooling (negative) periods. The rate of warming and cooling (in °C/decade) is shown. Breakpoints between periods follow Karl *et al.* (2000).

rature. As a consequence, this was a period of DTR reduction (except in Beja). The last period (1976-2000) shows significant warming at all stations, affecting both minimum and maximum temperatures. In the latter period most stations experienced a reduction in DTR, because minimum temperature increased at a faster rate (Fig 2.15). In fact, DTR decreased in 4 out of the 6 stations selected, is stable in Penhas Douradas and increased in Évora. In the country average (Fig. 2.13), the last warming period was associated with a decrease of DTR. Note that, in the cases of Lisbon and Beja, data prior to 1941 was corrected for homogenisation, and that correction implied, essentially, a reduction in the warming trend in the period 1910-1945.

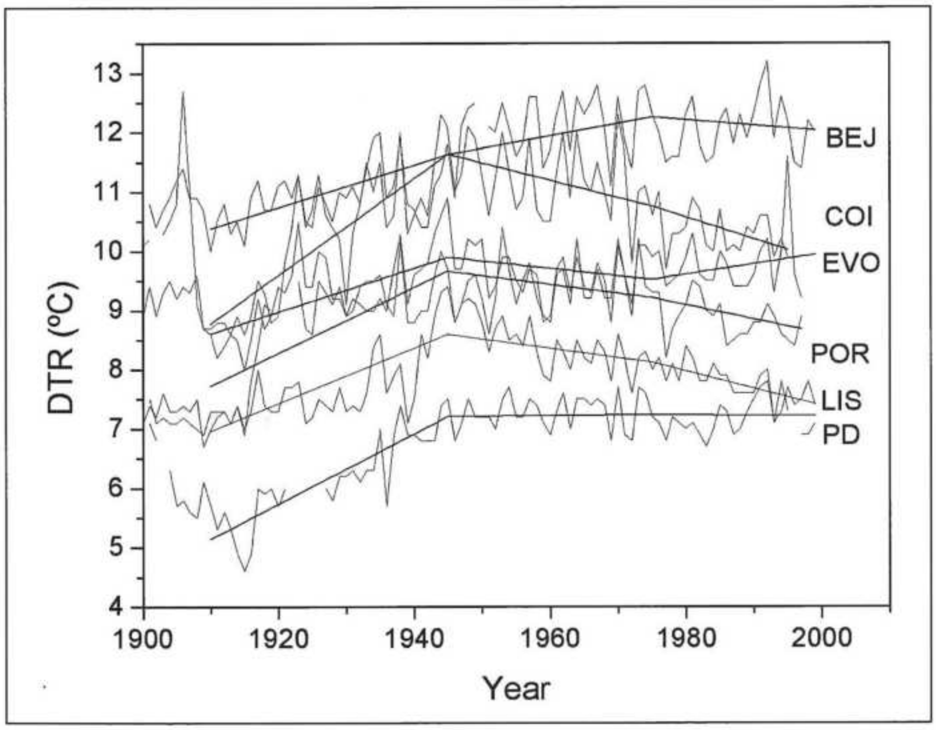


Fig. 2.15 – As Figure 2.14 for the annual mean DTR (diurnal temperature range). Curves are individually labelled (LIS – Lisbon, POR – Porto, COI – Coimbra, PD – Penhas Douradas, EVO – Évora, BEJ – Beja)

We will now look at the evolution of the annual temperature cycle. The Lisbon series will be chosen for that purpose, because it is the best documented series and is generally representative of the average Portuguese climate, although one should keep in mind that there may be some regional variations in the details, as found earlier. Fig. 2.16 shows the time evolution of seasonal mean minimum and maximum temperatures and DTR. Seasons are defined as 3-month periods, with spring consisting of the period March-May (MAM), summer, June-August (JJA), autumn, September-November (SON), and winter, December-February (DJF). Minimum temperatures (Fig. 2.16a) are increasing in all seasons, but the warming rate in winter is smaller. Warming rates for maximum temperatures (Fig. 2.16b) are much smaller. In the recent global warming period, from the 1970s onwards, the largest warming rates are found in the spring period, both for minimum and maximum temperatures. In the case of DTR (Fig 2.16c) all seasons show a clear downward tendency since the 1940s, less pronounced in winter.

Statistical significance of trend values was tested using an appropriate form of the t-test and they were found to be significant at the 1% level. In the second warming period (1976-1999) temperature trends are positive all over Portugal. The warming rate of mean temperature since 1976 is larger than the corresponding rate during the 1910-1945 period.

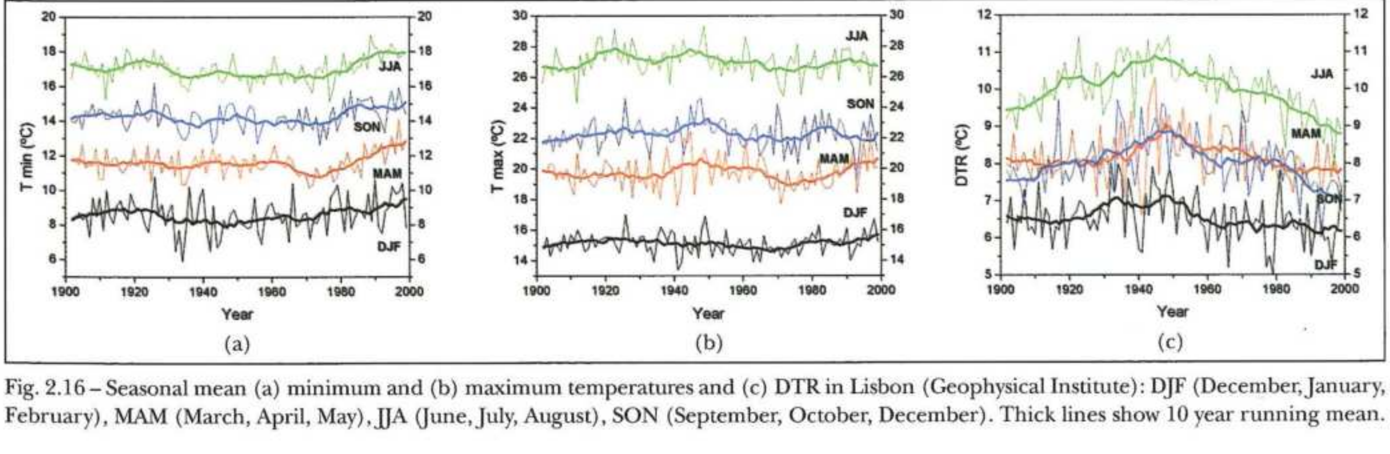


Fig. 2.16 – Seasonal mean (a) minimum and (b) maximum temperatures and (c) DTR in Lisbon (Geophysical Institute): DJF (December, January, February), MAM (March, April, May), JJA (June, July, August), SON (September, October, December). Thick lines show 10 year running mean.

Note, though, that, unlike what was found in many regions, this does not seem to be case of maximum temperature in Portuguese stations. The strongest changes in the DTR were in general in summer (JJA) and autumn (SON) (Figure 2.16 for Lisbon, others not shown). In the second warming period, the general warming tendency results mainly from warming in spring and summer.

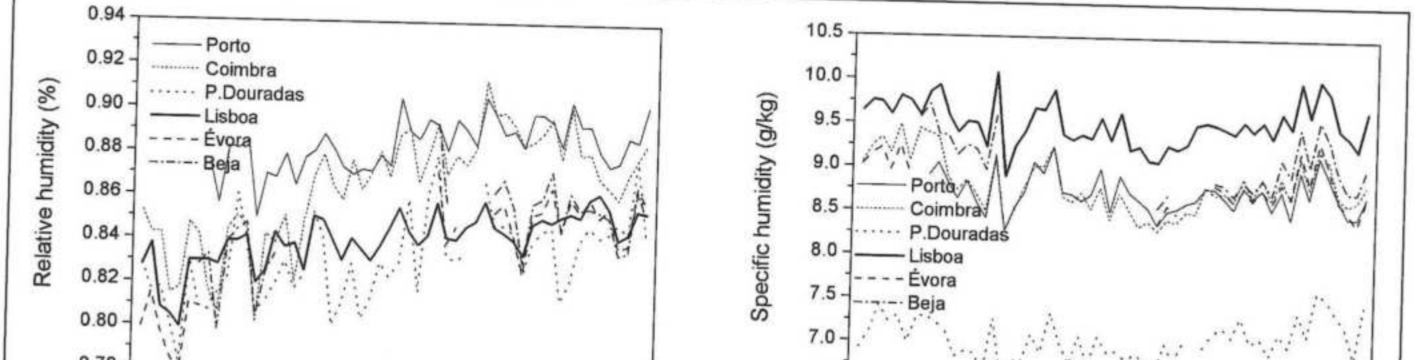
The strong increase in minimum temperature, when compared with maximum temperature, has raised questions about whether the growth of the urban heat island effect might be responsible for a substantial portion of the observed mean temperature increase, because it is well-known that local warming associated with the urban effect is more efficient at night. At the global scale, Jones *et al.* (1990) and Easterling *et al.* (1997) concluded that urban effects on 20th century globally and hemispherically averaged land air temperature time series do not exceed about 0.05°C/century, and so cannot be blamed for most of the observed temperature trends. An analysis of the evolution of atmospheric humidity, cloud cover and hours of sunshine, in the following section, may contribute to clarify that issue.

### 2.2.2.5 Trends in humidity and cloud cover

The evolution of annual mean atmospheric humidity, computed from wet bulb temperature observations in 6 Portuguese stations at 9h, is shown in Fig. 2.17. In what concerns relative humidity (Fig. 2.17a), observations show a systematic increase in the 1941-1994 period, in the 4 stations with complete records, with larger trends in Coimbra (1.2%/decade, with correlation coefficient r=0.73) followed by Penhas Douradas (0.7%/decade, r=0.55), Lisbon (0.6%/decade, r=0.73) and Porto (0.5%/decade, r=0.58). Trends in the mean seasonal values of relative humidity (not shown) are, in general, less significant, but the increase in summer relative humidity in Lisbon (1%/decade, r=0.68) and Coimbra (1.7%/decade, r=0.72) seem rather important. Observations made at Évora and Beja, also shown in the figure, do not cover the full period, but show similar trends.

Trends in specific humidity (Fig. 2.17b) are less clear. Visual inspection of the graphic suggests that a downward trend in specific humidity was observed until the 1970s, followed by a period with positive trend, in line with the observed evolution of mean temperature. While the global trends in annual mean specific humidity are not significant, there is a significant decrease in mean spring specific humidity (not shown) in Lisbon, Coimbra, Porto, Évora and Beja at a rate of 0.1 g/kg/decade.

Although observations of cloud cover are rather qualitative and probably unreliable, one must keep in mind the great importance of any long term trends. Annual mean values of total cloud cover, at 9h, shown in Fig 2.18, indicate a slight upward trend in Lisbon. Trends in the other stations are not statistically significant. Unfortunately, we don't have, at this time, reliable records for other stations or at other times in the daily cycle. Taken by itself, the Lisbon trend would probably be disregarded, but when taken together



(a)

(b)

Fig. 2.17 – Annual mean (a) relative humidity and (b) specific humidity in 6 Portuguese stations, at 9:00 UTC, as labelled.

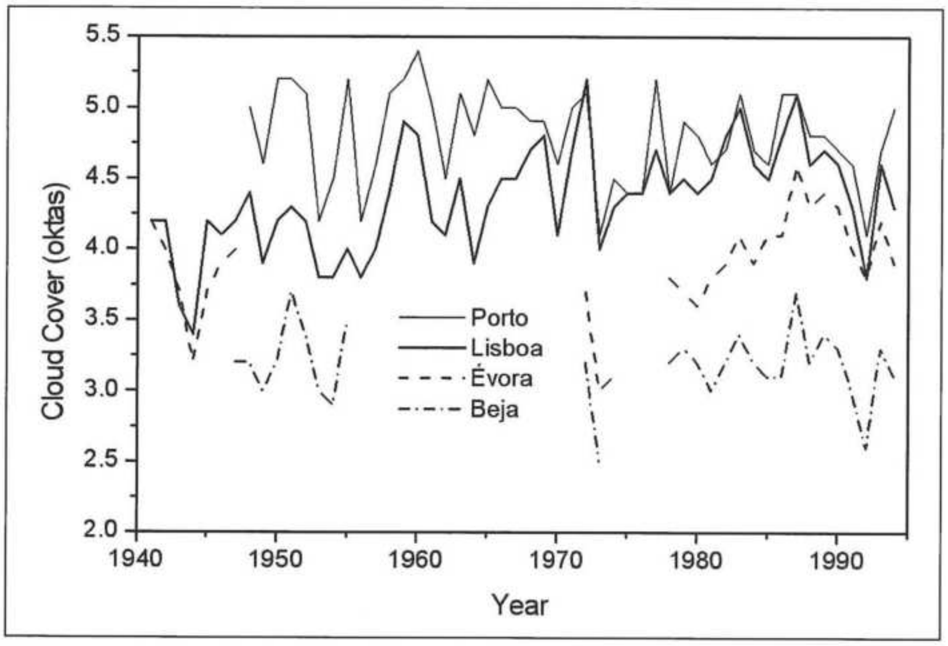


Fig. 2.18 – Time series of cloud cover at 4 climate stations in Portugal at 9:00 UTC, as labelled.

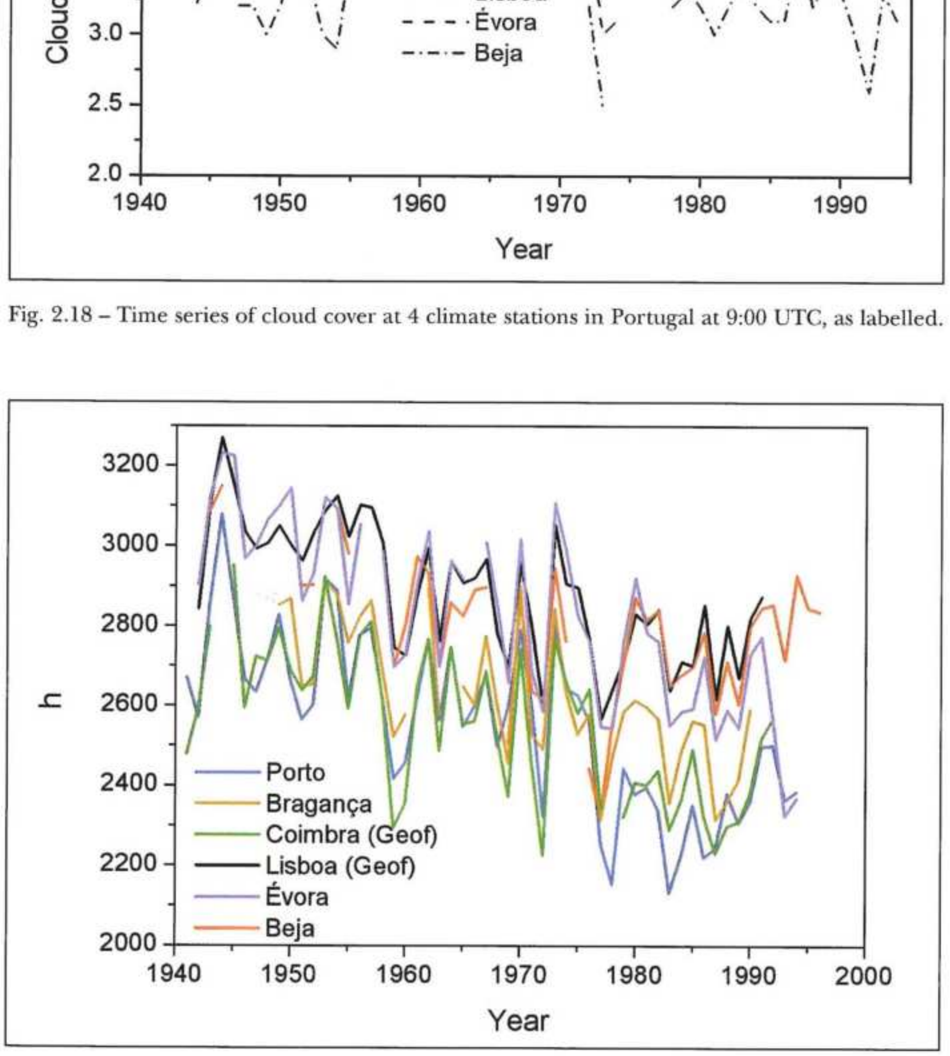


Fig. 2.19 – Time series of sunshine hours at 6 climate stations in Portugal, as labelled.

with the upward trend in relative humidity and the downward trend in sunshine hours, it may provide relevant information for future studies.

Another way to look at daily average cloud cover is given by the number of sunshine hours, estimated from Campbell-Stoke's heliographs. This record is also not entirely reliable, as it depends on the properties of the card and on subjective criteria for its classification. The Portuguese annual record is shown in Fig 2.19, and it indicates a clear and substantial downward trend until the beginning of the 1990s. Although the trend shown in Fig 2.19 is so large (almost 20%) that may look suspicious, it must be said that systematic downward trends were also reported for southern Spain (Wheeler, 2001).

Although, as previously stressed, results presented in this section have to be taken with some caution, it is clear that they are consistent with each other and with the temperature record. A slight increase in low-level clouds is consistent with an increase in near-surface relative humidity, with a decrease in the number of sunshine hours and with a decrease in the diurnal temperature range (DTR). On the other hand the decadal trends in specific humidity can be explained by the corresponding near-surface temperature trends, although they also depend on the boundary layer depth and, possibly, on the low level atmospheric circulation, which have not been analysed. Information currently available on the Portuguese climatology of cloud cover, a key issue in the understanding of climate change, is rather poor and more efforts to recover, correct and analyse historical records are needed.

#### 2.2.2.6 Observed trends of Portuguese precipitation

A statistical analysis of long climatological series of annual precipitation over mainland Portugal in the period between 1931 and 2000 shows that in the last 20 years occurred only 6 years with precipitation values above the mean 1961-1990 values. Looking at the evolution of seasonal mean values in the same period

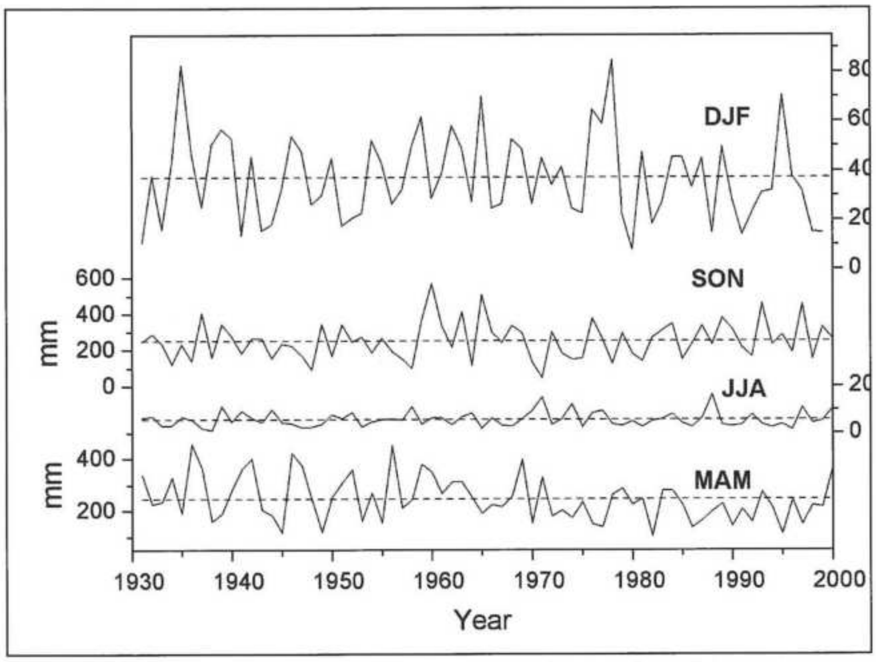


Fig. 2.20 – Evolution of seasonal accumulated precipitation – mainland Portugal average. Dashed lines indicate the 1931-2000 mean values.

(Fig. 2.20, see also Table 2.1) the main feature that comes out is the systematic reduction of spring accumulated precipitation, accompanied by slight increases in the other seasons. Because of the large interannual variability of precipitation, only the spring reduction is statistically significant. That reduction is most prominent in early spring, during the month of March, for which mean accumulated precipitation has been falling in all stations in mainland Portugal as found by Casimiro Mendes and Coelho (1993). The relation of this trend with the large scale circulation will be further discussed.

Some of the trends encountered in the 20th century Portuguese climate lead to significant differences between the 1931-1960 and the 1961-1990 climate normals. Fig. 2.21 shows the difference between 1931-60 and 1961-90 monthly mean precipitation, indicating the already mentioned tendency for lower precipitation in March and, to a lesser extent, in December, partially compensated by increased precipitation in February and October. Other months show little change. These results seem to indicate a tendency for a reduction in the duration of the rainy season, a result that is in the same direction as found in some climate change scenarios. Finally, Fig. 2.22 shows the ratio of 1961-90 to 1931-60 mean precipitations. In February (Fig. 2.22a) the precipitation increase was above 40% of the 1931-1960 values over most of the country. Fig. 2.22b, corresponding to the month of March, shows that precipitation in this month has been falling all over the country, by more than 40% of its 1931-60 value in some places. In the annual mean (Fig 2.22c) changes are not evident.

**Table 2.1 – Seasonal and annual variation of precipitation (mm)**

| | Autumn | Winter | Spring | Summer | Annual |
|---|---|---|---|---|---|
| 1961-1990 | 251.1 | 391.3 | 224.7 | 60.4 | 927.5 |
| 1931-1960 | 236.2 | 373.0 | 274.3 | 53.7 | 937.1 |
| Δmm | 14.9 | 18.3 | -49.5 | 6.8 | -9.6 |
| Δ% | 6.3 | 4.9 | -18.5 | 12.6 | -1.0 |

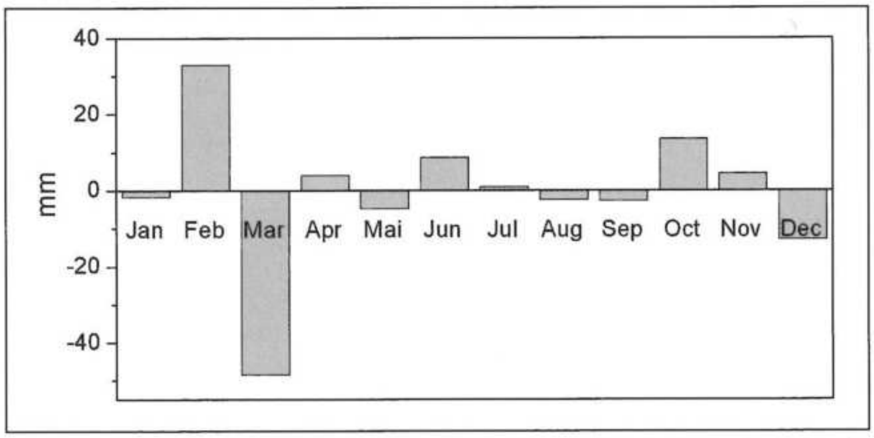


Fig. 2.21 – Annual cycle of the difference between monthly mean precipitation in the 1931-60 and 1961-90 climate normals. Positive values imply that the 1961-90 normal was, in the corresponding month, wetter than the previous period.

More recent precipitation data allows the construction of a new climate normal (1970-1999) that can now be compared to the previous 30 years (1940-1969). Fig. 2.23 shows the monthly mean difference between the two periods. Two of the main features of this figure are that the loss of precipitation in recent years during March has increased to 70 mm, whereas the month of February registers now a loss of 22 mm in relation to the previous 1940-1969 period. The months with deficit in precipitation now predominate over the months with

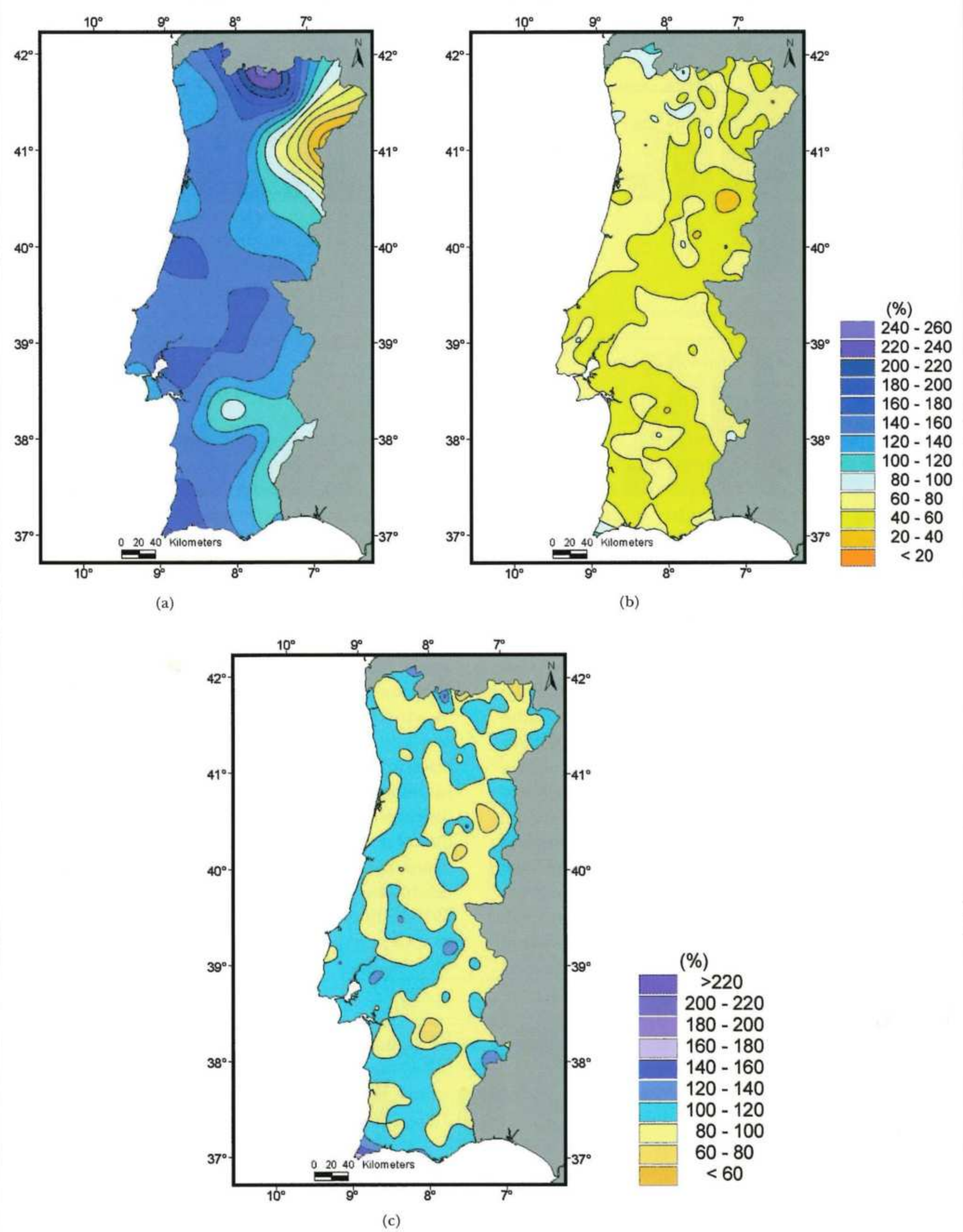


Fig. 2.22 – Ratio between mean precipitation in the 1961-90 and 1931-60 climate normals: (a) February, (b) March, (c) annual.

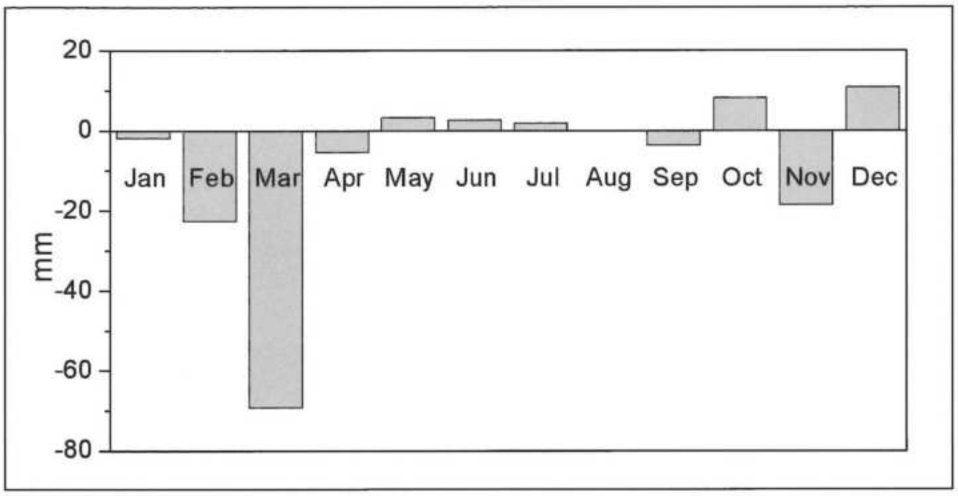


Fig. 2.23 – Annual cycle of the difference between monthly mean precipitation in the 1940-69 and 1970-99 climate normals

gains and the result is a mean total loss of almost 100mm per year in the last three decades of the 20th century in comparison to the previous 30 years (see Fig. 2.24a). This result, together with the strong temperature increases observed previously, highlights the contribution of the last decade to climate change in Portugal.

The seasonal variation of the mean accumulated precipitation between the last two climate normals is shown in Fig. 2.24b. All the seasons except summer exhibit a reduction in precipitation, which is again more statistically significant in spring. The gains in precipitation in summer are too small to be significant.

Fig. 2.24a,c show the standard deviations of annual and seasonal precipitation, illustrating a change in interannual variability between the considered climate periods. The winter and summer seasons register more variability in the period 1970-1999 than in 1940-1969. The difference in winter (DJF) precipitation variability is also detected in Fig. 2.20, where the 1970-1999 period is characterized by very wet years followed by very dry years. On the other hand the 1940-1969 period is characterized by winter precipitation values with a smaller amplitude oscillation, around the mean values. Because the two normals correspond to different trends in global mean temperatures, as previously shown, the past behaviour of regional precipitation may be an important clue to its response in future warming periods.

On the other hand, in spring there is not only a reduction in the mean precipitation but also in its standard deviation in the three last decades, a fact that is due to the disappearance of years with accumulated precipitation above 350 mm, as shown in the histograms in Fig. 2.25b.

A more detailed view of the evolution of the distribution of precipitation is given by the analysis of histograms, shown in Fig. 2.25, where statistics for the 1940-1969 and 1970-1999 periods are compared. In the case of winter (Fig. 2.25a) the change in interannual variability is very clear, with the occurrence of very wet classes (above 700 mm) in the latter period. The summer histograms (Fig. 2.25c) also show important differences between the 2 climate normals. Although the total amount of precipitation is very similar in the two periods, there is a tendency for drier summers (less than 40mm) to become more frequent in the 1970-1999 period, whereas wetter summers also start to appear, explaining the increased standard deviation

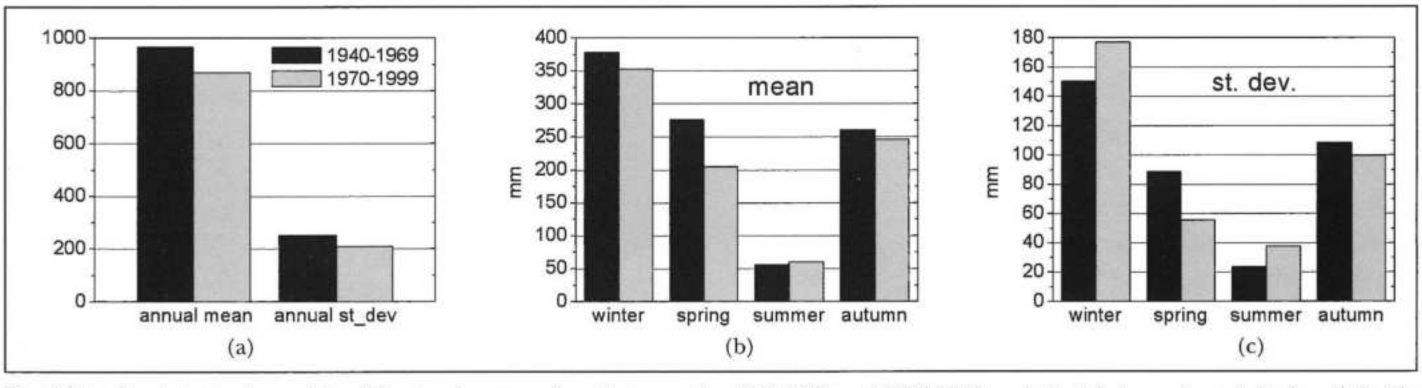


Fig. 2.24 – Precipitation in mainland Portugal - comparison between the 1940-1969 and 1970-1999 periods: (a) Annual precipitation (left side bars), annual standard deviation (right side bars);( b) Average seasonal precipitation; (c) Seasonal standard deviation

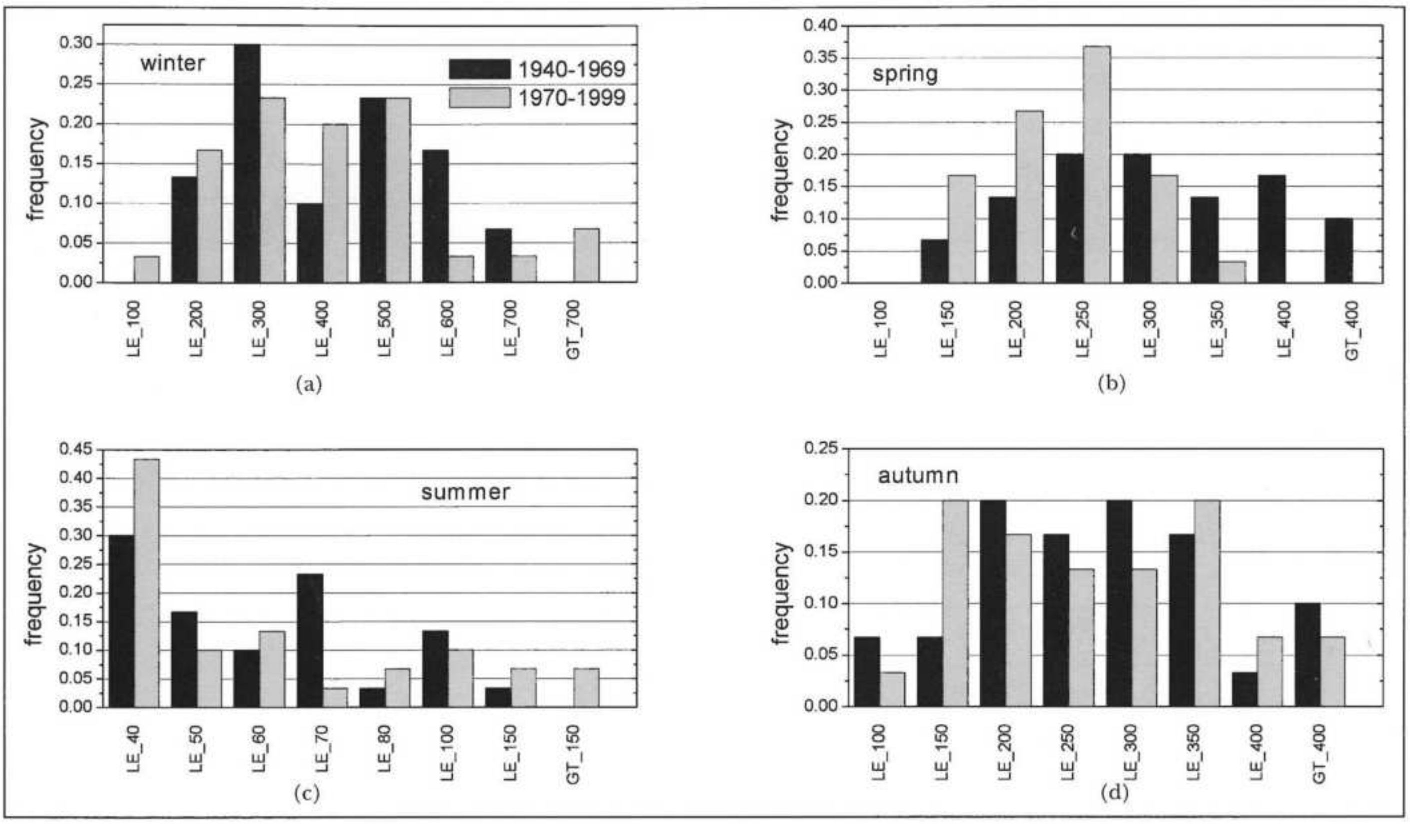


Fig. 2.25 – Precipitation histograms for mainland Portugal in: (a) winter, (b) spring, (c) summer and (d) autumn. Precipitation classes in mm. LE stands for "less or equal than", GT stands for "greater than".

in this period. The autumn histograms are more difficult to interpret, showing a redistribution of the precipitation by the different classes.

If one looks at time series of precipitation in individual stations (not shown) it is easy to conclude that precipitation trends in mainland Portugal show less spatial coherency than temperature trends. It is also clear that trends computed for single stations tend to have little statistical significance, and so they will not be discussed in this text.

### 2.2.2.7 Pressure and the NAO index

Observations (Fig 2.26) indicate that annual mean station level pressure at 9h has been increasing in the last decades, with the exception of the Penhas Douradas mountain station, which shows a downward trend. However, the Penhas Douradas negative trend is conditioned by a step-like change in 1950s that may be spurious and which is followed by a slow upward progression of mean annual pressure. The Lisbon signal has also some known calibration problems (Antunes and Ferreira, 2000) but they don't affect too much the long term tendency. In all stations, there are very significant annual cycles of pressure and it is found that the upward trend is greater in winter and small in summer. The winter trends are, though, less statistically significant than the trend in the annual mean, due to the large interannual variability of winter mean pressure.

Pressure is an important parameter for the understanding of the large scale atmospheric circulation and its relation with weather. In southern Europe, and particularly in the Iberian Peninsula, precipitation is well known for its interannual variability (e.g. Rodriguez-Puebla *et al.*, 1998; Serrano *et al.*, 1999). In recent years, researchers have been looking for explanations of that variability in the low frequency modes of the large scale atmospheric flow in the North Atlantic region and for simple dynamical indices that correlate well with the observed seasonal climate. In synoptic terms, observed oscillations in annual precipitation have been associated with changes in the frequency of certain regional circulation patterns, namely those associated with blocking conditions, when frontal perturbations are displaced to northern Europe, avoiding Iberia. Using that mechanism, the mean atmospheric

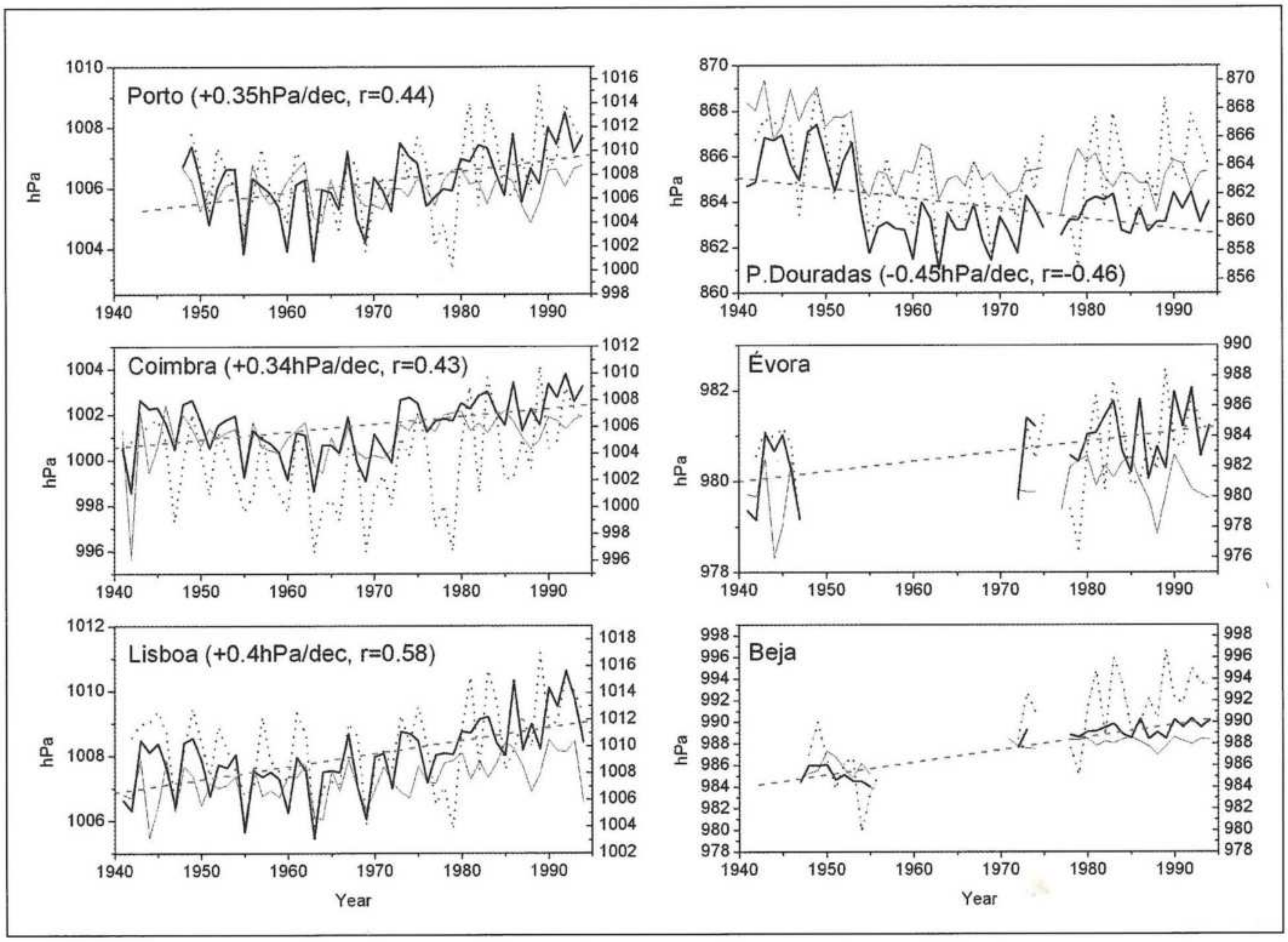


Fig. 2.26 – Time series of 9h pressure in 6 stations, as labelled: mean annual pressure (thick line, left axis), mean summer pressure (JJA, thin line, left axis) and mean winter pressure (dotted line, right axis). Also shown (dashed line) the trend of mean annual pressure and the corresponding correlation coefficient (r).

circulation in the Atlantic sector may modify the climate in southwest Europe through perturbations in the mean location of the storm track. The mechanisms of establishing and maintaining those anomalous patterns are rather subtle, and generally difficult to predict with numerical weather prediction models, and it is not at all clear how much they depend on internal atmospheric variability and on external forcing.

The explaining success of the El-Niño/Southern Oscillation mode of variability, coupling atmospheric low frequency variability with oceanic processes in the Pacific, has led many researchers to look at similar couplings in the Atlantic and to consider the North Atlantic Oscillation (NAO) index, proposed by Walker (1924). The NAO index, consisting in the pressure difference between Iceland and the Azores, or between Iceland and Lisbon or Iceland and Gibraltar (Jones *et al.*, 1997a), measures the strength of the zonal flow across the North Atlantic. The NAO can be interpreted in terms of a large scale meridional exchange of atmospheric mass (van Loon and Rogers, 1978) or as the oscillation of a large scale anomalous pressure (or geopotential) pattern (Wallace and Gutzler, 1981), and has been found to correlate with mean regional temperatures and precipitation (Hurrell, 1995; Hurrell and van Loon, 1997; Trigo *et al.*, 2002). In the case of the Iberian Peninsula, the trend of NAO was also found (Zhang *et al.*, 1997) to correlate with the observed trend in March precipitation.

The reason why the NAO index correlates with western Iberian precipitation lies in the fact that most precipitation in this area is of frontal origin, depending very much on the exact location of the Atlantic storm track. Low values of the NAO index are associated with larger than usual precipitation amounts in western Iberia, while large values of the index correspond to smaller than usual precipitation amounts (e.g. Trigo *et al.*, 2002). Fig 2.27 shows the time series of winter (DJF) and March mean NAO index (Hurrell, 1995, 2001) and the corresponding values of average Portuguese precipitation. 10-year running means of both variables are also shown. A visual inspection of the Figure indicates a significant negative correlation between NAO and precipitation both for the annual values and for the running means. Monthly mean correlations are shown in Figure 2.28 both for the 1931-2000 period and for two independent 30 year periods (1940-69 and 1970-99). While all periods indicate significant correlations, in the extended winter period (December to March) there is also significant interdecadal variability, not only in the NAO index but also in its correlation with precipitation. On the other hand it has been shown (Rodó, 1997) that the NAO-precipitation correlation varies substantially within the Iberian Peninsula, with larger values in the SW.

## The NCEP/NCAR reanalysis Data Set

In recent years, the National Center for Atmospheric Research (NCEP/NCAR, Kalnay *et al.*, 1996) and the European Centre for Medium Range Weather Forecasts (ECMWF, Gibson *et al.*, 1997) have produced sets of gridded meteorological variables, obtained by "reanalysis" of the observations from 1948 onwards, with modern weather prediction and data assimilation

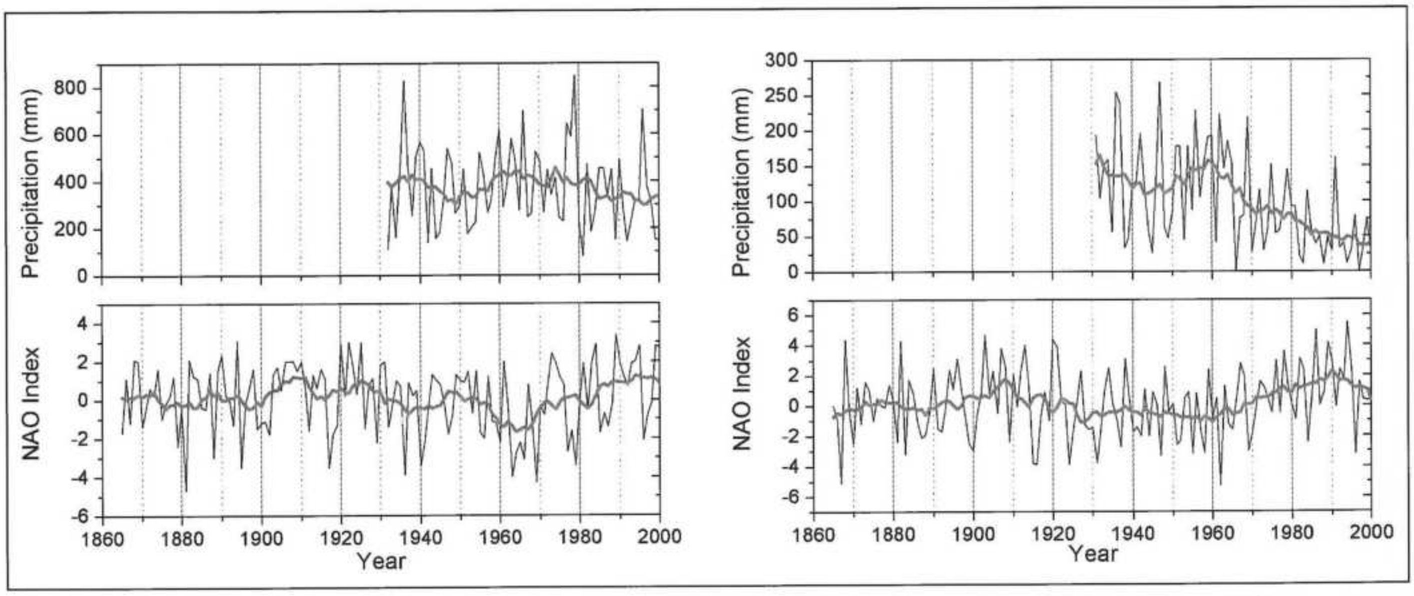
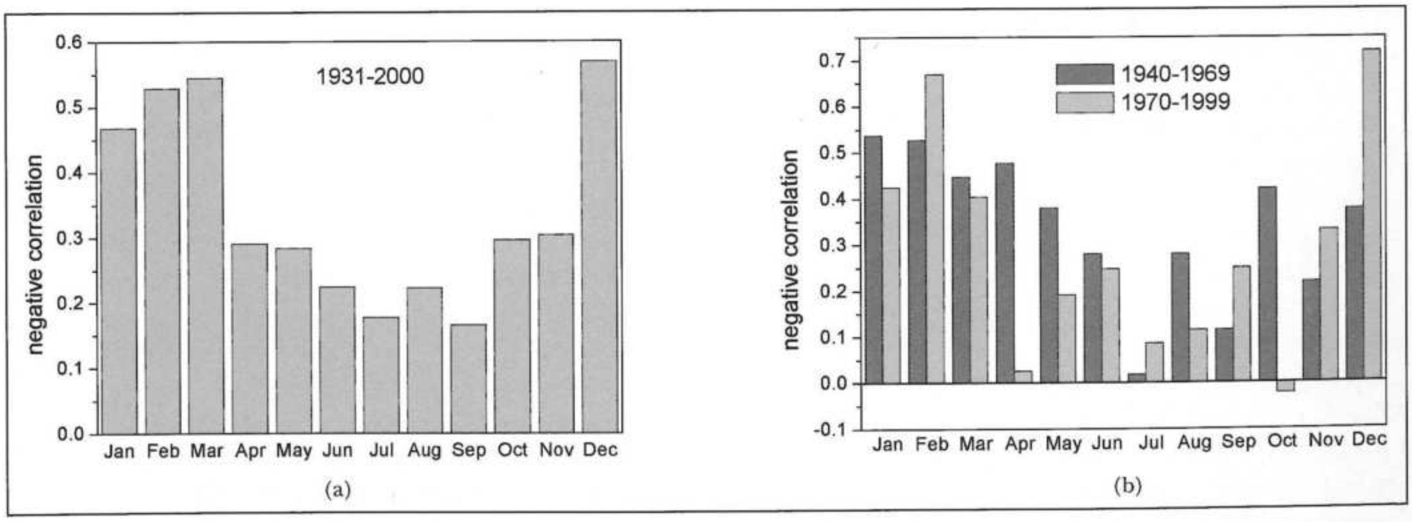


Fig. 2.27 – NAO index, calculated with the pressure difference between Iceland and the Azores (Hurrell, 2001) and average Portuguese precipitation (observations) in the periods DJF (left panel) and March (right panel). A 10-year running mean is superimposed (thick line).



(a)

(b)

Fig 2.28 – Monthly mean negative correlation between average Portuguese precipitation, computed from observations, and the NAO index (Hurrell, 1995, 2001): (a) Mean values for the period 1931-2000; (b) Mean values in the two 30 year periods 1940-69 and 1970-99.

systems. These datasets, NCEP being the one that is already available, constitute the best possible estimate of the large scale meteorological evolution in the past decades. However, because the reanalysis procedure combines raw observations with numerical model analyses of the atmosphere, there may be model-dependent biases in the data set (Kalnay *et al.*, 1996). Furthermore, some variables in the data set are entirely derived from the model (e.g., latent heat flux) and therefore may include a more significant bias than variables that are based on primary measurements (e.g., wind speed and humidity).

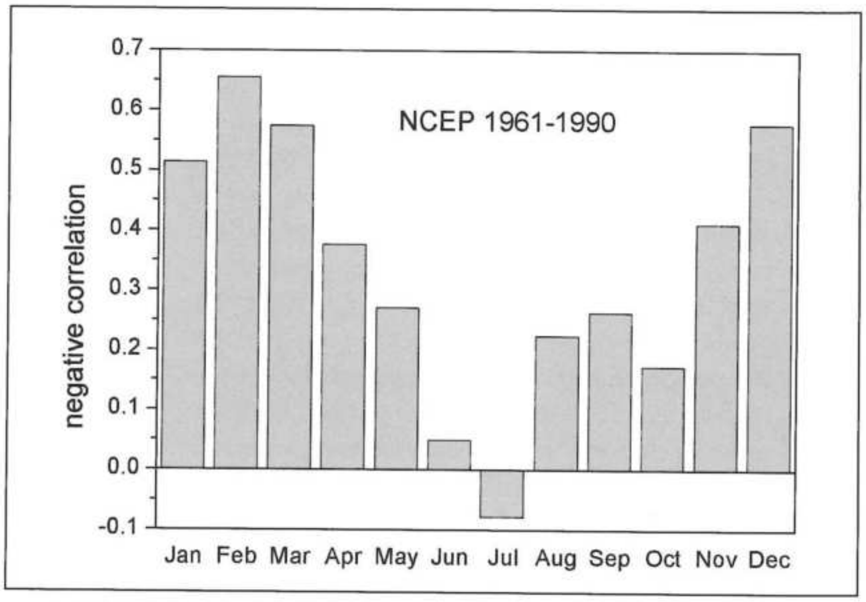


Fig 2.29 – Monthly mean correlation between NCEP NAO (computed as a difference of sea-level pressure between the Azores and Iceland, with grid point pressure data) and observed average precipitation in Portugal.

Although there is already data available from the NCEP/NCAR reanalysis since the year of 1948, we use in this work data for the 41 years period spanning 1958--1998, coming from the annual CDROMs distribution. The sea level pressure was obtained from the 1000hPa and 500hPa geopotential height fields, by extrapolation. In the NCEP/NCAR reanalysis, surface variables are available on a T62 Gaussian grid (1.875°×1.905° resolution), and atmospheric data are available on a 2.5° latitude by 2.5° grid longitude, with 17 levels in the vertical.

Fig. 2.29 shows the monthly mean correlation between the NCEP/NCAR NAO and the observed Portuguese precipitation in the period 1961-1990. Note that the NCEP/NCAR NAO presented here was computed solely as the difference between the Iceland and Azores sea level pressures, whereas the Hurrel (2001) NAO index presented before is a non-dimensional quantity. Fig. 2.29 is useful for comparison purposes with the reference periods of the climate model simulations, performed with the Hadley Centre model HadCM3, presented in the forthcoming climate scenarios section.

## Circulation Weather Types in West Iberia

While the NAO index characterizes the North Atlantic atmospheric circulation as a whole, local analysis of the pressure field can provide additional detail and support a strong link between regional climate variability and the atmospheric dynamic fields. Jones *et al.* (1993) and Jenkinson and Collison (1997) developed such a scheme for the British Isles, based on the computation of local geostrophic wind direction and vorticity. An adaptation of that classification scheme to Portugal, made by Trigo and DaCâmara (2000), showed significant correlation with observed precipitation, suggesting that it could be applied to the analysis of past climate variability.

The weather type classification method applied to Portugal is based on grid point values of pressure in a discrete grid centred west of Lisbon, as shown in Fig. 2.30. In the present study, the methodology will be applied, first, to the analysis of climatological data, then to the study of climate simulations performed by the Hadley Centre global model (HadCM3). The climatological weather types computed in this section are comparable to those published by Trigo and DaCâmara (2000), although the dataset used here is and extended and improved version of the one that was available at that time.

The circulation weather types (CWTs), as defined by Trigo and DaCâmara, were divided into ten pure types (one cyclonic type, C, one anticyclonic type, A, and eight directional types, NE, E, NW, SE, S, SW, W, and N) and in sixteen hybrid types, combining the geostrophic wind direction and vorticity. The hybrid classes account for nearly 27% of all cases and, if they

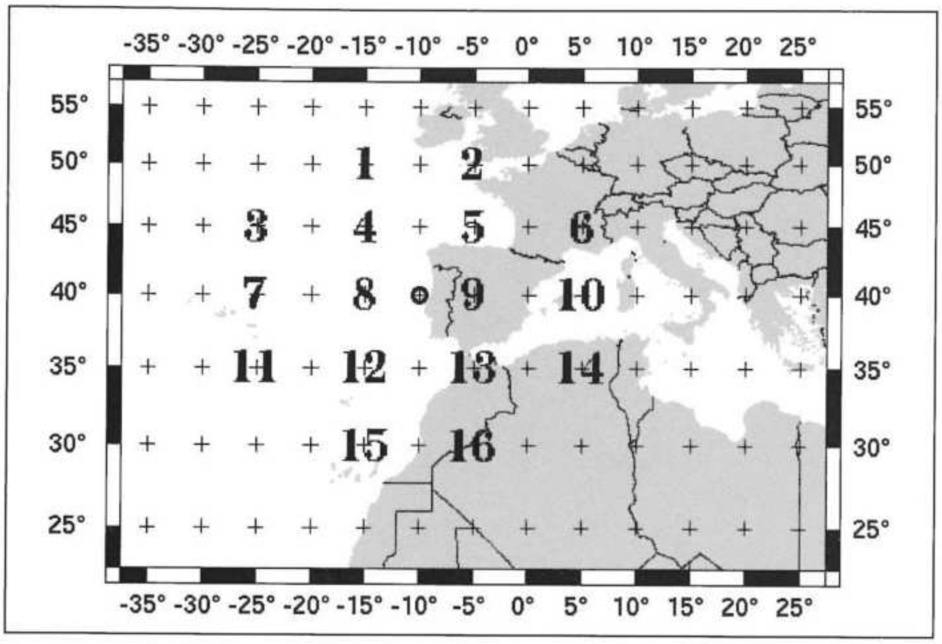


Fig. 2.30 – The 16 points used for evaluating the set of geostrophic indices in a point near Lisbon (the small circle in the figure)

**Table 2.2 – CWTs frequency (%) in the NCEP/NCAR reanalysis data**

| Time | A | C | NE | E | SE | S | SW | W | NW | N | hANE | hAE | hASE | hAS | hASW | hAW | hANW | hAN | hCNE | hCE | hCSE | hCS | hCSW | hCW | hCNW | hCN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 00h | 17.4 | 3.8 | 12.5 | 9.5 | 4.1 | 2.5 | 4.2 | 7.4 | 5.9 | 6.4 | 4.6 | 2.5 | 0.9 | 0.4 | 1.0 | 3.2 | 4.1 | 3.9 | 1.0 | 1.1 | 0.8 | 0.7 | 0.7 | 0.5 | 0.5 | 0.6 |
| 12h | 16.1 | 3.3 | 14.7 | 9.6 | 3.5 | 2.0 | 3.6 | 6.8 | 6.2 | 7.9 | 5.2 | 2.3 | 0.6 | 0.4 | 0.8 | 2.9 | 4.3 | 4.3 | 1.1 | 1.0 | 0.7 | 0.6 | 0.6 | 0.5 | 0.4 | 0.6 |

were well distributed among them, it would represent less than 2% for each one and we could, as done by Trigo and DaCâmara, disseminate the hybrid classes in the pure classes. However, as shown in table 2.2, there are hybrid classes with a frequency higher than some pure classes and, as will be seen later, some of the hybrid classes have an interesting connection with precipitation. So we will keep the hybrid classes but we will only discuss the most frequent, and the ones who have an interesting signal when correlated with precipitation, for keeping an understandable text. The symbols used to name the several classes are the ones used by Trigo and DaCâmara, but for the hybrid classes we prefixed an h for a better distinction.

Table 2.2 presents the frequency distribution of the 26 CWTs for the period 1958-1998 using the sea level pressure field at 00h and 12h UTC. It is clear that the anticyclonic type is the most frequent, followed by the NE and E types. Among the hybrid types the more frequent are the hANE, hAW, hANW and hAN. An interesting result when comparing the 00h with the 12h is that the occurrence of northerly geostrophic wind is slightly more frequent at 12h (44.7% versus 41.7%), especially in summer months (69.3% versus 60.3% in July, not shown), which can be explained by the establishment of the Iberian thermal low (e.g. Font 1983, Gaertner *et al.* 1993). This difference would certainly be larger if 18h UTC data had been used, but, unfortunately, these datasets are not available in the NCEP/NCAR reanalysis. Because the HADCM3 dataset only includes one daily instantaneous value for the sea level pressure, we will focus the analysis on the 00h UTC.

Fig. 2.31 presents monthly mean frequencies of the 26 CWTs. The chart on the left presents the monthly distribution of the ten pure CWTs, the middle chart the anticyclonic hybrid types and the rightmost chart the cyclonic hybrid types. From this figure one can conclude that in the summer months there is an increase of the CWTs (pure and hybrid types), associated with easterly geostrophic wind, and an accentuated decrease of the CWTs associated with westerly wind. As we shall see, precipitation is mainly associated with the westerly CWTs.

Fig. 2.32 shows 9 charts representing the average precipitation rate (mm/day) associated with each of the CWTs in the grid points centred at 7.5W/41N (a, b and c), 7.5W/39N (d, e and f) and 7.5W/37.1N (g, h and i). When we compare the right column charts (the cyclonic hybrid CWTs) with the left column charts (the pure types), it becomes obvious that some hybrid types have a stronger connection with precipitation than the pure types, and their frequency (shown in table 2.2 and Fig. 2.31) is not

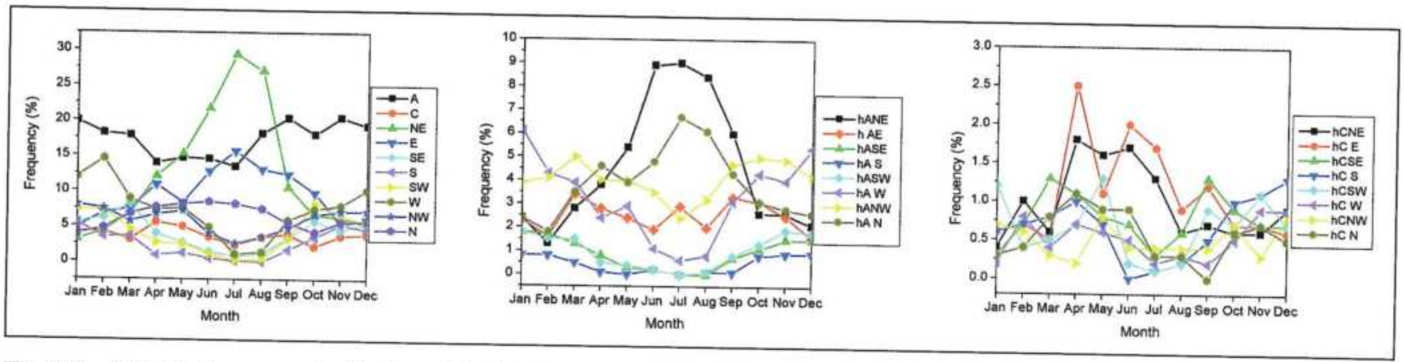
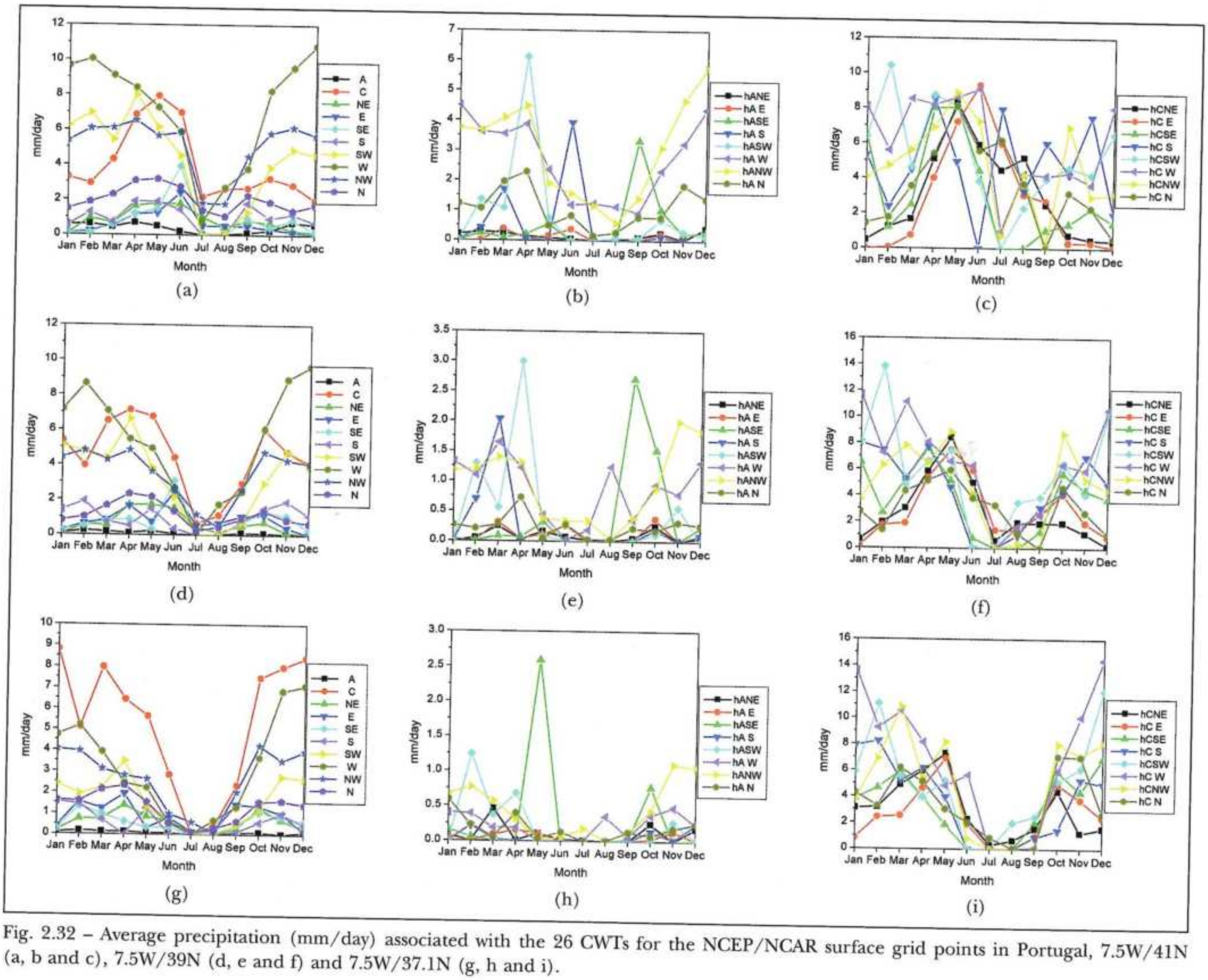


Fig. 2.31 – Monthly frequency distribution of the 26 CWTs using the sea level pressure at 00h from the NCEP/NCAR reanalysis.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 2.32 – Average precipitation (mm/day) associated with the 26 CWTs for the NCEP/NCAR surface grid points in Portugal, 7.5W/41N (a, b and c), 7.5W/39N (d, e and f) and 7.5W/37.1N (g, h and i).

negligible. When we compute the standard deviation in mm/day we observe that the ratio mean/(standard deviation) is, in general, higher for the hybrid types, indicating that the precipitation associated with an individual CWT is less spread around the mean value in the hybrid types than in the pure types.

The analysis of Fig 2.32 also allows one to conclude that the CWTs more effective in terms of precipitation are, at the southern and centre grid points in winter, the hCW, hCSW, W and C types, and, as a rule, the CWTs with some westerly wind component are more effective than the others. For the northern grid point we see that the CWTs with a westerly wind component are still the more effective but, for this grid point, the A type, although still relatively dry contributes significantly to the total precipitation due to its high frequency (19.9% in January and 18.2% in February). The increased wetness of the anticyclone type in the Northern region may be understood noting that some anticyclonic situations lead to westerly flow in that sector (cf. top charts of Fig. 2.33).

One more interesting result concerning Fig. 2.32 is the precipitation efficiency of all the cyclonic hybrid types. In April and May these types account on average for about 8.5% of days, becoming an important factor for the accumulated precipitation in spring. This efficiency is stronger in the northern half of the country.

For illustrative reasons we choose four of the CWTs, the A and W types, because of their high frequency, and the hCW and hCSW types because they are among the most effective in terms of precipitation. Fig. 2.33 presents the mean sea level pressure associated with each of these four CWTs, for the periods DJF, MAM and SON. The summer period was intentionally left out because its precipitation is insignificant.

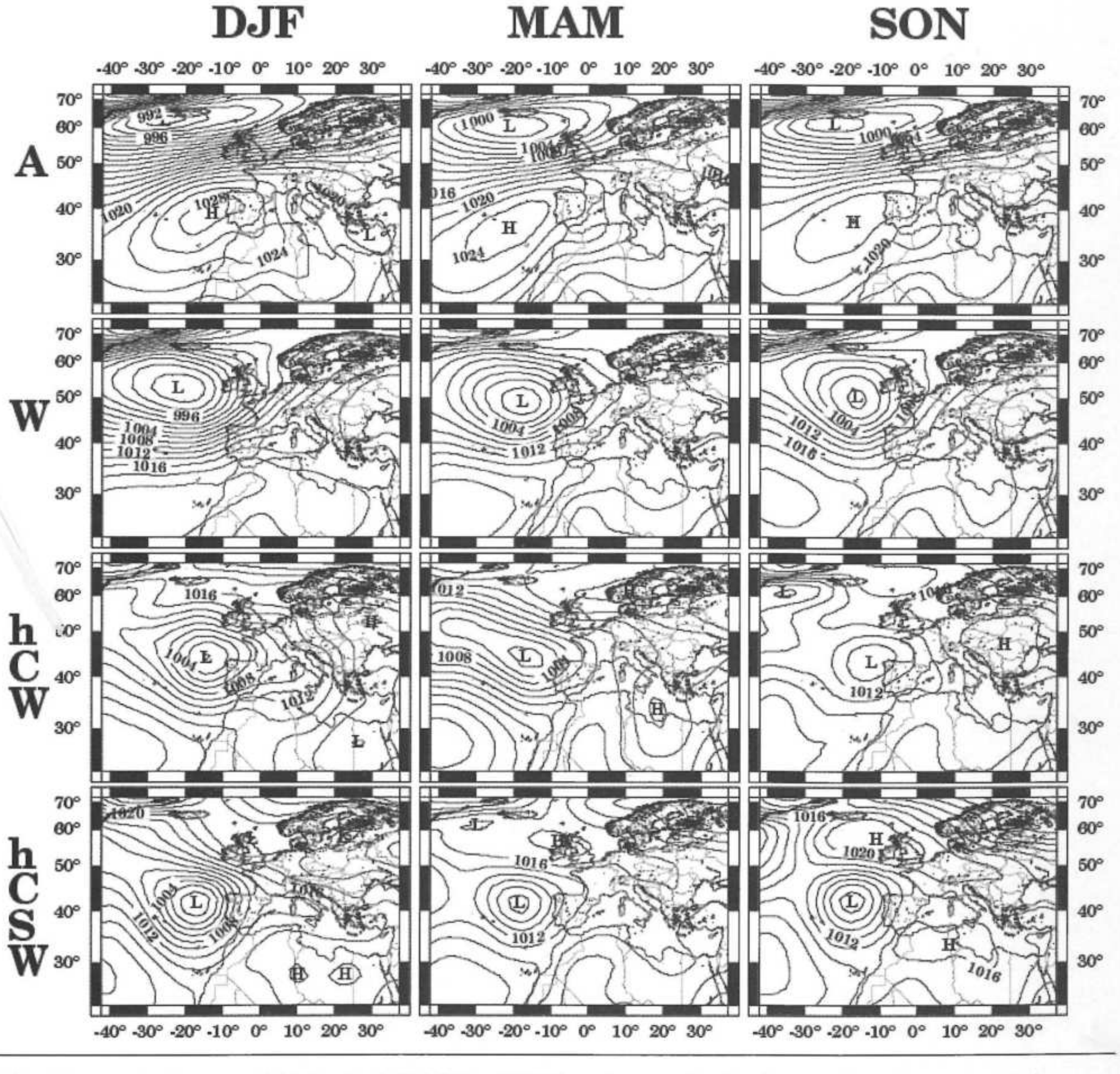


Fig. 2.33 – Mean sea level pressure fields for the A, W, hCW and hCSW weather types for the winter, spring and autumn period.

For the period of reanalysis, the frequency of the most effective hybrid CWTs, hCW and hCSW, doesn't show a significant trend, but the wettest pure types, W and C, have a negative tendency of -1.6 days/decade and -0.5 days/decade, respectively. On the other hand, the frequency of the most frequent and driest type, the A type, has a positive tendency of +5 days/decade for the whole period, increasing from +0.2 days/decade in the period 1958-1975 to +8.3 days/decade in the period 1975-1998. One can conclude that in the last quarter of the 20th century the anticyclonic type suffered a significant increase in frequency.

**Table 2.3 – Some climate indices**

| | TEMPERATURE INDICES |
|---|---|
| Su | Summer days (Nr. of days with maximum temperature above 25°C) |
| Tr | Tropical nights (Nr. of nights with minimum temperature above 20°C) |
| HWDI | Heat Wave Duration Index (Maximum period >5 consecutive days with Tmax>5°C above the 1961-90 daily Tmax normal) |
| | PRECIPITATION INDICES |
| R10 | Nr. of days with precipitation amount ≥ 10 mm |
| CDD | Maximum number of consecutive dry days (Maximum nr. of consecutive days in a period with precipitation amount <1mm) |
| R5D | Greatest 5-day precipitation total (Maximum 5-day precipitation sums) |

### 2.2.2.8 Climate indices

Extreme climate events and climate variability can be defined in a number of different ways. In this study, we choose indices to analyse variability and extremes following Nicholls and Murray (1999), Folland *et al.* (1999) and related work. The majority of indices are based on data with daily resolution. The use of daily data was recommended at the CLIVAR/GCOS/WMO workshop on indices and indicators for climate extremes (Karl *et al.*, 1999).

The indices selected highlight changes in mean, variability and extremes, for time scales in the range between days and decades. The indices for extremes are defined as (non) exceedances of given thresholds. The set of indices considered in this work is presented in Table 2.3.

## Changes in temperature related indices

One of the temperature indices with a larger variation from 1976 (the start of the warming period) onwards is the annual number of "tropical nights" (Table 2.3) shown in Fig. 2.34 for Lisbon. At this station, the number of tropical nights has increased from an average value of 7 days, in 1970s, to around 20 days by the end of the 20th century. This increase is clearly related to the positive trend of minimum temperatures registered from 1976.

An index related to the maximum temperature is the annual number of "summer days", also shown in Fig. 2.34 for Lisbon. There is a slight positive trend in this index from the 1970s, although by the end of the century it has not recovered the larger values registered in the 1940s. The smaller increase in this index

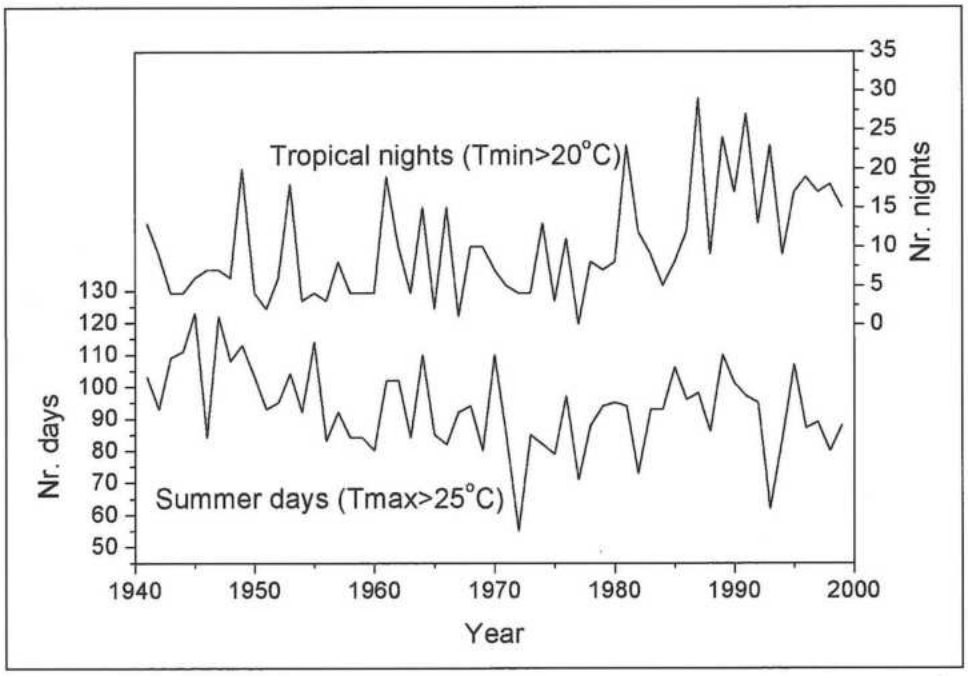


Fig. 2.34 – Lisbon time series of the number of "tropical nights" per year (minimum temperature above 20°C – right axis) and the number of "summer days" per year (maximum temperature above 25°C – left axis).

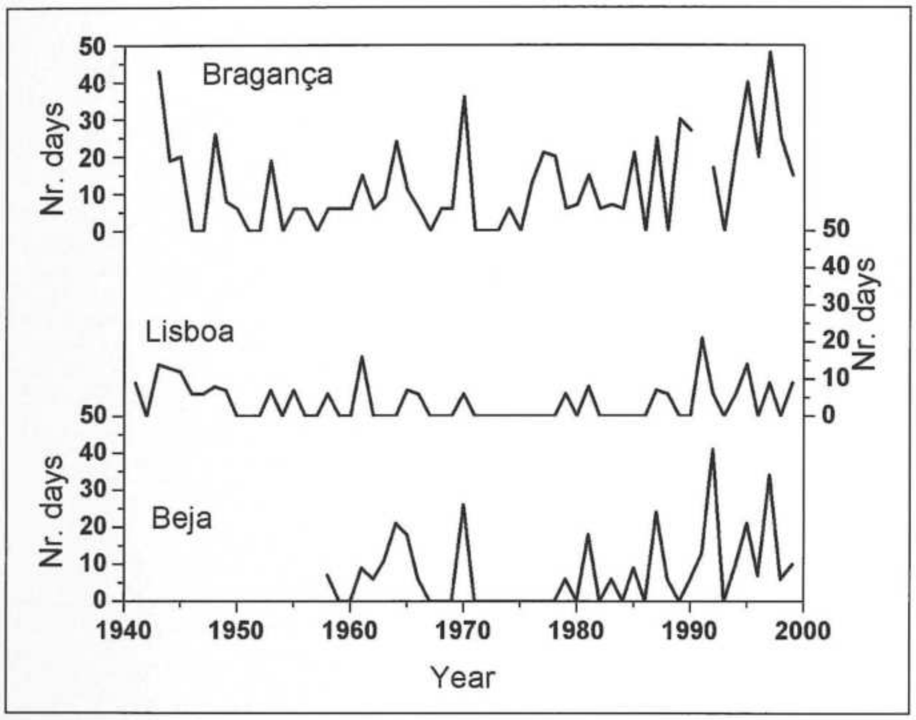


Fig. 2.35 – Time series of heat wave duration index (see Table 2.3) at Bragança (upper left axis), Lisbon (middle right axis) and Beja (bottom left axis).

in the last 3 decades is related to the smaller positive trend of the maximum temperature in comparison to the minimum temperature trend.

With respect to ecosystems and societal impacts, the persistence of relatively warm periods is even more important than the frequency of individual events. To study the changes in the persistence of periods with anomalously high temperatures one may look at trends in the index HWDI (table 2.3) that represents the duration of heat waves (Fig. 2.35).

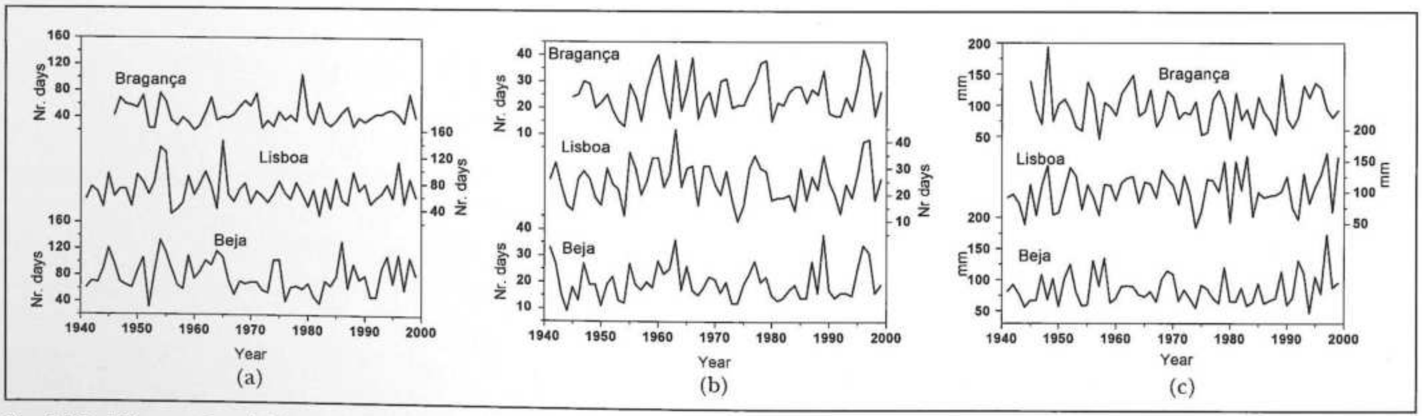
The duration of the heat waves has clearly increased after 1976 in Bragança and Beja, the most interior stations, having reached maximum values near or above 40 days in the 1990s. In Lisbon, a coastal station, the increase is not evident. The cooling period between 1946 and 1975 is also detectable in Fig. 2.35.

## Changes in precipitation related indices

The IPCC Report (1996) projected an intensification of the hydrological cycle due to global warming. This intensification is bound to lead to more extreme precipitation events. Increases in heavy precipitation rates have already been reported in certain areas, even in regions where the total precipitation has decreased (Kunkel *et al.*, 1999; Plummer *et al.*, 1999; Brunetti *et al.*, 2000; Groisman *et al.*, 1999). The precipitation indices can be used to identify both episodes of heavy rain and the occurrence of anomalous dry periods, and they are important in assessing the risk of floods and droughts.

The number of consecutive dry days (CDD) is presented in Fig. 2.36a for 3 stations in Portugal, and records do not show a significant trend. The number of days with precipitation ≥ 10mm (Fig. 2.36b) also has a somewhat irregular variation throughout the last 60 years, with no significant trend so far.

The maximum 5-day precipitation total (Fig. 2.36c) is an indicator of flood-producing events and shows some increase from the 1970s in Beja, where the last



(a) (b) (c)

Fig. 2.36 – Time series of (a) maximum consecutive dry days (CDD), (b) number of days with precipitation ≥ 10mm (R10), (c) greatest 5-day precipitation total (R5D). Bragança (upper left axis), Lisbon (middle right axis), Beja (bottom left axis).

decade has produced severe episodes of flooding, but changes are not yet significant. The other stations do not show a clear signal in this indicator during the last warming period.

In conclusion, this set of precipitation indices has a weaker signal in the warming period 1976-2000 than the temperature indices. In general the indices detect a weak growing tendency for more extreme events of precipitation in this period, especially in the south of Portugal, but trends are not statistically significant.

### Drought index

Mainland Portugal is especially prone to episodes of drought, due to its geographical location, with the south of the country being the most vulnerable area. The indicator chosen in this work to characterize drought severity is the Palmer Drought Severity Index – PDSI (Palmer, 1965), which combines the effects of temperature and precipitation. This index measures the accumulated effect of monthly rainfall deficit/surplus relative to the monthly "climatologically appropriate rainfall", defined as rainfall needed to maintain adequate soil water content for normal (water stress free) growth of plants in a region. This appropriate rainfall is a function of time and its monthly values are calculated from surface and soil water balance among evaporation, plant transpiration, runoff and available soil water for evaporation and transpiration (Hu and Willson, 2000; Palmer, 1965). The appropriate rainfall is a function of air temperature, through the evaporation and transpiration.

In this subsection the objective is to follow the time evolution of the PDSI at several climate stations in Portugal, and to determine whether drought episodes have become more frequent in the latter part of the 20th century. The PDSI was then calculated on a monthly basis for 4 stations in mainland Portugal (Porto, Lisbon, Évora and Beja), and the time series obtained are shown in fig. 2.37. The classification of the PDSI, concerning dry periods and wet periods, is as in table 2.4.

Fig. 2.37 reveals a high frequency oscillation of the PDSI between negative and positive values, superimposed with periods of consecutive months with negative or positive values, which are almost coincident for the 4 stations presented. The south station of Beja registers the greatest frequency of extreme droughts (3.8%), with Lisbon and Évora showing very similar frequencies (1.7% and 1.8% respectively). The Porto station has the lowest incidence of extreme droughts (0.6%).

**Table 2.4 – PDSI classification**

| Index | Description |
|---|---|
| 4.00 or above | Period of heavy rain |
| 3.00–3.99 | Period of severe rain |
| 2.00–2.99 | Period of moderate rain |
| 0.50–1.99 | Period of light rain |
| 0.49– -0.49 | Normal period |
| -0.50– -1.99 | Period of light drought |
| -2.00–2.99 | Period of moderate drought |
| -30.00– -3.99 | Period of severe drought |
| -4.00 or less | Period of extreme drought |

With respect to the change in variability of the PDSI, the negative values dominate the last 20 years of the 20th century, especially in the south interior stations of Évora, Beja and also in Lisbon. The 1980s decade starts with a sudden and large decrease of the PDSI, maintaining the negative values through several years. According to Fig. 2.37 the values of the PDSI in the cooling period 1946-1975 are less negative than in the warming period 1976-2000, suggesting an increased frequency of droughts in the south of Portugal.

## 2.3 CLIMATE SCENARIOS FOR THE 21ST CENTURY

### 2.3.1 GLOBAL SCENARIOS

#### 2.3.1.1 Global Circulation Models - GCMs

Numerical Atmosphere-Ocean Global Circulation Models (GCMs) are the best way known to simulate climate change scenarios, such as the impact on Earth climate of the increase of greenhouse-gas concentrations in the atmosphere. State of the art GCMs are now able to accurately reproduce the large scale seasonal distributions of pressure and temperature. These models are mathematical representations of the physical processes in the atmosphere and ocean, including ice and land processes, and their interactions. The atmospheric and ocean models consist of a discrete representation of the fluid equations, with

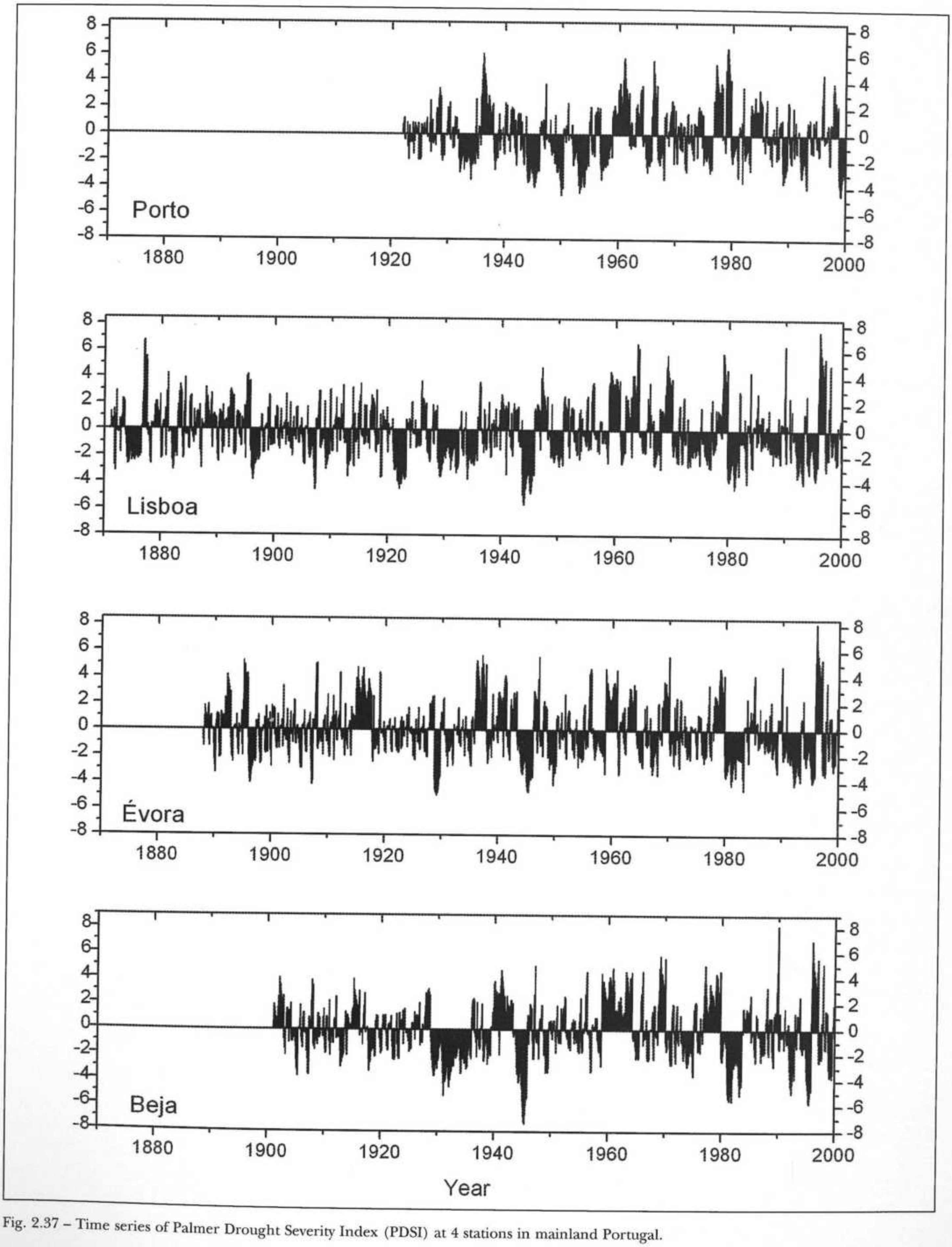


Fig. 2.37 – Time series of Palmer Drought Severity Index (PDSI) at 4 stations in mainland Portugal.

typical horizontal resolutions of a few hundred kilometres and time steps around 30 minutes. Many smaller scale processes have to be parameterised, including cloud processes, orographic gravity waves and atmospheric boundary layer effects.

In recent years, the confidence in the ability of GCMs to project future climate has increased significantly. As the models resolution increases and more complex processes are added to the GCMs formulation, they are starting to simulate more accurately some feed-backs and regional features (IPCC WGI, 2001). Several recent versions of GCMs (such as the Hadley Centre HadCM3 model) were capable of reproducing the main features of the observed mean global temperature trends, up to the end of the 20th century (Hadley Centre Report, 2001). Nevertheless, there are still many uncertainties associated with GCM simulations, either relating to the model formulation, where cloud representation is a particular problem, or to the uncertainties in the greenhouse gases future emissions scenarios. Moreover, the spatial resolution of GCMs is still too coarse to take into account the details of topography and coastal lines, among other factors. With these shortcomings in mind, this section proceeds to analyse GCM simulation data for the 21st century in the Iberian Peninsula and more specifically in Portugal.

The GCM data used in this section has been obtained through the IPCC Data Distribution Centre as of April 2001 (table 2.5). All the IPCC GCMs from which data was used in this study are fairly recent coupled atmosphere-ocean models. Most of the simulations go as far in the future as the 2100 year. Many runs start in the middle industrial revolution era (1860) when the carbon dioxide $CO_2$ (the main greenhouse gas in terms of climate change forcing) concentration is perceived to have been slightly above 280 ppmv (IPCC WGI, 1996). For the period 1860 to 1990 the models consider the historic concentrations of greenhouse gases. In 1990 the $CO_2$ concentration in the atmosphere was about 350 ppmv. From 1990 onwards the models consider an idealised emissions scenario with a

**Table 2.5 – GCMs from which data was used in this section (from IPCC-TGCIA, 1999)**

| Model | Entity | References | Emissions scenario |
|---|---|---|---|
| CSIRO Mk2 | Commonwealth Scientific Industrial Research Organisation (Australia) | Hirst et al. (1996), Gordon and O'Farrell (1997), Hirst et al. (2000) | 0.9%/year |
| ECHAM4/OPYC3 | European Centre/ /Hamburg/Deutches Klimarechenzentrum (Germany) | Roeckner et al. (1996), Zhang et al. (1998) | 1%/year compound |
| HadCM2 Simulations: GGa1-GGa4, GSa2 | Hadley Centre for Climate Prediction and Research (UK) | Johns et al. (1997) Mitchell and Johns (1997) | 1%/year compound |
| HadCM3 Simulations: GG, GS | Hadley Centre for Climate Prediction and Research (UK) | Gordon et al. (2000) | 1%/year |
| CGCM1 | Canadian Center for Climate Modelling and Analysis (Canada) | Reader and Boer (1998), Boer et al. (2000) | 1%/year |
| GFDL–R15a | Geophysical Fluid Dynamics Laboratory (USA) | Manabe and Stouffer (1996), Haywood et al. (1997) | 1%/year compound |
| NCAR DOE-PCM | National Center for Atmospheric Research (USA) | Washington et al. (2000), Meehl et al. (2000) | 1%/year linear |
| CCSR/NIES | Center for Climate Research Studies/National Institute for Environmental Studies (Japan) | Emori *et al.* (1999) | 1%/year compound |

1%/year increase in the $CO_2$ compound concentration (includes other greenhouse gases, such as methane $CH_4$, nitrous oxide $N_2O$, halocarbons and ozone $O_3$). This is close in terms of radiative forcing to the IPCC IS92a ("business as usual" scenario) (Leggett *et al.*, 1992, IPCC WGI, 1996). The 1%/year scenario considers a doubling of $CO_2$ compound concentration in 70 years (from 1990), whereas the IS92a scenario predicts a doubling of $CO_2$ compound concentration after 95 years (from 1990).

The Hadley Centre models have also included sulphate aerosol emissions in some runs. The aerosol particles, which have a short residence time in the atmosphere (of the order of a few years), are mainly produced by anthropogenic activity (agriculture, industry, transport) and natural causes (such as volcanoes). Some aerosol particles act as reflectors of the incoming solar radiation, thus reducing the global warming effect, whereas others reinforce the warming greenhouse effect. The projected evolution, for the 21st century, of aerosol concentration indicates a decrease in the values, which is already taking place in the developed countries. Nevertheless, the aerosol emission scenario used in the HadCM2 and 3 simulations (GS) has a levelling of the concentration at very high values, which seems somewhat unrealistic when compared to the new emissions scenarios (SRES) presented in the last IPCC WGI (2001) report (Parry, 2000).

The CSIRO, ECHAM4, CGCM1, GFDL, NCAR, CCSR, HadCM2 GGa1-GGa4 and HadCM3 GG runs do not include aerosol emissions. The HadCM2 GGa1-GGa4 simulations are an ensemble of four runs, starting from the control integration at successive 150-year intervals. The control integration is performed with constant greenhouse gas concentrations. The HadCM2 GSa2 and HadCM3 GS simulations include sulphate aerosol emissions based on the IS92a scenario. The HadCM2 GSa2 simulation is the second member of a 4-run ensemble, similar to the GG ensemble described for the HadCM2 model. The abbreviation GG in the HadCM3 GG run stands for GGa1.

The IPCC GCM data is stored on a monthly basis. For the impact studies presented in chapters 5-11 there was a need for daily data. Through the LINK project (Viner, 1996), based at the University of East Anglia (UK), it was possible to obtain daily data for the HadCM3 GGa1 simulation.

The HadCM3 model (Gordon *et al.*, 2000) is the most recent GCM developed at the Hadley Centre. This model does not require a flux correction to counteract the climate drift experienced by the earlier versions (HadCM2 included). The atmospheric model has a resolution of 2.5°-3.75° in latitude-longitude, being one of the highest resolution GCMs used for climate change impacts. The 3 grid points that fall in or very near the Portuguese area are presented in Fig. 2.1.

### 2.3.1.2 Time series of mean temperature in various GCMs in the Portuguese mainland area

Fig. 2.38 shows the time series of mean temperature anomalies in the Iberian Peninsula obtained with the different GCMs presented in table 2.5 and the corresponding time varying $CO_2$ scenarios described before.

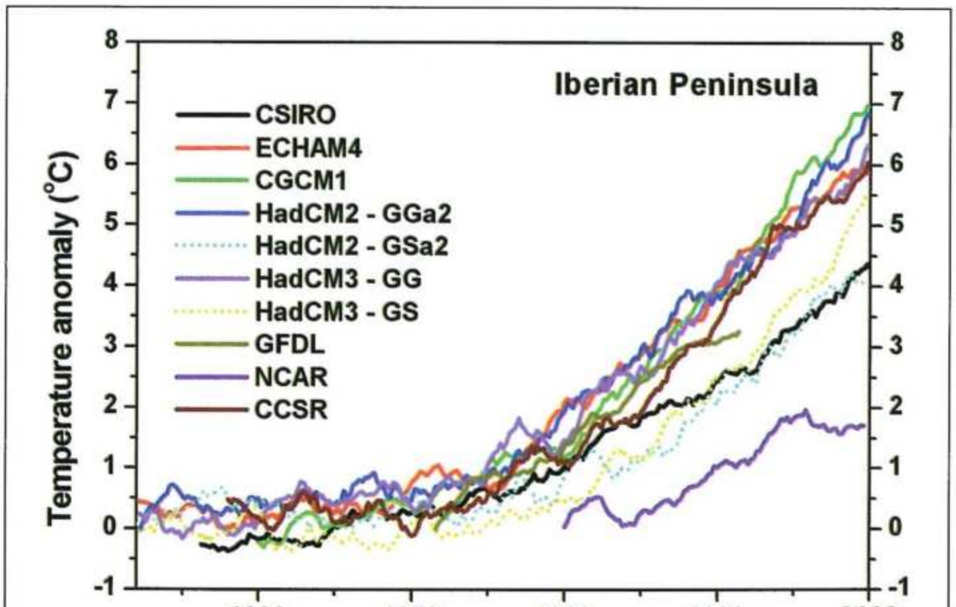


Fig. 2.38 – Mean temperature anomalies in the Iberian Peninsula obtained with the GCM data available at the IPCC DDC.

The curves have been smoothed using a 10-year running average. The temperature anomalies were calculated in relation to the control run of each model, which maintains the $CO_2$ concentration constant in time and, in most cases, at levels comparable to the baseline period 1961-1990. The HadCM control runs are performed with $CO_2$ concentrations of 323 ppmv. Nevertheless Fig. 2.38 indicates that the radiative forcing in the control runs is comparable to that of pre-industrial levels, as the temperature anomalies in 1860 are close to zero.

Fig. 2.38 shows an upward trend of the temperature anomalies, illustrating the mean warming of the Iberian Peninsula from the first half of the 20th century up to the year 2100. From 1950 to 2000, on average, the temperature increase is of the order of 1°C, being in line with the start up of the global warming process. By 2100 the GCMs predict a temperature increase in the interval 1.7°C – 7°C in relation to the control runs. It should be stressed that as all GCMs predict a significant warming in the 21st century, this is a qualitative result that has a fairly high confidence level. Nevertheless, as would be expected, the uncertainty in the temperature anomaly (difference between model results for a given year) increases with time, being highest in 2100.

The NCAR model predicts the smallest temperature increase, whereas the CGCM1 presents the steepest temperature increase. It should be kept in mind that the emissions scenarios are slightly different from model to model (table 2.5). The average warming rate varies from 0.17°C/decade (NCAR), passing through 0.4°C/decade (CSIRO), up to 0.6°C/decade (CGCM1). A discussion on the reasons of specific model discrepancies can be found in the literature (IPCC WGI, 1996 and model references in Table 2.5). The Hadley Centre runs including aerosol effects (HadCM2 - GSa2 and HadCM3 - GS) show, as expected, a systematic decrease in the temperature anomaly of the order of 1 to 3°C in 2100, when compared with simulations with greenhouse gas concentration (compound $CO_2$) increase only.

The ACACIA report (Parry, 2000), which was a major attempt to regionalize climate change scenarios for different regions in Europe, suggests that simulations including aerosol effects may not be as reliable as runs with $CO_2$ increase only. Aerosols scatter and absorb solar radiation and modify the reflectivity of the clouds. Both effects are thought to decrease the absorption of short-wave radiation by the Earth, exerting a cooling influence on climate. But, on top of that, it is argued that the aerosol effect can be either to decrease the temperature by reflecting the incoming short wave radiation or to increase the greenhouse effect, depending on the type of aerosol. Moreover the interactions between aerosol and clouds are not well understood yet, and are very poorly accounted for in the models. Finally, as was mentioned previously, the IPCC IS92a scenario used by the HadCM models probably overestimates the aerosol concentrations for the 21st century. Therefore another emissions scenario with smaller aerosol concentration could have less effect in moderating the greenhouse-gas induced warming, as is predicted by the latest GCM simulations using the new SRES emissions scenarios in the new IPCC WGI report (2001).

#### 2.3.1.3 Time series of total annual precipitation in various GCMs for the Portuguese area

A set of annual precipitation time series in the three grid points (see Fig. 2.1) falling in Portugal (Centre and South points) and Galiza (North point) are shown in Fig. 2.39 for the HadCM3 GG and HadCM2 GGa2 runs (with $CO_2$ concentration increase only). Again, a ten-year running average was applied to the annual data. It should be noted that the precipitation values have a more irregular variation from year to year than the mean annual temperature values. It was also observed that the precipitation signal varies much more from model to model than the temperature signal. In general, the precipitation is a more unpredictable field than the temperature, in particular because its distribution is associated with small scale processes, not resolved by large scale models.

The graphics in Fig. 2.39 show a slight downward trend in the annual precipitation in the three grid points from 2000 onwards, except for the HadCM2 – South point, which shows almost no trend in the evolution of precipitation.

On the other hand, Fig. 2.40 presents the same HadCM models annual precipitation time series, but in this case for the simulations with sulphate aerosol effects (GSa2 and GS). A comparison between Figs. 2.39 and 2.40 indicates that, not only there is a systematic difference in precipitation between the two versions of the model, but also that the introduction of the aerosol effect has significant impact in the results. The impact is much stronger in the older version of the model, where it leads to larger interdecadal precipitation variability, which makes the detection of a long term trend rather uncertain. In the HadCM3 simulation there is still a clear downward trend in precipitation, as found in the run shown in Fig 2.39. These results stress the difficulty in predicting the future precipitation trends even on a qualitative way. The signal of the precipitation variation due to greenhouse gas increase is more clearly represented by the anomaly shown in Fig. 2.41 obtained with some of the GCMs in table 2.5. The anomaly was computed using the mean precipitation in the $CO_2$ increase period 2070-2099 and the mean precipitation in the control simulations. Also represented in Fig. 2.41 are the simulations with aerosol effects. It should be noted that the grid points differ from model to model, but those points, located in Portugal or very near, have been gathered in the general designation North, Centre and South, representing their approximate locations. Nevertheless the HadCM2 and HadCM3 simulations consider the same grid points, as do the ECHAM4 and NCAR models.

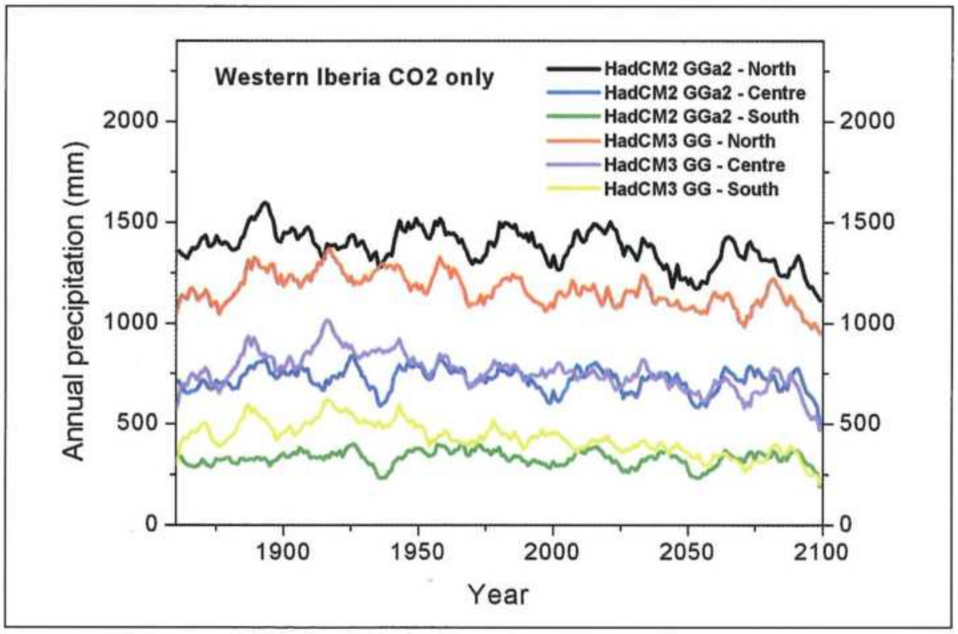


Fig. 2.39 – Annual precipitation from 1860 to 2100 in the 3 western Iberia HadCM2 and HadCM3 grid points (see Fig. 2.1). Simulations with $CO_2$ increase only.

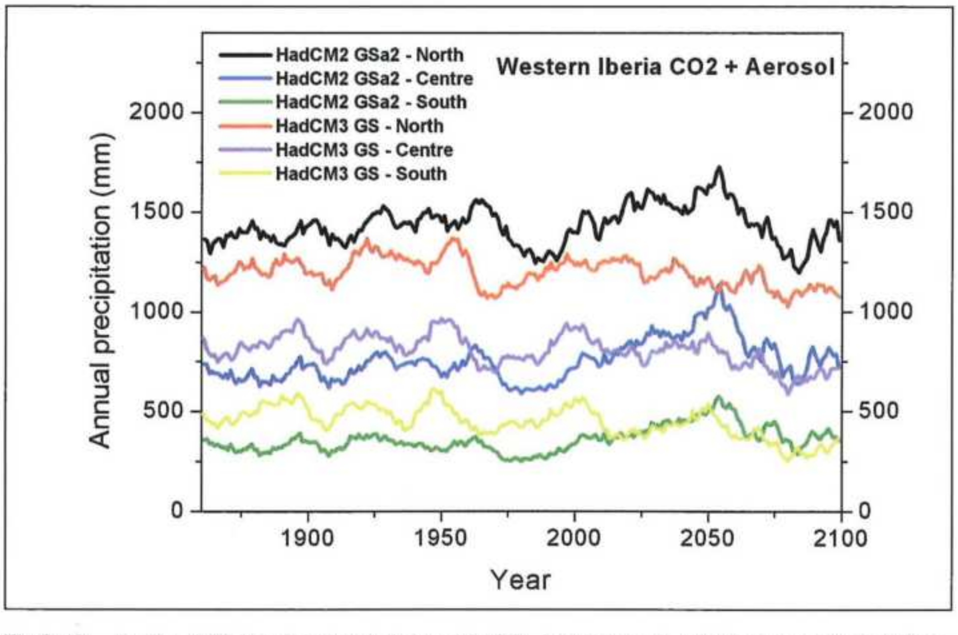


Fig.2 40 – As Fig. 2.39 but for simulations with $CO_2$ increase and sulphate aerosol emissions.

All but one of the model runs (the HadCM2 GSa2 aerosol run) indicate a decrease in precipitation due to greenhouse gas increase. The HadCM2 GSa2 aerosol run predicts an increased precipitation in the Centre and South regions of Portugal in the period 2070-2099. The magnitude of the decrease in precipitation is highly variable from model to model, spanning a wide range, especially in the Centre and South points. The Northern region focuses more the precipitation losses between 50mm and 200mm per year. Again, the difficulty of presenting a reliable scenario for the evolution of the precipitation is evident, due to the wide spread of results.

These annual precipitation results broadly agree with those of the ACACIA report (Parry, 2000), which refers to a gradual decrease in annual precipitation in Southern Europe (maximum -1%/decade) up to the end of the 21st century. The recent Hadley Centre research update report (2001) also indicates a decrease in annual precipitation in the Iberian Peninsula of up to

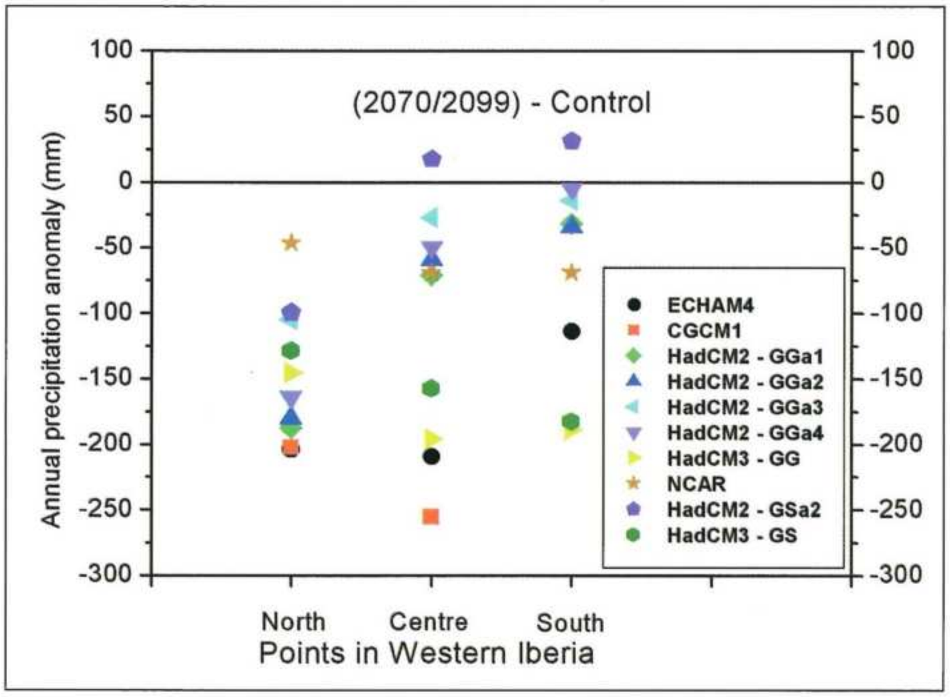


Fig. 2.41 – Annual precipitation anomalies in Western Iberia obtained with the IPCC DDC GCM data.

almost –1 mm/day by the 2080s, obtained in some simulations. The Hadley Centre results were obtained with the HadCM3 model and the new IPCC SRES scenarios (2001).

It should be noted that global warming in the 21st century leads to a greater average content in atmospheric water vapour and, consequently, to an increase in global average precipitation. However, the regional variations are large, and some land areas in the mid and low latitudes, such as southern Europe, southern Africa, Australia, Central America and the northern region of South America, are expected to suffer a decrease in precipitation (Hadley Centre, 2001).

### 2.3.1.4 Annual cycle of precipitation in various GCMs in the Portuguese area

The annual cycle of precipitation also suffers a distinct change when the CO$_2$ concentration increases, as shown in Fig. 2.42, presenting monthly anomalies from the reference 1961-1990 period of the increasing CO$_2$ concentration simulations. In the winter months (DJF) most models predict a slight increase in precipitation in the northern grid points (black curves), whereas the Centre and Southern points (red and green curves respectively) have a different behaviour in each model. In the other seasons, all models predict a reduction in precipitation, although with different values. This result is compatible with the ACACIA report's (Parry, 2000) findings for southern Europe (and more specifically for Spain), which suggests an increase in precipitation in the DJF months and a reduction in the summer months (JJA). The GCM based studies of Trigo and Palutikof (2001) and Hulme and Sheard (1999) for the Iberian Peninsula also corroborate the increase in precipitation in winter and reductions in the other seasons in its Western sector.

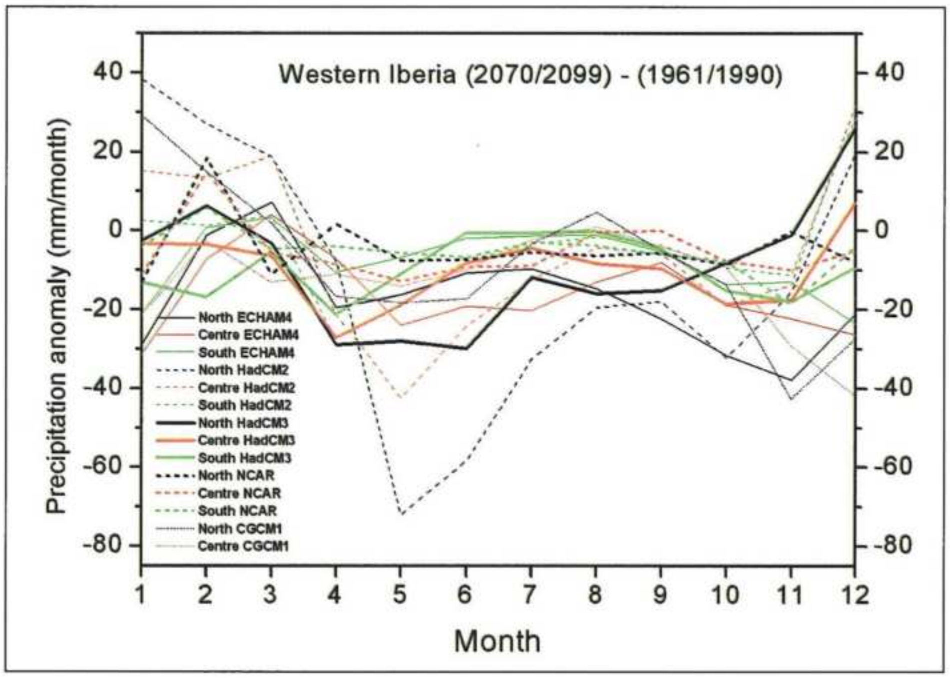


Fig. 2.42 – Monthly precipitation anomalies in western Iberia obtained with the IPCC DDC GCM data. Black curves – North points, red curves – Centre points, green curves – South points. Simulations with CO$_2$ increase only.

It should be noted that the HadCM2 GGa2 simulation, which forces the boundaries of the Regional Climate Model HadRM used in the following sub-sections, has the greatest variations in anomaly precipitation along the year, particularly in the North point during winter and spring. These extreme changes do not seem to be matched in such intensity by the other models. It is not clear how this fact can affect the HadRM results used in the impact studies presented in this book.

## 2.3.2 REGIONAL SCALE SCENARIOS

### 2.3.2.1 Regional Climate Models - RCMs

This work uses a Regional Climate Model (RCM) to assess in greater detail the impacts of global warming in Portugal. The RCM used is the HadRM (version 2) Hadley Centre model (Jones *et al.*, 1995; Jones *et al.*, 1997b; Noguer *et al.*, 1998; Murphy, 1999), which is nested inside the Hadley Centre GCM HadCM2, the previous version of the current HadCM3 model. The HadRM uses a grid with about 50km horizontal resolution and is run with a 5 minutes time step. The model is integrated in spherical polar coordinates, with the coordinate pole shifted so that its domain appears as a rectangular equatorial segment on a rotated grid (rotated polar projection to give equal area grid cells). It covers an area corresponding to Europe and the North Atlantic. At its lateral boundaries, the HadRM is driven by the HadCM2 (one-way nesting). At the sea grid points, values of sea surface temperature (SST), among other parameters, are prescribed from the HadCM2 fields saved every 5 days.

As with the HadCM3 data, the LINK project (Viner, 1996) supplied the daily and monthly HadRM data used in this work. The data is taken from two sets of simulations:

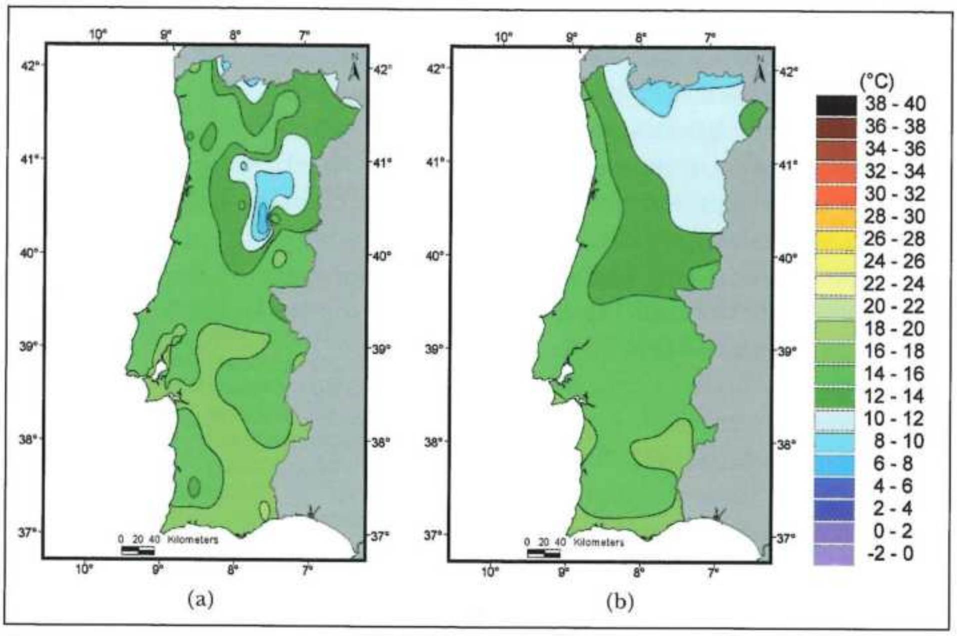
1 – the control simulation performed with a constant value of $CO_2$ compound concentration (323 ppmv), which is compared with climatology in the baseline period 1961-1990. The period supplied is 2006-2036 for the daily data and 2010-2035 for the monthly data;
2 – the increasing $CO_2$ compound concentration simulation (1%/year from 1990 – no sulphate aerosol effects) forced by HadCM2 GGa2 (see table 2.5), for the period 2080-2100 (monthly and daily data).

There are several advantages in using a Regional Climate Model, instead of a GCM, for the purpose of performing regional scale studies, such as climate impacts in Portugal. GCMs have a horizontal resolution on the order of hundreds of kilometres, whereas RCMs resolve scales of tens of kilometres. Therefore in regions where smaller scale features strongly affect the local climate, the RCMs can provide better climate fields. RCM simulations embedded in a GCM downscale the global results to the scale needed for regional studies. In RCMs the orography and coastal lines are much better represented than in GCMs, improving the spatial distribution of precipitation, especially when associated with mountainous regions. Also the occurrence of localised extreme events, such as extreme rainfall episodes, is better modelled by RCMs. The Hadley Centre report (2001) asserts that the confidence in predictions of changes in extremes (in climate impact assessments) from HadRM is higher than those from the HadCM models. However the report also warns that as the RCMs are forced by the GCMs, they are affected by the large-scale uncertainties in the GCM. A study of the performance of HadRM in predicting the distribution of extreme daily precipitation has been recently published by Durman *et al.* (2001), indicating that the HadRM results significantly improve GCM scenarios in the control simulations.

Some authors (e.g. von Storch *et al.*, 1993) have developed statistical methodologies to downscale GCM fields to the regional scale, making use of observed data. When the methodology was proposed, that was the only approach that could be applied, and it may still have its appeal considering the fact that real observed data implicitly includes many phenomena that cannot be simulated even by RCMs. On the other hand, there is no guarantee that the statistically downscaled fields will be physically consistent, as there is no guarantee that the transfer functions – from large scale to regional scale fields – will remain unchanged in climate change scenarios. While both approaches are scientifically sound, we believe that the dynamical downscaling provided by RCMs is, when available, the best choice. A systematic comparison of dynamical and statistical downscaling techniques, based on the same HadRM simulations that are used in the present study, was performed by Murphy (1999) indicating a better performance for the dynamical (HadRM based) approach in western Europe, justifying the choice made here.

### 2.3.2.2 Comparison between regional climate control simulations and climate observations

To test the accuracy of the HadRM model in the Portuguese area, a comparison was made between the control run annual mean temperature and precipitation and 1961-1990 climate data from the Portuguese Institute of Meteorology (IM), already shown in section 2.2.1. The climatology results are repeated in figures 2.43a and 2.44a, whereas the HadRM annual mean temperature plot is shown in Fig. 2.43b and the annual precipitation in Fig. 2.44b.



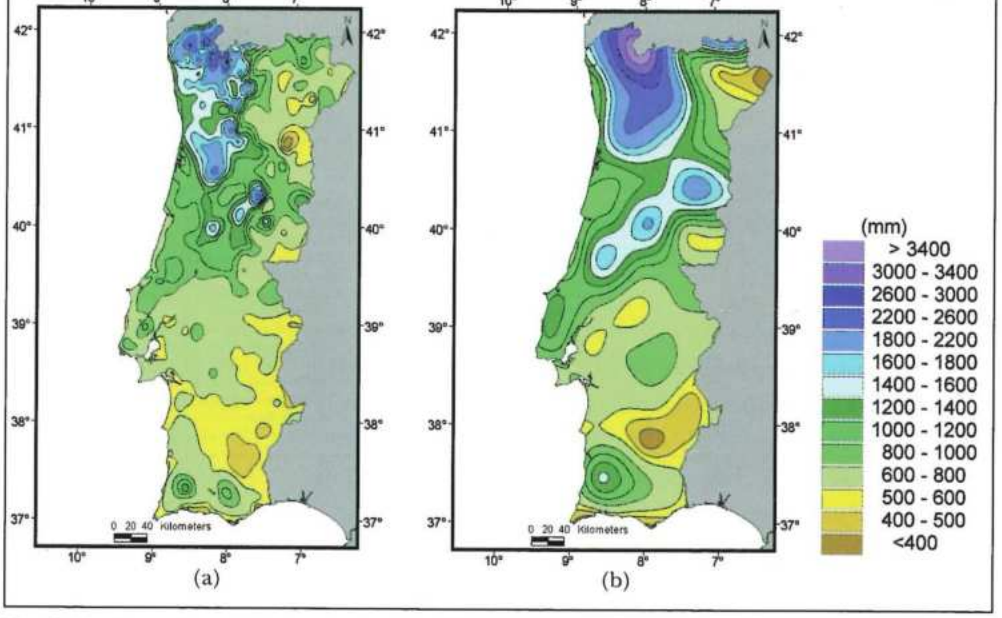
(a) (b)

Fig. 2.43 – Annual mean temperature in the (a) 1961-1990 climatology and (b) the HadRM control simulation.

The two mean temperature plots in Fig. 2.43 have very strong similarities. The temperature magnitudes are comparable and vary approximately between the same values. Both maps show a north-south temperature gradient of the same magnitude. However, the lower temperatures seen in the north and centre highlands are not correctly represented by the model. The model also has a slight cold bias (0.5°C to 2°C) in respect to the climate data, more evident in the north of the country. It should be noted, though, that one should expect some differences in these fields, due to the smoothness of model orography when compared with the real terrain.

The similarities between the control annual precipitation and the climate data (Fig. 2.44) are also striking. The precipitation contours show much more spatial detail than was found for temperature, and the main features of the spatial configuration in the observations are well modelled by HadRM. There are, nevertheless, areas where the model gives an excess of precipitation, such as the western coast northwards of Lisbon, and the Montejunto-Estrela mountain ridge (almost parallel and slightly to the north of the Tagus river), which appears too wide in the model. Again, there is a strong north-south (negative) precipitation gradient, coupled with a seaside-interior gradient. The model represents correctly the wettest northwest region of Portugal and the effects of the highlands in the centre of the country.

The results shown in Fig. 2.43 and 2.44 are an indication that the HadRM model is able to represent with



(a) (b)

Fig. 2.44 – Annual precipitation in the (a) 1961-1990 climatology and (b) the HadRM control simulation.

some accuracy the recent past Portuguese climate, with its regional variations. This fact allows us to assume that the forthcoming results obtained with the future greenhouse gas increase scenarios have some degree of credibility, keeping in mind, though, the many uncertainties of long term precipitation prediction. Throughout the rest of this chapter other control run maps will be compared with the observations provided by the IM, shown already in section 2.2.1.

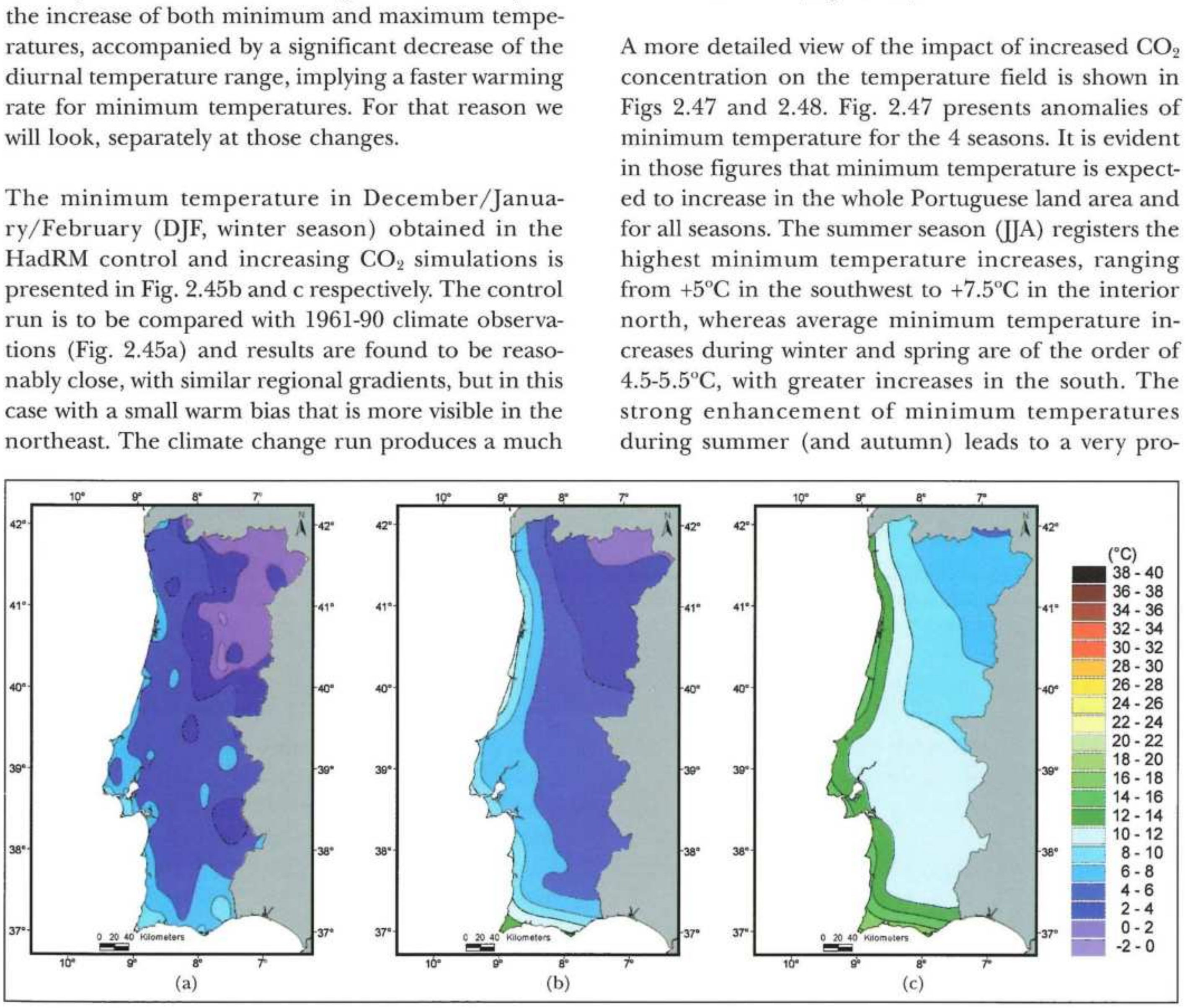
### 2.3.2.3 Changes in temperature

Minimum and maximum temperatures may change in different ways in climate change scenarios. Late 20th century observations showed a general tendency for the increase of both minimum and maximum temperatures, accompanied by a significant decrease of the diurnal temperature range, implying a faster warming rate for minimum temperatures. For that reason we will look, separately at those changes.

The minimum temperature in December/January/February (DJF, winter season) obtained in the HadRM control and increasing $CO_2$ simulations is presented in Fig. 2.45b and c respectively. The control run is to be compared with 1961-90 climate observations (Fig. 2.45a) and results are found to be reasonably close, with similar regional gradients, but in this case with a small warm bias that is more visible in the northeast. The climate change run produces a much warmer climate, with significant increases in the average minimum temperature in the winter season.

The average maximum temperature in June/July/August (JJA, summer) presented in Fig. 2.46 also suffers a substantial enhancement with the greenhouse gas concentration increase. The regional model suggests that seasonal average values as high as 38°C may be encountered in the south interior of Portugal in the climate change scenario (Fig. 2.46c). Results for the control run reveal, for the summer maximum temperature, a significant cold bias of the model results in the north of Portugal. In this region, the control run predicts maximum temperatures in the range of 20-24°C (Fig. 2.46b) where observations are in the interval 26-30°C (Fig. 2.46a).

A more detailed view of the impact of increased $CO_2$ concentration on the temperature field is shown in Figs 2.47 and 2.48. Fig. 2.47 presents anomalies of minimum temperature for the 4 seasons. It is evident in those figures that minimum temperature is expected to increase in the whole Portuguese land area and for all seasons. The summer season (JJA) registers the highest minimum temperature increases, ranging from +5°C in the southwest to +7.5°C in the interior north, whereas average minimum temperature increases during winter and spring are of the order of 4.5-5.5°C, with greater increases in the south. The strong enhancement of minimum temperatures during summer (and autumn) leads to a very pro-



(a) (b) (c)

Fig. 2.45 – Minimum temperature in winter (DJF) for the (a) 1961-1990 climatology, (b) HadRM control run and (c) HadRM GGa2 simulation (2080-2100 period).

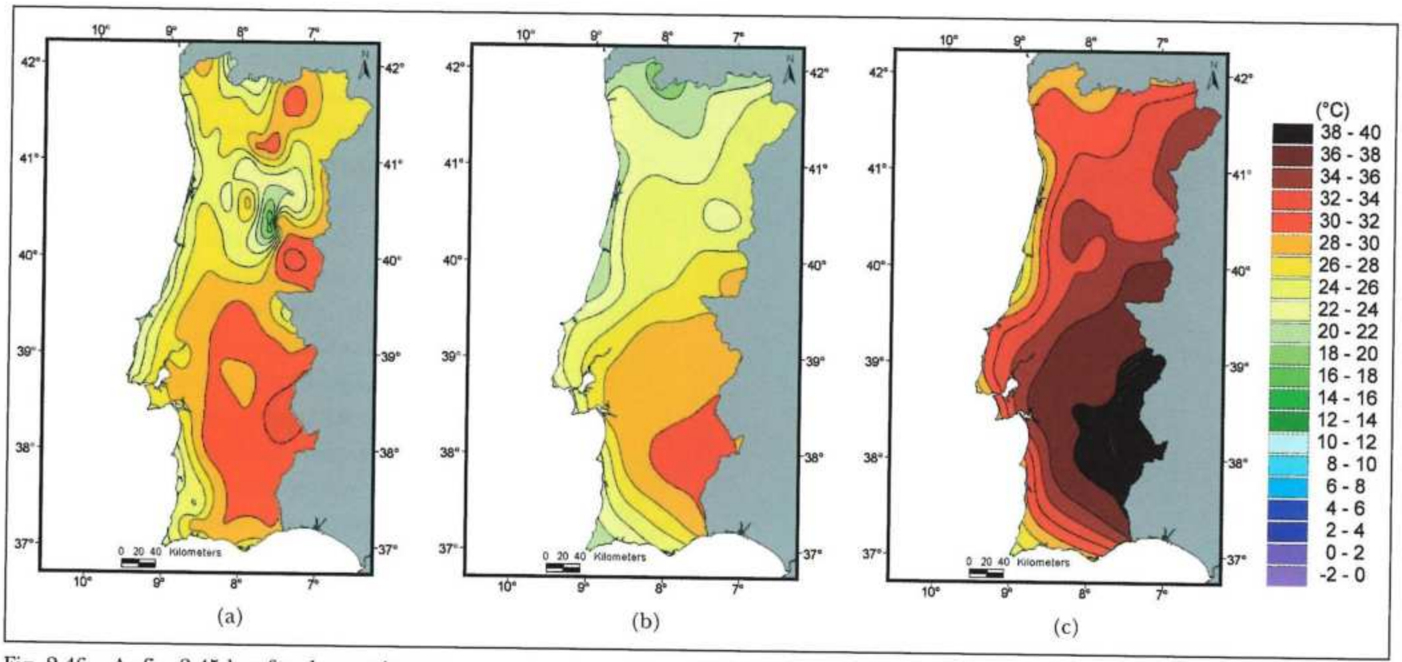


Fig. 2.46 – As fig. 2.45 but for the maximum temperature in summer (JJA)

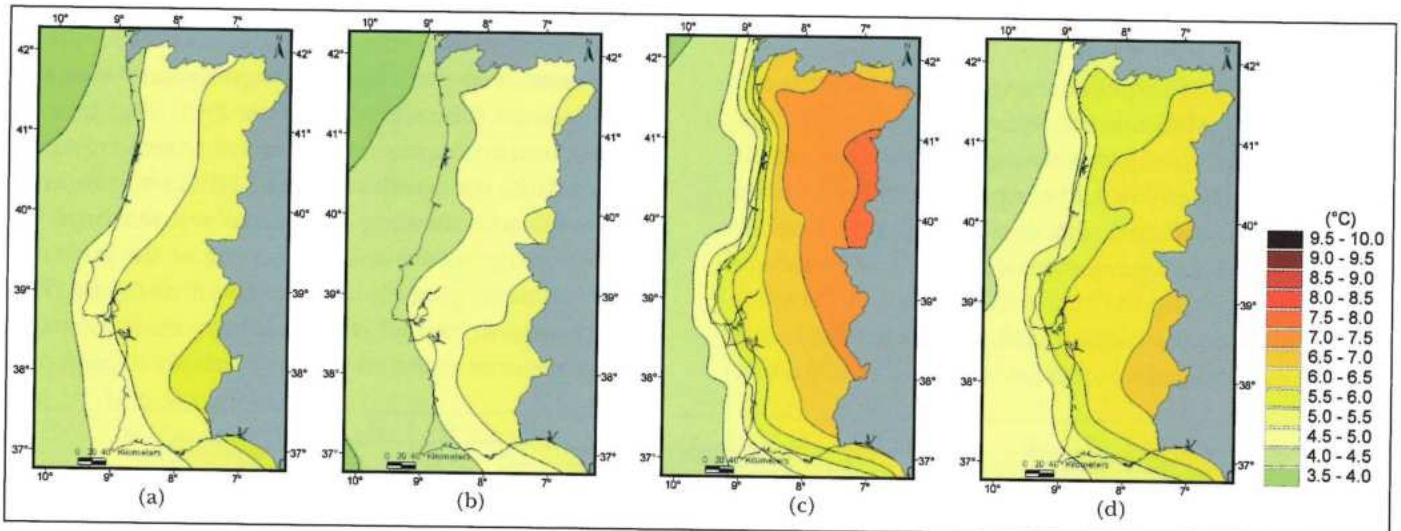


Fig. 2.47 – Seasonal minimum temperature anomalies (HadRM GGa2 - Control) in (a) winter (DJF); (b) spring (MAM); (c) summer (JJA); (d) autumn (SON).

nounced increase in the number of tropical nights during these seasons. In all seasons, but especially during summer, the overall warming is accompanied by an intensification of the seaside-interior thermal gradient.

The seasonal maximum temperature anomaly maps are shown in Fig. 2.48. It can be immediately concluded that the annual cycle of the maximum temperature anomaly is stronger than that of the minimum temperature anomaly. This is in part due to the very intense maximum temperature summer anomaly, which can reach 9-9.5°C in the interior centre and shows again a very pronounced seaside-interior gradient. This gradient is expected to reinforce the intensity of the low pressure centre which forms on the Iberian Peninsula especially during summer. What could follow is an intensification of the northern breeze affecting the coastal zones of the Peninsula. That process is probably poorly represented by the regional model, and it will be further discussed, later in the text.

In winter the maximum temperature anomaly is much smaller, of the order of 4°C, and shows a small north-south gradient, with no coastal signature, whereas

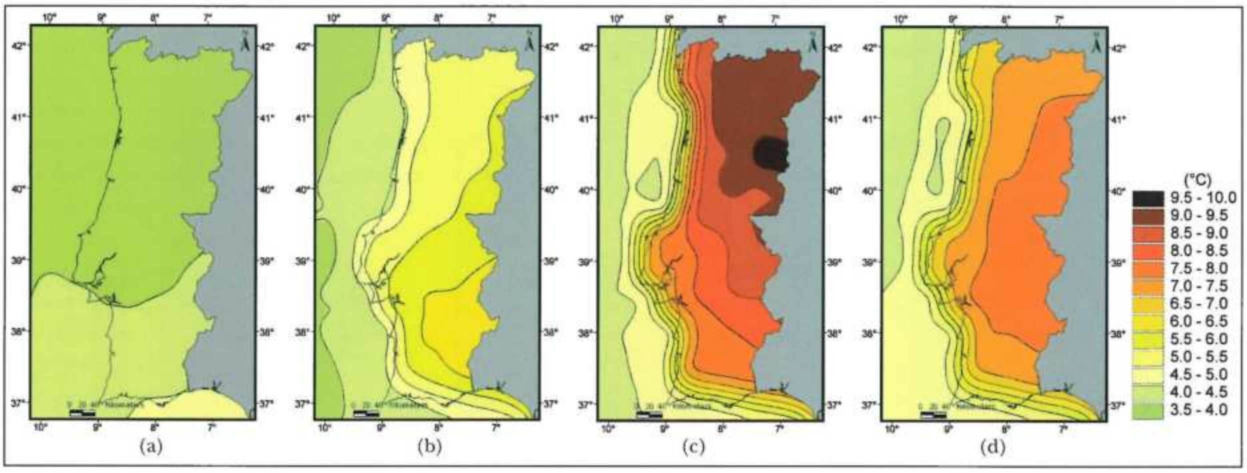


Fig. 2.48 – As fig. 2.47 but for the seasonal maximum temperature anomalies.

anomaly contours in all other seasons are almost parallel to the coastline. It is curious to observe that the largest maximum temperature anomaly moves substantially in the annual cycle, from the south in winter, to the south interior in spring, then to the interior north in summer and occupies most of the interior in autumn.

Associated to the maximum temperature and minimum temperature anomalies are the anomalies in the diurnal temperature range (DTR=Tmax-Tmin) for each season, shown in Fig. 2.49. Because the minimum temperature anomaly in winter is greater than the maximum temperature anomaly, Fig. 2.49a shows a negative DTR anomaly. The situation is inverted in the remaining seasons, which have positive anomalies, with maximum values in summer and in the north, as expected. This means that the diurnal temperature amplitude is expected to decrease in winter, probably due to increased cloud cover, which favours increases more of the minimum temperature than of maximum temperature. In the other seasons, DTR is expected to increase because the increase in maximum temperature dominates.

Another good indicator of climate warming is the number of days per year or season that are above or below a certain threshold temperature. The following figures compare this indicator with the corresponding control simulation for the threshold temperatures 25°C, 35°C, 20°C and 0°C, already used in the analysis of climate observations.

We will first look at the number of "summer days", defined as days with maximum temperature above 25°C (Fig. 2.50). The control simulation (Fig. 2.50b)

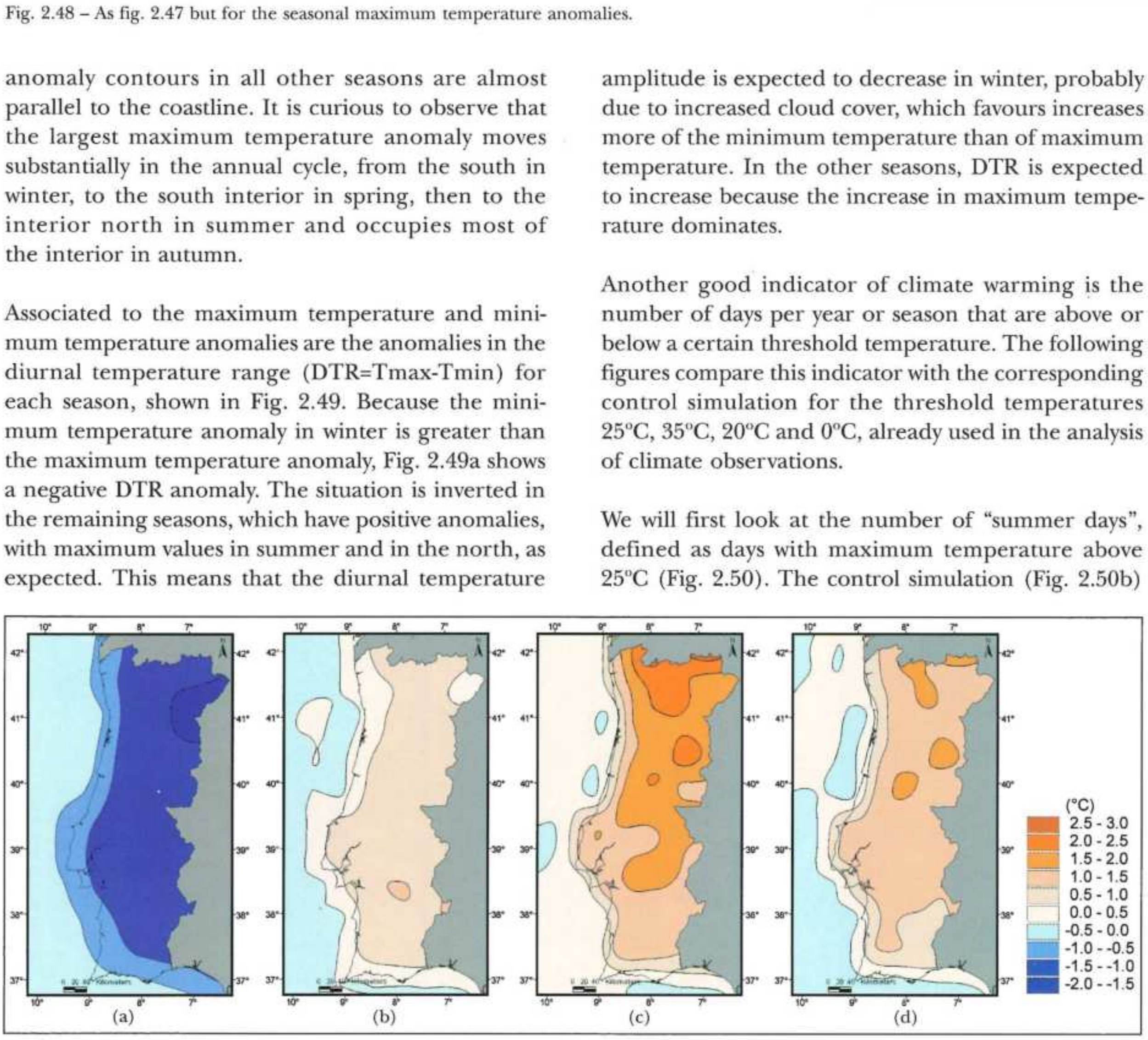


Fig. 2.49 – As fig. 2.47 but for the diurnal temperature amplitude anomalies (°C).

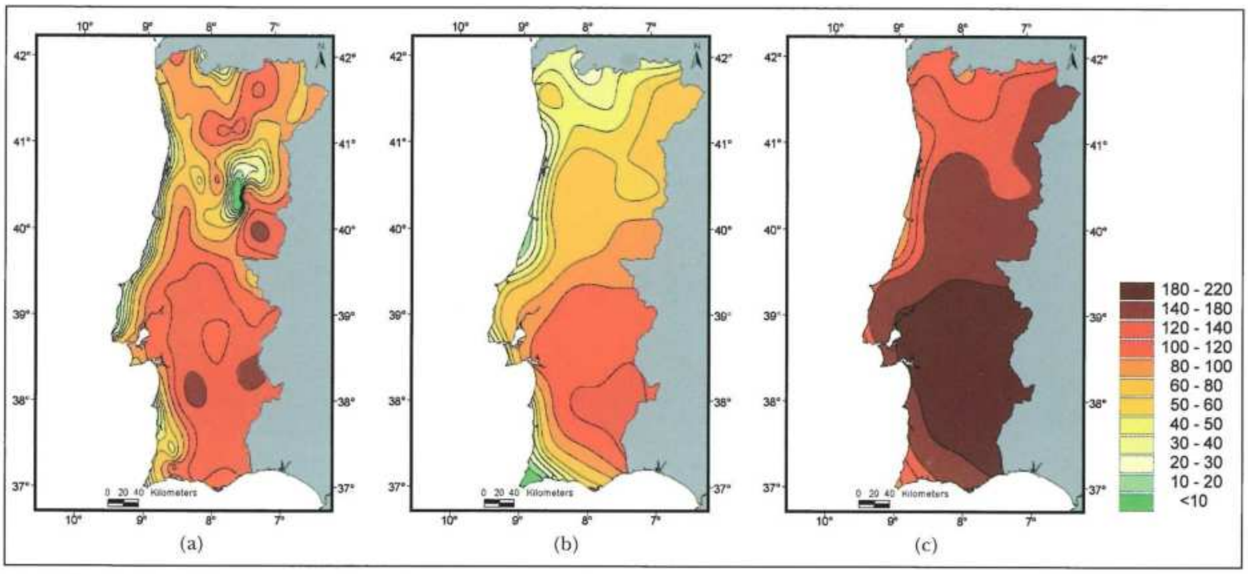


Fig. 2.50 – Number of days per year with maximum temperature above 25°C ("summer days") for the (a) 1961-1990 climatology; (b) HadRM control simulation; (c) HadRM GGa2 simulation (2080-2100 period).

indicates that this number is clearly higher in the interior south of Portugal, where, on average, more then 120 days belong to this class. Again, it should be kept in mind that the model has a cold bias that is stronger in the north of the country (compare with observations in Fig. 2.50a). In the control simulation, days with maximum temperature above 25°C occur mainly in the summer (JJA) period. In the climate change scenario, both spring and autumn have a significant number of days above the 25°C threshold, implying a significant increase in the annual average frequency of "summer days" to 120 days in the north, 150 in the centre and more than 180 in the interior south (Fig. 2.50c).

Even more significant is the change in the number of "hot days", with maximum temperature above 35°C, shown in Fig. 2.51. In the control simulation (Fig. 2.51b), which compares very well with climatology (Fig. 2.51a), the number of "hot days" is only signi-

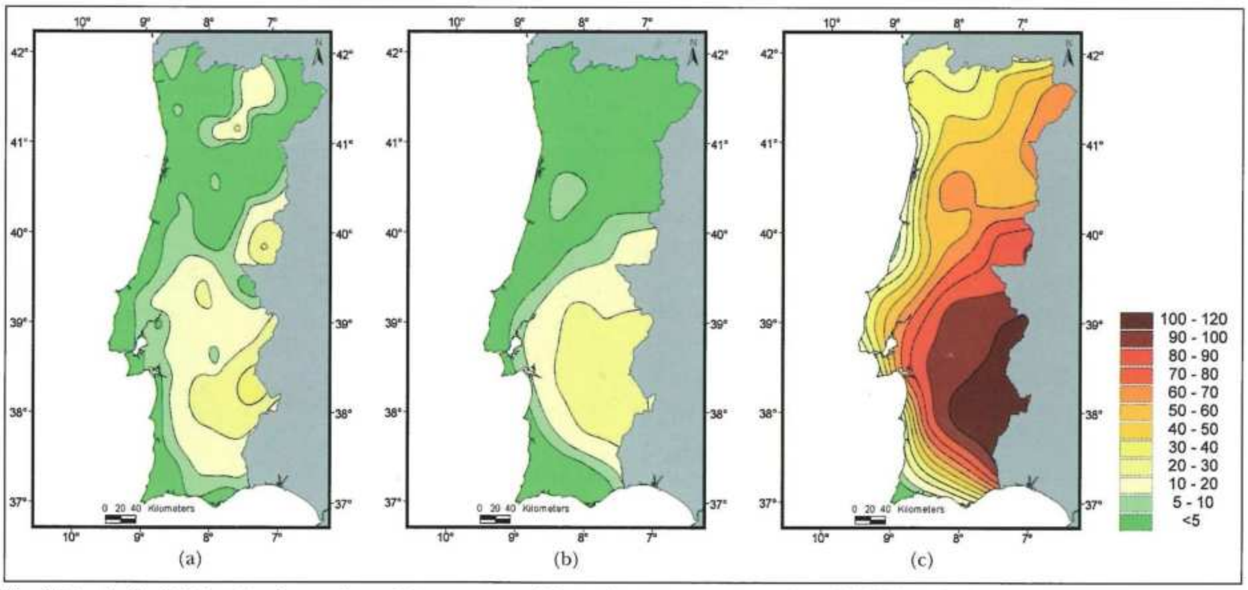
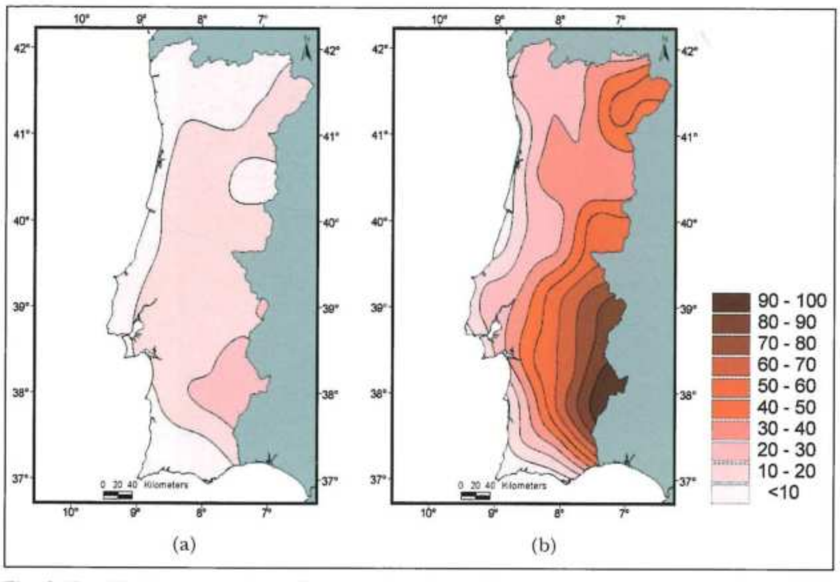


Fig. 2.51 – As fig. 2.50 but for the number of days per year with maximum temperature above 35°C ("hot days").



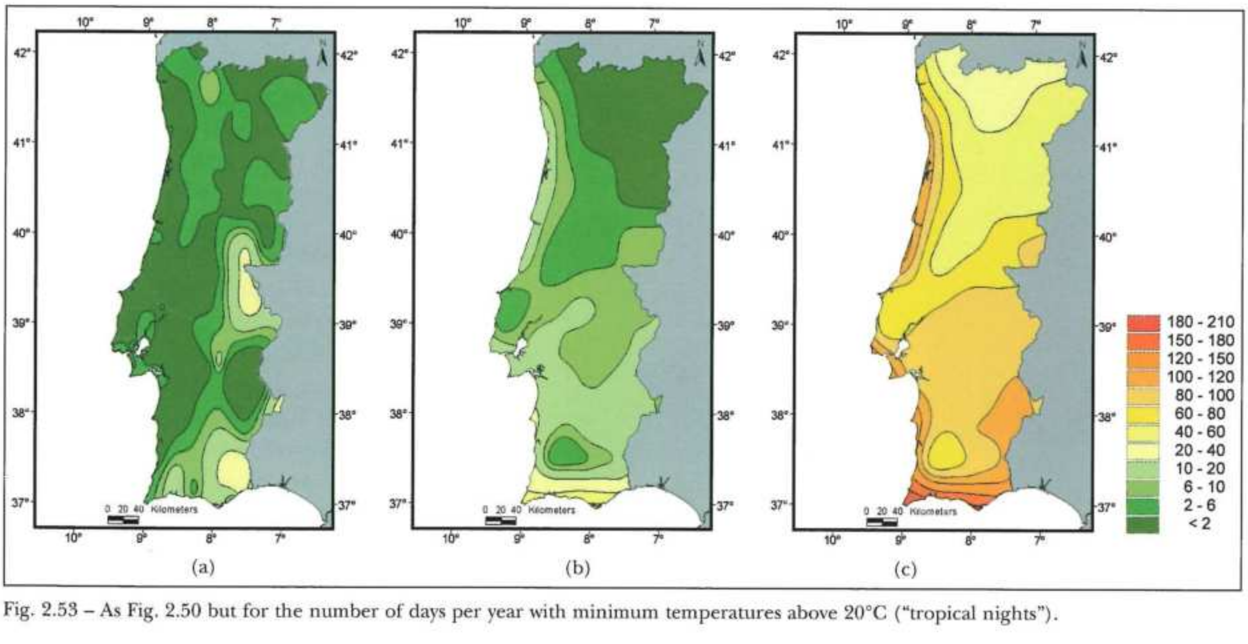
(a) (b)

Fig. 2.52 – Maximum number of consecutive days with maximum temperature above 35°C ("longest hot spell") for (a) HadRM control run (30 year period); (b) HadRM GGa2 simulation (2080-2100 period).

ficant in the interior south, where this number surpasses 20 days. That number is dramatically increased in the climate change scenario (Fig. 2.51c), with maximum values in excess of 90 days in the same interior south region. The increase in the rest of the country is also very significant. For instance Lisbon, which in the control run has an average of 8 "hot days" per year, is expected to have approximately 50 days in these conditions. The 50 days contour covers most of the Portuguese mainland territory.

Heat stress is not only a function of the current value of maximum temperature but also of the persistence of hot weather in consecutive days. To assess that aspect of the problem, Fig. 2.52 represents the maximum number of consecutive days with maximum temperature above 35°C in each model run, a number that corresponds to the "longest hot spell". Considering the large values encountered in Fig. 2.51c, indicating that a large fraction of the days in the extended summer corresponds to "hot days", it is not surprising that the model predicts extremely long hot spells in most of the country, from 20 consecutive days in the coast to more than 2 months in the interior south.

We will now turn our attention to impacts on minimum temperature. Fig. 2.53 shows the average annual number of days with minimum temperature above 20°C ("tropical nights"). The control run plot (Fig. 2.53b) can be compared to observations, shown in Fig. 2.53a. As was previously mentioned, some differences



(a) (b) (c)

Fig. 2.53 – As Fig. 2.50 but for the number of days per year with minimum temperatures above 20°C ("tropical nights").

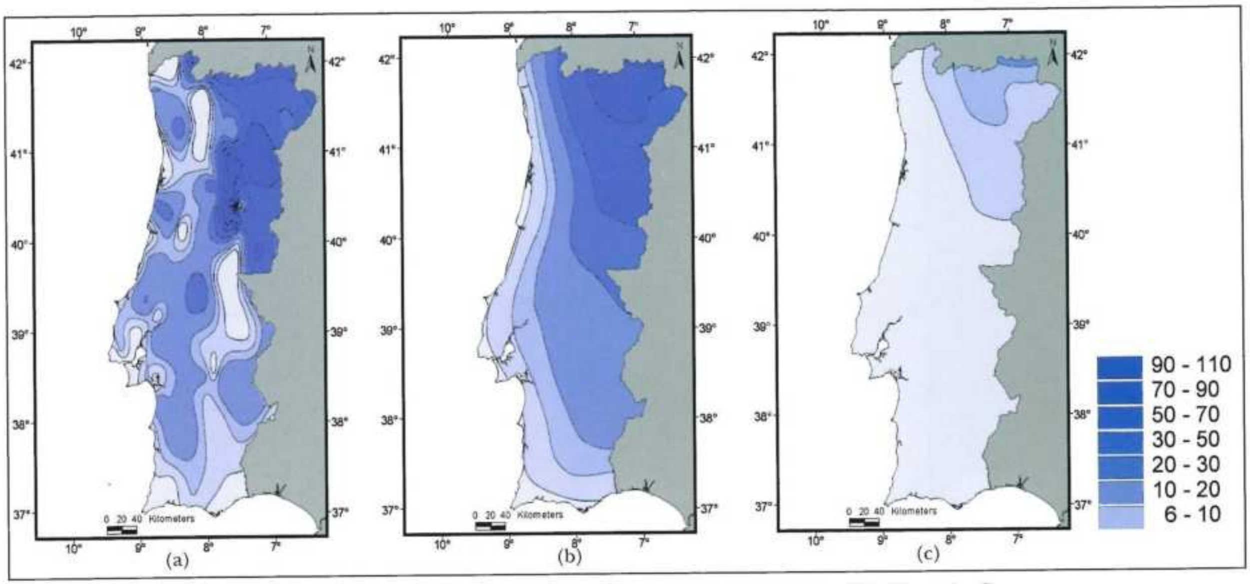


Fig. 2.54 – As fig. 2.50 but for the number of days per year with minimum temperatures below 0°C ("frost days").

should be expected in all fields because the model's orography is much smoother than reality. In fact, the HadRM control run seems to overestimate the number of "tropical nights" in the centre and south of Portugal. On the other hand, some of the spatial detail of the observations is lost in the simulation, a consequence of the limited model spatial resolution. One unrealistic feature of the simulations that may be noted is the fact that the control run positions the highest number of "tropical nights" near the coast, which doesn't seem to be the case of the observations in the western Portuguese coast. This is, probably, due to a deficient representation of the atmospheric coastal circulation, a fact already mentioned.

In the climate change scenario the number of "tropical nights" increases substantially, as expected, with changes of an order of magnitude (Fig. 2.53c). This will add to the discomfort after hot days. Because summer sea temperatures approach the "tropical night" threshold in the climate change scenario, the coastal areas show a larger number of "tropical nights", even in the northwest coast. It is possible, though, that the model is underestimating the sea-breeze effect and its feedbacks on coastal water temperature, which would probably reduce somewhat that temperature, through upwelling.

On the other hand, the average annual number of "frost days" (days with minimum temperature below 0°C, Fig. 2.54) is bound to almost disappear due to climate warming. The interior centre of Portugal, where observations indicate over 20 frost days per year (Fig. 2.54a), is likely to have significantly less than 6 days per year, with the south being frost free.

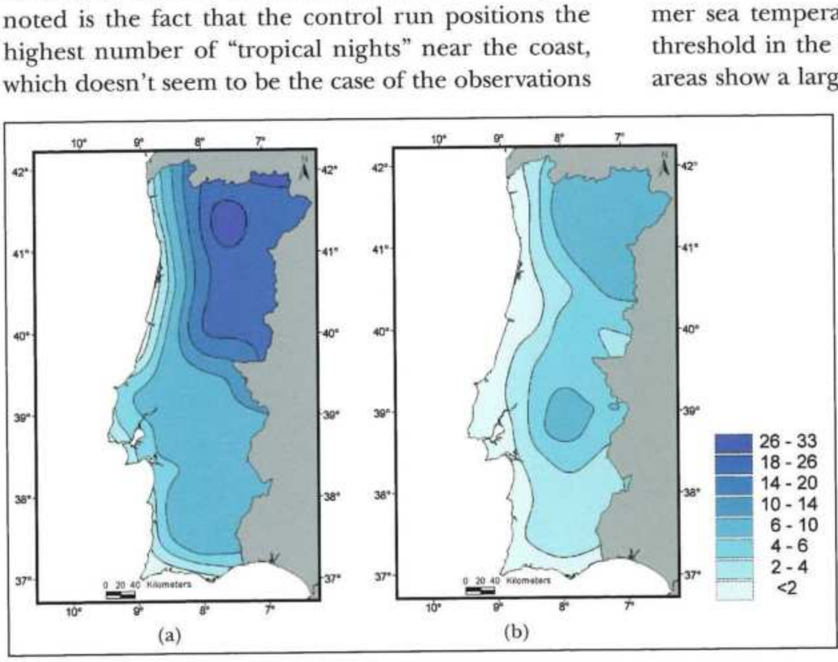


Fig. 2.55 – Maximum number of consecutive days with minimum temperatures below 0°C ("longest cold spell") for (a) HadRM control run (30 year period); (b) HadRM GGa2 simulation (2080-2100 period).

The next plots represent the maximum number of consecutive days with minimum temperature below 0ºC ("longest cold spell" in the HadRM simulations, Fig. 2.55). It should be kept in mind that this is not an annual average but a multiyear extreme. As expected, a decrease in length of cold spells comes as a consequence of climate warming. As is seen in Fig. 2.55b, the longest cold spells decrease most significantly in the interior north of the country.

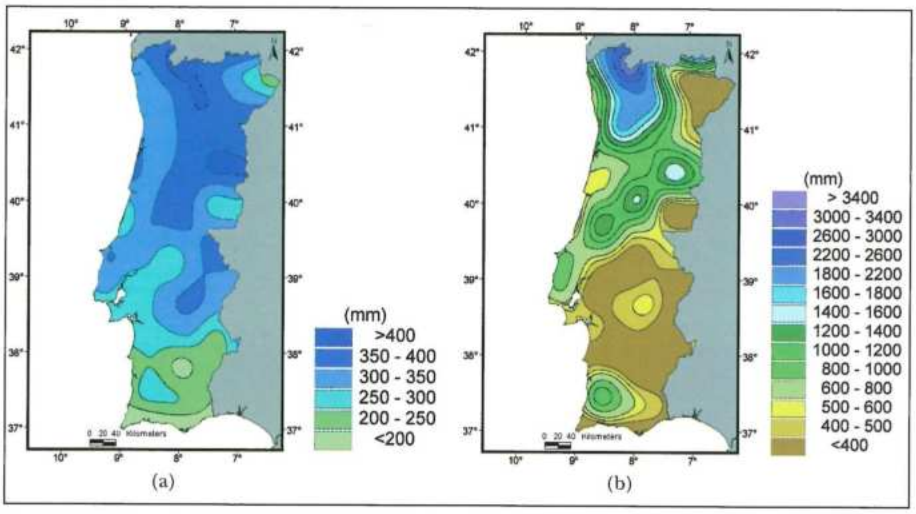


Fig. 2.56 – Annual precipitation for the HadRM control run due to precipitation rates (a) between 1mm/day and 10mm/day; (b) ≥ 10mm/day.

All these temperature results are in line with the ACACIA (Parry, 2000) predictions, indicating that cold winters are bound to disappear by the 2080s and that hot summers will become the norm in the Iberian Peninsula in this period. The ACACIA report defines cold winters and hot summers as the mean seasonal temperature that may be exceeded on average once per decade under the 1961-1990 climate conditions.

### 2.3.2.4 Changes in precipitation

This subsection is dedicated to discussing the changes in accumulated precipitation in the HadRM climate warming scenario. Fig. 2.56 shows accumulated precipitation in the control run due to rates between 1mm/day and 10mm/day (moderate rain – Fig 2.56a) and to rates ≥ 10mm/day (heavier rain) (Fig. 2.56b).

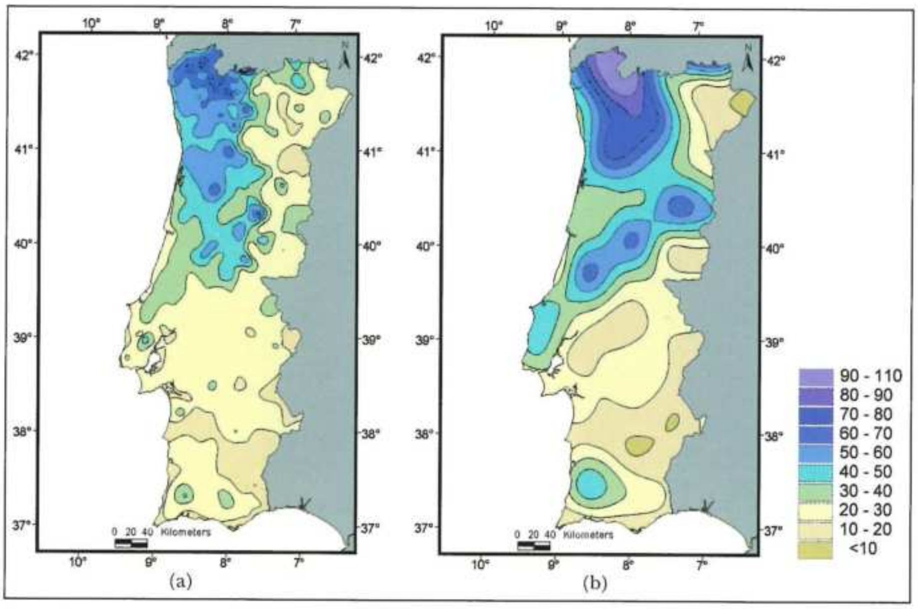


Fig. 2.57 – Number of days per year with precipitation rates ≥ 10mm/day: (a) 1961-1990 climatology, (b) HadRM control run.

The accumulated precipitation in the wetter days (above 10mm/day) dominates in the northwest and centre of the country (to the north of the Montejunto-Estrela mountain range) and in the higher terrain of the Algarve (corresponding, roughly, to the Serra de Monchique), whereas in the south and northeast both classes of precipitation contribute in the same order of magnitude to the total amount of precipitation.

The number of days with precipitation above 10 mm in the control run (Fig 2.57b) compares fairly well with observations (Fig. 2.57a), apart from the enhanced number of precipitation days in the control run in the northwest highlands and in central coastal zones. As before, the maximum values due to mountains are somewhat widened and enhanced in the model.

Anomalies of the accumulated precipitation in the range 1mm-10mm /day are presented in Fig. 2.58 for the year and the 4 seasons. The corresponding anomalies for precipitation ≥ 10mm/day are shown in Fig. 2.59. The annual anomaly (Fig. 2.58a) indicates that in the increased $CO_2$ simulation the contribution from this class of precipitation is reduced by values between 30 mm (in the Algarve) and just over 100 mm. This decrease is distributed by the seasons MAM, JJA and SON, whereas the winter season suffers a very

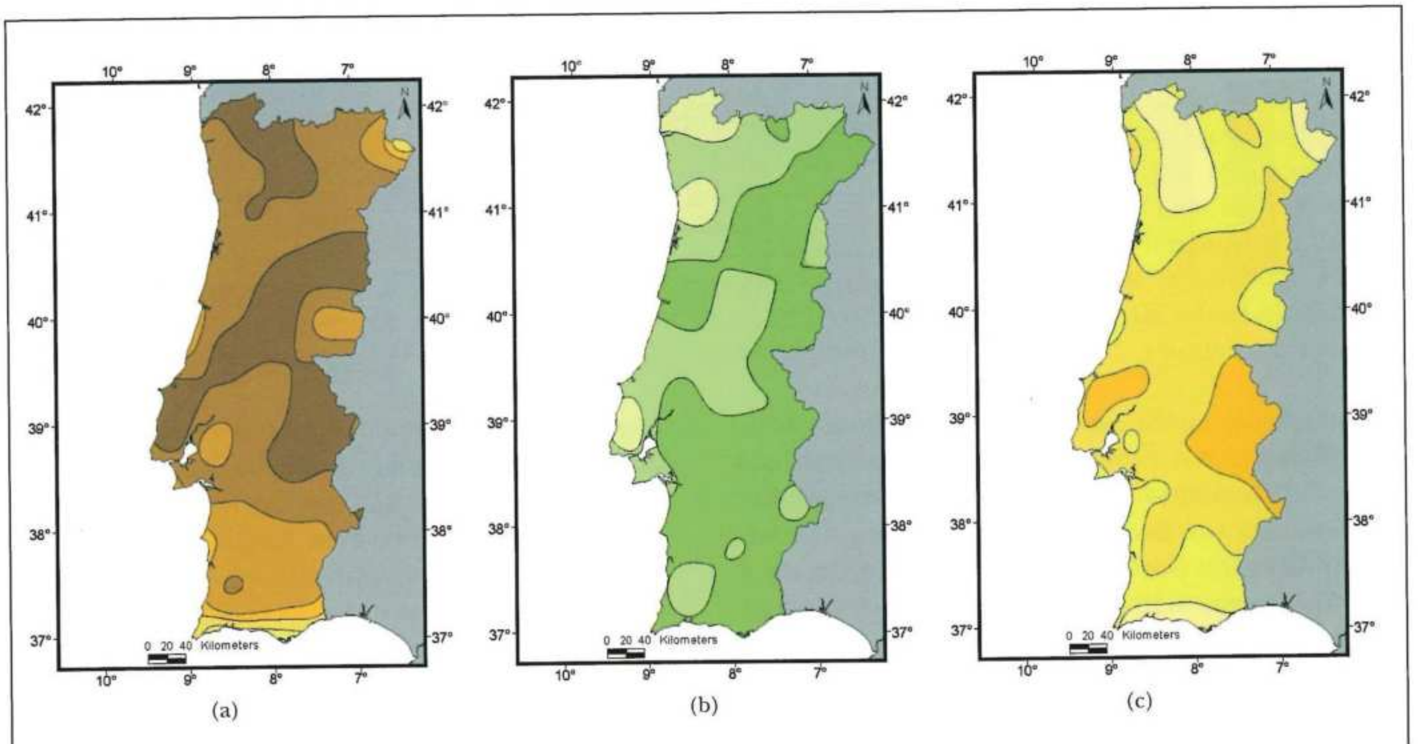


Fig. 2.58 – Annual and seasonal precipitation anomalies due to precipitation rates between 1mm/day and 10mm/day (HadRM GGa2 – control). (a) annual; (b) winter (DJF); (c) spring (MAM); (d) summer (JJA); (e) autumn (SON).

small increase in the precipitation in most of the country, of up to 25 mm.

On the other hand, the annual anomaly of the precipitation occurring in very wet days (above 10mm/day, Fig 2.59a) is negative in fairly restricted regions (Montejunto-Estrela, south Alentejo), but is positive in other regions (centre, Algarve and most of the north). Therefore, the accumulated contribution of very wet days to the annual precipitation is not reduced in the climate warming scenario. In fact, the contribution from this type of precipitation is significantly increased during the winter season (Fig. 2.59b), especially in the north and centre of the country and the Serra de Monchique in Algarve. Some regions see an increase of 300mm during winter.

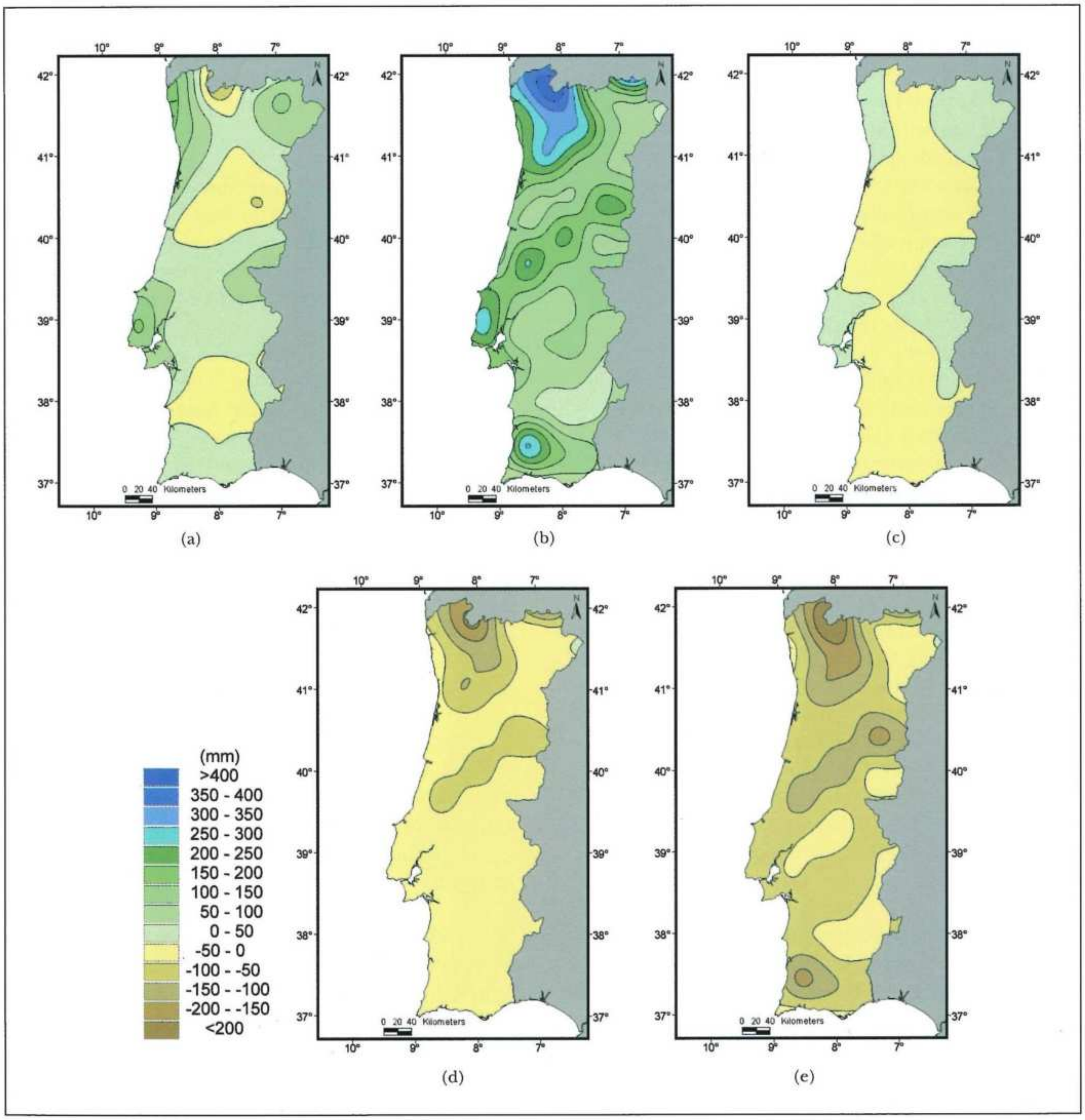


Fig. 2.59 – Annual and seasonal precipitation anomalies due to precipitation rates ≥ 10mm/day (HadRM GGa2 – control). (a) annual; (b) winter (DJF); (c) spring (MAM); (d) summer (JJA); (e) autumn (SON).

Heavy precipitation in the spring season (Fig. 2.59c) is much less affected by climate warming, whereas the autumn registers the greatest reduction in absolute values (50-200mm). During summer this class of precipitation is also reduced, but the reduction is smaller in absolute values because the summer season is rather dry in both scenarios.

The main conclusion that can be obtained from Figs 2.58, 2.59 is that the accumulated precipitation in moderately rainy days (1-10mm/day) tends to decrease, whereas heavier rain (≥10mm/day) is bound to be concentrated in the winter and to become more intense. It was verified that the number of days with precipitation above the 10mm/day threshold also increases in winter, but not proportionally to the anomalous accumulated precipitation. In fact, the amount of precipitation per rainy day increases, which may lead to an increase in flooding episodes.

Fig. 2.60 shows the relative change of accumulated precipitation in the climate warming scenario. This is calculated as the ratio between the precipitation in the GGa2 simulation and the precipitation in the control run. The total annual precipitation decreases in most of the country, especially in Alentejo (interior South) where values go down to 85% of the control precipitation . During the winter season, total precipitation increases to 120%-150% of its reference value, with the highest increases happening in the south and central coastal zones (Fig. 2.60b). The remaining seasons register a loss of precipitation. In percentage terms the decrease in summer is greater (only 25-35% of the control precipitation remains) than in spring or autumn, but the total amount of precipitation in summer is far smaller than during the other seasons. Therefore, the decrease observed in autumn (to 40%-65% of the control precipitation) and spring (to 70%-100%) is more important, representing the main cause of the deficit seen in Fig. 2.60a.

Fig. 2.61 shows thermo-pluviometric anomaly graphics for 4 grid points of the HadRM model that fall in the Portuguese area, approximately near the towns or regions named in the figure. The red and blue curves represent, respectively, the maximum and minimum temperature anomalies, whereas the bars are the mean monthly accumulated precipitation anomalies. These graphs reflect, in more detail at the corresponding location, the characteristics of the anomalies presented before on a seasonal basis. The major increases in the maximum temperature occur in the summer and autumn. The anomaly of minimum temperature is also positive throughout the year being greater than the maximum temperature during the winter months. The monthly precipitation anomalies are positive in the winter months at the 4 chosen grid points and are slightly positive at the NW point (North coastal region) during March/April (note the differently scaled axes for each grid point). Another interesting feature is that the maximum precipitation anomaly happens in February in the north of the country and in January in the south.

The negative monthly precipitation anomalies are most prominent in the May and October months in the seaside grid points, whereas the South interior point S registers a strong decrease in rain also in November. The NE grid point (interior north) has a greater negative precipitation anomaly in October, with the period May-September having very similar negative monthly anomalies. The graphs show that the main loss of precipitation happens in spring and autumn, extending the duration of the dry season. The minimum and maximum temperature and precipitation anomalies suggest that the summer period is extended from May to October with the winter becoming shorter and wetter.

#### 2.3.2.5 Regional Iberian model PROMES

Some groups in the SIAM project also worked with output from another regional climate model developed at the Universidad Complutense de Madrid, the PROMES model that was developed for the Iberian Peninsula. This model also uses the same Hadley Centre HadCM2 model to force its boundaries. A recent paper (Gallardo *et al.*, 2001) describes the model and its results.

The PROMES model used a horizontal resolution comparable with HadRM but in a much smaller horizontal domain, comprising the Iberian Peninsula and surrounding ocean waters. Another essential difference in the setup of the experiments comes from the fact that PROMES used a 10 year control simulation (instead of 30 years) and a 10 year climate change simulation, corresponding to the period 2040-2049 of the HadCM2 simulation (HadRM uses the period

2080-2099). Especially because of the difference in the target decade, results from PROMES cannot be compared with results from HadRM. So, the PROMES climate change experiment corresponds to a different, less warm, scenario. On the other hand, the model has many differences in formulation and the results from the control run show, for the Portuguese area, significantly higher systematic errors than were found for HadRM.

Fig. 2.62 shows the anomaly of the average DJF minimum temperature and the anomaly of the average JJA maximum temperature. As the concentration of greenhouse gases in the 2040 decade is, for the

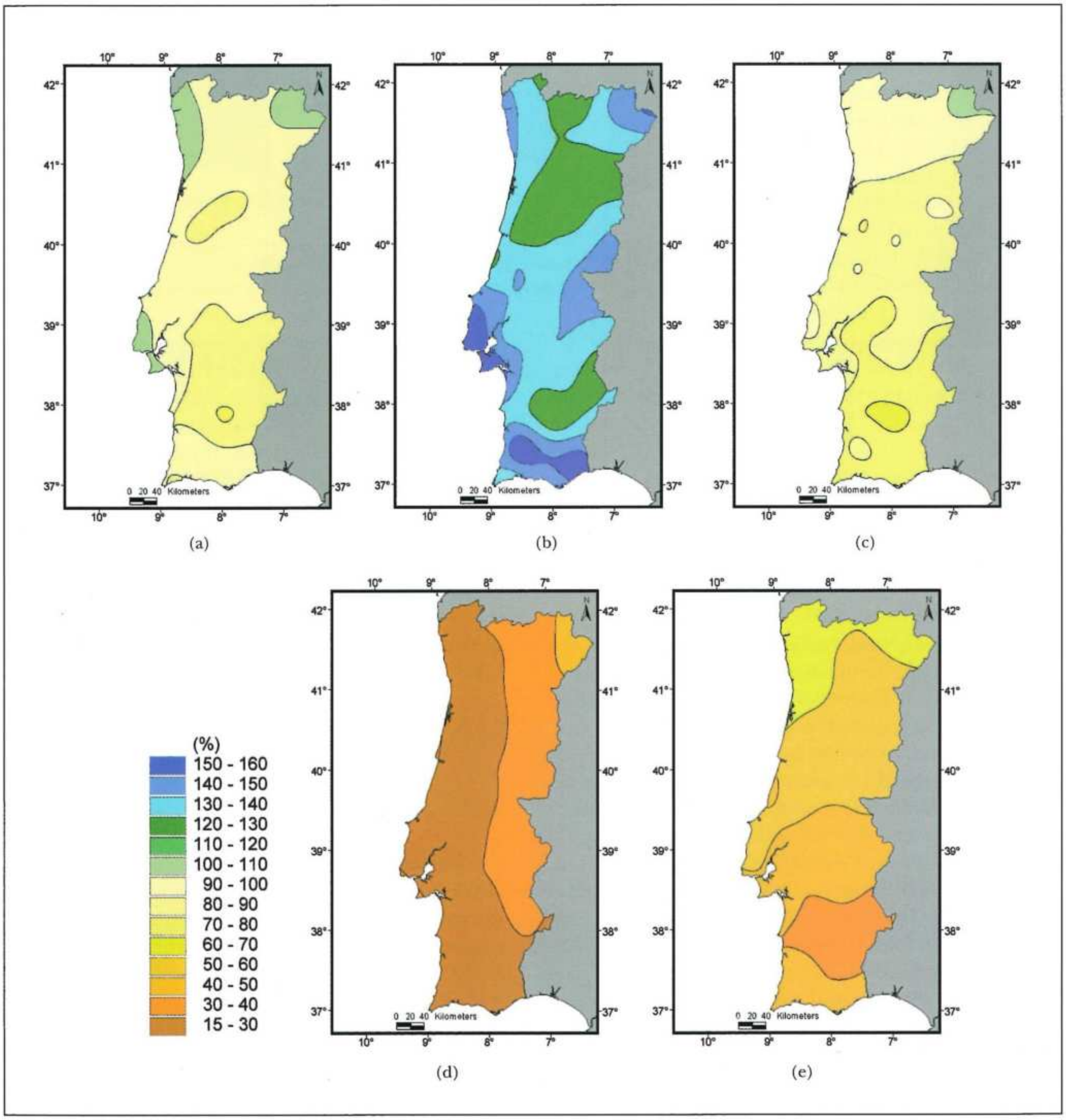


Fig. 2.60 – Annual and seasonal total precipitation in the HadRM GGa2 simulation in percentage (%) (100 × GGa2/control). (a) annual; (b) winter (DJF); (c) spring (MAM); (d) summer (JJA); (e) autumn (SON).

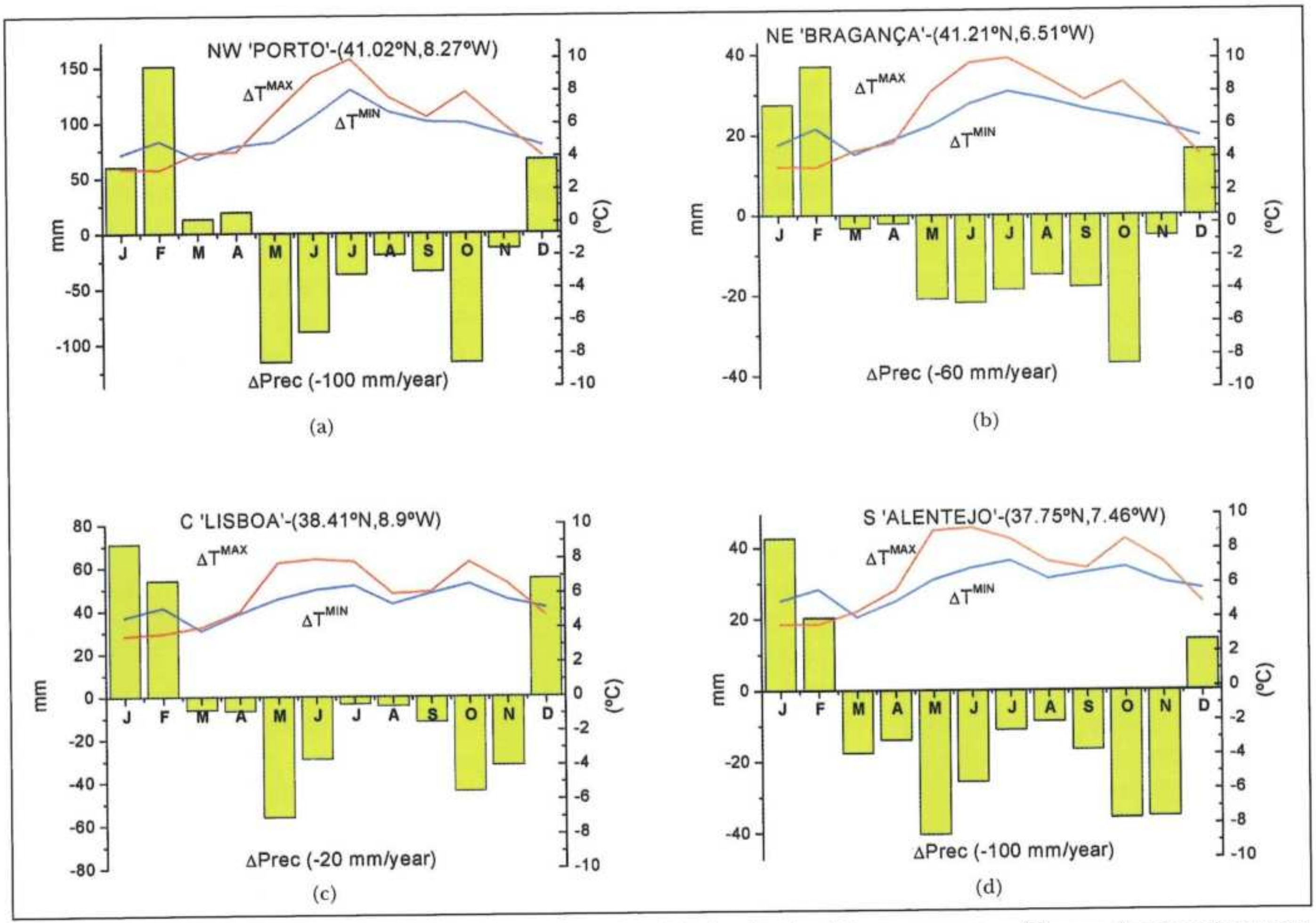


Fig. 2.61 – Monthly thermo-pluviometric graphs for the anomalies of precipitation (bars), minimum temperature (blue curve) and maximum temperature (red curve) in 4 HadRM grid points localised in the (a) Northwest (NW); (b) Northeast (NE); (c) Centre (C); (d) South (S) of Portugal (see HadRM grid points in Fig. 2.1).

chosen emission scenario, significantly smaller than in the 2090s, the anomalies shown in Fig. 2.62 are smaller than the anomalies obtained in the HadRM climate change scenario, presented in Figs. 2.47 and 2.48. The anomaly of average DJF minimum temperature varies from 3.1°C to 3.3°C, whereas the anomaly of average JJA maximum temperature is of the order of 4 to 4.5°C. The DJF minimum temperature anomaly pattern is very similar to the one presented in Fig. 2.47a, whereas the JJA maximum temperature anomaly configuration in Fig. 2.62b is somewhat different from the one shown in Fig. 2.48c. In Fig. 2.62b the maximum anomaly is located in the southwest coast of Portugal, and not in the interior north/centre of the country. The summer seaside-interior gradient does not seem to have been substantially intensified in the PROMES model simulation presented here, but values for the mean temperature anomaly all over Iberia, shown in Gallardo *et al.* (2001) indicate a maximum summer warming in central Iberia, in the same sense of HadRM results.

### 2.3.3 CHANGES IN THE NAO INDEX AND REGIONAL CIRCULATION PATTERNS

#### 2.3.3.1 NAO index

Considering the significant correlation between the NAO index and Iberian winter precipitation, it is worth looking at time series of simulated NAO in the control and scenario periods of the Hadley Centre HadCM3 GG simulation. In this case, to avoid correcting any model biases in the pressure field (Osborn *et al.*, 1999) the NAO is computed as a grid point pressure difference, as in Fig. 2.29 which was plotted using the NCEP/NCAR pressure difference between Iceland and the Azores. Fig 2.63 shows the anomaly in the monthly mean Azores-Iceland pressure differences computed from two periods of the GG

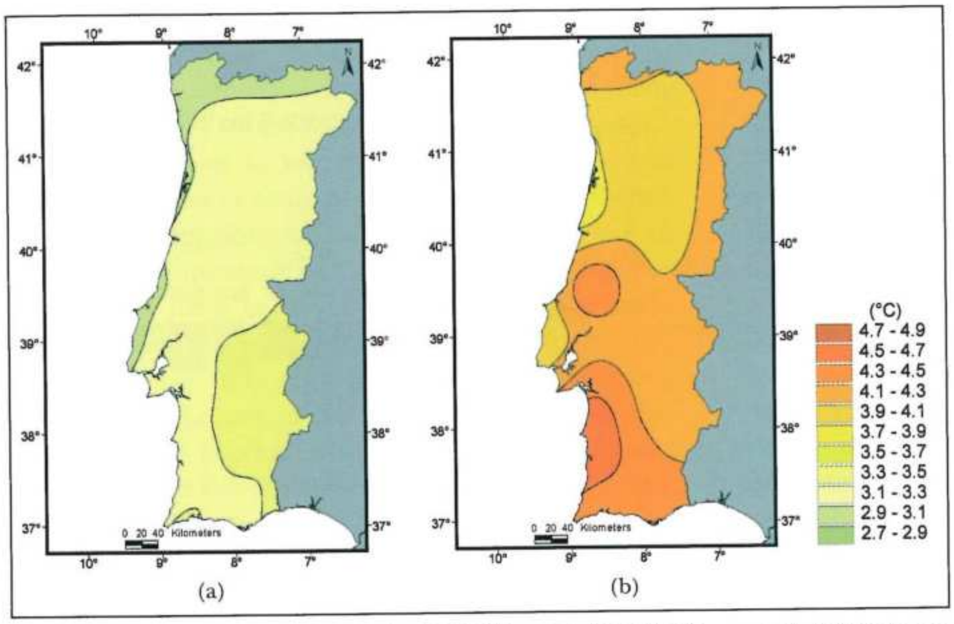


Fig. 2.62 – Temperature anomalies in the PROMES model (2040/2049 – control): (a) Minimum temperature anomaly in winter (DJF); (b) Maximum temperature anomaly in summer (JJA).

HadCM3 run. The control period is 1961-1990, whereas the scenario period is 2070-2099. Overall, there is an increase in the NAO intensity, except in the month of March, which shows a significant decrease of almost 1hPa, and April, which shows a very small decrease. Very substantial increases are found for December and January.

Fig 2.64 shows the NAO-precipitation correlation in both control and scenario periods of the HadCM3 GG simulation, using grid-point precipitation values in the 3 western Iberia points (see Fig. 2.1). Correlations in the control run are comparable with climate (NCEP – see Fig. 2.29), specially considering the fact that we are now using grid point precipitation in a low resolution grid, whereas the 1961-90 NCEP correlation was computed with average station precipitation data. The most remarkable features of the evolution of the NAO-precipitation correlation between the control and scenario periods occur at the North grid point, for which correlations are already smaller in the control experiment and where the January correlation disappears. In the South grid point correlations are slightly reduced but remain significant in the extended winter period (December to March).

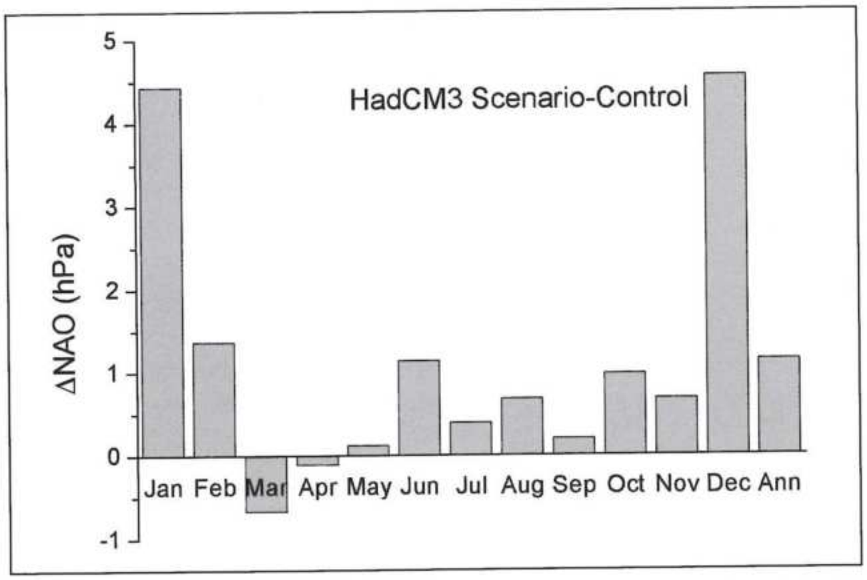


Fig 2.63 – Monthly and annual mean anomaly of (non-normalized) HadCM3 NAO: difference between monthly mean Azores-Iceland pressure difference in the GG simulation period 2070-2099 and control period 1961-1990.

Changes in the correlation between winter precipitation and NAO in Northwest Iberia are related to the fact that, in the scenario period, winter precipitation increases in that region (see Fig. 2.64, right panel) in spite of the significant increase in the mean NAO (Fig. 2.63). In fact, December and January experience the largest increases in the NAO index (above +4hPa) and are months of increased precipitation in northern Portugal. In the HadRM simulations that increase in winter precipitation was also found for the centre and south of the country. Looking in more detail to time series of pressure in the Azores and Iceland (not shown), one can conclude that the increase in the NAO index, which comes from both a decrease in Iceland sea-level pressure and an increase in the Azores, is not generally accompanied by an increase in the sea-level pressure in Lisbon. On the contrary the mean winter sea-level pressure in Lisbon decreases slightly. In other words, the model predicts that, in winter, Iberia will be further away from the influence of

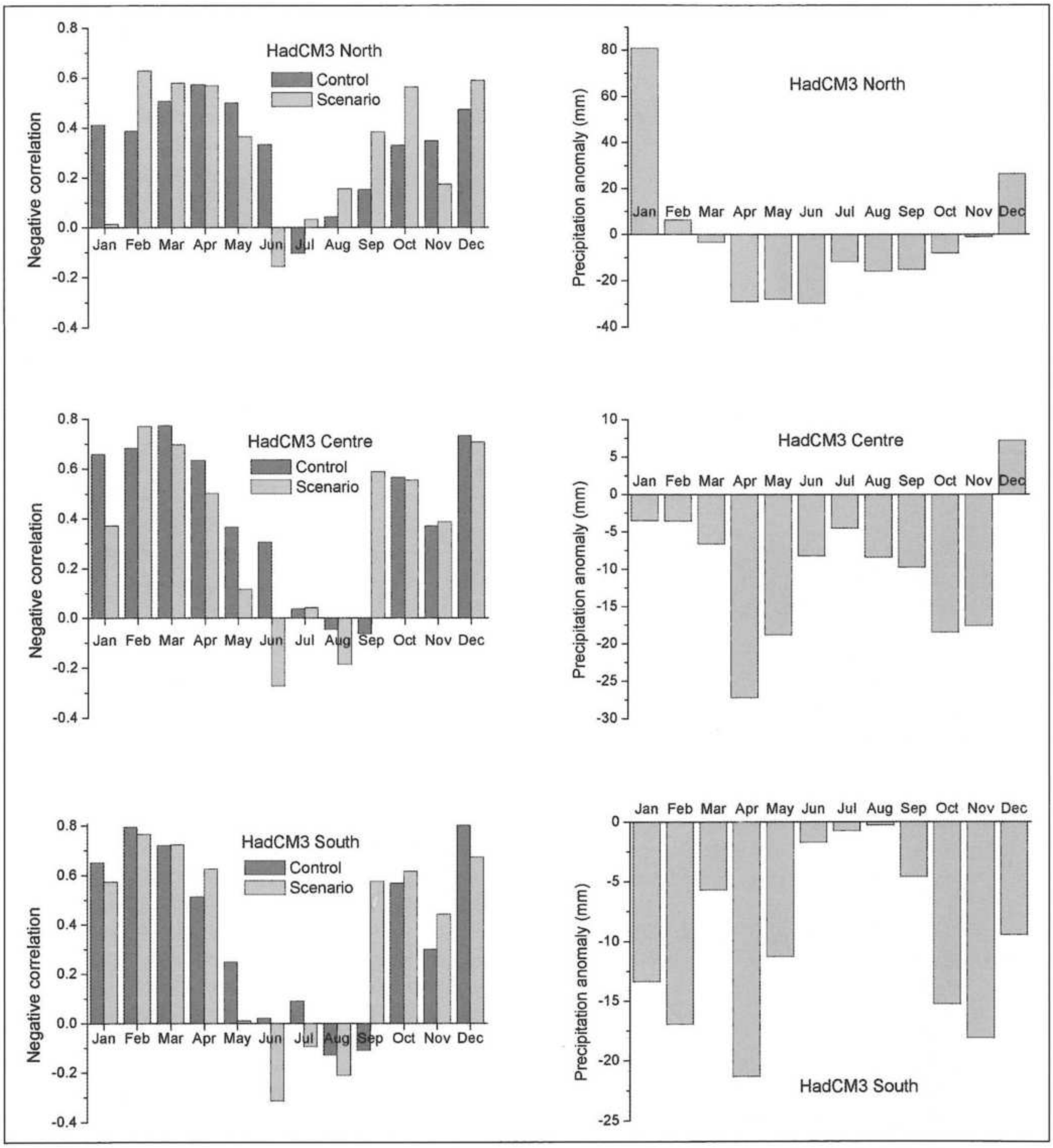


Fig 2.64 – Left pannel: monthly mean correlation between HadCM3 NAO (Azores-Iceland pressure difference) and grid point precipitation in the control period (1961-1990) and scenario period (2070-2099) of the GG simulation. Right panel: monthly mean precipitation anomaly (difference between precipitation in the scenario and control periods). Values are presented for the three western Iberia grid points, as labelled. Note the difference in scale between the different precipitation anomaly graphics.

the Azores anticyclone, an evolution that is in the opposite sense of what has been found for the recent evolution of Iberian pressure (section 2.2.2.7). Finally, it should be mentioned that if one had used a NAO index based on the difference in pressure between Lisbon and Iceland (Jones *et al.*, 1997a), the NAO-precipitation correlation in the scenario simulation would be different.

It is also important to say that the NAO-precipitation connection is bound to be affected by the change in atmospheric humidity that accompanies global warming. In a warmer winter it is likely that fewer but wetter systems can lead to increased precipitation. More detailed analysis of simulated weather systems, including detail diagnostics of precipitable water in storms and the development of storm tracking algorithms, are needed for a better understanding of the dynamical forcing of precipitation, and they will certainly be done in the next generation of climate scenarios, which are expected to have higher horizontal resolution and to produce richer archives of simulated data, required for that kind of diagnostics. A simple dynamical analysis, using Circulation Weather Types is presented in the following section.

### 2.3.3.2 Circulation Weather Types in HadCM3

The HadCM3 grid is not the same as the NCEP/NCAR reanalysis grid and the 16 sea level pressure points used to evaluate the set of indices needed for the weather type classification are not in the HadCM3 grid. Because of the possible sensitivity of the empirical set of rules that distribute the CWTs we choose to interpolate the sea level pressure field in the HadCM3 runs to the NCEP grid points using spherical harmonics. This method has advantages over pointwise grid interpolation schemes on the sphere. It is highly accurate and is consistent with methods used to generate data in numerical spectral models.

Table 2.6 presents the frequency distribution of the CWTs for the control and for the GG scenario. A comparison of that table with Table 2.2 indicates that the control period (1961-1990) reproduces quite well the frequency distribution of the NCEP/NCAR CWTs. The main differences are a slight increase of the NE type and a relatively large decrease in the hAN type. However, when one considers the monthly distribution of CWTs there are considerable differences between the NCAR/NCEP data and the HadCM3 control period. In the NCEP/NCAR case, the anticyclonic CWTs were almost equally distributed between all months, while in the HadCM3 control period the frequency of the anticyclonic type for the months July and August is only near 5%. This decrease is compensated by a large increase in the frequency of the NE type that for these months attains near 47%. The other types, although presenting slightly different values, follow a monthly distribution that resembles the NCEP/NCAR CWTs monthly distribution.

**Table 2.6 – Frequency distribution (%) of the CWTs for the HadCM3 control period (1961-1990) and the HadCM3 GG scenario (2070-2099)**

| CWT | Frequency (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Control | | | | | Scenario | | | | |
| | Year | DJF | MAM | JJA | SON | Year | DJF | MAM | JJA | SON |
| A | 15.8 | 17.8 | 21.0 | 7.8 | 16.6 | 14.3 | 20.5 | 18.5 | 2.0 | 16.3 |
| C | 2.1 | 3.1 | 3.4 | 0.6 | 1.4 | 1.8 | 1.7 | 2.6 | 0.8 | 2.1 |
| NE | 15.8 | 3.3 | 9.9 | 40.0 | 10.0 | 22.2 | 2.9 | 12.2 | 57.9 | 15.7 |
| E | 10.9 | 3.6 | 9.2 | 16.4 | 14.3 | 12.8 | 4.5 | 12.7 | 17.2 | 16.8 |
| SE | 3.5 | 4.3 | 3.3 | 0.7 | 5.8 | 3.7 | 4.6 | 5.5 | 0.6 | 4.2 |
| S | 2.0 | 4.1 | 1.3 | 0.0 | 2.5 | 1.2 | 2.3 | 1.0 | 0.0 | 1.3 |
| SW | 5.0 | 11.6 | 2.7 | 0.0 | 5.5 | 3.8 | 9.4 | 2.0 | 0.0 | 3.9 |
| W | 7.6 | 16.5 | 6.4 | 0.7 | 6.8 | 6.5 | 15.7 | 4.8 | 0.0 | 5.7 |
| NW | 5.4 | 7.6 | 7.2 | 1.7 | 5.1 | 5.0 | 8.3 | 6.2 | 0.6 | 5.1 |
| N | 6.6 | 3.6 | 9.4 | 8.5 | 5.0 | 6.1 | 4.6 | 7.5 | 7.2 | 5.4 |
| hANE | 5.7 | 1.6 | 4.7 | 11.1 | 5.2 | 4.8 | 2.0 | 6.3 | 5.7 | 5.3 |
| hA E | 3.0 | 1.3 | 3.5 | 2.6 | 4.5 | 2.8 | 2.4 | 4.1 | 1.4 | 3.2 |
| hASE | 1.0 | 1.5 | 1.0 | 0.0 | 1.5 | 0.8 | 1.5 | 0.6 | 0.0 | 0.9 |
| hA S | 0.6 | 1.2 | 0.6 | 0.0 | 0.7 | 0.3 | 0.7 | 0.3 | 0.0 | 0.1 |
| hASW | 1.0 | 1.9 | 0.4 | 0.0 | 1.5 | 0.9 | 2.1 | 0.5 | 0.0 | 0.9 |
| hA W | 2.8 | 5.6 | 2.2 | 0.4 | 1.5 | 2.5 | 5.4 | 2.3 | 0.0 | 2.3 |
| hANW | 3.2 | 3.8 | 4.2 | 1.4 | 3.4 | 3.2 | 5.6 | 3.9 | 0.3 | 3.1 |
| hA N | 4.1 | 2.8 | 5.0 | 5.5 | 3.1 | 3.4 | 3.1 | 4.7 | 2.2 | 3.7 |
| hCNE | 0.6 | 0.2 | 0.7 | 0.7 | 0.7 | 1.0 | 0.2 | 0.8 | 2.0 | 0.8 |
| hC E | 0.6 | 0.3 | 0.5 | 0.7 | 0.9 | 0.9 | 0.2 | 0.8 | 1.1 | 1.4 |
| hCSE | 0.5 | 0.5 | 0.5 | 0.2 | 0.7 | 0.4 | 0.3 | 0.5 | 0.1 | 0.7 |
| hC S | 0.5 | 0.8 | 0.6 | 0.0 | 0.6 | 0.3 | 0.5 | 0.4 | 0.0 | 0.3 |
| hCSW | 0.4 | 1.1 | 0.4 | 0.0 | 0.3 | 0.2 | 0.6 | 0.2 | 0.0 | 0.1 |
| hC W | 0.6 | 1.2 | 0.8 | 0.0 | 0.3 | 0.3 | 0.6 | 0.6 | 0.0 | 0.1 |
| hCNW | 0.4 | 0.6 | 0.4 | 0.1 | 0.3 | 0.2 | 0.3 | 0.5 | 0.0 | 0.1 |
| hC N | 0.4 | 0.2 | 0.6 | 0.4 | 0.4 | 0.3 | 0.2 | 0.3 | 0.4 | 0.3 |

Table 2.6 shows that the frequency of CWTs that were more productive, in terms of precipitation, in the NCEP/NCAR climatology, has decreased from the control period to the scenario period (2070-2099). We observe a generalized increase in the frequency of most types, pure and hybrids, with an easterly geostrophic wind. At first sight one could immediately conclude that if the connection between the CWTs and precipitation in the model is the same as in the NCEP/NCAR dataset, the annual precipitation would decrease in the HadCM3 scenario period.

On the other hand, if the increase in frequency of the more unproductive CWTs happens in the summer months, the effect in the decrease in precipitation will not be very strong. Fig. 2.65 shows that this is indeed the case and that the decrease of the more effective CWTs in the winter period is not very pronounced, and is partially compensated by an increase of frequency of hANW and NW types which have, for the NCEP/NCAR reanalysis, a high correlation with precipitation in the winter months (Fig. 2.32), especially in the northern region. So, in terms of the total amount of precipitation in the GG scenario, changes in the CWTs do not imply a decrease of total precipitation in the winter season. On the other hand, the small decrease in absolute value, but a large relative decrease, of the cyclonic hybrid types in spring can be an important factor for the decrease of precipitation in this season, due to the strong signal that this hybrid types have in the spring months (Fig. 2.32).

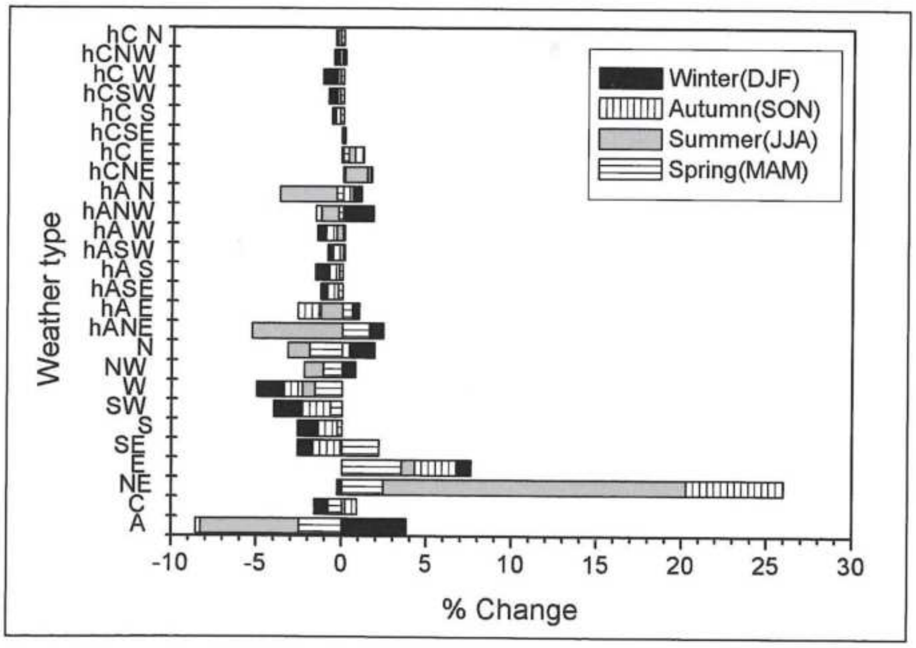


Fig. 2.65 – Seasonal difference between the frequencies of the different weather types in the HadCM3 GG scenario (2070-2099) and the control period (1961-199).

It is possible that the correlation between precipitation and CWT frequency is not maintained in the HadCM3 model. That correlation can be easily computed for grid point simulated precipitation. Results (not shown) lead to comparable annual cycles and to a significant correlation between westerly CWTs (hCW, hCSW, W and C) and precipitation. So the hypothesis of precipitation decrease in spring season due to a considerable decrease in the cyclonic hybrid types still holds when we consider the HadCM3 control precipitation field versus CWTs.

### 2.3.3.3 The Iberian pressure field

The increase of atmospheric greenhouse gases has an impact in the mean sea level pressure patterns in the Iberian Peninsula. Fig. 2.66 and Fig. 2.67 show, respectively, the mean sea level pressure in the HadRM control and increased $CO_2$ simulations for the DJF and JJA periods respectively. These figures also show the mean sea level pressure anomalies.

In DJF the predominant pressure pattern has a southwest-northeast orientation over the Portuguese area, with the lowest pressure values in the northwest and high pressure over the southern Iberian Peninsula and Africa. This mean configuration is linked to the passage of low pressure centres associated with frontal systems. The mean geostrophic wind has a southwesterly direction over the Portuguese area, being more intense in the northern region and advecting maritime air to the Iberian Peninsula. A comparison between Figs. 2.66a and b reveals a slight change in regional pressure patterns, associated with an increased pressure gradient (higher geostrophic wind) and an eastward shift of the high pressure centre over north Africa, in the GGa2 scenario. In this scenario, there is also a clear reduction of the mean winter sea-level pressure in Iberia, clearly shown in Fig 2.66c, especially in the west sector where pressure falls by 5-6 hPa. This anomaly pattern is consistent with an increase of the frequency of the passage of frontal systems over Iberia during winter, in the global warming scenario, which would justify the

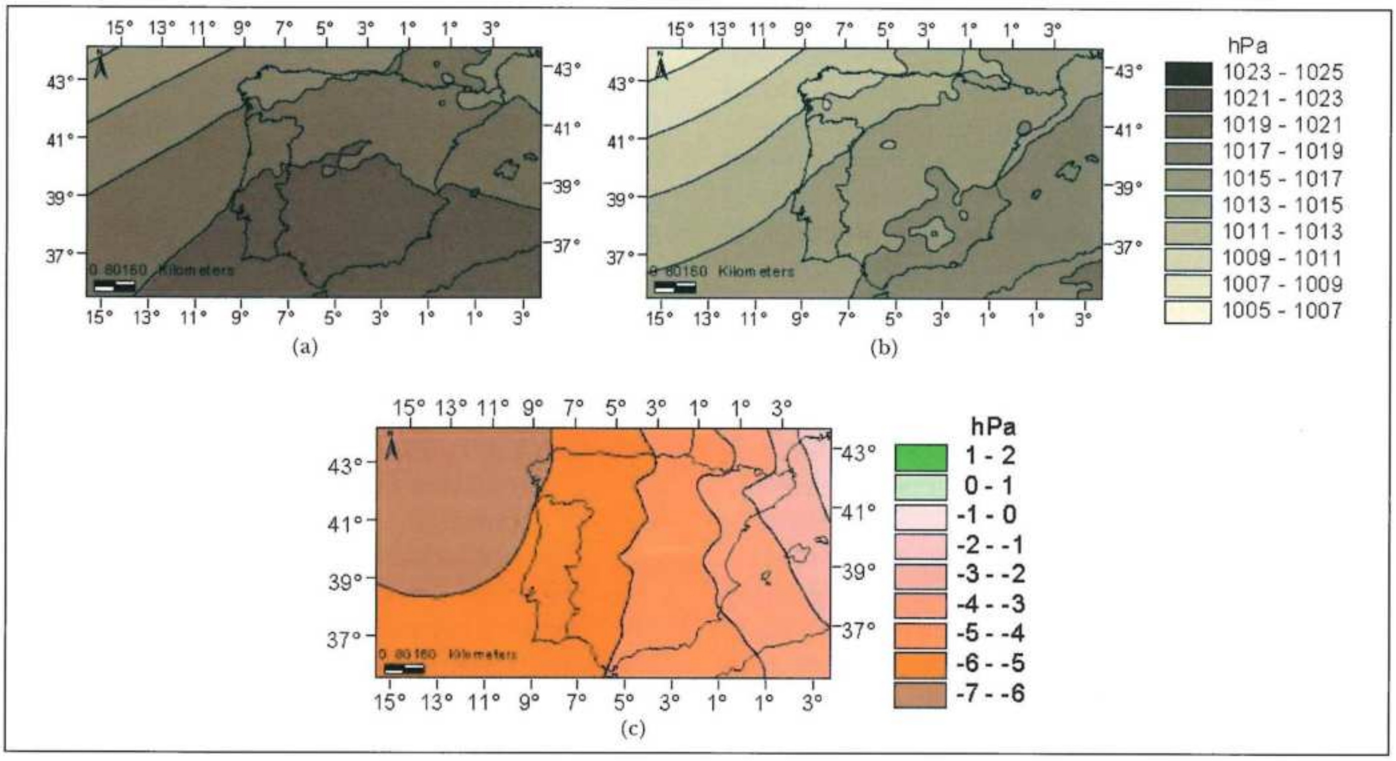


Fig. 2.66 – Mean sea level pressure in winter (DJF) in the (a) HadRM control run; (b) HadRM GGa2 simulation; (c) Mean sea level pressure anomaly HadRM (GGa2-Control).

increased precipitation in winter predicted by HadRM for the period 2080-2100. On the other hand, this change in Iberian sea-level pressure occurs in spite of an increase in the winter mean value of the NAO index discussed previously.

The mean sea level pressure pattern in the JJA HadRM control simulation (Fig. 2.67a) reveals a lower pressure zone over the Iberian Peninsula that is essentially of thermal origin. The great land-sea temperature contrasts that already occur in the Iberian

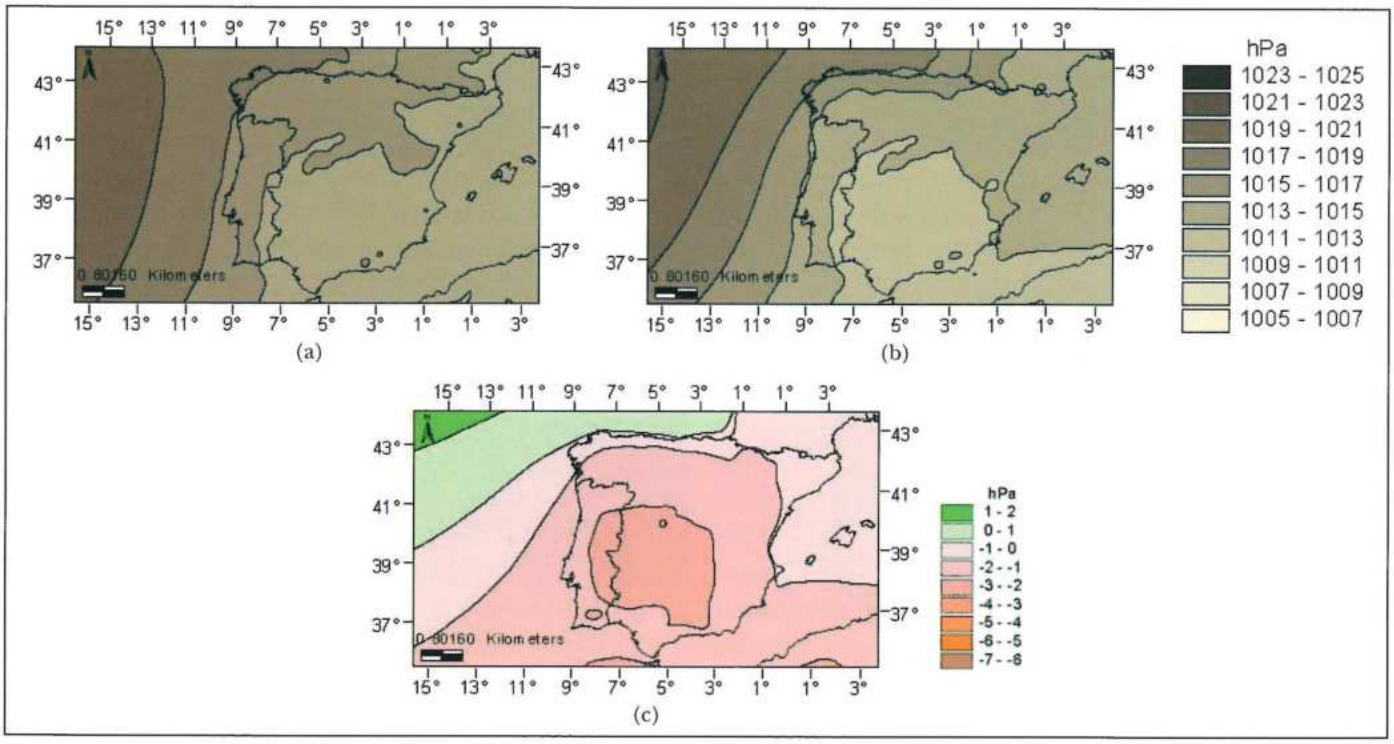


Fig. 2.67 – As Fig. 2.66 but for the summer (JJA).

summer often lead to the establishment of a quasi stationary "heat low" (Gaertner *et al.*, 1993; Portela and Castro, 1996). This effect is substantially enhanced in the climate warming scenario, where average summer pressure (reduced to sea level) in central Iberia experiences a reduction of about 2hPa, while mean values over the neighbour Atlantic change much less. The intensification of the thermal low-pressure centres is closely linked to the enhanced seaside-interior temperature gradient observed over Portugal in the previous Figures 2.47 and 2.48 during summer. This is bound to intensify the northerly breeze mentioned previously. In fact, Fig. 2.67b has more tightly packed isobars near the Portuguese coast than the control map in Fig. 2.67a, which indicates a stronger geostrophic wind magnitude in this region. It must be stressed though that, as mentioned before, the full development of the sea-breeze circulation system and its interactions with coastal waters, through upwelling enhancement, is probably not well represented by this kind of model.

### 2.3.4 SEA SURFACE TEMPERATURE

To complete the series of comparisons between HadRM control simulation and scenario, we look at the mean sea surface temperature (SST) for DJF and JJA (Fig. 2.68). The SST is actually given by the HadCM2 simulations and represents one of the interfaces between the global and regional model (one-way nesting).

In the HadRM control simulation the winter SST along the Portuguese coast varies between 14°C and 16°C (Fig. 2.68a). The DJF SST positive anomaly for the scenario simulation is of the order of 3-4°C, being almost constant in the area shown in Fig. 2.68b. This brings the DJF scenario SST to values between 18°C and 20°C, which is very close to the values occurring in the control JJA plot (Fig. 2.68c), apart from the Algarve coast where the summer waters are substantially warmer than in winter. The SST increase in the JJA scenario is slightly higher than in DJF, being now

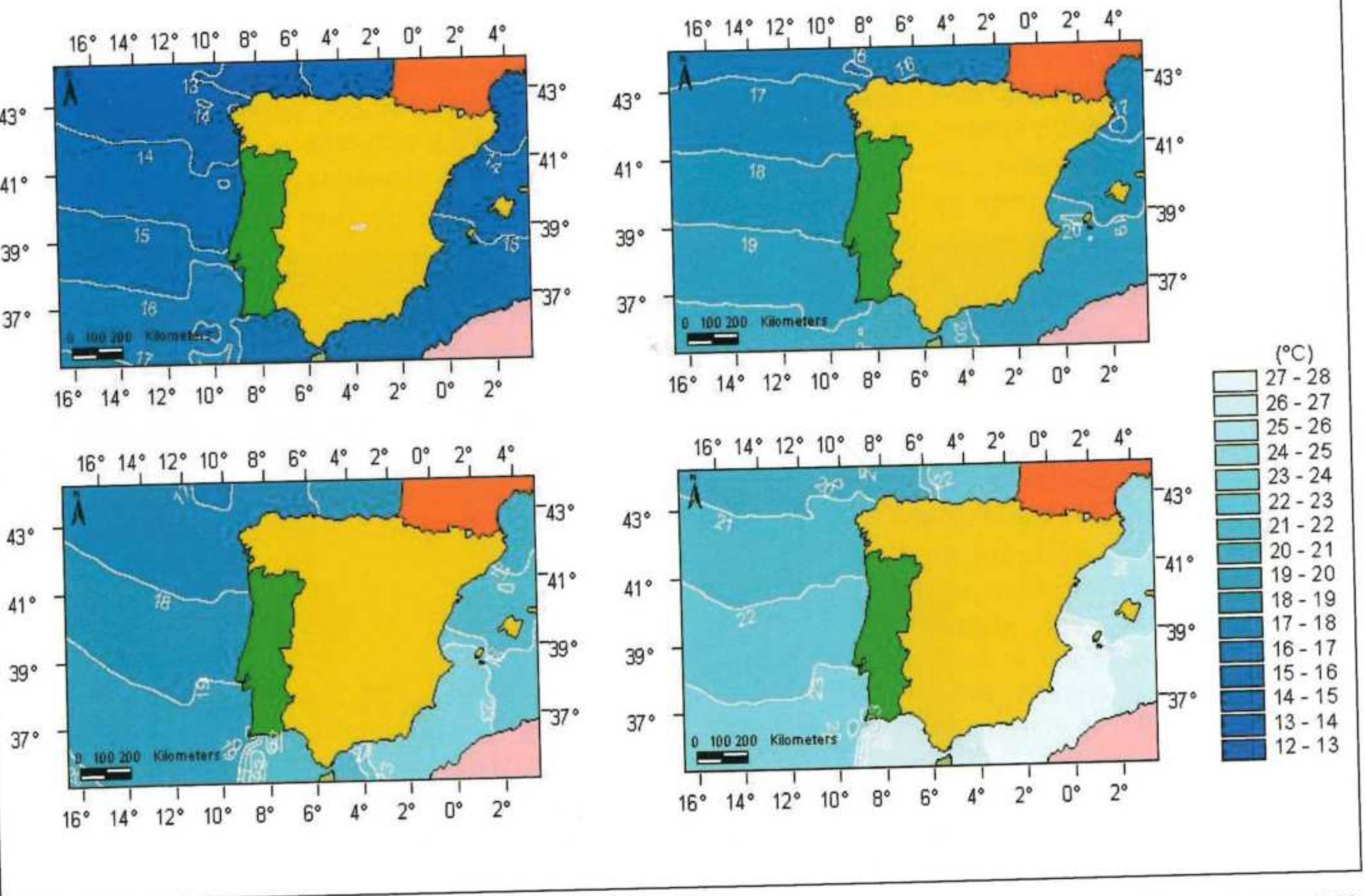


Fig 2.68 – Mean seasonal sea surface temperature in HadRM: DJF control, top left; DJF 2080-2100, top right; JJA control, bottom left; JJA 2080-2100, bottom right. Contour labels are also plotted.

more close to 4°C. In Fig. 2.68d the summer SST near the Portuguese coast varies between 22°C and an astonishing 26°C in the eastern coast of Algarve. It should also be noted that the Mediterranean waters between Spain and Africa can reach summer SSTs higher than 27°C according to the HadRM scenario for 2080-2100. This temperature increase is likely to have a significant impact on the sea fauna and flora around the Iberian Peninsula.

## 2.4 DISCUSSION

Both observations and model simulations indicate that climate change is taking place both at the global and regional levels. While some parameters, such as mean temperature, already show significant trends, others, such as mean precipitation and climate variability indices, are still rather difficult to analyse.

Some observed trends are in line with model predictions and show a high degree of spatial coherency at the regional scale, strengthening the case for their interpretation as climate change signals. That is the case of the observed trends in mean temperature, which adjust quite well to the global warming and cooling periods detected in average global temperature series. In the case of precipitation there are also significant clues of coherent changes at the regional scale, like the clear decrease of mean spring precipitation, especially during the month of March, affecting all stations in Portugal, and a possible tendency for a reduction of the duration of the rainy season, with more variable winters and drier springs. These latter changes have been attributed to systematic changes in the North Atlantic Oscillation index, associated at the regional scale with an increase in mean winter sea-level pressure in Portugal.

Along with the trends in temperature and precipitation, other intriguing changes can also be detected in the Portuguese climate, suggesting a slight modification of cloud cover. While these changes are supported by the consistency of trends in a set of independent variables (diurnal temperature range, cloudiness, sunshine hours and near surface relative humidity), the quality of the records is not sufficient to guarantee its significance. In this respected there is a clear need for further work in the preparation and analysis of historical observations.

Global and regional model simulations project a scenario of warming with dramatic impacts in the Portuguese region. Increases of near surface temperature in Portugal in those scenarios are far higher than the predicted changes in global mean temperature, and translate into dramatic changes of all temperature related climate indices. Impacts are higher in summer and autumn and in the interior of the country. In what concerns precipitation, models project a drier climate, with a shorter and wetter rainy season followed by a long dry summer. The projected reduction in mean precipitation is likely to affect more the southern regions of the country, which already experience shortage of water and large interannual variability. Projected changes in precipitation seem to be related with slight changes in the large scale circulation patterns in the Iberian/Atlantic region, driven by corresponding changes in the North Atlantic circulation.

The United States Environment Protection Agency states that "the projections of climate change in specific areas are not forecasts but are reasonable examples of how the climate might change". Indeed every climate change projection has high levels of uncertainty associated with it, and so is the case of the studies presented in this chapter. There are several factors contributing to the uncertainty. First it is difficult to predict the future greenhouse gas emissions scenarios. They depend intrinsically on many social and economic factors, such as the size of the future world population, the levels of development and evolution of technology, for which there are no reliable long term predictions. To deal with that uncertainty, the IPCC (2001) climate impacts assessments, constructed several emissions scenarios (SRES B1, B2, A1 and A2) covering a range of the greenhouse gas emissions published in the literature. We don't have yet, though, a corresponding ensemble of global and regional climate simulations. Instead, the HadRM simulations used a single emissions scenario, which was built before the IPCC (2001) work.

Another problem is the fact that current models use prescribed greenhouse gas concentrations (e.g. equivalent $CO_2$ concentrations), whereas emissions scenarios only provide values for the fluxes of those gases into the atmosphere. The transfer function between emissions and concentrations is still a rather controversial issue, source of great uncertainty in the long term.

A third source of uncertainty comes from the numerical models used in climate change studies. The physical processes may have different representations in each model, and also the spatial resolutions are widely variable from model to model. The representation of some critical processes, such as cloudiness and precipitation, are among the weakest points in any model. As a result, climate change fields are very often different from model to model, even for the same emissions scenario.

While the scientific community is building better climate models and feeding them with more reliable emission (or concentration) scenarios, there is a need to make climate impact assessments at the regional scale, keeping in mind that they are intrinsically provisional, but using at each time the "best available science". Those assessments will certainly have to be updated on a regular basis, at the pace of the scientific and technological advancements that are taking place.

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# 3

# Socioeconomic Scenarios

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Pedro Barata
*Euronatura*

CONTENTS

## EXECUTIVE SUMMARY

Social and economic scenarios have only recently been used in climate change impact assessments.

There are essentially two kinds of interactions between human society and climate: on the one hand, climate is influenced via emissions of greenhouse gases from economic activity. On the other hand, climate change will have impacts upon economic and social activities well into the future. Emission information is imbedded in this study via the emission scenarios, which are imbedded in climate models.

A major distinction should be made from the outset regarding this socio-economic analysis. This chapter focus on scenarios rather than socio-economic forecasts. A forecast is the product of a modelling exercise, based on a structured representation of a given phenomenon in society or nature. A scenario, like a forecast, is a decision-making tool. Unlike forecasts, scenarios do not claim to represent likely reality but rather a range of possible outcomes. Furthermore, the scenarios used are futures scenarios, encompassing different possible futures regarding the general evolution of society. This distinguishes them from emission scenarios, also used in damage assessment studies, but focused on the forecasting of emission trends (usually predicated on some sort of futures scenarios).

The modelling effort focuses initially on those main distinctive features that may be considered as the main driving forces of socio-economic change. While many similar exercises take indicators such as demography, economic growth or the rate of technological change as fundamental drivers of change in society, this study deliberately takes a value-oriented approach.

Social values regarding political organisation are distributed into two groupings: a 'globalist' and a 'localist' one. Globalists support the notion that supra-national organisations and institutions should increasingly play a role in social life, as these alone can deal with the increasingly international nature of our problems. Localists hold the view that the 'nation-state' should remain strong, and hold serious concerns over the dispersal of sovereignty entailed by the construction of supra-national entities such as the European Union.

The combination of the two dimensions involved in the previous analysis helps us map four different scenarios in a two-dimensional chart. The four scenario types can be seen in the four quadrants, as resulting from these combinations. For each of these four scenarios, a qualitative storyline is developed, along with an attempt at quantification based on expert judgement.

# 3. Socioeconomic Scenarios

## 3.1 INTRODUCTION

Social and economic scenarios have only recently been used in climate change impact assessments.

There are essentially two kinds of interactions between human society and climate: on the one hand, climate is influenced via *emissions* of greenhouse gases from economic activity. On the other hand, climate change will have *impacts* upon economic and social activities well into the future. Emission information is imbedded in this study via the emission scenarios that are imbedded in climate models. For background information on emission scenarios, the reader is referred to the Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change (IPCC, 1998).

The bulk of this chapter will therefore deal with social and economic scenarios for the next 25 years. These will be relevant insofar as they relate to possible social outcomes, which will be impacted upon by climate change, and will provide a clearer picture of the possible range of impacts on Portugal.

### 3.1.1 THE DISTINCTION BETWEEN SCENARIOS AND FORECASTS

A major distinction should be made from the outset regarding this socio-economic analysis. This chapter will not produce socio-economic forecasts, but rather scenarios.

A forecast is the product of a modelling exercise, based on a structured representation of a given phenomenon in society or nature. It has the nature of a prediction, although couched mostly as a probabilistic outcome, depending on the nature of the model. A forecast will only be as good as the model and the inherent assumptions, and is intended to provide decision-makers with background information.

A scenario, like a forecast, is a decision-making tool. However, scenarios do not claim to represent likely reality but rather a range of possible outcomes. Their use is warranted, when the underlying uncertainty of the exercise is such that no forecasting model can be used. Scenarios cannot be used therefore to assert, "what the future will be", nor even "what will the future likely be", but rather "what the future could possibly be".
In the study of climate change, the use of scenarios is entirely justified for several reasons:

- Firstly, the global nature of climate change impacts on economies and societies far removed from the scope of this exercise (Portugal) entails significant indirect impacts that can neither be accurately predicted nor forecasted.
- Secondly, the ubiquitous nature of climate change impacts on society and economic activity would make immensely complex any attempt at long-term forecast of climate change impacts. Even macroeconomic modelling at a national level is ill suited to cope with the scale and magnitude of climate change effects on the Portuguese economy.

The inexistence to date of Portuguese scenarios for the appropriate time-scale led this study to produce its own scenarios, on the basis of scenarios produced by the UK Climate Impacts team (SPRU, 1999)

### 3.1.2 EMISSION SCENARIOS AND FUTURES SCENARIOS

A further distinction should be made between emissions scenarios (see, e.g. IPCC (1998) and futures scenarios. The first category of scenarios involves assumptions on economic and technological development, which may or may not be grounded on particular futures scenarios. Their purpose, however, is to supplement climate change scenarios in producing a clearer picture of the rate of change in greenhouse gas concentrations in the atmosphere. This kind of scenario is therefore only relevant at a global scale, as it is global emissions that need to be evaluated with regard to the global concentration of greenhouse gases. Emission scenarios would only be relevant in a national study with regard to mitigation efforts and the evaluation of related social and economic costs, in a long-term perspective.

Futures scenarios relate to more general features of national society and economy. Their use is justified in the study of long-term trends and projections that go beyond the scope of any specific modelling. Unlike emission scenarios, which regard essentially one "component" of the future – greenhouse gases – future scenarios attempt at giving a coherent picture of possible future trends. The focus is not on probabilities (no such probabilities could be determined), but on the internal and external consistency of scenarios. Internal consistency means that there shouldn't be contradictions regarding the co-evolution of social variables. External consistency means that these scenarios are deemed possible, in that they somehow adhere to current trends. The emphasis is not on probability, but on plausibility.

### 3.1.3 STRUCTURE OF THIS CHAPTER

In the following chapter, a review will be made of the approach followed in this exercise. A brief review of scenario exercises conducted in Portugal is reflected in the following sub-section, with a view to their appropriateness for SIAM. The following sub-chapters will describe the scenarios constructed by the team, their driving forces, and what they entail for climate adaptability of the Portuguese society.

### 3.1.4 THE APPROACH TO SCENARIO-MAKING IN THIS STUDY

Given the uncertainty of social and economic outcomes over a period of 25 to 50 years, a predictive approach is not applicable. Unlike climate change scenarios, futures scenarios tend therefore to be used in the realm of planning more as a mental exercise, which tends to highlight driving forces and the questions that developments in the climate field may pose to the social and economic system. Social and economic scenarios should therefore be seen as a communication tool in the engagement of stakeholders in the climate debate. In this context, its must be said that the range of scenarios developed reflects the author's views on many of the assumptions underlying the study. The next step will be to develop stakeholder understanding of these scenarios, which are understandably open to contest.

The lack of background scenarios with particular relevance to the climate change and environmental field led the team to develop a set of scenario which closely mirror the exercise conducted in the United Kingdom in 1999 (SPRU, 1999) which was in turn developed on the basis of the UK Foresight Programme's Panel on Natural Resources and Environment.

As with the UK exercise, this study initially comprised several stages:

- a review of relevant futures scenarios already in use in Portugal;
- an assessment of the needs of the sectoral impact teams, and
- the development of draft scenarios.

The testing of scenarios and their review by the policy community will be conducted in Phase II.

## 3.2 BACKGROUND – A LOOK AT SCENARIO-MAKING IN PORTUGAL

As outlined in the previous section, the first stage of the construction of social and economic scenarios involved the review of relevant policy documents, to ascertain whether futures scenarios had already been constructed, which might have provided guidance to the team. There are several additional reasons why this review was conducted:

*Policy coherence* – When previous scenarios compatible with the objectives of this study existed, it was decided that these should be used. The nature of SIAM as a science-based policy tool required that assumptions on economic and social development should be integrated with current policy, as determined in general policy statements and plans.

*Information sourcing* – Social and economic scenarios, even when constructed with other purpose in mind, can provide relevant information on current trends across many indicators that have an impact on the adaptive capacity of societies to climate change impacts. For example, scenarios for fisheries policy would certainly involve the construction of general trends and indicators, which would be relevant to the study of adaptability of coastal communities in Portugal.

*Generation of long-term indicators* – in some limited cases, the existence of shorter-term scenarios led to the possibility of developing extrapolation exercises, thereby generating more adequate trends. This possibility, however, was only conducted for some very general indicators – population and gross domestic product.

The review of policy documents did not reveal much previous use of scenarios for planning and policy. Only the most general policy documents have some consideration of scenario making, although usually presented as a single vision of prospects for the economy, with little consideration for alternative paths. Insofar as scope is concerned, most scenarios deal only with the short-to-medium term (2010 to 2010, at most), a time span that is insufficient for the needs of a climate impact assessment study.

### 3.2.1 PLANO NACIONAL DE DESENVOLVIMENTO ECONÓMICO E SOCIAL (NATIONAL ECONOMIC AND SOCIAL DEVELOPMENT PLAN)

The NESDP (MEPAT, 1998) was developed as the starting point for negotiations between Portugal and the European Commission on the Third Community Support Framework, the overall plan for support for regional policy through European Union Structural Funds. As such, it represents the government's perspective on social and economic development for the period between 2000 and 2006.

The Plan builds on scenarios produced by the Department on Planning and Forward Studies of the Ministry of Planning (DPP-MES). Its scenarios are, however, restricted, as they rarely apply to beyond 2006. Most of the information is reflected only in qualitative terms. The introductory chapters of the NESDP integrate the proposed expenditures into a more general framework of the evolution of international and European society and economy.

### 3.2.2 RELATÓRIO PORTER (THE PORTER REPORT ON THE COMPETITIVENESS OF THE PORTUGUESE ECONOMY)

The Porter Report (Porter, 1994) was produced in 1994, at the request of the Ministry of Industry, by the Monitor Company consultants, under the overall coordination of Michael Porter. As with the previous document, no attempt was made at quantifying scenarios. However, as the study involved extensive stakeholder input, it allowed for the identification of variables determining the competitiveness of different sectors.

### 3.2.3 PLANO DE DESENVOLVIMENTO SUSTENTÁVEL DA FLORESTA PORTUGUESA (SUSTAINABLE FORESTRY PLAN)

Produced by the Ministry of Agriculture and Forestry in 1998, the SFP (DGF, 1998) is the first attempt by the government at a general policy document for the forestry sector. Although strong on its characterization of the current situation with regard to the forestry sector, with an impressive data set, no attempt at using social or economic scenarios of an international or European nature was made. Policy options are mostly reactive, and an implicit assumption is made that current trends and imbalances will continue indefinitely.

### 3.2.4 PLANO NACIONAL DE POLÍTICA DE AMBIENTE (NATIONAL ENVIRONMENTAL POLICY PLAN)

Although admirable in many of its features, such as the integration of environmental concerns into transsectoral policies, e.g. taxation or foreign policy, the NEPP (MARN, 1995), commissioned in the latter days of the 1991-95 Government, was never applied into policy, and has since been subject to revision, with no date set for the publication of a new Policy Plan. Innovative as it was in its content, the NEPP did not rely on any futures scenarios for the development of its prescribed policy approach.

### 3.2.5 ENERGIA 1995-2015 – ESTRATÉGIA PARA O SECTOR ENERGÉTICO (ENERGY 1995-2015 – STRATEGY FOR THE ENERGY SECTOR)

A more thorough analytical endeavour, this study of the energy sector builds upon scenarios conducted in a former study by the Department of Planning and Forward Studies of the Ministry of Planning, and sets out three possible scenarios for the economy, based on a similar set of scenarios for the European economy: a 'slow', a 'moderate' and a 'high' growth alternative. The scenarios do not place any emphasis on social behavioural change and restrict themselves to general macroeconomic content. The aim of the study as a planning tool for medium-term policy (20 years) time span makes consideration of these variables most likely irrelevant. Furthermore, energy policy as reflected in this document is very much supply-driven, and most of the impact of different scenarios is reflected in different possible combinations of energy supply sources.

### 3.2.6 CONCLUSIONS FROM THE REVIEW OF POLICIES AND PROGRAMS

The initial review, along with personal communication with some of the authors, in particular with the authors of the NESDP, the SDP and the Energy Sector study, led the team to confidently assess that no previous long-term scenarios could be used which would encapsulate the total range of scenarios over the appropriate time span. This conclusion led to the realisation that the team would need to develop own scenarios. In doing so, we decided to follow the approach used by the UK Climate Impact team, for the following reasons:

- —Easiness of use: the approach, based on qualitative storylines, supplemented by quantitative headline indicators, is generally easy to use and communicate to the final user of the climate impact assessment study;
- —Participatory approach: the approach requires the involvement of the whole climate team and of outside experts, as well as interested stakeholders. Arguably, this will lead to increased confidence in the appropriateness of the results and a larger sense of ownership on the part of stakeholders.
- —Integration with the objectives of climate assessment: the scenarios are built with the explicit purpose in assisting the study of vulnerability and capacity to adapt of both society and economy. As such, those social values that have a bearing on the capacity to adapt are more readily displayed in a purpose-built scenario-making exercise. The SIAM team accepted the general setting of the four scenarios proposed, and considered them in their impact assessment studies.

## 3.3 THE FRAMEWORK

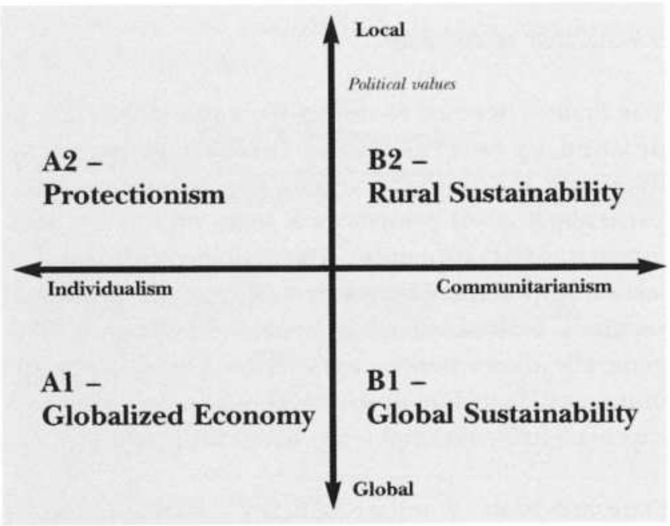
There are numerous methodologies to construct scenarios. As previously stated, our methodology closely mirrors that of the UK Climate Impact team. The modelling effort focuses initially on those main distinctive features that may be considered as the main driving forces of socio-economic change. While many similar exercises take indicators such as demography, economic growth or the rate of technological change as fundamental drivers of change in society, we deliberately take a value-oriented approach.

In line with the UK study (SPRU, 1999) we consider the aforementioned indicators as results of more fundamental choices society and individuals face regarding their values in relation to moral and ethical themes, as well as to the desirable organisation of society. In doing so, we will explicitly ignore feed-back loops that flow between values and technological change, settlement patters and values and many other possible combinations, out of a concern for practicality and expedience. In doing so, we nevertheless aim at internal coherence of both value systems and its scenario outcomes. For a detailed analysis, the reader is referred to the aforementioned study.

Social values regarding political organisation are distributed into two groupings: a 'globalist' and a 'localist' one. Globalists support the notion that supranational organisations and institutions should increasingly play a role in social life, as these alone can deal with the increasingly international nature of our problems. Localists hold the view that the 'nation-state' should remain strong, and hold serious concerns over the dispersal of sovereignty entailed by the construction of supra-national entities such as the European Union.

Social values regarding our approach to social organisation are organised into two distinct groups: individualists, grouping all those that stress individual freedom of choice, and communitarians, grouping those who stress rather the importance of collective action towards socially desirable goals.

The combination of the two dimensions involved in the previous analysis helps us map four different scenarios in a two-dimensional chart. The four scenario types can be seen in the four quadrants, as resulting from these combinations. For each of these four scenarios, a qualitative storyline is developed in the following chapter.



Source: adapted from SPRU (1999).

## 3.4 THE SCENARIOS

### 3.4.1 A1 - Globalized Economy

This scenario is characterized by a move towards unprecedented globalisation of markets, increased liberalization of trade flows and movement of labour across borders.

#### *3.4.1.1 Values*

Citizens of the global economy are primarily concerned with personal well-being and 'consumerist' values are prevalent. The market, rather than the state, is deemed to be the best provider of these goals. There is strong desire for mobility. Ideals of community life are forsaken for a more global identity.

#### *3.4.1.2 Role of the State*

The state retains its role as arbitreur of markets, but in many aspects, the State is seen to retire from its usual dominance over national institutions. Power is dispersed both to the international level and to non-state actors, particularly in the realm of economic affairs. Trade and fiscal policies are increasingly harmonised in the European Union, and a number of WTO rounds manages to decrease tariff and non-tariff trade distortions. Social Security and other national services are increasingly replaced or supplemented through private schemes, including the provision of health and other welfare benefits.

#### *3.4.1.3 Civil Society*

Transnational corporations and the private sector play an increasing role in public policy and to a large extent determine much of the economic activity. Non-governmental organisations in the environmental field and others tend to become more professional, but also more distant from the individual member. There is less voluntary work.

#### *3.4.1.4 Population*

Family size continues to be small. Increasing mobility and a push for higher levels of economic growth require increasing levels of immigration, from both Eastern Europe and, later on, from Africa. This leads to higher levels of social tensions, as immigrants compete with poorer sections of the resident population for low-pay jobs.

#### *3.4.1.5 Economic activity*

Agriculture is modernised, insofar as it is viable with the pro-market reforms introduced in the Common Agricultural Policy. These tend to favour concentration of property and cash crop production. Agriculture becomes viable only in the most productive soils (Tejo estuary, Setúbal province and areas around Beja). Large areas of the country are set aside from production and regress into wildlife areas. Industry is modernised, and concentrates along existing centres (Ave, Setúbal) with high growth in export industries, e.g. automotive industry, textiles. Lisbon develops as a second-order financial and services centre for the Western Iberian Peninsula.

#### *3.4.1.6 Urban settlements and regional distribution of wealth*

Urban centers develop even further in this scenario, and the traditional disparity between income levels in the urban centers and the other regions is further increased. Lisbon and Oporto concentrate most of the population and the wealth of the country. There is increased renovation of town centres, as rent controls are progressively abolished and upmarket housing is developed in central areas of larger cities. Tourism is well developed along the coastline, but increasingly takes up niche markets in the rest of the country. The border regions and Alentejo lose most of the remaining population and are increasingly viable only in niche markets (golf, leisure activities) and as an area of secondary housing for urban dwellers. Industry is modernised, and most will concentrate along the existing centres (Ave, Setúbal) with high growth in export industries, e.g. automotive industry, textiles. Lisbon develops as a second-order financial and services centre for the Western Iberian Peninsula.

#### *3.4.1.7 Environmental awareness and policy*

Environmental awareness is generally low and tends to focus on local and regional issues rather than global ones, such as climate change. There is an increasing reliance on market-based instruments in environmental policy, and competitiveness issues predominate over concerns for the environment.

**Table 1. Globalized Economy**

| Economic and Social Indicators | Today | Globalized Economy |
|---|---|---|
| GDP (per cent average growth) (per cent average growth) | 3 | 4 |
| GDP/capita (€/year) | 7260 | 13110 |
| Income distribution (ratio of first to tenth decile) | 1/5 | 1/6,5 |
| Poverty rate (% below 60% median income) | 23 | 23 |
| Government final consumption expenditure (%GDP) | 51 | 45 |

### 3.4.2 A2 - Protectionism

#### *3.4.2.1 Values*

There is a strong consumerist approach on the part of most sectors in society, with little interest in the pursuance of more altruistic goals. Self-reliance on the part of the individual reflects in little concern for social equity or public participation.

#### *3.4.2.2 Role of the State*

The State is deemed to reflect the national interest, as defined by several strong interest groups who dominate the political arena. The private sector is particularly given priority as it seeks protection from international competition. The State provides only the most traditional public goods – defence, international relations, basic standards in health and education, but generally allows markets to determine most economic outcomes. Transfers of sovereignty to other spheres – supra- or infra-national – are successfully resisted.

State provision of welfare benefits is fairly limited, as working against the predominant nature of society as 'consumerist' in outlook.

#### *3.4.2.3 Civil Society*

Strong interest groups dominate civil society. The nature of governance, less participatory and more reliant on traditional means of influence, tends to discriminate towards smaller and less organized groups and inequality of treatment between organisations and regions increases. Organisations connected with traditional industrial sectors gather relatively more influence, as they seek patronage from the State.

#### *3.4.2.4 Population*

Family size is slightly higher. Immigration is relatively low, as illegal immigration is curbed and a general policy of local preference provides disincentives for immigrants. Average household size remains fairly stable.

#### *3.4.2.5 Economic activity*

Due to a policy of import substitution and a lack of foreign investment, economic growth is slower than potential, leading to generally lower levels of economic activity. The beneficiaries of protection are traditional activities, including agriculture and traditional industry activities. There is an active policy on the part of the State to diversify economic activity across sectors and throughout regions. This will counteract the naturally higher growth of the financial and services sectors, concentrated in Lisbon and Oporto, and favours industrial activity around smaller urban centres.

**Table 2. Protectionism**

| Economic and Social Indicators | Today | Protectionism |
|---|---|---|
| GDP (average growth) | 3 | 2 |
| GDP/capita (€/year) | 7260 | 10760 |
| Income distribution (ratio of first to tenth decile) | 1/5 | 1/6 |
| Poverty rate (% below 60% median income) | 23 | 25 |
| Government final consumption expenditure (%GDP) | 51 | 48 |

#### *3.4.2.6 Urban settlements and regional distribution of wealth*

Urban settlements stagnate at their current levels, with slight increases in concentration in the large metropolis and in regional centres such as Évora and Aveiro, due to local protection of industrial activities and active policies for establishment of State institutions (e.g. universities, hospitals).

#### *3.4.2.7 Environmental awareness and policy*

Awareness of environmental problems is relatively low and is focused especially on local problems. Environmental policy takes second place to economic considerations, and environmental policy measures tend to focus on clean air, the built environment (heritage sites) and scenic areas. More affluent areas tend to concentrate the bulk of environmental concern, along with Nature Reserves and Natural Parks.

### 3.4.3 B2 – Rural Sustainability

#### *3.4.3.1 Values*

There is a predominance of communitarian values, and a focus on self-reliance at the local level. Environmental and social goals take precedence over economic goals and sustainability issues take centre stage. There is a emphasis on equity and participation in social and political structures.

#### *3.4.3.2 Role of the State*

The State comes increasingly under pressure from localized and regional interests, and pressure for more decentralisation of power increases. Municipalities and regional governments are increasingly more important in political life, along with non-state actors, in particular those acting at the local level and volunteer-based. Traditional interest groups connected to the private sector increasingly come into partnership with these new actors. The European Union becomes more democratic and accountable, with a stronger European Parliament, to the detriment of the European Commission and Council.

#### *3.4.3.3 Civil Society*

As the State wanes its influence, non-state actors are increasingly responsible for the management at local levels, of the resource base, mostly in partnership with municipalities. Civil society organisations increase their influence through their increased role in consultation and other participatory approaches to governance, including local and regional hearings and referendums.

#### *3.4.3.4 Population*

The population remains stable. Although household numbers decline, average household size increases as a result of more communitarian values and a return to the extended family. Planning controls on new housing for environmental reasons also imply a higher cost for newlyweds in purchasing housing.

#### *3.4.3.5 Economic activity*

Economic activity grows less than in other scenarios, as a result of the lack of emphasis on economic growth as a social goal, but also as a result of increased attention to the attainment of social balance (implying a larger role for expenditure in the social and environmental sectors) and restrictions on economic activity induced by environmental reasons. Industry suffers major restructuring, with a bigger emphasis on manufacturing for local and regional markets. Industry suffers from heavy restrictions on loca-tion. Investment declines and the financial and services sectors reorient themselves to service new products in a more local and national market.

**Table 3. Rural Sustainability**

| Economic and Social Indicators | Today | Rural Sustainability |
|---|---|---|
| GDP (average growth) | 3 | 1,75 |
| GDP/capita (€/year) | 7260 | 9735 |
| Income distribution (ratio of first to tenth decile) | 1/5 | 1/3,5 |
| Poverty rate (% below 60% median income) | 23 | 12 |
| Government final consumption expenditure (%GDP) | 51 | 55 |

### *3.4.3.6 Urban settlements and regional distribution of wealth*

There is a slow but steady reversal of the trends towards increased concentration in the two large cities in the country. This will lead to a renaissance of some particular centres in middle-sized towns such as Évora, Aveiro or Coimbra, which increasingly are seen as offering a better quality of life than Lisbon and Oporto.

### *3.4.3.7 Environmental awareness and policy*

Environmental awareness is high and environmental policy assumes a high profile. Policy is structured around the preservation of local natural values, with special focus on protection of local biodiversity and scenic values. An informed public is concerned about global environmental issues and solutions to these problems is sought at the local level, through the application of emission controls and planning regulations, which are generally accepted by the public. There is as much emphasis on technological solutions as there is on behavioural and societal change.

## 3.4.4 B1 – Global Sustainability

### *3.4.4.1 Values*

Communitarianism reflects itself in the general view of the world as a 'global village'. There is a strong emphasis in the media and in public opinion on the need for global solutions and global responsibility to cope with the problems of sustainability. These are seen to derive from the flaws of a process of globalisation that focuses on global markets rather than the sharing of global information and participation in common endeavour. There is consensus on the need to promote at the international level, through official development aid, but also through partnerships with different sectors, equity and global participation. This is aided by the emergence of new global communities, formed by the new media.

### *3.4.4.2 Role of the State*

Global problems are perceived to be best addressed through international cooperation through the United Nations systems. Strong international regimes are favoured over more voluntary-based approaches for regulation of access to natural resources. This is the case, for example, with climate change. At EU level, increasing integration follows the federalist route. The State actively promotes discussion and consensus across stakeholders on solutions at the local level to international or national priorities. The role of local government is especially important, as the lowest link in a hierarchical model that ties global decisions to local implementation. Participation is highly stressed in the political system.

### *3.4.4.3 Civil Society*

Civil society is particularly strong in this scenario, due to the nature of governance as being more participatory and inclusive. Non-state actors, whether private sector or environmental and other organisations, are called upon to share in global decision-making and, most particularly, to co-implement decisions at the national and sub-national level. At the local level, consultative processes take precedence over more traditional decision-making, and local government increasingly assumes the function of provider of services to the population, in line with regional priorities, as determined in consultation with stakeholders.

### *3.4.4.4 Population*

Higher incomes tend to decrease average household size, but the impact on overall population numbers is diminished by a larger influx of migrants from the North. Lisbon and Oporto remain important centres, but new centres arise in other areas with increasing vigour. Although open international markets work towards great centralisation at home, this is partly offset by the perceived need to manage delicate ecosystems outside the two main areas, whether in the border and mountain regions or in coastal wetlands. High mobility of labour is facilitated by technology and the emergence of more knowledge-based professions.

### *3.4.4.5 Economic activity*

Growth, while not seen as a priority, is still relatively strong, due to the openness of markets and the existence of a competitive international market for most goods. Research & Development is promoted through public-private partnerships. International regulation in the economic field is strengthened by the larger powers given to the European Union, and the greater degree of compliance with international economic institutions such as the Word Trade Organisation.

**Table 4. Global Sustainability**

| Economic and Social Indicators | Today | Global Sustainability |
|---|---|---|
| GDP (average growth) | 3 | 3 |
| GDP/capita (€/year) | 7260 | 12 425 |
| Income distribution (ratio of first to tenth decile) | 1/5 | 1/5 |
| Poverty rate (% below 60% median income) | 23 | 15 |
| Government final consumption expenditure (%GDP) | 51 | 51 |

### *3.4.4.6 Urban settlements and regional distribution of wealth*

Regional development is distributed equally across the continent, due to planning controls and tighter restrictions on economic activity and concentration. A policy of preservation of wildlife areas provides new role for professions in the countryside, and social costs of this 'caretaker' attitude are assumed through transfer payments to rural populations. Lisbon and Oporto remain important centres, but smaller cities increase in wealth and population, and there is a renaissance of small community life. There is significant structural change in industrialised areas, which will compete for the new standards in quality of living with unspoilt areas.

### *3.4.4.7 Environmental awareness and policy*

Environmental awareness is very high, and there is a general commitment to resource efficiency both in industry and in personal consumption, spurred by regulation and market-based approaches. There is particular importance attached to greater, global challenges, such as the protection of biodiversity and the mitigation of, and adaptation to, climate change.

## 3.5 NEXT STEPS

These scenarios were not put to a more formal testing and reviewing for consistency. It is therefore appropriate to note at this stage that the following stage in this methodology would be to convene a workshop and to establish a process of review by both the sectoral impact teams and by others outside the team with experience in forward-looking studies. Finally, a thorough review by stakeholders in the climate and other fields must be conducted. The exercise is, as yet, incomplete, but some preliminary conclusions from the work so far may be drawn.

The use of quantified indicators is warranted, as it acts to focus researchers and stakeholders in the exact nature of the change being described. The exercise must be approached with caution however, especially in communicating with non-experts, who may be tempted to use these as forecasts. In particular, quantification may convey the false impression that the results were obtained from a particular model

Secondly, society and economy being such complex systems, it is doubtful that any mass of intelligence applied to modelling will ever produce clearer results than the ones given here. As such, the main advantage of conducting these exercises is the possibility it gives to highlight choices in societal and individual behaviour and relate them to a specific and concrete problem. These choices are inherently rooted in preferences of individuals over their desired future. It is difficult to avoid value judgements on "how the world should look like" and not reflect it in the exercise. The exercise can only be valid, once it is deemed credible and consistent outside of the narrow circle of its authors and by a wider and disparate audience.

Thirdly, a recommendation is needed for both future users and future developers of socio-economic scenarios regarding the appropriate development of these scenarios. Whenever possible, the team has decided to consult extensively and interact with the other teams in the project. The need for integration is nowhere more present than in this exercise, which is only fruitful if used by others.

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## ANNEX – SUMMARY TABLE OF SCENARIOS

| Indicators | Today | 2020 (linear projection) | Globalized | Protectionism Economy | Global Sustainability | Rural Sustainability |
|---|---|---|---|---|---|---|
| **Economic Development** | | | | | | |
| GDP average growth rate | | 3 | 4 | 2 | 3 | 1,75 |
| GDP factor cost, current prices, billion € | 68,85 | 124,265 | 150,755 | 102,24 | 124,265 | 97,34 |
| Per capita GDP (market prices) in € | 7260 | 2539 | 13110 | 10760 | 12425 | 9735 |
| Income distribution (ratio of first to tenth decile) | 1:5 | 1:6 | 1:6.5 | 1:6 | 1:5 | 1:3.5 |
| Poverty rate (% below poverty line = 60% median income) | 23 | 23 | 23 | 25 | 15 | 12 |
| Government final consumption expenditure (% GDP) | 51% | 45% | 45% | 48% | 51% | 55% |
| Exports (%GDP) | 30% | 30% | 35% | 32% | 20% | 35% |
| Value Added | 13461831 | | | | | |
| services | 60% | 73% | 85% | 75% | 85% | 62% |
| industry | 35% | 25% | 14% | 22,5% | 12% | 34% |
| agriculture | 4% | 2% | 1% | 2,5% | 3% | 4% |
| **Demographics and living conditions** | | | | | | |
| Population | 9474070 | 9788222 | 11500000 | 9500000 | 10000000 | 10000000 |
| Immigration (official numbers) | 177774 | 285000 | | | | |
| Total immigration | 500000 | 801580 | 1500000 | 700000 | 800000 | 700000 |
| Immigration rate | 7% | 5% | 13% | 7% | 8% | 7% |
| Average household size | 3 | 3,05 | 3 | 3 | 3 | 4 |
| Hoseuhold numbers | 3,15 milhões | 3,2 | 3,8 | 3 | 3,3 | 2,5 |
| Occupaction of dwellings | 3,3 milhões | | | | | |
| Average construction area (m²) | 83 | 110 | 115 | 100 | 110 | 100 |
| Length of daily stay in house | 15 horas | 15 horas | 13 horas | 15 horas | 15 horas | 16 horas |
| **Geographical Distribution of Housing** | | | | | | |
| North | 34 | | 35 | 35 | 34 | 32 |
| Centre | 19 | | 19 | 20 | 20 | 20 |
| Lisbon and Tagus Valley | 37 | | 38 | 39 | 35 | 31 |
| Alentejo | 6 | | 4 | 3 | 8 | 8 |
| Algarve | 4 | | 4 | 5 | 6 | 6 |
| % apartaments | | | | | | |
| North | 36 | | 40 | 40 | 35 | 36 |
| Centre | 21 | | 21 | 21 | 21 | 20 |
| Lisbon and Tagus Valley | 65 | | 70 | 65 | 62 | 60 |
| Alentejo | 22 | | 30 | 25 | 25 | 22 |
| Algarve | 37 | | 50 | 42 | 42 | 35 |
| Percentage housing with heating equipment | 70 | | 95 | 85 | 90 | 80 |
| Percentage housing with cooling equipment | 2 | | 95 | 85 | 90 | 80 |
| **Bodiversidade** | | | | | | |
| Área protegida (% do total) | 20% | - | 20 | 25 | 30 | 40 |

# 4

# Sociological Analysis

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## EXECUTIVE SUMMARY

The focus of this chapter is the decision-making process. Decision-making has been undertaken by using risk and cost-benefit analysis, which helps nation states define primary goals to sustain within consensual international agreements. However, uncertainties of climate prediction, and inter-subjective cultural risk definitions bring up the problem of reaching easy consensus. In fact consensus building tends to be a highly conflictual process. The justifications for acting against climate change impacts vary from a range of moral and cognitive issues, economic interests and political objectives. These differences affect the decision making process at the national, as well at the international level and decision makers play particular roles in competing interest groups. These groups must be able to communicate rapidly and effectively. In order to achieve positive and efficacious implementation of strategies and measures, the importance of reducing communication disruptions between stakeholders has been stressed, through the establishment of communication flows in the interchange of climate knowledge and stakeholders interests. This has become one of the recommendations of the UNEP Handbook. The general methodological approach starts with impact assessment and impact consensus building. It is subsequently possible to specify the most important impacts and identify adaptation options as well to examine natural and social constraints imposed during their implementation among the different stakeholders. This was the general approach adopted in this chapter, where the identification of consensual impact values was undertaken within the present research.

# 4. Sociological Analysis

## 4.1 INTRODUCTION

During recent decades climate change as become a major environmental problem. Relative uncertainty on when climate changes impacts will occur and the strong human dependence on activities producing greenhouse gases, like $CO_2$ have necessitated an analysis of climate change in terms of its risks to human and natural systems[1]. Additionally it has brought nations together for international cooperation on the global environment.

Climate change gained major focus with the Earth Summit in 1992 in Rio de Janeiro, and, in particular after the Kyoto Protocol which obliged nation states to be involved with international decision making on climate change. To sustain the implementation of the UN Framework Convention on Climate Change (UNFCCC) an intergovernmental panel specialised on climate issues (Intergovernmental Panel on Climate Change-IPCC) was created to provide scientific knowledge and complete information on climate change impacts, adaptations and vulnerability. The UNFCCC, the Kyoto Protocol and the IPCC theoretically, place climate change as one of the primary goals for institutionalising ecological interdependence.

Even with the probable ratification of the Kyoto Protocol, which obliges nations to develop solutions each government may tend to differently prioritise their approach to the issue. Given differing issues, strategies and economic paradigms, a negotiation ground is permanently determined for climate agreements (Laird, 2001). Actually, considering the developments for Kyoto's Protocol implementation, it is possible to observe the difficulties in bringing together countries to agree on policies and strategies for greenhouse gases reduction.

One of the functions of IPCC is to produce information, which helps on producing standard climate definitions and concepts, such as mitigation, adaptation and vulnerability. Science is the basis upon which agreements and strategies are developed regarding global environmental risks (IPCC, 1995). The function of the IPCC is to provide clear and standard information about global climate change upon which other cognitive, social and political definitions may be established. The IPCC provides information about the probable consequences on climate of greenhouse gas producing economic activities in range of socioeconomic scenarios. In this sense, IPCC alerts us to the consequences of current trends of global development, as well as underlines the importance of sustainability.

Politically decisions are to be made regarding policies and strategies for mitigation and adaptation. As climate change impacts already affect natural and social systems, the IPCC recommends that countries establish national policies to adapt to climate impacts. It also recommends the assessment of vulnerabilities as a way to anticipate positive actions in face of climate effects. These recommendations were developed in the IPCC guidelines and in the Handbook on Climate Change Impacts and Adaptation Measures (Handbook), which provides the main guidelines for regional impacts and adaptation research (Carter et al, 1994. Feenstra et al, 1997).

The focus of this chapter is the decision-making process. The general approach adopted in international decision-making can be described as bottom-up, which some authors define as the realistic model for decision-making. According to this model nation-states determine their policies according to their governmental procedures and laws, and come together to generate an international consensus (Rayner, 1991). Theories approaching climate change through decision-making issues place climate change at the level of a paradigmatic change on state governance. The use of a term such as paradigmatic change stems from the need of legal and administrative changes that incorporate the cross-cutting features of ecological interdependence, superimposed over classical legal and administrative departments. Moreover, the responsibilities associated with the consequences and risks of climate change demand pluralistic models of decision-making, as opposite to the traditional technocratic model, as well the integration of forums of public debate (Jasanoff and Wayne, 1998). This last model as been described by anthropologists as the polycentric model. As important as incorporating concepts and policies

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[1] As risk we generally consider the environmental impacts derived from anthropogenic causes, which are different from hazards, derived from unpredictable natural causes (Beck, 1992).

defined by the scientific community into custom law, is ensuring cultural and social participation on the conceptual and political definitions (Rayner, 1991).

Decision-making as been undertaken by using risk and cost-benefit analysis, which helps nation states define primary goals to sustain within international agreements. However, uncertainties of climate prediction, and inter-subjective cultural risk definitions bring up the problem of reaching easy consensus (Rayner and Malone, 1997). In fact consensus building tends to be a highly conflictual process. In cases where perceived risk is high, the importance of the debate is higher. Cost evaluation and risk perceptions tend to be different among members of governments, stakeholders and civil society affecting nation states' choices for strategies over climate change (Rosa and Dietz, 1998). The same risk perceptions differ accordingly to worldviews and social organisation as, for example, within a frame of sustainability, the issue tends to become more relevant than within liberal economies (Cotgrove, 1982). Moreover, issues on global equity and environmental equity for future generations affect the structure of risk definition (Redclift and Sage, 1997). The justifications for acting against climate change impacts vary from a range of moral and cognitive issues, economic interests and political objectives. These differences affect the decision making process at the national, as well at the international level.

Decision makers play particular roles in competing interest groups. These groups must be able to communicate rapidly and effectively with actors from other countries. As the author refers, "In this way, communication across national cultures by common institutional cultures can lay the groundwork for internationally shared understanding" (Rayner, 1991: 80). In order to achieve positive and efficacious implementation of strategies and measures, the importance of reducing communication disruptions between stakeholders as been stressed, through the establishment of communication flows in the interchange of climate knowledge and stakeholders interests. This has become one of the recommendations of the Handbook. The general methodological approach starts with impact assessment and impact consensus building. Scientists need to achieve a certain degree of conformity within their community around the impact analysis in order to gain a higher lever of confidence on the results obtained. It is subsequently possible to specify the most important impacts and identify adaptation options as well to examine natural and social constraints imposed during their implementation (Feenstra et al, 1997). The value of this method lays in the chance of promoting a consensus around the information that could otherwise lead to conflicts of interest, thereby helping measures to be implemented effectively. When there is relative consensus on the political decisions and the choice of measures to be taken, they can be implemented within a greater context of political and social security. However, it is not only relative to a political decision that this methodology is useful.

This was the general approach adopted in this chapter, where the identification of consensual impact values was undertaken within the present research.

## 4.2 PROBLEM

Specific impacts are uncertain, but climate scientists maintain that it is possible to forecast the types of impacts. This requires an exchange of information between the stakeholders to reach a consensus around the impact degree as well the expected time span for the impact to occur. This consensus helps validate information that scientific forecasting models cannot give with certainty. In this sense, through agreement over the impacts it's possible to undertake the debate on the possible strategies and measures to be designed for future implementation (Robinson, 1990).

If communication flows clearly, bringing in consensus, the measures under discussion between stakeholders may be accepted as socially valid. This might avoid later conflict or disruption along the implementation procedures. For instance, for the government taxes and incentives might be a proper strategy for achieving behavioural change in cases of change use adaptation measures. However for environmental NGO's the proper and qualified information concerning climate impacts might be more useful policies than taxes and market policies. For scientists, regulation and innovative techniques introducing new productive practices, or investing in research and development, might work better. The communication issues and the development of communication channels are considered as central variables for successful planning of effective measures.

The problem is how to ensure communication flows, of information and concepts between those who participate in the climate policy, in order to achieve effective policies and measures. How should we approach the debate? To answer this question we have decided to apply the method proposed by the Handbook, using the impact scenarios as the point of departure to reach decisions on adaptation. However, instead of working with a group that would debate around the main impacts and adaptations options, we have decided to complete the research using a survey based on the Delphi technique.

## 4.3 METHOD

To identify the chances to advance a certain adaptation measure (developed by the sectors teams) we used a model based on future expectations of impacts and of the evolution of national climate policy. The choice of a research model, based on expectations is justified by the fact that climate effects will occur over a wide time frame, as much as approximately 100 into the future. Some authors argue that present expectations of future societies are able to better predict how institutions and people will act regarding the future. This is because present planning will be organised around the needs and beliefs of what is expected to be the future society (Robinson, 1990; Vilkensen and Tirkkonen, 1997). In this sense, it is important to identify the convergence point of stakeholders' different beliefs and expectations over climate change issues.

The first stage of the research was undertaken using the Delphi technique with a survey designed to find the most preferred and most consensual opinions on climate impacts. This survey was then, followed by a group interview to validate these primary results. The research does not build future scenarios of policies and measures implementation it merely evaluates them. This analysis is based on impacts and adaptation measures identified at a preliminary stage of the research by the teams, which was further developed by the impacts teams when new data became available. Given the pioneering nature of this project, each of the techniques is partially experimental.

The survey was applied to a sample of three groups of stakeholders: public sector decision-makers, business decision-makers and opinion leaders. The latter was comprised of environment journalists, for their capacity of mobilising and circulating information, and environmentalists. This choise is based on the fact that their discourse is permeated by the interest in the defence and protection of the environment (Vlachos, 1989). However, this sample is flexible and capable of including other entities as needed for a given impact sector.

The using of political decision-makers as a sample group derives from the ultimate objective of this work concerning the definition of a strategic climate policy (Rayner and Malone, 1998). With respect to the scientific community, it is believed that besides endorsing and explaining the impacts in each of the sector areas, they will be able to anticipate the correct mitigation responses. Bearing in mind the minimisation of impacts, it is believed that these individuals will have the capacity to propose response measures to diminishing vulnerability of a region or country. The adaptation, in this case, may consider the cost benefit ratio, but will be orientated from the beginning, in a way distinct from those of the politicians. Lastly, and as said before, we will consider this group's evaluation of the politicians and vice-versa. Each sample group works as a discriminating variable of the different positions. In this sense, it is understood that each group is internally consensual and distinctive from the others.

We took on the preliminary impacts as well the proposals for adaptation strategies determined by the sector teams and submitted them to the sample considering four types of questions for each impact and adaptation measure. Our questions were:

1. How stakeholders view the issue of climate change in terms of its regional impacts?
2. How serious is the problem?
3. When they will occur? And;
4. How and with what strategies should Portugal face this problem?

In spite of this focus, our survey served mainly, as a diagnostic evaluation for the positions of decision makers, experts and opinion leaders on the three topics in focus: impact, adaptation and socio-political scenarios. As well as producing an information basis of the subject, it is important to diagnose the vulnerability perceptions of each regional sector, based on the less controversial and more consensual proposals.

In the sense, the team decided to develop the first stage of analysis of assessing knowledge, expectations and beliefs of the informants, and to assess the differences found between them. Moreover, the team evaluated their expectations of the future engagement of governments in designing a climate policy and planning, as well its implementation time span. These variables were introduced as a way to understand how far knowledge play a role in splitting stakeholders positions.

In the second phase the consensual positions around the development and planning objectives for the country, which will guide national policies were analysed. For example, the objective of reduction in public spending and economic growth, or the implementation of environmental sustainability may be prioritized differently. As some authors argue, this consensus well as the objectives themselves could be appraised in terms of the hopes of the stakeholders that could be behind the planning and forecasts (Smith, 1997). Finally, our model identifies the expectations of government capability for action, through the evaluation of a variable of mobility/immobility of the players. This one will be analysed in their capacity to utilise technological, economical and political resources.

The survey evaluated the relative position of stakeholders to three main concepts of this project: Impact, Adaptation and Vulnerability. For impact we consider that the predictable impact to climatic changes (temperature, rainfall/sea level/evaporation) may have different effects according to the social context of a country/region and according to the adaptation capabilities to the same impact. For adaptation we assume that the adaptation to the effects/impact of climatic changes is an area of action contemplated in the Kyoto Protocol, as a means of reducing the intensity of the impact. This adaptation is a guarantee of the possibility to develop a natural process of adaptation, or in case that possibility does not materialise within a time limit, then the development of adequate planning for adaptation procedures. Vulnerability means the capacity that a natural or social system has to withstand the damage resulting from a climatic change. The vulnerability is measured by the exposure and sensitivity of the system to the climate changes in terms of the degree of response to a certain change and the adaptation capacity of the system. That is, a vulnerable system is the one that is very sensitive to climate changes and where its capacity for adaptation is constrained (IPCC, 1997).

The sampling method is based on a panel of people, selected from a universe of decision-makers, experts and opinion leaders. The sector teams of the project provided the first key contacts regarding their research areas. After this selection, and using contacts provided by these initial contacts, and soon in this manner, we constituted the panel. We achieved a total of 162 contacts of for all impacts sectors. These comprised, most of the expertise in the country. The sample was intended to be as wide as possible, considering that at this stage of the survey, it was important to get the opinions and answers from representatives covering all the sections defined in the project. The surveys were sent by postal mail and e-mail, from which we received back 63 surveys. Our final sample (n=63) corresponds to 39% of the total of surveys sent.

## 4.4 RESULTS

### 4.4.1 INTRODUCTION

The results are introduced as in the survey sequence of questions. We start with the identification of the sample, followed by the set of opinions on impacts, adaptation and social and political scenarios. The results are given by each set of the impact sectors: Climate, Energy, Human Health, Forest, Fisheries, Coastal Zones and Agriculture.

After the first description of results, we move into some hypothetical explanations of the most relevant data encountered along the survey analysis. In this sense we tried to work on the research model that was initially adopted by the team. For instance, we try to identify if the connection with a sample group, such has opinion-leaders, affect choices over types of adaptation strategies. In addition, we have included data pertaining to the second stage of the survey. That data included questions of a more generic nature, about climatic changes, such as expected consequences of the impacts, national planning objectives and criteria for the development of the country.

### 4.4.2 SAMPLE DESCRIPTION

The sample, based on the distribution of the importance of each reference group will serve as a basis for the hypothesis we set out from. That is: could belonging to a reference group or a professional category have an influence on the level of knowledge, beliefs, expectations and predisposition to act upon climate policy?

The sample was predominately male (66%) and women were only 29% (5% did not respond). They range from 40 to 49 years of age, which includes 41.3% of the people. The most significant is the middle age (from 30 to 59), they correspond to the active age and are well established in their professional position (Table 1).

**Table 1 – Age Range**

| Age Range | % |
|---|---|
| Till 29 years | 6.3 |
| 30 – 39 | 23.8 |
| 40 – 49 | 41.3 |
| 50 – 59 | 20.6 |
| 60 – 69 | 6.3 |
| Over 70 | 1.6 |
| Total | 100.0 |

The whole sample shows that the number of decision-makers is the highest (40%), followed by experts (38.1%) and opinion leaders (17.5%). These results validate the heterogeneity sought in this panel, despite the predominance of decision maker and scientists (Fig. 1).

### 4.4.3 KNOWLEDGE AND EXPECTATIONS OF CLIMATIC CHANGE IMPACTS BY SECTOR

The data analysis concerning the impacts refers to the four dimensions of this study. We are dealing with knowledge of impact, expected impact, importance of the subject and time span of impact occurrence. The dimensions shown will be interpreted for each of the impacts given by each sector. To illustrate better the answers options we provide the following example:

Given the forecast of the impact of average temperature raise between 3.5º and 5º, the informants were invited to show their general knowledge about this specific impact. The options given to answer vary from much knowledge, reasonable knowledge, limited knowledge, almost none and do not answer. Next, they were invited to say if they really belief and agreed in its probability of occurrence. The options vary from totally agree, partially agree, partially disagree, totally disagree and do not answer. After, they were asked about the general importance they gave to climate impacts over temperature. In this case the importance did not make any reference to the specificity of the forecasted impact. For this reasons sometimes happened that informants would affirm a reasonable, or limited knowledge about an impact of 3.5º raise in average temperature and at the same time they could say that, anyway, they partially believed that it could happen in future as they would also express that an expected impact over temperature in general was highly important to them, even without knowing the magnitude and degree of the impact mentioned. In this sense the knowledge of the subject was independent from the belief and importance given to the impacts in general.

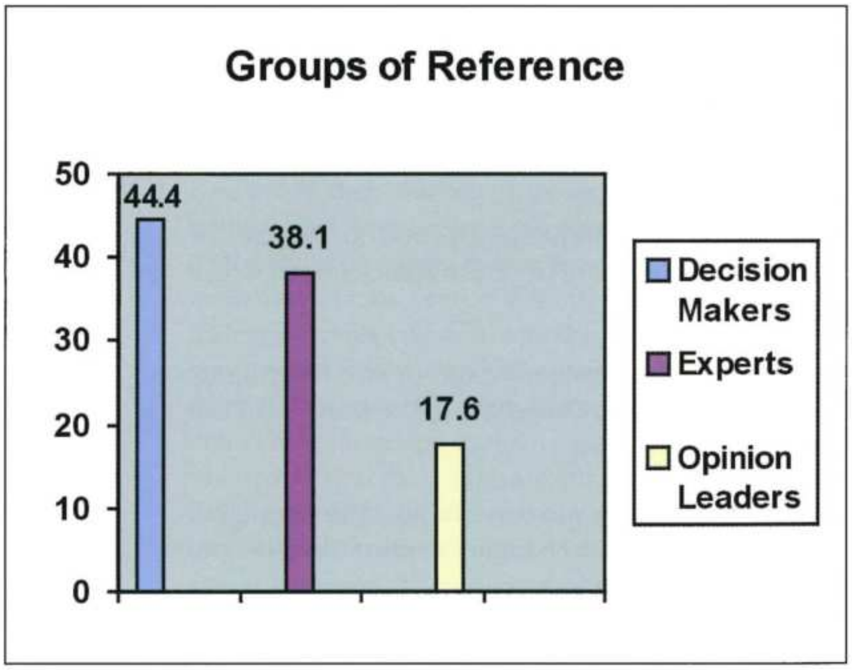

Fig. 1.

## CLIMATE

The first statement introduced in the survey mentioned a forecast of between 3.5° and 5° increase in average temperature in Portugal.

- The level of knowledge expressed by the majority of people was reasonable and very high (82.6%). The fact that only 15.9% of the sample having stated a limited knowledge of expected increase in temperature (1.6% did not respond) confirms the expertise character of our sample.
- The majority of people tend to agree with these changes. The tendency to disagree manifested by 25.4% may be a revealing sign of the uncertainty that dominates this subject. Only 1.6% of people did not respond the question.
- The level of concern was revealed through the concentration of response in the first level of importance, where 98.5% of the people rate this matter as highly important.
- The probability for the occurrence is expected by 49.2% of the individuals over a period of 50 years. Based on the distribution of responses, there is a tendency to expect temperature raise in the long term (over 80 years). Only 1.6% believes the impact will to take place within a 10-year period, while 3.2% did not respond the question.

In short, the sample shows a reasonable knowledge of the subject, but some uncertainty as to the values of temperature increase and a relative consensus regarding the period of the occurrence of impact, which is for a period of 50 years.

The second statement mentioned an impact of intensification of rainfall and displacement for the winter months.

- As for the knowledge, 74.6% of the informants show a good level. Only 3.2% of the people did not answer the question.
- Regarding beliefs, most individuals (80.4%) agree with the expected change for rainfall, and only 3.2% did not respond.
- The great majority of individuals (95.2%) rate the subject as important, while 3.2% did not answer.
- To finish the description of the results referring to the climatic changes, the 50 years span seems to be, again, the one that concentrates largest number of answers (44.4%). This is followed by the 20 years span according to 36.5% of individuals and 4.8% did not answer this question.

The knowledge about rainfall also proved to be reasonable. In that matter consensus is relative for both the period of occurrence of impact and the type of impact occurring from precipitation, the opinions about this change were more consistent than the ones over temperature. The importance is reasonably high for both of them.

The group interview did not add much to the discussion. The results included the problem of perceived uncertainty of the climate models; as one of the participants claimed: "there is too much controversy around the capability of accurate forecast and relative uncertainty regarding the temperature values". However, as he added there, is no doubt that climate change is of major concern independently of the range and intensity of impacts. For that reason they stressed the issue as a major environmental concern. Along with the debate, the group agreed with the statement, stressing that after that standpoint it was important to define how to cope with climate impacts. As with the survey the consensus around the concern and importance was easier to achieve than the values of the impacts. The knowledge concerning climate change impacts was high and balanced within the participants of the group interview.

## ENERGY

For this sector impacts we selected a phrase that said: "Energy consumed in building is expected to experience a seasonal change in the order of –10% during winter and +30% during summer".

- The Knowledge about this matter tends to be between reasonable and low, for 87.3% of the experts and 4.8% did not answer the question. These results indicate that this subject is less known to the panel if we compare with the impact expected in terms of temperature or rainfall.
- The belief in the occurrence of this seasonal change was high rate, given that 60.3% of the

sample tend to agree with the probability of this effect while the ones who disagreed was less than 10% and those who did not respond was 2.9%.

- The importance accorded was high, as 90.6% considered the matter rather or somewhat important. 4.8% were non-respondents.
- The time lapse of occurrence for this impact is also divided between 20 and 50 years. Despite the long term being the most plausible scenario for the occurrence of this impact (up to 50 years: 46%), individuals believe it may occur in the short or medium term; rather then in a distant future (over 50 years) and 6.3% did not answer the question.

The second statement referred that the expected increase of air conditioning would lead to the consequent stress on energy supply in Portugal.

- The knowledge was high, as 79.4% stated being well or reasonably well informed. However 9.5% did not answer this question.
- As regards agreement, we must stress that 46% of the panel tend to disagree. From the start, this indicator for belief in the change of energy supplies is linked with the diversity of positions concerning the importance of this subject. It is important to state that there was a high percentage of people who did non-respondent (19%).
- The exhaustion of energy supply capability due to an increase in the use of air conditioning was important for 60.3% of individuals. And 12.7% did not respond.
- That value implies a good knowledge of the subject by the majority. The most likely period for the occurrence of this impact, according to 39.7%, will be a period up to 50 years. In this one 15.9% were non-respondents.

Still in the energy context, scientists forecast that the increase in competition for water supply for land and municipal use, will force a reduction of around 30% in the availability of water for hydroelectric power.

- The awareness of this issue is high for the majority of the informants, but for 34.9% of them it is limited while 1.6% did not answer.
- Regarding beliefs, over half of the individuals tend to disagree this effect will ever take place. 3.2% did not answer.
- The environmental values are relatively strong when we consider the values associated to the importance attributed to this subject. 79.5% of the individuals rate the impact as highly important. In any case, there is still an absence of opinion not rating this issue as being important and that alone reveals an almost consensual concern over the consequences of climate changes. Analysis indicates that even though the individuals may not have a profound knowledge of the issues presented through their education or professional activity they still manifest their concern and belief in the occurrence.
- Nevertheless, most individuals (52.4%), for this particular topic, related to water availability for hydroelectric purposes, point to a long time lag for the event to take place, even if a group of 23.8% of the sample believe it will happen in medium term and 3.2% do not answer.

We should point out that other energy impacts might be more relevant for a sample. However, it was not possible to exploit them in this first phase of the analysis, having rather focused on changing consumption patterns. Changes regarding energy production did not show a great significance. This type of response may also be connected to the way of inquiring and questioning that will be thoroughly examined and reviewed at the end of this report.

As the interview later demonstrated, people confirmed their disbelief that any positive action will be taken on proper time regarding the energy field. At the same time energy was considered as one of the most important sector affecting climate change. Along the interview it was mentioned that since energy considered as the most important driving force of climate changes national actionsl were not being effective: "Energy should represent the major investment to face climate change in Portugal". Energy, both at the consumption as at the transformation levels should be at the core of political action with both preventive and pro-active measures. This is important in order to reduce the energetic dependency on fossil fuels. The suggestions of preventive measures to be adopted were forcibly changing consumers' behaviour, change commercial source, change energy patterns, more energetic efficiency and more rational energy use. The pro-active policy should be focussed on energy use, clean development technologies, changing behaviour and change in conventional energetic sources.

## HUMAN HEALTH

The human health researchers advanced a forecast regarding an expected increase in cardiovascular disease due to the heat waves produced by climate change.

- The majority of people (73%), indicated that their knowledge was limited and 11.1% didn't respond the question.
- As regards agreement, we conclude that 54% tends to agree with this impact and 12.7% do not respond.
- The importance rate of this topic is also higher, which may be associated to the way the individuals are affected and their sensitivity to health matters as 84.1% of the interviewed attribute a high importance to this impact. 11.1% did not answer the question.
- As to the probability of occurrence, the time lag expected is far or distant. Thus 39.7% believed it may happen 50 years from now and 20.6% chose a period of time of over 50 years and 11.1% did not answer.

The second statement for this sector was: "According to the scientists, the proliferation of mosquitoes derived from floods and storms will unleash the spreading of malaria in our country".

- A limited knowledge of this subject is noticed in a considerable part of the sample (50.8%), although the majority indicated reasonable or high level of knowledge and 9.5% did not answer.
- The beliefs associated to this impact are relatively strong, much as in the previous one. The agreement is of 76.2% and 6.3% did not respond.
- Naturally the concern over the spreading and localising of the malaria is very high; so much so that 90% consider this impact quite important. Only 6.3% did not answer.
- About 50% of the individuals believe in a period up to 50 years for the occurrence, although 31.7% believe it will happen within 20 years at the most. Again, 6.3% did not answer.

The fact that these last impacts are less visible can explain some of the values present up until now. However, they are still significant for the country, as the agreement and importance attributed to their occurrence revealed high consensual values. This issue of knowledge and impact rate for the human health must thus be explored deeper in future qualitative analysis in order to better approximate and develop the existing knowledge of this issue.

## FORESTRY

One of the forecasts for the forestry sector refers to the reduction of cork-oak plantation and holm oak in the south of the country.

- The majority (79.3%) again affirms to have relative knowledge of this issue. Only 1.6% did not answer this question.
- The agreement about the chance of occurrence of the impact is relatively high value as 42.9% totally agree with it. The percentages decrease as the scale moves towards disagreement and 4.8% did not answer.
- Thus, the coincidence between these last dimensions and the environmental values given by the panel is good, since more than 90% considers this an important subject, while 6.3% did not respond.
- Despite 63.5% of the informants having indicated that this would occur over a more distant period of time (more than 50 years), we may accept the idea of almost total concern, importance and belief in the future reduction of the plantation area.

The second impact given by the forestry informants refer to an increase in 50% area burnt in the national forestry.

- The sample is divided between those who have a good knowledge (62%) and those with a limited one (34.9%). 3.2% were non-respondents.
- Despite the dispersion found in the former positions, the informants tend to believe this impact may happen in the future, as 85% agree with its occurrence and 1.6% did not answer.
- The concern over this issue is considerable, since 79.4% say that the increase in forest fires as a consequence of climate changes is an important subject.
- The most likely time lag for this occurrence is the one up to 50 years, which was stated by 44.4% of the individuals. 3.2% were non-respondents.

Along the interview the expectation that forests will tend to disappear in the long term was confirmed; or, at least, forests as we know it. There was no doubt upon that issue. However, it was said that forests play an important role in climate change, especially in regard to mitigation measures, as $CO_2$ sink. In this sense, this area deserves special attention within national policy. In this matter see that regarding adaptation measures (p. 17), most of the informants from our panel stated that the responsibilities for the implementation of adaptation measures for national forestry was mainly national and only after European ones.

## FISHERIES

One of the questions of the survey stated that the distribution and quantities of fishery species, such as tuna and sardine would be affected by the migration of the marine population, as consequence of ocean warming.

- For most individuals (69.8) the knowledge about this issue is limited and 12.7% did not respond.
- However 60.3% tend to agree with the same statement while 7.9% did not respond to the question.
- The importance given to the issue is high for 71.4%, and reasonable important for 22.2%. In this question there are 4.8% of non-respondents.
- The period more selected is of 50 years or more.

A second statement regarding the future production of marine species, surmised about the consequent increase of imports and the reduction of production.

- 47.6% of answers were of limited knowledge. Only 6.3% proved to have rather good knowledge of this subject and almost 20% did not respond the question.
- 28.6% tend to agree with the phrase and 39.7% tend to disagree. While 17.5% did not answer.
- The importance rate is divided between 34.9% who gave it some importance and the same percentage of the others who gave it little importance. There is a rate of 14.3% of non-respondents.
- Around the majority forecasted this impact for the distant future (beyond 50 years).

Fisheries were a more controversial area in the group interview. A member of IPIMAR didn't agree that fisheries would be affected by climate impacts, simply because marine production will take the place of traditional fisheries in a large-scale economy as the European one. He also added that in a sense climate change impacts would justify the shift from classic fishery to marine production, legitimating an inevitable policy. Classic fishery will be mainly a tourists and sports activity.

## COASTAL ZONES

According to the informants, the average water level may raise 50 cm, provoking erosion, salt intrusion and floods along the coast.

- The impact that was forecast by the coastal area sector is known to a large majority of the inquired, and only 1.6% did not respond. In fact, 54% of the individuals indicated a reasonable knowledge about it.
- 81% state their agreement with the future occurrence of the impact and again there are 1.6% of non-respondents.
- 82.5% said this subject was of high importance.

- The majority of the sample considers this change may occur in the distant future, which is in over 50 years time and only 3.2% declined to reply.

The survey also referred the following statement: it is expected the migration of population from the coastal areas to the interior of the continent.

- The majority of answers were of 61.9%, on a medium to average knowledge.

- The beliefs on this future impact were strong as 70% of individuals agree with this forecast.

- 57.1% rate the importance of territorial migration rather high. However 33.3% rate it as only somewhat important and 3.2% did not answer.

- This impact may occur in either a period of 20 years (for 22.2%) or more consensual, within a period of 50 years for 54%. There were 3.2% that did not respond.

## AGRICULTURE

Agronomy informants foresee situations of shortage of water for some crops, as is the case of corn, resulting from greater rainfall intensity and longer drought periods.

- The knowledge of this subject is high. It should be mentioned that 40% admitted to limited knowledge and 3.2% declined to answer.

- 75% of individuals tend to agree with the future impact.

- The importance given varies from little to high without any strong consensual values and 6.3% of absence of answers.

- 50.8% consider that crops will experience water shortage within 20 years at the most. This fact is in itself surprising, since despite the limited knowledge, the forecast points to a shorter period than the majority of the previous impacts.

A second statement affirmed that the increase for irrigation, associated to temperature raise will imply a costs raise in the order of 20% per hectare.

- The majority indicated little knowledge of this matter. And 6.3% opted to not answer.

- The majority also tends to agree that this impact will occur in the future. However, 33.3% are more sceptical and, again, 6.3% avoid this question.

There was no significant reference to agriculture in the interview besides the confirmation that there would be significant changes in ecosystems and biodiversity and loss of climate patterns of reference to agriculture.

### 4.4.4 KNOWLEDGE AND EXPECTATIONS ABOUT CLIMATE CHANGE ADAPTATION BY SECTOR

The values shown in this chapter refer to seven types of questions: knowledge of the subject, beliefs about measures implementation, importance of the measures, time span for implementation, need for inter-institutional national cooperation, need for international cooperation and main responsible institutions. Each time there are no results on each of the entries mentioned before, is because the level of non-respondents was over 50%. As in the previous impact chapters, the ways of answering this group of questions was the same. This is, sometimes informants would say they had a reasonable knowledge about an adaptation measure and they would believe it will probable be without knowing much about the issue. However they will firmly express that they value a lot, giving an high importance to that subject, that is to the idea that there is planned an adaptation measure to face a impact on a given sector.

We remind that for Knowledge the possible answers were: very good knowledge; reasonable knowledge, limited knowledge and none. For the beliefs in the future implementation of the measure the choices for answer vary from: totally agree, tend to agree, tend to disagree, totally disagree and not knowing/not answer. Regarding the value given to the measures suggested in this survey the optional range goes from highly important, somewhat important, relatively important to not important at all. The time span given for implementing the measures was of: up to ten years, up to twenty, up to fifty years, over fifty and over 80 years in future.

## CLIMATE

The first statement was: To adapt to the expected impacts regarding climate more dams will be built to provide a 20% increase in hydroelectric capacity.

- From the total of answers, 66.7% said to have a reasonable knowledge of the issue.
- Answers can be divided between those who tend to agree (30.2%) and those who tend to disagree (49.2%). Only 7.9% indicated enough knowledge and agree totally with this planning measure.
- From the total, 61.9% rate it as somehow important, although 19% give it little importance and 14.3% only some importance.
- Most believe this measure will be applied within a period of over 50 years time (52.4%), although 22.2% believe in the feasibility of a 20-year time lag.
- Almost half (49.2%) indicated that an inter-institutional national cooperation is unnecessary. At the same time 27% considers this indispensable.
- The international cooperation is viewed by 47.6% as necessary, while the remaining individuals are divided between the ones who consider this kind of help indispensable (15.9%) and dispensable (22.2%).
- From the total of answers, 60.3% consider that national entities would be the main responsible for its implementation.

A second question referred that in future the transport fleets should be more efficient and use non fossil fuels energy sources.

- From the total of answers, 54% of our panel expressed good knowledge of the subject and 33.3% a reasonable one.
- Form the total, 74.6% agreed with this adaptation measure.
- Most of the people, 73%, rate it as rather important and 22.2% think it has some importance.
- Contrary to the previous measure, 47% of individuals consider that the European Union would be the main institution to act towards this change of transport fleets.

The third measure introduced in the survey stressed the objective of building of wind energy parks throughout the country.

- In this case, 52.4% expressed limited knowledge and 33.3% a reasonable one.
- From the total, 63% agrees with this measure.
- The majority, 92% considers it to be rather important.
- The likely period for the measure development is between the next 10 and 50 years.
- According to the informants (47.6%), national inter-institutional cooperation is needed, being indispensable for 36.5%.
- As far as international cooperation is concerned, 27% consider it indispensable while 27% regard it as unnecessary.

## ENERGY

The first statement said that, to optimise the development of water resources, including the re-use of waters, a plan for building hydroelectric power plants will be developed.

- The opinions vary from reasonable knowledge (33.1%) to limited knowledge (38.1%).
- The majority, 81% tend to agree with the measure.
- The importance is high for 63.5% of people and 31.7% attribute some importance.
- Most individuals (76.2%) consider the period of implementation to be in 20 years time.
- Regarding national cooperation, 92.1% of the informants consider action on the part of national institutions to be necessary or even indispensable.

- From the total, 46% indicated national institutions as the main responsible bodies.

Reduction in energy consumption will be one of the objectives to aim at in the process of climate change. It was proposed to the panel that 30% of existing buildings would be re-equipped, with double-glazing, insulation, shading and other techniques.

- The majority, 65.1% of the specialists have little knowledge of the subject and 12.7% indicated a good knowledge.
- Around 50% of the sample tends to agree with the statement.
- The level of importance (79.5%) is one of the highest.
- The sample is evenly divided between the three time spans, with the middle term (50 years) accounting for 44.4%.
- From the total, 68.3% thought that implementation responsibility will be in national followed by international organisations.

The replacement of classical domestic equipment such as refrigerators, air-conditioning, central heating or stoves, for more efficient models that run on natural gas or renewable energies, are also included in the measures in the energy sector.

- From the total, 57.1% of the sample declared a limited knowledge of this.
- Around 60% agreed that this measure should be taken.
- Regarding time span 36.5% do say 20 years to adapt equipment to more efficient energy use is plausible.
- From the total, 54% do appeal to the national administration, and the other 46% to European and International institutions.

To be able to respond to the increase in population and tourist activities on the coast, a revision of transport systems and energy supplies is planned.

- For 34.9% it deserves some attention while to 38.1% only a little.
- There was no consensual time scale to effect this measure, however the long term would be the more plausible for only 6.3%.
- The majority, 85% felt that national cooperation was indispensable.
- And, 69.8% also felt that international cooperation was necessary.
- The responsibilities for action fell almost totally on national institutions (42.9%) and European (44.4%).

## HUMAN HEALTH

To control illnesses caused by contemned water and bites from infected insects, associated with floods, storms or heat waves, the health sector of the project consider the possibility of applying laws against the production and distribution of certain foods.

- Almost 70% confessed to have limited knowledge in this area.
- A period for the adaptation of this measure was of 20 years for 63.5%.
- For 90% of the sample national and inter-institutional cooperation is necessary.
- The panel of specialists is categorical (82.5%) in the absolute necessity for the cooperation of international organisations.

Another prominent concern in this area comes from the need to define social plans to prevent mortality and mobility, in the most affected areas of the country.

- The majority, 69.8% of the people admitted limited knowledge of the subject.
- But 61.9% agreed with the measure.
- Around 65% of these people attribute some or a lot of importance to this subject.
- The time scale for the implementation of the measure varies appreciably with 46% pointing at the middle term and 27% at the long term.

- A large majority of 63.5% felt that international intervention from organisations such as World Health Organisation was indispensable to apply of these social plans.
- Nearly 50% hold the national authorities as primarily responsible for this level of action, followed by the international authorities and only later the European ones

## FORESTS

One of the adaptation measures that the Forestry team proposed is the covering of national forest area by species better adapted to the new climatic conditions, including the introduction of exotic plants.

- However, 58.7% of the panel admitted to have limited knowledge about the measure.
- And 44.4% of the sample disagreed with the measure.
- From the total, 75% of the individuals attributed a lot to some importance to the subject.
- It is the State's responsibility, through its various levels of administration, to react and apply this measure. 66.7% share this opinion, while 22.2% state that responsibility should be at the E.U. level.

Public funding will be made available for the introduction of new species better adapted to future climatic conditions.

- From the total of answers, 55.6% of the people stated little importance to the matter.
- The majority said that this measure would definitely be applied in a long-term period.
- Later, 63.5% said that the implementation was a responsibility of the national authorities and 25.4% of the European authorities.

Another adaptation measure proposed by the informants in forestry is the need to invest in genetic engineering to improve the species, especially those that have a higher ecological value.

- The majority, 71.4% have good knowledge of the subject.
- Again, 75% of the panel agree with this measure and consider it of great importance.
- There was no consensual period for the future investment in the genetic engineering.
- From the total of answers only 44.4% thought that international cooperation was indispensable.
- For 66.7%, the implementation responsibility is of national institutions.

Lastly we include the need to make investments in the forestry practices, such as irrigation and fertilisation, aiming to preserve the already existing forest population.

- The majority, 76.2% have limited knowledge of this issue.
- More than half of them (72.2%) give great or some importance to the matter.
- The period to bring about this measure was for 46% 50 years, although it should be pointed out that 25.4% indicated the short term.
- Curiously, about 50% of the sample considered Europe to be the responsible authority to introduce this measure.

## FISHERIES

The first statement said: In order to avoid the extinction of fishing as a viable business, the survival of the fishermen and the disappearance of fish from our diet, new types of fish and fishing must be discovered and developed.

- 52.4% of the panel admitted little knowledge about it.
- Faced with these uncertainties, and the lack of opinion about the future and the new types of fishing, no consensus was indicated relative to the timing of the introduction of measures. Although, one answer reflected that such a measure would

never happen, the answers were spread from short term to distant future.

- Opinions on national and international inter-institutional collaboration were also diverse, some saying indispensable, others saying unnecessary. The main bodies to institute the measure could be equally, national, international or European Union.

The second statement expresses: with the objective of increasing marine production, the recovery or reclamation of humid zones is forecast.

- Nearly 18% of the panel do not believe that such a measure will happen, the other 82% distributed among the other choices.
- 50.8% indicated that it is indispensable while 31.7% that it is unnecessary.
- There was no consensus as to which authorities should be responsible for the application of the measure.

With a view to a greater ecological balance of marine life, could be adopted a 25% reduction in the fishing of species intensively fished or over-fished could be adopted.

- In this case 50.8% admitted limited knowledge.
- However a majority of the panel agreed with the measure.
- Despite this limitation, the panel believe in this measure will be applied in the short term with 23.8%, 36.5% for the middle term and 31.7% for the long term.
- There were diverse opinions as far as national, international and European inter-institutional collaboration was concerned.
- From the total of answers 54% of the specialists said that the European authorities should be responsible for the implementation of the measure.

## COASTAL ZONES

As a response to erosion it is planned beaches and wetlands nourishment.

- Almost 70% state that they are well or reasonably well informed on the matter.
- A majority of 71.4% agree with this measure, which indicates a high degree of concern.
- Indeed the values or the environmental sensibility to the fragility of the coastal ecosystems is high; 65.1% gave it great importance and 20.6% some importance to this measure.
- Around half of the sample, stated that the process of bringing in more sediment to reclaim the effected areas would take place in the middle term.
- It is consensual that national inter-institutional cooperation is necessary as 47.3% deemed it indispensable or desirable.
- Opinions differed greatly as to whether international cooperation was needed; however 41.3% stated that it was unnecessary.
- 70% regarded the national authorities responsible for the implementation of this measure.

The next statement referred the building of sea walls against sea level rise. As knowledge was low, it is no surprise to find that 50.8% of them gave it little importance.

- Inter-institutional cooperation on a national level was indispensable, or necessary, but international assistance was unnecessary.
- However, 58.7% of the informants stated that national authorities should implement the measures, while 27% indicated European authorities.

The changes on drainage systems and building above the flood line are other measures being studied to combat the climatic impacts in coastal zones.

- Regarding this subject, 57.1% of the panel admitted limited knowledge of the subject.
- But 62% tended to disagree with these measures.
- It is considered of great importance by 38.1% and some importance by 46% of the panel.

- As for the timing of these measures, no consensus was demonstrated.

## AGRICULTURE

Given the predicament of lack of water for agricultural use, double the number of dams will have to be constructed and new wells bored on the smaller properties, especially in the drier areas of the country.

- Knowledge was high by 38.1% and limited by 31.7%.
- And 81% of the panel agree with the measure.
- Again 58.7% gave much importance and 33.3% some importance to the measure.
- More than half of the panel gave the timing as middle term or 20 years for its implementation followed by 30.2% who indicated the long term or 50 years.
- Almost all of them, 90.5% of the informants stated that national inter-institutional cooperation was indispensable or necessary. International collaboration was deemed desirable however 30.2% said that it was unnecessary.
- From the total of the answers, 60.3% said that national authorities should implement the measure in the first instance with European Authorities playing a secondary or no role, since only 6.3% considered the latter.

Just as in the forestry sector, it is proposed to introduce crops that better adapt to higher temperatures, as a way of combating the biological/ physical impact of the changed climate.

- However, only 33.3% indicated a high level of knowledge of the subject while 42.9% selected limited knowledge.
- It would be interesting to understand the reasons that explain why 52.4% of the sample tends to disagree with this measure.
- Only 41.3% attributed some importance to the measure.
- All the same, the majority or 61.9%, felt that the measure would be implemented within 50 years.
- Nearly 70% decided that national inter-institutional cooperation was desirable, and 55.6% considered the national authorities responsible for the implementation of the measure.

There were quite significant opinions within the panel when considering the doubling of government expenditure in the agricultural sector to stop the loss of arable soil in Portugal.

- The majority indicated good knowledge of the subject, while only 39.7% chose limited knowledge.
- Importance was high taking into account that 70% attributed much or some importance to the subject.
- The majority, or 63.5% believed that the measure would be implemented in 20 years.
- Both national and international cooperation was necessary for the majority, with preference for the EU authorities.
- 42.9% regarded EU as the source of funds compared with 20.6% for national bodies.

Genetic change of some food crops such as maize is conceived to be a way of making agricultural species less vulnerable to temperature fluctuations.

- The level of knowledge of the majority of the informants is good or reasonable.
- From the total of answers, 63.5% gave great importance to the subject.
- The majority, 81% said national inter-institutional cooperation was indispensable and 92% indicated the need for international assistance.

## SOCIAL AND ECONOMIC ADAPTATION

It is predicted that the environmental taxes that citizens will have to pay for energy will increase around 65%.

- The majority (66.7%) of the group admitted limited knowledge of the subject.

- Given that this is a purely economical measure, that will effect the financial situation of Portuguese families, opinions were diverse, with only 35% agreeing or tending to agree; 42.9% disagreeing and 21.6% did not respond.

- The same happened when the panel valued this adaptation measure as 36.5% gave it great importance, 28.6% some importance and 31.7% little importance.

- Almost all, 73% said that it would happen within the next 20 years.

- The majority also said that both national and international collaboration was indispensable or at least necessary, and 68.3% pointed to the national authorities as the main responsible bodies for its implementation.

Lastly, the sample was confronted with the idea of creating a tax on the emission of greenhouse gases, which would fund adaptation measures.

- In this case, 90% of the sample admitted good or reasonable knowledge of the subject.

- This would account for 95% of them stating agreement with the measure.

- The high value of opinions accompanied the values associated with the necessity to raise taxes, with 82.5% of the sample giving great importance to this.

- The most likely timing would be within 20 years.

- And according to the majority national inter-institutional and international collaboration were indispensable.

- There was more diversity of opinion as to which authority was to implement the measure, with 44.4% indicating international and 30.2% national intervention.

While taxes were part of the measures introduced in the survey other adaptation policies emerged during the interview. The answers were given spontaneously, and the reference to economic instruments was solely done regarding developing economic incentives. Land and urban management was the other strategies most referred to, as well as providing quality information to citizens and the market. During the interview, the need to develop an administrative reform that allows integrating the subject of climate change in cross-cutting administrative departments was mentioned. The general conclusion is that the administration cannot continue to function through segmented departments and with short term planning. Finally, the need to establish definite active social plans linking state, market and civil society, by using operational programmes, and through the management of public demand, was suggested.

### 4.4.5 MOST IDENTIFIED IMPACTS AND ADAPTATION MEASURES

The impact, to which a great importance was accorded by more than half of the sample, was identified for all sectors. Percentages above 50% were only found in Climate, Energy, Human Health, Forestry and Coastal Areas. Generally there were more replies to adaptation measures, rather than impacts.

A clear trend was identified to regard national authorities as responsible for implementation. Attribution of responsibility to regional or international authorities varied accordingly to the policy in question.

It is necessary to emphasise the measures for Energy and Forestry that achieved consensus regarding jurisdiction. Re-equipping buildings and planting forest areas, with species that are better adapted to new climatic conditions, were said that actions relied above all on National entities, such as Local, Regional and Central Government Administration.

Given the periods forecasted for climate change impacts and adaptation, in the attempt to find emerging consensus of opinion, we looked for the questions whose answers were above 50% in each of the time periods: short term (up to 10 years), middle term (up to 20 years), long term (up to 50 years) and distant future (more than 50 years).

Only one expected impact, in Coastal Zones, and one adaptation measure for Agriculture, were over 50%. For costal zones, 52.4% of the sample considered that in 50 years, the increase in the levels of the sea, would cause salinity of the soil, erosion, and flood the Coastal Area. In Agriculture, 63.5% of the specialists deemed it necessary that the Government double its expenditure to avoid the loss of arable soil in 20 years time. The other answers revealed a varied distribution across the time periods, depending on the expected occurrence of impacts and climate change and in accordance with the scenario presented. We can see however that there is a convergence to the middle to long term, which is in a period between 20 and 50 years.

Taking the answers from the perspective of the stakeholders; decision-makers, experts and opinion leaders we have found generally that the answers of decision-makers were dominant. However, we cannot conclude that they are better informed. In fact, we compared the average answer from the three groups using a compare means test (T-Test). The differences between the groups was not significant except for the knowledge of impacts over human health, where the opinion leaders average knowledge proved to be higher ($p<00.5$).

The answers based on knowledge of the impact can also vary in accordance with the type of professional activity. Thus, everything indicates that a tie to a sector of activity better determines the knowledge about the forecast impacts, than the linkage to the identity group. This is, independent of being part of decision makers, opinion leaders or experts their professional background determined to a greater extent their answers in this survey. Climate is the sector where generally experts show a better knowledge of the impacts. Few other answers are distinguished by the stakeholders' variable, since very nearly half of the total sample admitted to have good knowledge of the subject.

While observing the answers given both for impacts as adaptation, the data show the care that has been taken in affirming a good or relative knowledge of the subjects referred to, even the more specific or technical ones. The importance given to the various topics was also made very clear, even when there was not a great deal of knowledge.

To finish this first set of analysis, we included in the survey a general question related to the gravity of the impacts forecast for Portugal, and the planet in general. The answer was given using a scale that goes from positive impact, irrelevant impact, to negative impact. Different from the questions asked before, that referred to specific impacts for each sector, this question referred to the general opinion of our informants. We expect to get answers from people who did not reply before due to the specificity and rigour demanded. It is also possible to understand the general pattern of expectation associated with climatic changes (Fig. nº2).

In general (95.2%), consider the expected impacts to be negative on a global scale. For Portugal, the majority (77.8%) consider the impacts to be negative, although 20% considered that the consequences of climatic changes would be irrelevant.

Finally, the results emerging from the group interview confused this data. Part of the group agreed that climate change brings negative consequences, however these should be regarded together with its positive consequences, avoiding the idea of an overall inevitable threat. Climate change can mean a structural change that stands in between both visions, and, as its impacts might occur both gradually, or as a sudden dramatic event (the case of extreme events), responses should rely on flexible policies and

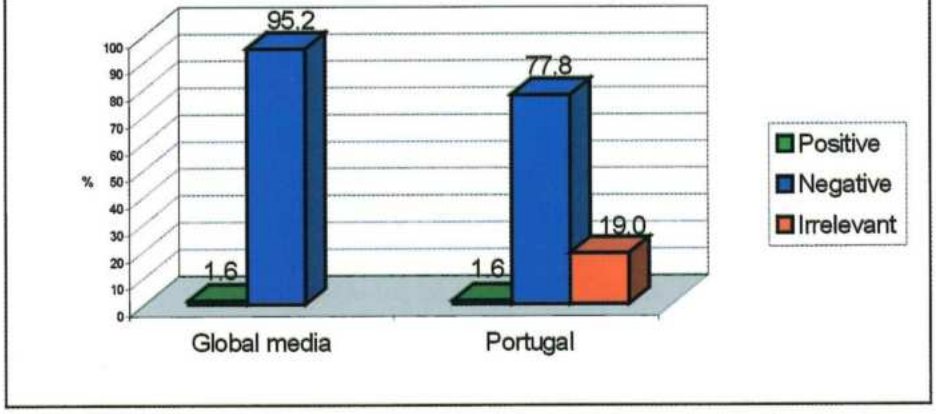

Fig. 2.

adjustments, in order to make it a positive change. These adjustments may be individual or collective.

### 4.4.6 PORTUGAL'S CAPACITY FOR ADAPTATION

In the following four sections we will try to describe the perspective of our panel of informants and their evaluation of the general effects of climate change. Is climate change an environmental problem involving ethics and values; a new subject for public policies or both? Do they believe climate change is an environmental problem that should be approached by addressing its causes through mitigation, trough prevention policies or both?

To start with we used a question where informants could express their preferences towards policies of mitigation or policies of adaptation in face of a climate impact scenario given in the survey. Next we provided them with a list of three different types of concerns involving climate issues, varying from socio-economic to environmental, in order to identify the values underlying informants' general opinion on climate change.

To identify the informants' opinions regarding national actions for climate change, we tested their opinions using a forecast climatic scenario for the next 80 years (Fig. nº3). According to this scenario temperature will rise in the order of 10oC, and rainfall will drop 50%.

Disbelieving almost totally in the possibility for the country to adapt naturally to these changes, 50.8% of the panel considered mitigation policies as a way to act over climate impacts, and 44.4% considered planned adaptation.

The same analysis was undertaken for the opinions given by stakeholders groups (Fig. nº4). For the replies on mitigation we observed values of 43.8% for the decision-makers, 37.5% for the experts and 18.8% for the opinion leaders. Regarding planned adaptation the opinions were distributed as described next. Half of the total of decision-makers favoured adaptation (50%) compared to 35.7% of opinions of experts and 14.3% of opinion leaders. Even though this was the predominant type of measures previously chosen, it is interesting to observe that, for both the experts and the opinion leaders, mitigation arises as the most appropriate response to climate change, while, against what we would expect, decision-maker considered adaptation as the most desirable solution.

From the opinions given during the group interview it was possible to further understand the opinions given before. As with the survey data, they attributed major importance to the present mitigation policies, however never neglecting adaptation. Adaptation, or anticipatory action, or adjustments, as it was also referred to, is relevant in the sense that it responds to specific regional vulnerability from current and former exposure to climate effects. Although it was accepted that in Portugal we will be able to adapt naturally to certain gradual impacts, there are main areas were an anticipatory action is still relevant. Those main areas where considered to be energy, land management, urban planning, biodiversity and coastal zones.

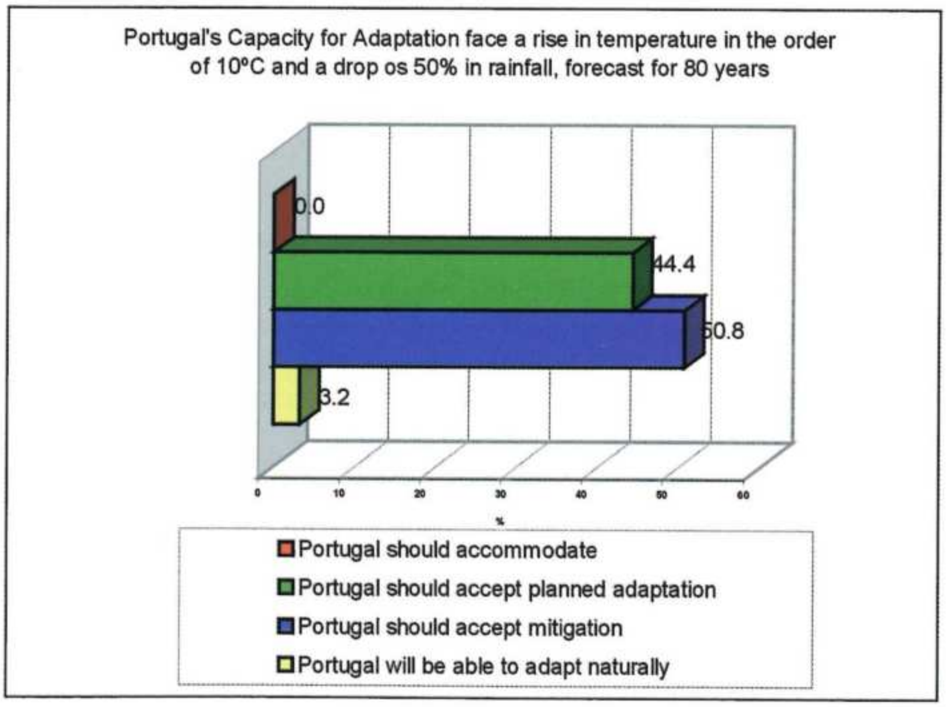

Fig. 3.

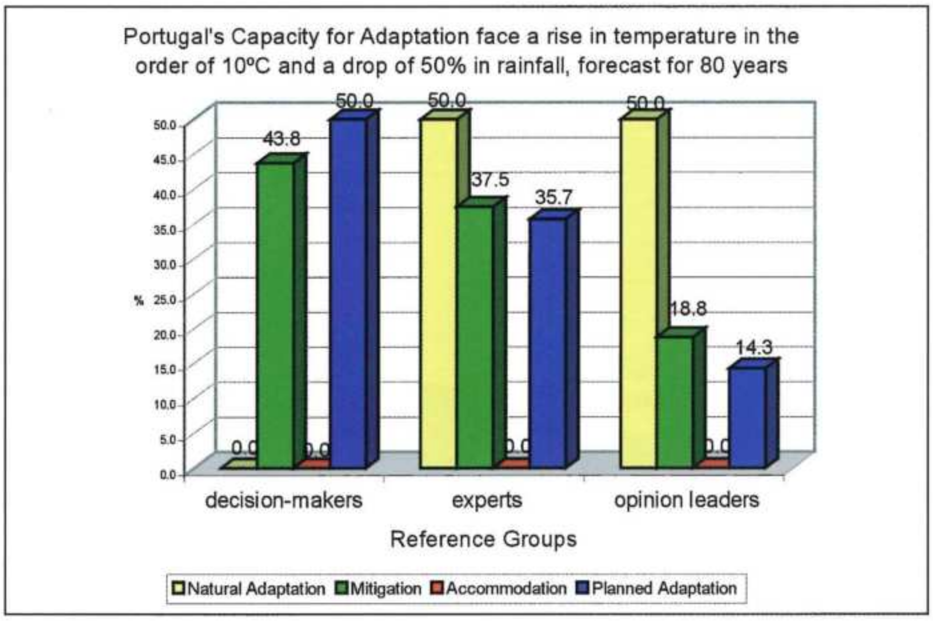

Fig. 4.

Moreover, while for mitigation we may rely on EU policies, in regard to adaptation the major responsibilities and capabilities are set at the national level, possibly being the reason, which makes decision-makers more amenable to, planned adaptation. As one of the informants said "we can not trust anyone else but us." However all the group agreed that the debate around adaptation is still weak and of a low profile, probably because of a divide between those in favour of differing policies. Nevertheless, most of the group agreed that both mitigation and adaptation complement each other, they are not mutually exclusive and, that implementing adaptation measures does not necessarily imply a lack of willingness to take mitigation actions

### 4.4.7 CONCERNS UNDERLYING IMPACTS OCCURRENCE

Under a more generalised analysis over the impacts concerns, this survey ascertained the position of individuals for a set of general values (Fig. nº5). According to 71.4% of the individuals, the importance of climate change impacts is due to their effect of reducing the sustainability of ecosystems. The remaining reasons pointed out: climate impacts produce significant changes in economic systems and that they produce social de-structuring are not consensual. Only 4.8% of individuals agreed that they produce social de-structuring and 23.8% that they would destabilise economic systems.

Fig. 6 displays results broken down by stakeholder category. As expected, most decision-makers, followed by opinion leaders, and by only 13.3% of the experts, expressed the concern over economic balance. All decision-makers expressed concerns with social de-structuration. Indeed, the effects on ecosystems and their maintenance, was considered more serious by experts, rather than any other group, given the rate of 48.9%, compared to 37.8% of decision makers and 13.3% of opinion leaders. In short, the decision-makers base their concerns on the socio-economic organisation whereas the experts tend to look for environmental prevention.

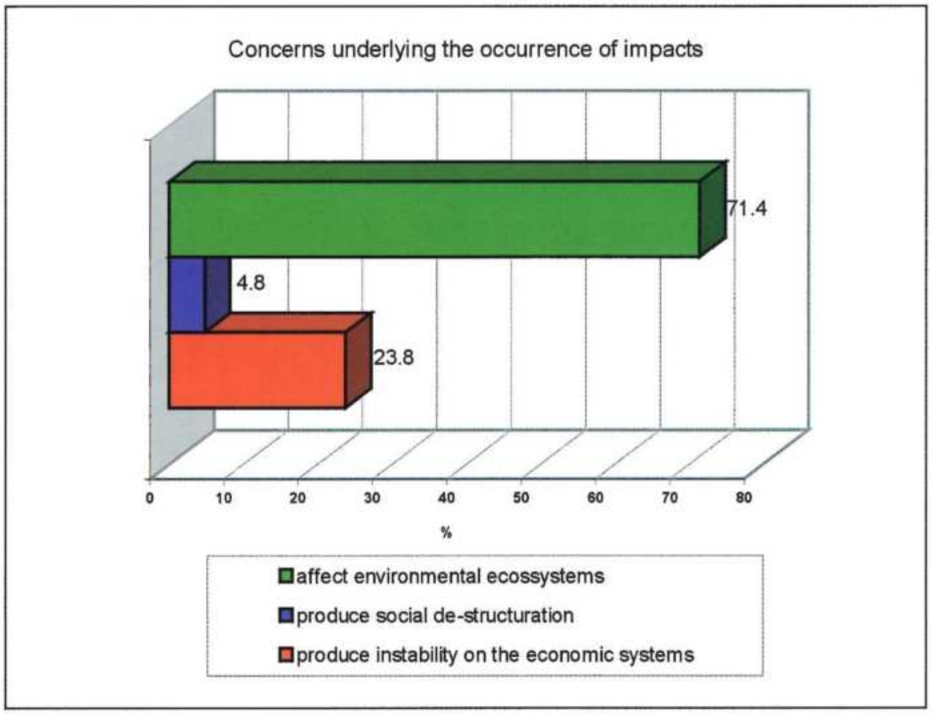

Fig. 5.

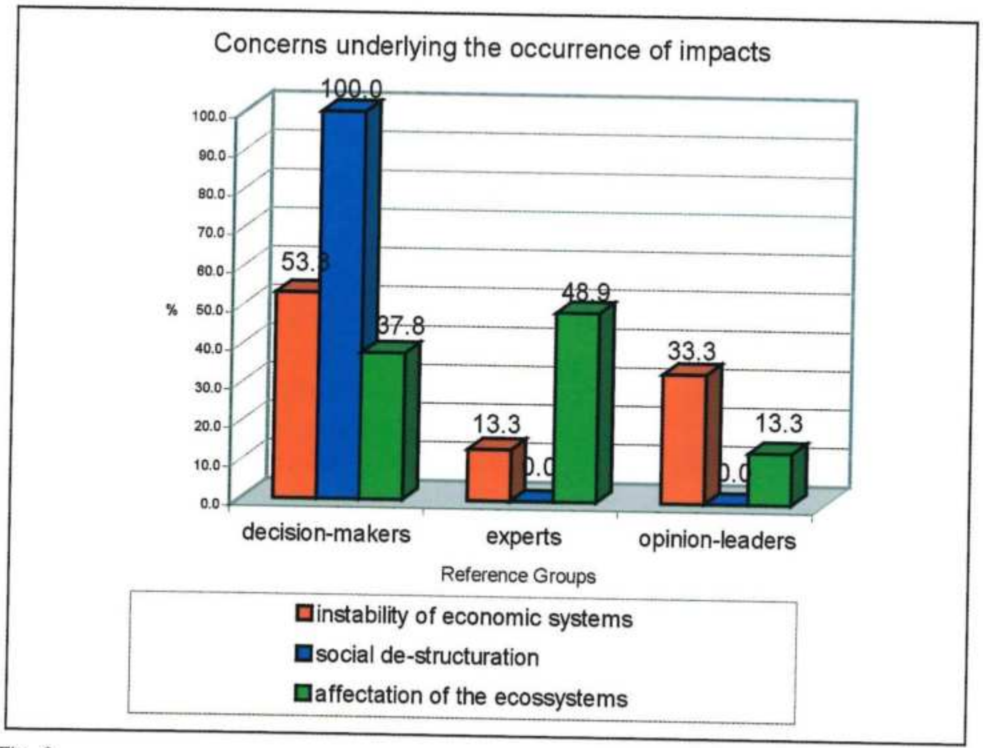

Fig. 6.

## 4.4.8 DEVELOPMENT OF PRIORITIES AND OBJECTIVES

Considering these differences concerning the evaluation of the main structural effects of climate change we decided to identify what should be the priority objectives to national planning in the face of climate change. Would they remain the classic objectives regarding economic growth or others such as environmental sustainability? How would this ranking be distributed among stakeholders? Later, and to complete the listing of objectives we asked informants to choose the most preferable targets to adopt regarding future planning.

The priorities were listed in a question of the survey. It was intended to discover which three objectives were more important in face of climatic change impacts. For this we took the three highest values marked on the chart of a multiple-choice question. The objectives were then typified in accordance with the rates registered in each one. They were categorised as follows: priority, strategic and others.

*Priority Objectives:* Environmental policies and greenhouses gases reduction are deemed to be priority objectives by the majority of the experts (48.6%). Policies to reclaim the environment were the main objective of decision-makers. It is important to stress that more than half of all the experts, (55.6%) considered both measures as priority objectives.

*Strategic Objectives:* The differences between the groups are not significant, generating in fact, an equitable distribution between decision-makers, experts and opinion leaders, for investments in scientific research (42.9% of each group). However we can conclude that the experts are more concerned with the need to invest in technological research, while the decision-makers prefer the more tried and trusted process of education (a more traditional political choice).

*Others:* Political measures of an economic nature were accorded the lowest values. More explicitly the maintenance of economic growth, the reduction in public expenditure, and the increase in exports, were objectives for low percentages across all three groups (19%, 11.1% and 9.5%). Investments in industrial production were also a low priority as only 17.5% of the total number of experts considered it to be a political objective.

Although the survey listed several objectives, along the interview the participants agreed that there was only one real climate change objective: for mitigation policies it was emissions reduction, and for adaptation policies it was spontaneously chosen by them the land management policies.

The related environmental objectives considered above as primary and strategic objectives were reclassified, as long-term strategies needed to achieve the above objectives. Both importing environmental technology and reducing public costs were considered too polemic and were set aside. The general opinion was that Portugal is not ready to face climate change impacts: "There was no proper consciousness of impacts and its opportunities. We are not ready."

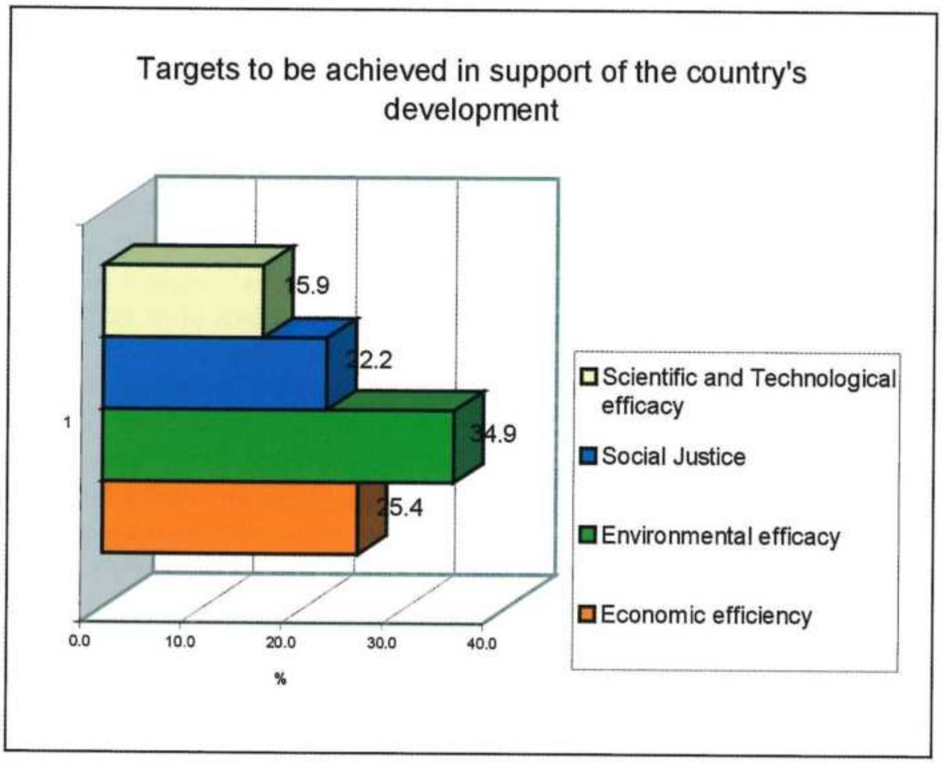

Fig. 7.

### 4.4.9 PLANNING TARGETS

In terms of the value criteria to take in consideration with regard to the county development, the opinions were divided between the choices offered by the survey (Fig. nº7). However, we can emphasise the value given to effective and sustainable measures for the resolution of environmental problems. This criteria was chosen by 34.9% of the total sample. Economic efficiency is a priority for 25.4%, social justice for 22% and scientific and technological efficiency for 15.9%.

As far as the position assumed by each group of reference goes, we observe that in comparison with other criteria, decision-makers are more concerned with scientific and technological efficiency and later with environmental efficiency and social justice targets (Fig. nº 8). Only 18.8% refer to economic efficiency, understood here as the implementation of effective measures in terms of cost/benefit. Perhaps it is for that reason that 62.5% of the experts consider economic efficiency as an important goal. However, 40.9% opt for environmental efficiency, for gaining effective and sustainable measures for the resolution of environmental problems. Half of the replies given to social justice, corresponding to fair measures in terms of social and environmental equity, are given by decision makers, and 30% of replies are by opinion leaders. Environmental efficiency, and social economic justice can be understood as absolute targets. Economic and scientific efficiency are understood not much as targets and rather, as processes by which the previous targets can be achieved. In this manner and taking into consideration the way the question was formulated, they fall into the background.

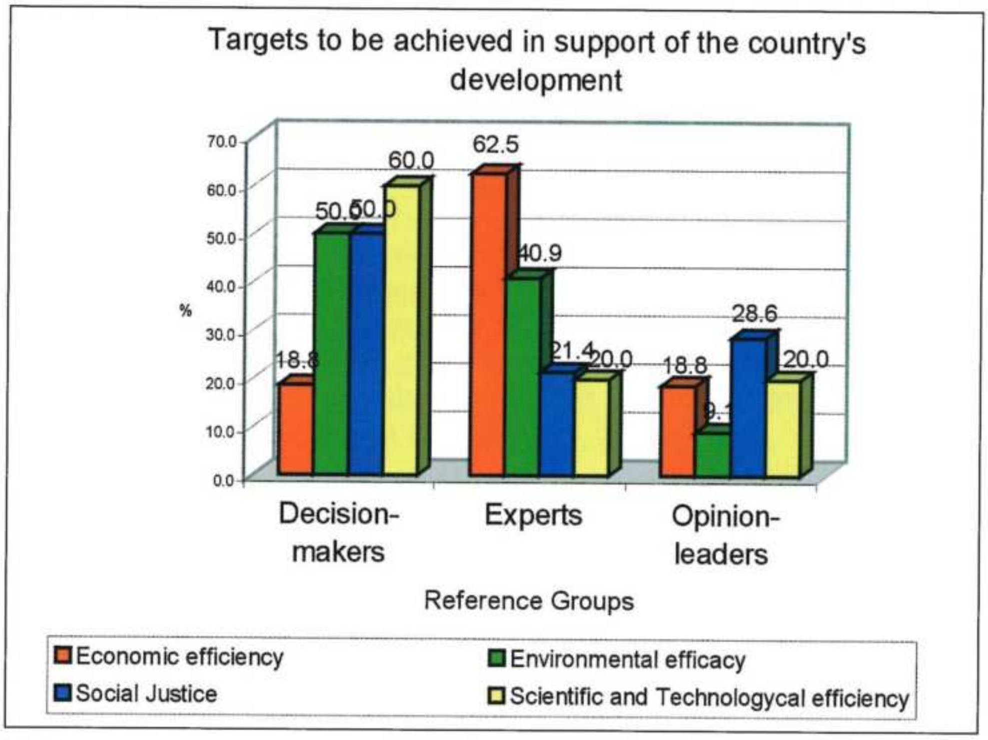

Fig. 8.

### 4.4.10 NATIONAL RESOURCES FOR CLIMATIC POLICY

Finally, after evaluating the main general positions regarding the strategies and measures to face climate change, and to identify the prior objectives to take into account in the policy design, we evaluated the most identified constraints for the policies and measures implementation.

According to our hypothesis, the means to face climate change will depend upon a set of variables considered relevant to undertake these policies. We submitted the informants opinions to a variable chart testing their positions using an agreement scale. The variables listed were: scientific and technological development; rigorous control of legal norms; most positive economic actions; increase in environmental knowledge and information; limits to market economy; decentralisation of State authority over policies and measures and development of scientific research. The scale levels are: total agreement, a tendency to agree, a tendency to disagree, total disagreement.

For the variable scientific and technological development, agreement was 70%. Regarding the role of more rigorous control of the legal norms, 54% agreed totally, and 31.7% tended to agree. From the total, 54% totally agreed totally with decentralisation of State control over policies and measures. Determination by increasing knowledge and making information available was generally well received with 41.3% of total agreement, the rest being spread across the other levels. Very nearly 50% tend to agree with investments on scientific research. The contrary must be said as far as the determination of the problems of climatic change with a view to positive economic actions in terms of cost/benefit, with 54% disagreeing totally. The majority of the informants on the panel tended to disagree that the limitation of market economy would be unlikely to invert or resolve the effects of climatic change.

### 4.4.11 EVALUATION OF RESOURCES

The evaluation of national capabilities in terms of capabilities to mobilise action was related to the value given to the existing national capabilities and resources to sustain a strategy for climate impacts adaptation. A list of available resources was submitted to the informants and led to the following results.

The capacity to invest in scientific research is insufficient and is thus an obstacle to any strategy according to 70% of the individuals (40% agreed totally, 30% tended to agree). About 50% of the individuals tended to agree that major resources constraints arose because of the lack of technological resources. Moreover, 68.3% of them said that frailty of debate regarding political measures to deal with environmental problems also impeded positive strategic planning. Also, 60.3% of the individuals consider that the political efficiency in the sectors dealing with environment is low. Nearly half the informants tended to disagree that the notion of lack of economic resources was a difficulty or a barrier to strategic planning. Finally, there was a tendency to disagree with the constraints related to the capacity to invest in a sustainable economy, although this was the view of only 38.1%. A consensus was also reached regarding the capacity for political action, it being considered the weakest resource for political action.

## 4.5 CONCLUSIONS AND RECOMMENDATION

Before we list our major conclusions and recommendations we would like to briefly summarise the analysis. First, we identified the most consensual values upon the expectations, knowledge, beliefs and importance given to climate change impacts forecasted for several sectors. This expectations evaluation related to both direct and indirect climate impacts for vulnerable sectors. Later, we identified for the same sectors the most consensual expectations regarding the implementation of adaptation measures as well the responsible institutions. The list of both impacts as well adaptations measures was provided by the different sectors teams in the project. At this level of analysis we were assuming that the adaptation options were dependent upon the previous impact list selection. After identifying the expectations towards this more accurate list of adaptation measures, we analysed of other factors that may affect engagement through a planned adaptation policy. This was undertaken through a set of broader questions designed to obtain the informants general opinion on main preferable strategies for climate policy, identification of main objectives and targets to consider along its implementation, and description of main constraints identified by our sample.

The potential of using methods such as scenarios building and simulations allows integrating ecological interdependence in a model of shared responsibility to support future decision-making. In this sense, evaluating the various positions and consensus emerging from stakeholders' positions when joined together, may be accepted as legitimating an effective implementation of strategies and measures. From the general concern, arising from the knowledge and importance acclaimed for some impacts expected in the near future, (namely in the area of climate, energy and human health), a consensual position is revealed, between the three groups. The guidelines for a climate policy were also consistent whether for mitigation or the adaptation measures. In the same way the integration of environmental objectives is consensual regarding the country development. These groups considered that the environment in general as well climate research should be included in a national strategic plan. The main resources regarded as insufficient for the implementation of policies and measures were the negotiation capability and enforcement.

From the results obtained, the expectations and knowledge expressed by this panel did not vary much from the expected and it was possible to confirm significant and negative impacts, in the sectors of energy, human health, and coastal areas connected with a reasonable knowledge of these subjects. Nevertheless the fact that these expectations are apparent in actual discussions, and debates on climate change, does not mean that these positions will be immediately integrated in the appraisals that take place before decisions are taken.

It was found that the "dimension" knowledge about the topic is what generates less consensus and higher no response rates. This is due to the specificity of the impacts and adaptation measures presented in the survey. The expectance of the impacts and measures time lag, as well as the importance given, are, in their turn, more consensual "dimensions". Independently of knowledge, it is consensual that climatic change will be, sooner or later, integrated in the national development plans and that a respective time scale of a period of at least 50 years is the most reasonable for impacts occurrence and measures implementation. In general terms, the assumed positions reveal, without doubt, high degree of concern, with questions associated with climate change, as for instance the expectation of negative impacts, whether in Portugal or whether on a global scale. Also, it was so with the consequent effects of ecosystems and their sustainability.

Finally, the areas showing greater vulnerability, according to this panel, are climate, energy, human health, forests and coastal zones. Therefore the panel suggested that a strategic plan for the next 50 years be drawn up to cover the expected impacts, in these areas. Investments in scientific and technical resources, information on climate impacts and also the distribution of information and clearer details of climate changes, should be made available. In the field of responsibilities attribution the restraints listed were tied to the capacity of political negotiation. The main objectives to follow within a climate policy are greenhouses gases levels reduction and investment in politics of environmental recovery. We also conclude that professions may affect the level of knowledge and expectations to act within the politics of climate.

The group interview highlighted a developing consensus on the specificity of climate impacts as well on the definitions helping facilitate the debate that sustains decision-making. Moreover, it helped in achieving an agreement upon the objectives that must be reached for each area when approaching different strategies for planned adaptation. Herewith, we summarise a list of recommendations that have emerged along with the group interview.

The first, reminds us the need of having more discussion around climate models used for assessing regional impacts and vulnerability. The values achieved are polemic and the research is too recent. The major areas focused for a stronger political planning are land management and energy. The major constraints that Portugal faces for finding solutions for climate change impacts are in the urban areas, information deficit; some uncertainty about the impacts and general political confusion with climate concepts and definitions. Moreover, lack of prioritisation of climate change within the political agenda, lack of leadership, lack of clear political and normative orientation were also mentioned. It is necessary to bring climate change into the core of the political agenda, as it is urgent to assume responsibilities for future political actions, as it was frequently stressed that the main responsibilities for a political action lay at the national level.

This panel also allowed to undertake and to test the method of asking for the positions and expectations of people as a way to identify the general acceptance for the implementation of future policies. This panel also showed that if applied to a wider sample, a more solid base of information could be constituted to give support to the policy decisions. Nevertheless, that information can be strengthened, when negotiated and debated publicly, which consolidates the positions initially expressed by the surveys, as was shown by the group interview.

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# 5

# Water Resources

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## CONTENTS

## EXECUTIVE SUMMARY

The change in precipitation and temperature regimes, induced by climate change, will lead to changes in the runoff, aquifer recharge, flood and drought frequency and magnitude, as well as in the quality of the water resources. This study focused on the impacts of climate change in the runoff regime.

The impacts were evaluated analyzing the output of several climate models to produce a set of climate scenarios. These scenarios were fed into an hydrological model to compute runoff scenarios.

The output of four global climate models (HadCM2, HadCM3, ECHAM4 and CGCM1) and two regional models (HadRM2 and PROMES) were studied and compared with the observed records from more than 500 climate stations. The Hadley Centre models (HadCM3 and HadRM2) are the ones that have produced the most consistent results with the Portuguese historical observations.

The climate scenarios presented by the various models indicate a small increase of annual precipitation for northern Portugal and a decrease for central and southern Portugal. Climate models also estimate an increase of seasonal asymmetry with relevant decreases in summer precipitation. The annual average temperature will also, likely, increase, particularly in the south.

The results obtained in this study indicate a progressive reduction in the annual river runoff during the 21st century. This runoff reduction appears to be small in the northern region of Portugal, but increases progressively towards the south. If confirmed, this trend will increase the current spatial asymmetry of water availability in Portugal.

There seems to be a systematic trend towards a concentration of the river runoff in winter, induced by a similar pattern of change in the precipitation distribution. If confirmed, this trend will increase the current seasonal asymmetry of water availability in Portugal.

The concentration of precipitation in winter and the estimated general increase in the frequency of heavy precipitation events is likely to increase the flood magnitude and frequency, particularly in the northern part of the country.

The challenge of climate change must be addressed with a renewed interest on water resources management strategies and policies. The predicted decrease of river flow in southern Portugal towards the end of the century, associated with an increase in the spatial and temporal asymmetry of water resources distributions, may have dramatic consequences, and therefore, be a cause of significant concern. Thus, it does not seem wise to ignore the impacts of climate change in water resources planning and management in Portugal.

Given the importance of the transboundary river basins for the Portuguese water resources it is of paramount importance to develop joint projects in cooperation between Portugal and Spain on this topic. This question should be considered with particular relevance in the general framework of bilateral scientific and technological cooperation.

# 5. Water Resources

## 5.1 INTRODUCTION

The water resources sector is arguably the most important domain to be evaluated in a climate change impact assessment study. This importance stems from the fact that climate change has direct impacts on the availability, timing and variability of water supply and demand, but also because these impacts have profound implications on many other sectors of our society. Water is used for human consumption, industrial purposes, irrigation, power production, navigation, recreation and waste disposal, as well as for the maintenance of healthy aquatic ecosystems. Its availability and the occurrence of extreme events like floods and droughts condition the location of cities, industrial and agriculture areas, power generation plants and trading centres.

Water resources are irregularly distributed both in time and space. This is particularly true in Portugal where the annual precipitation may vary three fold from year to year and five fold from the dry interior south to the wet mountainous northwest. This irregularity is related to many of the problems arising in water resources management and is responsible for a significant number of water stress situations. Climate change may contribute to the worsening or the alleviation of these water stress situations, either by affecting the water supply or the water demand.

The impacts of climate change on water resources may be classified as direct, i.e. those directly resulting from climatic changes, or as indirect, such as those derived from changes in the economic and social development. One can therefore appreciate the complexity of the problem under discussion, which requires an interdisciplinary approach.

One of the earlier descriptions of the more relevant hydrological effects of climate change was provided by one of the authors (Cunha, 1989) as follows:

- Changes in the global amount of water resources available and in the spatial and temporal distribution of these resources;
- Changes in soil moisture;
- Changes in extreme phenomena related to water resources, i.e. floods and droughts;
- Changes in water quality;
- Changes in sedimentation processes;
- Changes in water demand.

The effect of climate change on stream flow and groundwater recharge largely follows projected changes in precipitation. According to the findings of the International Panel on Climate Change (IPCC, 2001), the region around the Mediterranean, where the southern part of Portugal is included, is one of the areas showing broadly consistent decreases in stream flow.

Flow magnitude and frequency are likely to increase with climate change in most regions. This is the consequence of a projected general increase in the frequency of heavy precipitation events, although the actual effects also depend on river basins characteristics.

Water quality may be degraded by higher water temperatures that induce changes in the rates of biochemical processes and, most importantly, a decrease of the dissolved oxygen concentration in water. However, changes in flow volume may constitute the most important factor, exacerbating or lessening the effect of temperatures in water quality, depending upon the direction of change in flow volume.

The pollutants inflow rates may also be affected either by rainfall pattern changes and its erosive capacities, or by changes in land and water uses. Erosion and sediment transport play a crucial role in the pollutants inflow to watercourses, which make up an important fraction of the total pollution of water streams. The trend is not obvious as decreased precipitation opposes to increase of extreme rainfall events (namely in the northern and central regions), which are responsible for greater erosion and sediment transport.

Climate change is unlikely to have a large effect on municipal and industrial water demand, but may substantially affect withdrawals for irrigation: higher temperatures, and hence crop evaporative demand, would mean that the general tendency would be towards an increase in irrigation water demand. However, water demand forecasts for this sector are extremely difficult to put forward, even if we assume that the current crops and agriculture areas are maintained.

Warmer air temperatures increase evaporation capacities but since increased $CO_2$ concentrations affect the mechanisms by which plants use water, the outcome is hard to predict. Increased $CO_2$ levels decrease plant transpiration on one side, but on the other side increase plant growth and consequently its leaf size, i.e., transpiration area. The result of such balance is not yet clear.

Furthermore, climate change may lead to crop replacement, as new climate conditions may hinder the practice of some and promote the use of others. But climate is not the only feature influencing crop choice. Once again it is unclear what the outcome may be.

There is, however, a growing belief that climate change will lead to an increase in water demand for irrigation. Ayala-Carcedo (2000) studied this problem for Spain and estimated an increase between 5% and 10% for the present crops of the Douro, Tejo and Guadiana river basins by 2060.

Aquatic ecosystems are likely to suffer from the changes in water quality, including the rise of water temperatures. Ecosystems located in costal regions will suffer an additional stress caused by the potential saline intrusion due to a rising sea level, associated to climate change.

The impact of climate change on water resources depends not only on changes in the volume, timing and quality of stream flow and recharge, but also on the system characteristics, the changing pressures on the system, how the management of the system evolves and what adaptation measures to climate change are implemented. In some cases, non-climatic changes may have a greater impact on water resources than climate change itself.

Climate change challenges existing water resources management practices, by adding additional uncertainties. An integrated water resources management is, therefore, needed to enhance the capacity for adaptation to change.

Several international research centres have already studied the potential impacts of climate change. Countries like the US, Canada or UK have elaborated national impacts assessment studies in order to identify and explain the science behind such changes and to propose mitigation and adaptation measures. Given the real threat of climate change and the global concern of world governments, the United Nations created the International Panel on Climate Change (IPCC) as a way to give political credibility to the various results and analysis of climate change studies and also to present their own assessment plan based on numerous contributions of their international scientific experts.

The IPCC Third Assessment Report (IPCC, 2001) estimates a global increase of mean annual temperature of 0.8°C to 2.6°C by 2050 and 1.4°C to 5.8°C by 2100. The study also reports results that indicate an increase in annual precipitation induced by climate change in high and mid latitudes and most equatorial regions, as well as a general decrease in the subtropics. Results also show that flood magnitude and frequency is likely to increase, due to the concentration of precipitation in winter in most areas of the globe. Simultaneously, the decrease of low flows in many regions associated with higher temperatures constitutes a serious threat to the quality of water resources.

The ACACIA project (Parry, 2000), which provided the European input for the preparation of the IPCC Third Assessment Report, indicates that the annual mean temperature will continue to increase, particularly in the southern Europe Atlantic coast (0.4°C per decade or higher). This trend is particularly pronounced in summer, where it is expected a warming at twice the rate of northern Europe. Annual mean precipitation, over southern Europe, may slightly decrease at a maximum rate of 1% per decade. However, relevant changes are expected at the seasonal scale. Winter is expected to get wetter at a rate of 1% to 4% per decade, while in the summer southern Europe may observe a drying up of up to 5% per decade or so.

A consequence of such scenarios is a likely decrease in annual stream flow in southern Europe. As precipitation tends to be concentrated in winter, the seasonal variability of stream flow will likely increase. Summer drought risk will also probably increase in southern Europe and its impacts will be conditioned by the available storage capacity of winter runoff. The frequency and magnitude of intense precipitation events are likely to increase, especially in winter, leading to an increased flood risk, not only in winter but also in summer and autumn, due to convective rainfall. It is also very likely that the frequency and intensity of summer heat waves will increase. Other conclusions point to adverse changes in river water quality, particularly in the regions where quality is already under threat.

Given the working scale of the IPCC and ACACIA studies, its results do not have the needed detail to evaluate the impacts of climate change on water resources at a national or basin level. This study attempts to overcome such handicap by presenting predictions of runoff change for various regions of Portugal. An analysis of the precipitation scenarios allowed the identification of some general trends on flood occurrence. The impacts of climate change in groundwater and in water quality have not yet been studied, but some general comments on the likely trends are provided.

This study will mainly focus on climate change direct impacts on water resources and in particular, on water availability. Further work is needed to provide some insight on the other very important aspects related to this issue. Section 5.2 presents a brief overview of water resources situation in Portugal. Section 5.3 presents the framework adopted to assess climate change impacts on water resources in Portugal. It describes the selected approach as well as the datasets used. The forecasted climatic and runoff scenarios are presented in Section 5.4. Section 5.5 discusses future research needs to fully evaluate the impacts of climate change on the Portuguese water resources. Finally, Section 5.6 summarizes the main conclusions of the chapter.

## 5.2 BRIEF DESCRIPTION OF THE WATER RESOURCES SITUATION IN PORTUGAL

### 5.2.1 INTRODUCTION

Due to its position on the southwestern coast of Europe, the climate of Portugal is strongly influenced by the Atlantic Ocean. In summer, the Azores high pressure centre is the main climatic drive providing stable climate conditions, with low precipitation and high air temperatures. In winter, the Azores high pressure moves south, letting the mainland exposed to weather fronts coming from the west that are responsible for the winter precipitation. A sequence of mountain ranges, that includes Gerês, Marão, Caramulo, Estrela and Malcata, creates a NW-SE barrier that concentrates the precipitation on its western regions. Temperatures are drastically reduced in wintertime

Figure 5.1 – National and transboundary Portuguese river basins

as continental polar air advection over the Iberian Peninsula becomes more frequent.

This section presents a brief description of the water resources in Portugal. The main sources of data for this analysis were the National Water Plan (INAG, 2001) and the data sets described in Section 5.3.2. Figure 5.1 shows the national and transboundary river basins of Portugal.

### 5.2.2 PRECIPITATION

On an average year, Portugal receives 960 mm of precipitation (INAG, 2001). The spatial distribution of the precipitation is far from uniform, with the Tejo river basin constituting a transition zone between the wetter north region and the drier south region. The northwest river basins of Lima and Cávado experience annual rainfall values of approximately 2,200 mm, with the region of Gerês reaching values above 3,000 mm. In contrast, the Guadiana basin, receives 570 mm, but in some places precipitation is below 450 mm (Figure 5.2 and Table 5.1). Some inland parts of the Douro river basin also experience an annual precipitation value below 450mm.

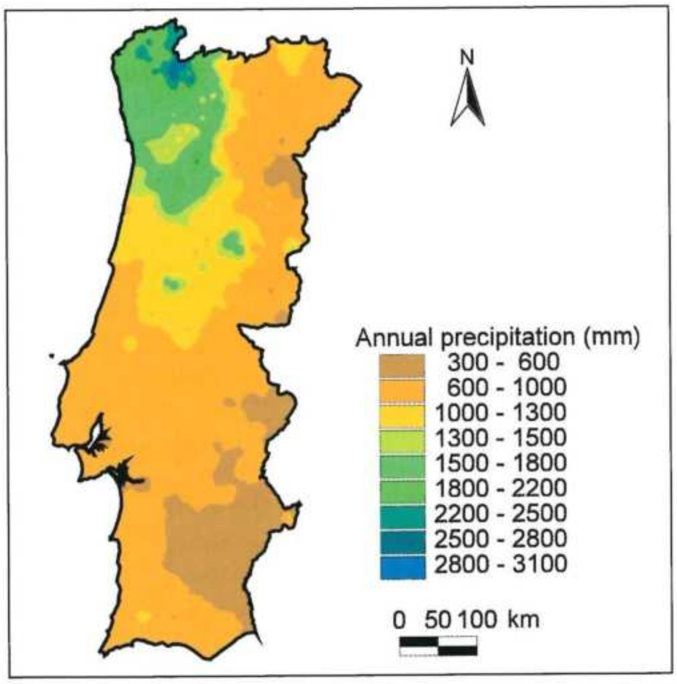

Figure 5.2 – Average annual precipitation observed in the 1941/42-1990/91 period

In addition to an irregular spatial distribution, there is also a marked seasonal distribution pattern (Figure 5.3). The highest monthly precipitation value is normally observed in December or January, while the minimum is observed in July or August. Such distribution leads to a wet semester, from November to April that accounts for 70% of the annual rainfall. South of river Tejo, this percentage can reach 80%.

Furthermore, precipitation may vary significantly from year to year. Historical observations show that the

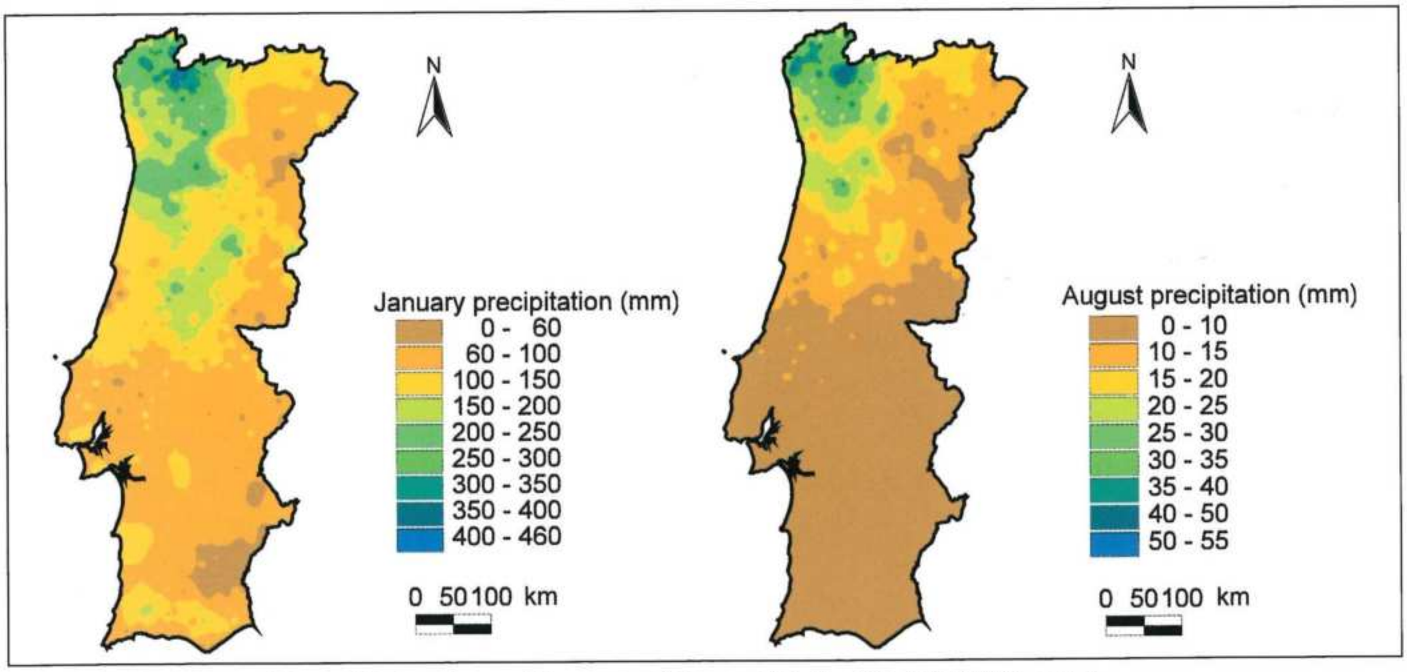

Figure 5.3 – Average monthly precipitation observed for a wet and dry month in the 1941/42-1990/91 period

**Table 5.1 – Average monthly and annual precipitation for the period 1941/42-1990/91** (INAG, 2001)

| River | Precipitation (mm) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| basin | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Year |
| Minho* | 185 | 232 | 275 | 265 | 248 | 206 | 145 | 141 | 77 | 31 | 46 | 103 | 1,954 |
| Lima* | 205 | 257 | 316 | 318 | 278 | 241 | 153 | 152 | 84 | 34 | 50 | 120 | 2,208 |
| Cávado | 200 | 255 | 309 | 306 | 277 | 244 | 156 | 151 | 88 | 33 | 46 | 107 | 2,172 |
| Ave | 170 | 205 | 258 | 252 | 227 | 198 | 137 | 134 | 81 | 36 | 44 | 88 | 1,830 |
| Leça | 134 | 166 | 192 | 189 | 159 | 145 | 101 | 95 | 51 | 17 | 24 | 61 | 1,334 |
| Douro* | 96 | 122 | 140 | 131 | 129 | 108 | 82 | 76 | 47 | 17 | 17 | 51 | 1,016 |
| Vouga | 142 | 186 | 220 | 216 | 204 | 170 | 119 | 109 | 58 | 18 | 25 | 66 | 1,533 |
| Mondego | 131 | 153 | 153 | 145 | 128 | 99 | 86 | 56 | 21 | 16 | 43 | 93 | 1,124 |
| Lis | 97 | 122 | 141 | 136 | 124 | 109 | 79 | 67 | 31 | 7 | 11 | 40 | 964 |
| Tejo* | 88 | 116 | 125 | 120 | 112 | 101 | 74 | 61 | 31 | 8 | 8 | 40 | 884 |
| Oeste | 84 | 114 | 119 | 113 | 101 | 90 | 71 | 55 | 26 | 5 | 8 | 35 | 821 |
| Sado | 64 | 82 | 93 | 85 | 81 | 75 | 56 | 38 | 17 | 4 | 3 | 24 | 622 |
| Mira | 73 | 98 | 108 | 94 | 88 | 85 | 59 | 40 | 15 | 2 | 3 | 24 | 689 |
| Guadiana* | 60 | 75 | 83 | 73 | 70 | 70 | 53 | 36 | 19 | 3 | 3 | 23 | 568 |
| Algarve | 85 | 122 | 138 | 120 | 111 | 102 | 70 | 44 | 17 | 2 | 4 | 25 | 840 |
| Average | 94 | 121 | 136 | 129 | 122 | 108 | 79 | 67 | 37 | 11 | 13 | 44 | 962 |

* Values for the Portuguese territory only.

mean annual precipitation varied between 550 mm and 1,450 mm in the period 1941/42-1990/91. It is also observed that 25% of annual precipitation values are either below 800 mm or above 1,100 mm. This variability increases from north to south.

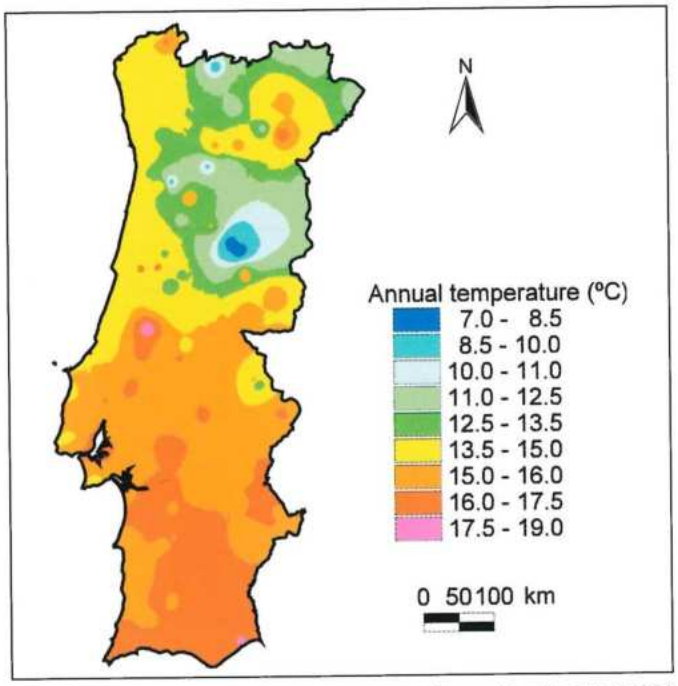

Figure 5.4 – Average annual temperature observed in the 1961-1990 period.

### 5.2.3 TEMPERATURE

The average annual temperature in Portugal is about 14°C (INAG, 2001). It is mainly distributed as a function of altitude, latitude and proximity to the ocean, varying between 7°C in the Douro river basin and 19°C in the Guadiana river basin (Figure 5.4).

Temperatures present a clear seasonal pattern. The average monthly minimum is usually observed in January or February. The river basin with the lowest spatial average temperature is the Guadiana with a value of 8°C. In areas above 1,000 m, average monthly temperatures may reach 1°C (Figure 5.5). The highest values occur in July or August, varying from 15°C in the northern basins to 26°C in the southern Guadiana. Daily average temperatures are however higher, as during the day values can exceed 40°C.

### 5.2.4 POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration is not systematically measured over Portugal, and it is therefore necessary to estimate this variable from temperature, relative humidity, insolation and wind speed values.

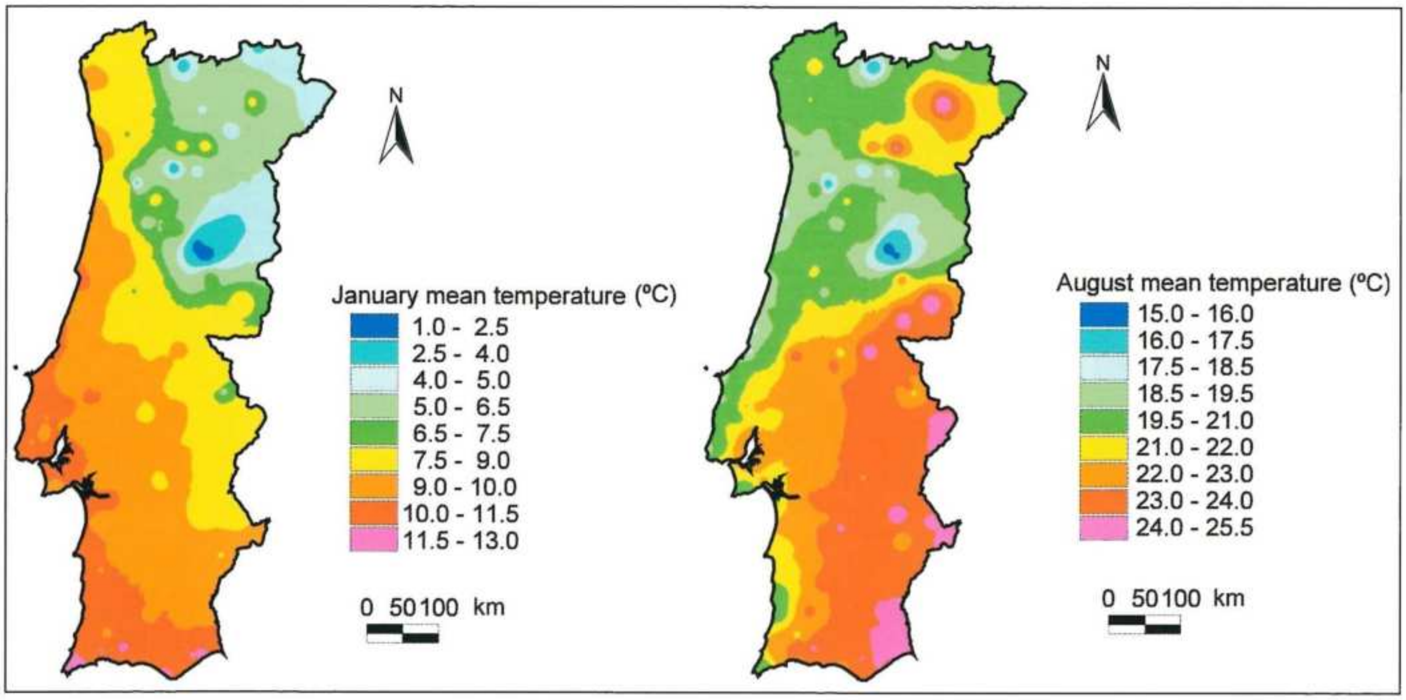

Figure 5.5 – Average monthly temperature observed in a cool and hot month of the 1961-1990 period.

Using the Penman-Monteith method, the average potential evapotranspiration over Portugal is estimated to be 1,100 mm varying from 900 mm, in the north region, to 1,200 mm in the south (Table 5.2).

Similar to the temperature regime, potential evapotranspiration variability is also highly seasonal reaching a minimum in December or January and a maximum in July or August.

**Table 5.2 – Average monthly and annual potential evapotranspiration for the period 1941/42-1990/91** (INAG, 2001)

| **River** | **Potential Evapotranspiration (mm)** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **basin** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Year** |
| Minho* | 70 | 40 | 29 | 30 | 40 | 65 | 92 | 129 | 150 | 172 | 159 | 105 | 1,081 |
| Lima* | 68 | 40 | 29 | 30 | 40 | 66 | 93 | 124 | 144 | 164 | 150 | 102 | 1,050 |
| Cávado | 62 | 35 | 25 | 25 | 35 | 61 | 86 | 113 | 135 | 156 | 141 | 97 | 971 |
| Ave | 62 | 36 | 26 | 26 | 35 | 62 | 87 | 111 | 131 | 149 | 134 | 95 | 954 |
| Leça | 62 | 37 | 29 | 29 | 37 | 62 | 86 | 107 | 125 | 140 | 127 | 91 | 932 |
| Douro* | 64 | 35 | 24 | 24 | 34 | 62 | 88 | 117 | 144 | 172 | 156 | 105 | 1,025 |
| Vouga | 71 | 42 | 31 | 31 | 44 | 66 | 89 | 116 | 139 | 162 | 150 | 106 | 1,047 |
| Mondego | 75 | 46 | 34 | 33 | 45 | 63 | 84 | 111 | 135 | 162 | 154 | 110 | 1,052 |
| Lis | 109 | 80 | 58 | 48 | 95 | 49 | 65 | 83 | 115 | 144 | 153 | 130 | 1,129 |
| Tejo* | 80 | 48 | 34 | 33 | 43 | 65 | 88 | 120 | 146 | 181 | 167 | 119 | 1,124 |
| Oeste | 104 | 73 | 53 | 45 | 52 | 54 | 71 | 94 | 125 | 163 | 161 | 131 | 1,126 |
| Sado | 74 | 40 | 29 | 31 | 42 | 71 | 98 | 133 | 158 | 184 | 168 | 117 | 1,145 |
| Mira | 76 | 44 | 33 | 35 | 44 | 72 | 97 | 129 | 151 | 177 | 159 | 117 | 1,134 |
| Guadiana* | 80 | 43 | 29 | 32 | 42 | 74 | 103 | 142 | 174 | 206 | 187 | 130 | 1,242 |
| Algarve | 85 | 51 | 40 | 40 | 49 | 79 | 104 | 137 | 158 | 186 | 174 | 126 | 1,229 |
| Average | 72 | 40 | 29 | 30 | 40 | 69 | 94 | 126 | 151 | 177 | 162 | 112 | 1,102 |

* Values for the Portuguese territory only.

### 5.2.5 RUNOFF

The runoff regime is greatly influenced by seasonal and space variability of climate variables, in particular precipitation. Consequently, the runoff regime in Portugal is highly irregular, a common feature to other southern European regions. The wet northern coastal river basins contrast with the dry inland southern basins. Wintertime river flows account for the majority of river runoff and are followed by a long and dry summer period. Similarly to precipitation, river flow interannual variability is also pronounced. The annual mean runoff is 385 mm (INAG, 2001).

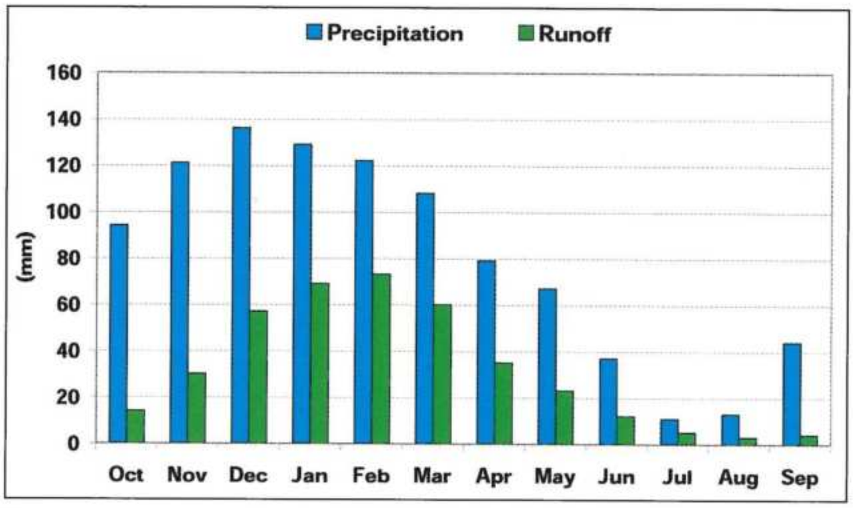

Figure 5.6 – Average monthly precipitation and runoff for the 1941/42-1990/91 period (based on INAG, 2001)

The highest runoff values are observed in February, two months after the rainfall peak in December (Figure 5.6). The low soil moisture at the beginning of the hydrological year explains this precipitation runoff peak offset, which results from higher values of aquifer recharge during the first rainfall events. As the soil moisture increases throughout autumn and winter, recharge rates decrease and direct runoff increases.

The highest runoff values are observed in the north-western river basins, in contrast with the lowest levels observed in the Guadiana and Sado river basins (Table 5.3). The Tejo river basin constitutes, also in this case, a transition area between the wetter north and drier south.

Portugal shares with Spain five river basins: Minho, Lima, Douro, Tejo and Guadiana, which in Portugal cover almost 65% of the territory. This percentage

**Table 5.3 - Average monthly and annual runoff for the period 1941/42-1990/91** (INAG, 2001)

| River | Runoff (mm) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| basin | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Year |
| Minho* | 103 | 160 | 222 | 228 | 210 | 158 | 84 | 66 | 21 | 3 | 8 | 39 | 1,301 |
| Lima* | 69 | 124 | 200 | 240 | 233 | 197 | 125 | 94 | 50 | 21 | 12 | 26 | 1,390 |
| Cávado | 61 | 112 | 181 | 219 | 221 | 195 | 125 | 94 | 53 | 23 | 12 | 21 | 1,318 |
| Ave | 31 | 59 | 113 | 149 | 159 | 145 | 102 | 75 | 45 | 21 | 11 | 10 | 920 |
| Leça | 19 | 39 | 71 | 95 | 99 | 91 | 62 | 44 | 24 | 10 | 4 | 4 | 562 |
| Douro* | 20 | 43 | 76 | 89 | 94 | 73 | 43 | 29 | 14 | 6 | 3 | 4 | 495 |
| Vouga | 31 | 65 | 124 | 151 | 154 | 118 | 67 | 48 | 26 | 14 | 8 | 7 | 814 |
| Mondego | 16 | 36 | 72 | 93 | 99 | 79 | 49 | 33 | 19 | 10 | 5 | 4 | 515 |
| Lis | 8 | 17 | 42 | 61 | 69 | 54 | 31 | 17 | 6 | 3 | 1 | 1 | 310 |
| Tejo* | 10 | 20 | 26 | 28 | 28 | 26 | 19 | 13 | 6 | 2 | 1 | 2 | 181 |
| Oeste | 6 | 14 | 30 | 42 | 49 | 46 | 29 | 19 | 10 | 5 | 2 | 2 | 252 |
| Sado | 3 | 9 | 29 | 36 | 39 | 29 | 7 | 2 | 0 | 0 | 0 | 0 | 155 |
| Mira | 5 | 14 | 39 | 43 | 43 | 36 | 9 | 3 | 0 | 0 | 0 | 0 | 191 |
| Guadiana* | 6 | 15 | 35 | 36 | 35 | 26 | 8 | 3 | 1 | 0 | 0 | 0 | 167 |
| Algarve | 6 | 16 | 39 | 39 | 41 | 35 | 18 | 8 | 3 | 1 | 0 | 0 | 207 |
| Average | 14 | 30 | 57 | 69 | 73 | 60 | 35 | 23 | 12 | 5 | 3 | 4 | 385 |

* Values generated in Portugal only.

value reveals, by itself, the importance these basins have in the Portuguese water management policies. Since, as much as 80% of the total area of these transboundary river basins is located in Spain (Figure 5.1 and Table 5.4), bilateral discussions and agreements are needed to ensure a meaningful water management in Portugal.

**Table 5.4 – Area of the transboundary river basins** (INAG, 2001)

| Transboundary<br>River basins | Area (km²)<br>In Portugal | <br>In Spain | <br>Total |
|---|---|---|---|
| Minho | 846 | 16,235 | 17,081 |
| Lima | 1,177 | 1,303 | 2,480 |
| Douro | 18,710 | 78,972 | 97,682 |
| Tejo | 24,860 | 55,769 | 80,629 |
| Guadiana | 11,700 | 55,260 | 66,960 |
| Subtotal | 57,293 | 207,539 | 264,832 |
| National river basins | 32,007 | | |
| Total | 89,300 | | |

**Table 5.5 – Average annual flows of the transboundary river basins** (INAG, 2001)

| Transboundary<br>River basins | Flow assuming pristine conditions (hm³/yr)<br>In Portugal | <br>In Spain | <br>Total |
|---|---|---|---|
| Minho | 1,059 | 11,050 | 12,109 |
| Lima | 1,629 | 1,900 | 3,529 |
| Douro | 9,192 | 13,660 | 22,852 |
| Tejo | 6,164 | 10,880 | 17,044 |
| Guadiana | 1,887 | 5,470 | 7,357 |
| Subtotal | 19,931 | 42,960 | 62,891 |
| National river basins | 10,848 | | |
| Total | 30,779 | 42,960 | 73,739 |

Under natural conditions, 60% to 75% of the total outlet flow (hm³/year) of the Douro, Tejo and Guadiana has its origin in Spain, although the runoff (mm) observed in Portugal is larger than the one produced in Spain. The total available mean annual runoff in Portugal is about 74,000 hm³, which includes approximately 43,000 hm³ originated in Spain (Table 5.5).

### 5.2.6 FLOODS

Floods are a recurring problem in Portugal, occurring throughout the country in both small and large river basins. According to Brandão and Rodrigues (1998) the daily precipitation values for a hundred year event range from 70 mm to 310 mm and the 30-minute rainfall values for a hundred year event range from 26 mm to 66 mm (Figure 5.7). These maximum values occur in the high altitude areas of the northwestern river basins and Algarve. Despite having less intense rainfall events, regions like the Tejo Valley and the Mondego river basin also observe flooding on a regular basis.

Depending on the basin area, floods can last a few hours to a couple of weeks. An intense rainfall event over a small river basin can produce a sudden flood, resulting in property inundation after one to two hours. These precipitation events can occur not only in winter but also in autumn. Given the small dimensions of these basins, flood peak discharge per unit of area is high. As an example, a hundred years flood in small river basins in the Tejo river basin region is about 9 m³/s/km² and 4 m³/s/km² for basins with 10 km² and 100 km² areas, respectively.

For larger basins like Tejo or Douro, longer rainfall events are needed to produce flooding. Successive winter precipitation events reduce the infiltration capacity and increase reservoir levels. Only when such conditions last for some weeks, flooding becomes a potential risk. In these cases flood magnitude is far greater. For example the hundred years Douro flood flow is close to 16,000 m³/s (Serra, 2001).

The impacts of floods include the inundation of roads, farms, residential and industrial areas and, less frequently, the loss of human lives. The magnitude of such impacts are not only directly linked to the flood size but also to the rate of water level increase and to the population response time.

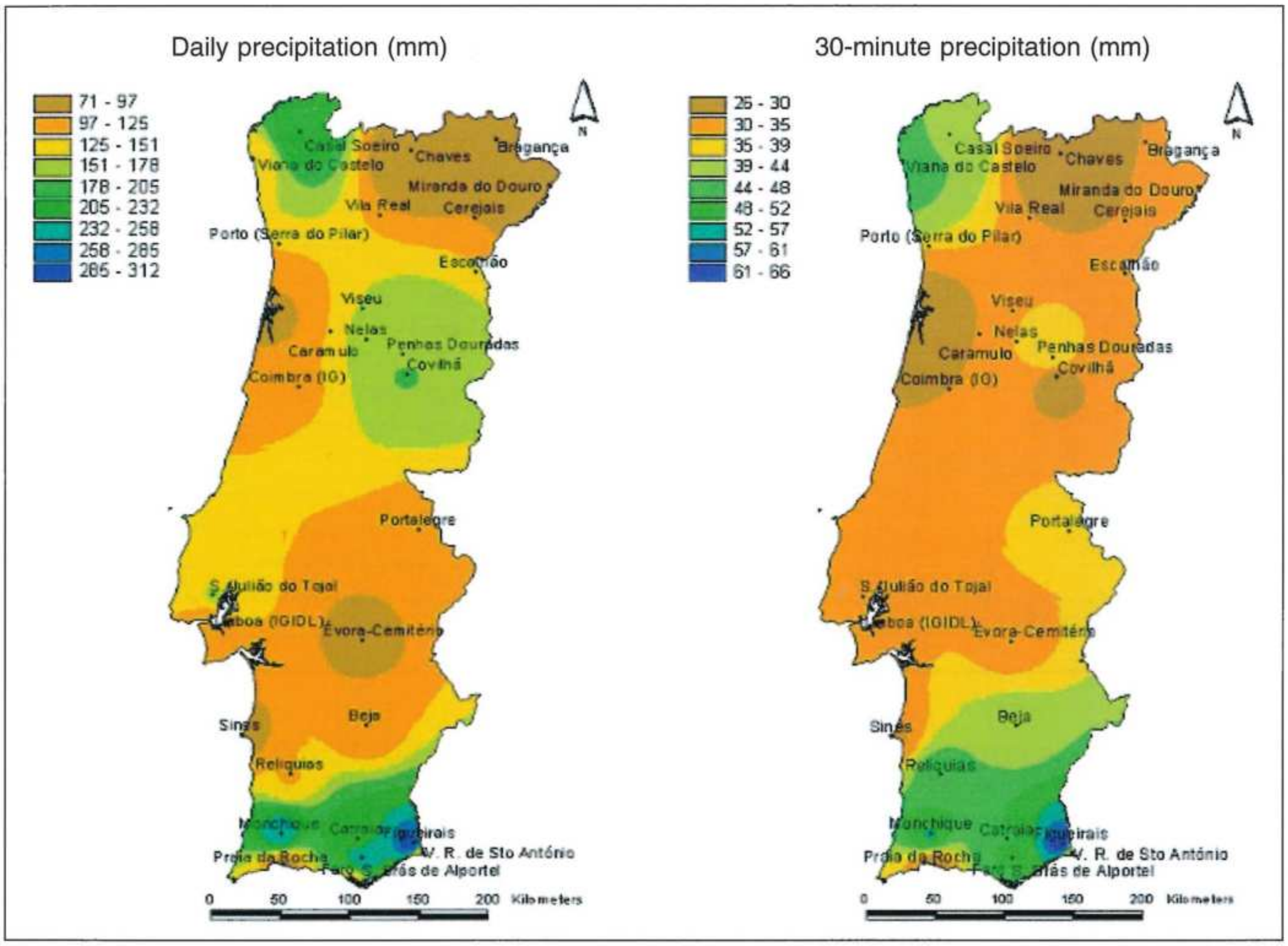

Figure 5.7 – Daily and 30-minutes maximum precipitation for a hundred year event, (Brandão and Rodrigues, 1998).

### 5.2.7 WATER USES

Consumptive use of water is related mainly to urban settlements, industry, agriculture and tourism. Other uses such as power production, aquaculture and leisure fishing do not involve high consumptions. In fact, although power production is one of the largest water users, its final net consumption is not significant. The amount of water that is actually consumed in hydropower production, as well as in power plants cooling systems corresponds to evaporation losses that occur within these processes. Nevertheless, the use of water for hydropower production has significant impacts on water resources due to the large modification of flow regimes.

Table 5.6 presents the estimates of annual water demand according to the National Water Plan (INAG, 2001). The Tejo and Douro river basins are responsible for half of the national water demand.

Urban water uses include all the water supplied to the population as well as to commerce and public services. It also includes all the water losses within the supply system. In Portugal about 85% of the resident population are currently supplied with potable water. The volume of water annually supplied to population is currently of 623 hm$^3$.

The National Water Plan estimates that 385 hm$^3$ of water is annually supplied to industrial activities. Currently, 80% of water demand is concentrated on only four industrial sectors, the paper and pulp industry and the beverage and food industry being the main users. Such needs are mainly located in the Tejo, Mondego, Sado, Douro, Vouga and Leça river basins, with the Tejo and Mondego basins standing out with 147 hm$^3$ and 71 hm$^3$, respectively.

The agriculture sector is the largest water user in Portugal, using approximately 75% of the Portuguese

**Table 5.6 - Average annual water demand** (INAG, 2001)

| **River basin** | **Urban ($hm^3$)** | **Industry ($hm^3$)** | **Agriculture ($hm^3$)** | **Tourism ($hm^3$)** | **Total ($hm^3$)** |
|---|---|---|---|---|---|
| Minho | 4 | > 1 | 107 | > 1 | 118 |
| Lima | 10 | 10 | 214 | > 1 | 235 |
| Cávado | 18 | 3 | 316 | > 1 | 337 |
| Ave | 34 | 8 | 365 | > 1 | 407 |
| Leça | 26 | 16 | 39 | > 1 | 81 |
| Douro | 102 | 34 | 1 793 | 1 | 1 930 |
| Vouga | 39 | 28 | 475 | > 1 | 543 |
| Mondego | 41 | 71 | 832 | > 1 | 945 |
| Lis | 10 | > 1 | 69 | > 1 | 79 |
| Oeste | 47 | 4 | 207 | 2 | 260 |
| Tejo | 223 | 147 | 2 655 | 3 | 3 030 |
| Sado | 25 | 58 | 588 | 1 | 670 |
| Mira | 1 | > 1 | 126 | > 1 | 128 |
| Guadiana | 17 | 3 | 536 | 1 | 557 |
| Algarve | 26 | 2 | 410 | 11 | 449 |
| Total | 623 | 385 | 8 732 | 20 | 9 760 |

total water demand, corresponding to an annual volume of 8,732 $hm^3$ of water. The irrigation efficiency is low (usually less than 65%) and it is estimated that a small fraction of the water supplied (about 20%) is returned to the environment. The largest needs are concentrated in the Douro and Tejo river basins, accounting for approximately 50% of the total water uses. On average only 70% of the water demand is fulfilled.

The water demand for the tourism sector includes lodging facilities needs and golf courses irrigation needs. The water supplied to the first sector is normally withdrawn from the public water supply system, whereas for the second one is usually withdrawn from local aquifers, surface waters or both. It is estimated that the tourism water annual needs add up to 20 $hm^3$, approximately, evenly split between lodging facilities needs and golf courses needs.

In summary, the total water demand in Portugal is close to 10,000 $hm^3$, with the larger needs occurring in the larger basins, Tejo and Douro. The agriculture sector is the most water dependent sector, using almost 75% of the total water supplied. Population, industry and tourism water demand do not actually have a significant percentage impact in the available resources but require a higher reliability level of supply.

## 5.3 FRAMEWORK FOR THE ASSESSMENT OF CLIMATE CHANGE IMPACTS ON WATER RESOURCES

### 5.3.1 OUTLINE OF THE ASSESSMENT APPROACH

To evaluate the impacts of climate change on water resources one must compare two sets of statistics of climate and hydrological variables, one assuming a steady climate scenario and a second one assuming a given scenario for greenhouse gases emission.

The current global climate models (GCMs) and regional climate models (RCMs) are able to produce time series of a set of climatic variables under different emission scenarios. The basic scenario, commonly referred to as the control run, consists in simulating the conditions in the absence of any $CO_2$ increase, thus producing a stationary climatic scenario, where each climatic variable varies throughout the simulation periods but its overall average is not expected to change. The other scenarios, identified as perturbed scenarios, simulate the climate trend and variability associated with a given greenhouse gas emission scenario. These emission scenarios assume different $CO_2$ increase rates and may also include the combined effect of greenhouse gases and aerosols.

The comparison of different sets of model results between themselves and with the observed historical record is the basis for most of climate change assessment studies that attempt to quantify expected changes in the main climatic variables, namely temperature and precipitation.

To evaluate the impacts of climate change on water resources one must go beyond these climatic variables and assess the changes in runoff. Unfortunately, the scale used by both global and regional climate models is too coarse to allow for an appropriate simulation of hydrological processes at the basin level.

To overcome this difficulty, most studies have used the climate models results as the input of an hydrological model that simulates the mechanism of interception, infiltration, aquifer recharge and runoff at the basin scale. This approach, followed by a number of authors, e.g. Arnell (1996), was also adopted in the present chapter.

The climate change impacts on water availability were evaluated by comparing the results from a hydrological model, which was run under different climatic scenarios. Historical monthly precipitation and temperature records describe the current climate. Future climatic scenarios were built by perturbing the historical records with expected changes predicted by GCMs or RCMs, as depicted in Figure 5.8.

The hydrological model used in this chapter is a continuous, aggregated and deterministic monthly precipitation – runoff model that simulates the transformation process of precipitation into runoff on a given river basin. It assumes a monthly time step and since it is an aggregated model, it assumes a uniform spatial distribution of the conditions that affect the transformation process.

The hydrological model structure is similar to the one used by the Stanford Watershed Model presented by Linsley in 1960 (Linsley and Crawford (1960); Crawford and Linsley (1966)). The model is normally known in Portugal as the Temez model and corresponds to a simplification of the Stanford model. The formulation includes four parameters that need to be estimated from the observed historical values.

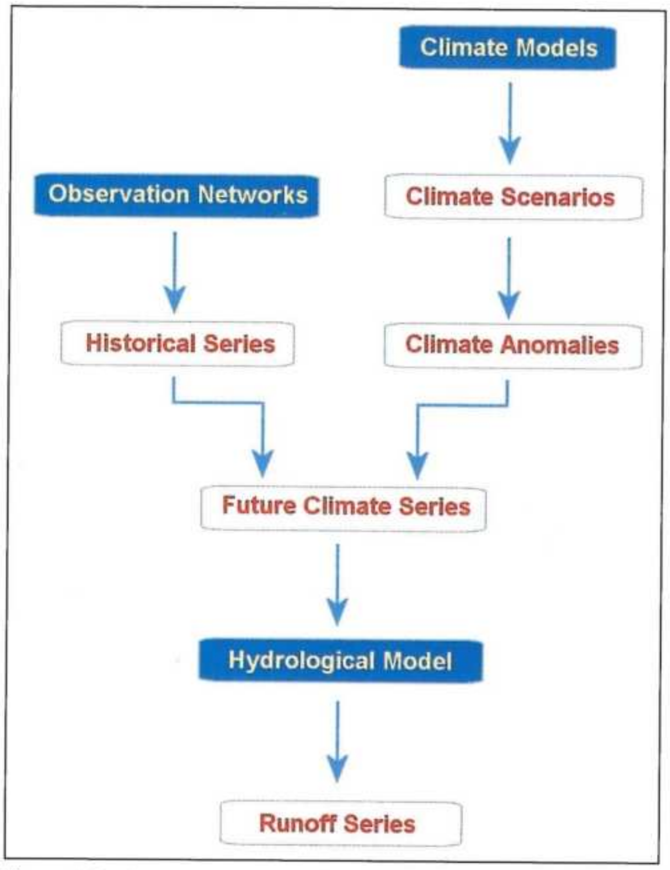

Figure 5.8 – Assessment approach

As input, the model requires the river basin precipitation and potential evapotranspiration monthly series, which have been estimated from climatic records using the Penman-Monteith method. As output the model produces runoff, aquifer recharge and effective evapotranspiration monthly time series.

In the present chapter 62 river basins with no major human intervention, at least in their calibration period, have been selected (Figure 5.9). These basins, with areas ranging from 15 km2 to 1,000 km2, are distributed throughout the country, ensuring a nationwide picture of the hydrological regimes. The model was calibrated for each river basin. The length of observed records used for calibration range from 5 to 50 years.

To estimate the runoff regime under current climatic conditions, the historical precipitation and temperature records from the 1961-1990 period have been used. The runoff regime for future climatic conditions was estimated from different climatic scenarios, derived from the output of two climatic models. Section 5.3.2 presents the datasets used in this chapter.

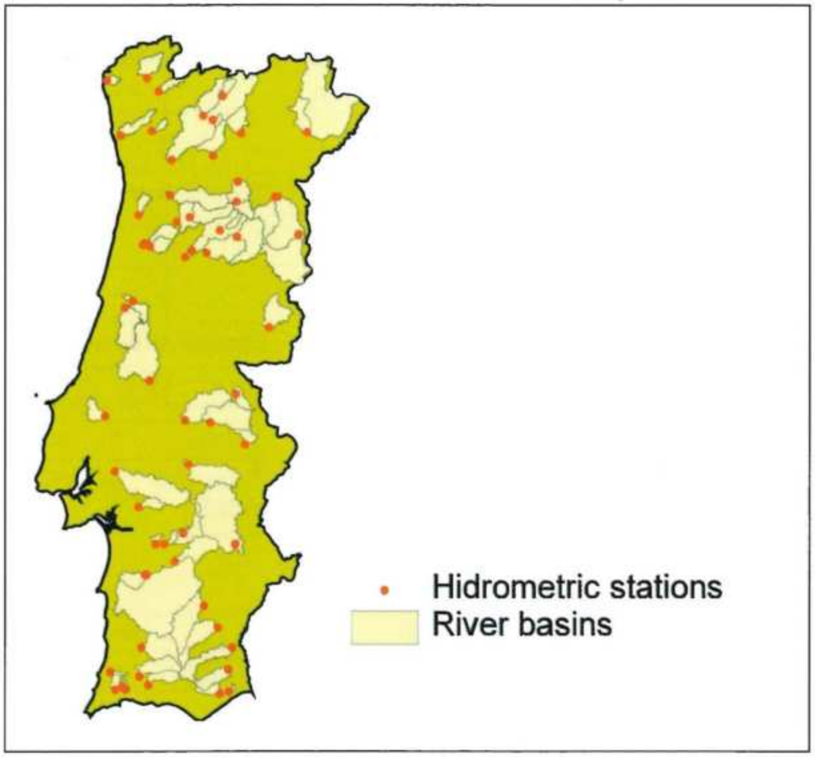

Figure 5.9 – Hydrometric stations considered in the study

This chapter evaluates the performance of four global climate models and two regional climate models to identify the ones that produce the most consistent results with the Portuguese climate. Such evaluation required the comparison of the control run scenario of each climate model with the historical precipitation and temperature records. The results of this analysis are presented in Section 5.3.3.2.

The precipitation and temperature records for future scenarios were estimated by adding an expected change to the historical record. As the expected change varies from month to month, twelve values were needed for each variable. The change in precipitation was obtained from the ratio between the monthly mean for the future scenario and the present scenario. The historical record was multiplied by these twelve monthy ratio values to obtain a new precipitation record. The change in temperature was computed as the difference between the monthly mean for the future scenario versus the present scenario. The twelve monthly difference values were then added to the historical record to obtain a new temperature record.

Based on these future climate scenarios and using the hydrological model, several runoff scenarios were produced in 62 Portuguese river basins. The results are presented in Section 5.4.

### 5.3.2 OBSERVED DATA

To characterise the present climate conditions, the historical precipitation and temperature records of about 500 rain gauges stations and about 200 climate stations, from the Portuguese Meteorological Institute and the Portuguese Water Institute, were analysed. Data from the Spanish Meteorological Institute covering the Spanish territory in a region surrounding Portugal, and in particularly the Galicia region, north of Portugal, were also included in the dataset (Figure 5.10). The analysis period was 1961-90 and monthly values were used.

Precipitation data was mainly obtained from the Portuguese Water Institute because its measurement stations outnumber the Portuguese Meteorological Office stations and because the data recorded is more easily accessible and readily available. In what concerns temperature, the Water Institute network is smaller in the number of stations and records, which means that the data collected by the Meteorological

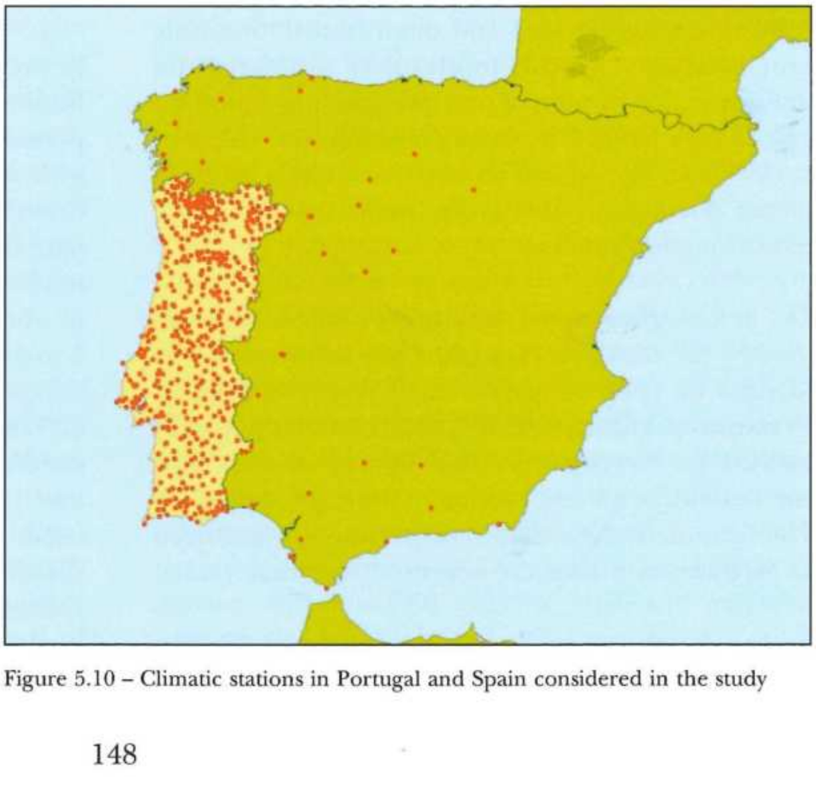

Figure 5.10 – Climatic stations in Portugal and Spain considered in the study

Office was essential to characterize the temperature regime in Portugal. Other climatic variables time series were also completed or fully constructed using additional data from the Portuguese and Spanish Meteorological Office.

**Table 5.7 – Climate models considered in the study**

| Acronym | Source | Scale | Resolution* (lat × long) |
|---|---|---|---|
| HadCM2 | Hadley Centre for Climate Prediction and Research | Global | 2.5° × 3.75°<br>(220 × 420 km) |
| HadCM3 | Hadley Centre for Climate Prediction and Research | Global | 2.5° × 3.75°<br>(220 × 420 km) |
| ECHAM4 | Deutsches Klimarechenzentrum | Global | 2.8° × 2.8°<br>(250 × 310 km) |
| CGCM1 | Canadian Centre for Climate Modelling and Analysis | Global | 3.7° × 3.7°<br>(320 × 410 km) |
| HadRM2 | Hadley Centre for Climate Prediction and Research | Regional | 0.44° × 0.44°<br>(40 × 50 km) |
| PROMES | Grupo de Modelado Atmosférico de la Universidad Complutense de Madrid | Regional | 0.44° × 0.44°<br>(40 × 50 km) |

* Grid size in kilometres corresponds to the latitude of Portugal.

## 5.3.3 SOURCES AND EVALUATION OF DATA

### 5.3.3.1 Climate Models Considered

It seems to be clear that current GCMs perform a reasonable job modelling the historical climate and there is a well established confidence in their current capabilities to simulate the future climate conditions. And research continues in order to enhance and upgrade the present versions of the various models.

Table 5.7 shows the models that were considered in this chapter. It includes two types of climatic models with quite different spatial resolutions, the GCMs and the RCMs. All models have been reviewed by the Intergovernmental Panel on Climate Change (IPCC, 2001), with the exception of the PROMES model, and a thorough description of their capacities and limitations can be found at the IPCC Data Distribution Centre site.

Global models simulate the climate at the global scale using a computational grid of about 3° by 4°, which at Portugal's latitude corresponds roughly to 300 km by 400 km. Such grid enables the observation of regional trends but it is too coarse to address local climate patterns, such as the ones induced by thermal contrasts between coastal and inland regions or by its orography. These local phenomena are particularly important in Portugal, namely around the NW-SE oriented mountain range that include the Gerês and Estrela mountains.

Depending on the model, the Portuguese territory can be covered by one to three grid cells, with the Hadley Centre models (HadCM2 and HadCM3) showing the most appropriate grid to the location and shape of Portugal (Figure 5.11). Moreover, the three

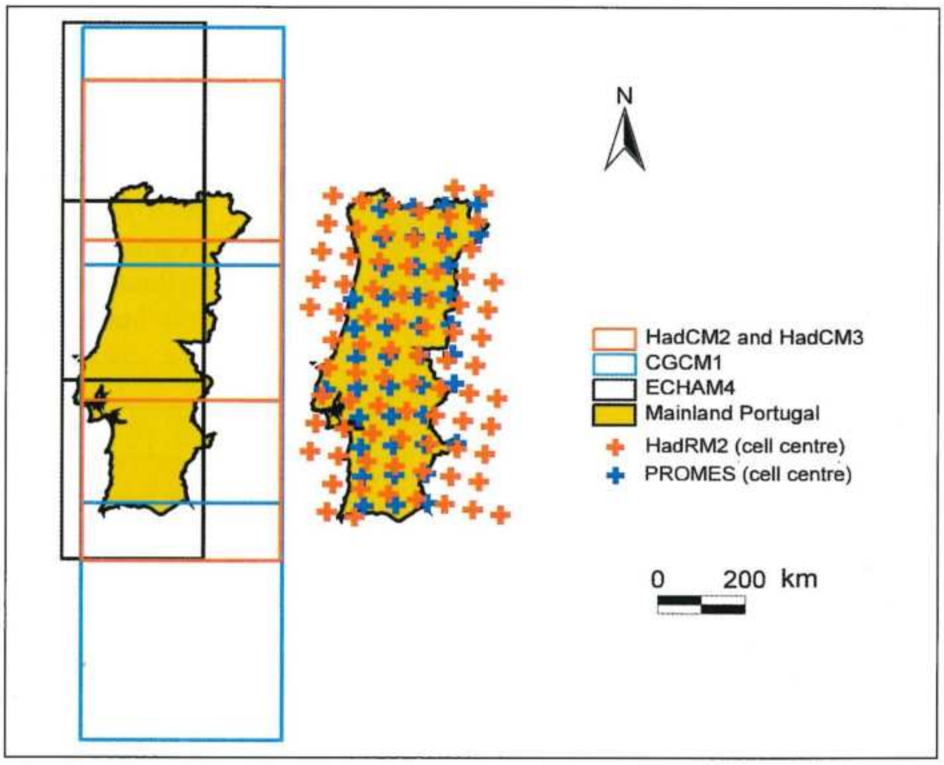

Figure 5.11 – Global and regional models grids over Portugal

HadCM cells are assumed to be land cells, whereas CGCM1 and ECHAM4 assume that some cells are ocean cells.

The assumption that a cell is an ocean cell admits that the water volume available for evaporation is unrestricted, which results in computed evapotranspiration values less accurate than desired. Furthermore, the daily thermal amplitudes are smaller over the oceans when compared to the ones observed over land, which again affects the evapotranspiration rate. As a result the predictions for these ocean cells may be questionable.

The regional models attempt to simulate climate more accurately by focusing on a particular region of the globe, for example, Europe. Driven by some global model simulations output, these regional models use a more detailed computational grid, about 0.5° by 0.5° cells (approximately 40 km by 50 km at Portugal's latitude; Figure 5.11), which allows for a more accurate geomorphologic representation of the territory. However, such enhanced resolution has not yet been translated in a consistent improvement of the outputs.

For each climate model, two sets of output were studied, corresponding to two different simulations: (i) the control run and (ii) the perturbed run. The control run assumes a stable $CO_2$ concentration throughout time, while the perturbed run assumes a $CO_2$ annual increase rate of 1%. At this rate, $CO_2$ levels double every seventy years. Such increase is believed to have started at the onset of the industrial revolution somewhere in late 19th century, when fossil fuel burning reached significant levels. This means that today's climate is already undergoing important changes that may be reflected in present temperature observations.

The control runs of all models assume an historical record of $CO_2$ concentration until 1990, and from then on a steady value is assumed. All other existing greenhouse gases concentrations, like methane or nitrous oxide, are proportionally accounted in this $CO_2$ concentration. Table 5.8 compares the $CO_2$ concentration level assumed by the control run of the various models with some estimates of the historical pre-industrial and 1990 levels.

**Table 5.8 – $CO_2$ concentration levels assumed in the control run of the various models (IPCC-TGCIA, 1999)**

| | $CO_2$ concentration (ppmv) |
|---|---|
| ECHAM4 | 354 |
| CGCM1 | 295 |
| HadCM2, HadCM3 and HadRM2 | 323 |
| PROMES | 473 |
| Pre-industrial (circa 1860) | 280 |
| Year of 1990 | 365 |

For each GCM, the IPCC Distribution Data Centre makes available the precipitation and the temperature monthly data for the control run and for a set of perturbed scenarios. The length of each run is approximately 200 years. The available daily data for the GCMs cover two periods of 30 years (Figure 5.12).

The data available for the RCMs are limited due to the size of the data sets. Monthly values from the control run for the 2010-2035 period are available together with daily values from the 2005-2035 period. A perturbed run covers the period 2080-2100 for daily and monthly values (Figure 5.12).

Given the natural variability of climatic variables, short simulation periods such as the ones available from HadRM2 are insufficient to characterize a climatic scenario. The statistics of these simulated twenty-year periods may be biased due to the occurrence of particularly wet and dry years, which may have a significant weight in the case of short records. The capability to evaluate the regional models performance is therefore limited.

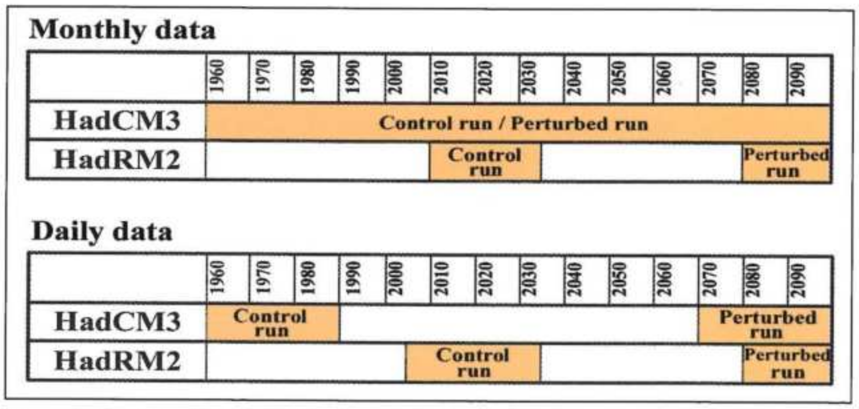

Figure 5.12 – Monthly and daily data considered

### 5.3.3.2 Performance of the Climate Models

To assess the capability of each model to reproduce climate in Portugal, the precipitation and temperature results from the control run were compared with the 1961-90 historical records, for three cells coinciding with the Hadley Centre modelling grid and corresponding to northern, central and southern Portugal (Figure 5.11). The northern cell also covers Spanish Galicia.

Figure 5.13 and Figure 5.14 aim to evaluate the climatic models performance by comparing the control run annual and monthly mean temperature scenario results with the historical average values for annual and monthly values, respectively. Most of the annual simulated values fall within a 2°C interval from the historical average values. The Hadley Centre models, in particular, perform very well in the central and southern regions of Portugal. The temperature seasonal distribution is also well characterized, although the difference between simulated and observed values exceed in some cases 2°C. Overall HadCM3 and HadCM2 show the best results, both annually and monthly, in most cases drifting away only 10% from the historical observations.

Figure 5.15 and Figure 5.16 compare the control run precipitation scenario results from each model with the historical observed records. Precipitation predictions are not as accurate as the temperature predictions and results from different models show a significant dispersion. Precipitation simulation is one of the greatest challenges for climate models developers, since rainfall regimes depend on several local phenomena that occur at a much smaller scale than the one used by global models. Looking at the annual precipitation, the improvement of HadCM3 results as compared to the HadCM2 results is clear. HadCM3 shows consistent results with the annual historical observations with a deviation below 10%. Other global models underestimate precipitation values in more than 20% for the northern, central and southern regions, while the two regional models overestimate it.

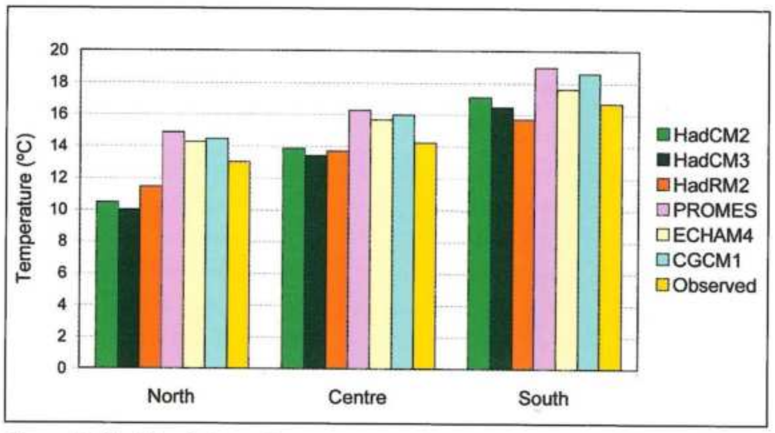

Figure 5.13 – Simulation of average annual temperature according to the various models (1960-1994 period)

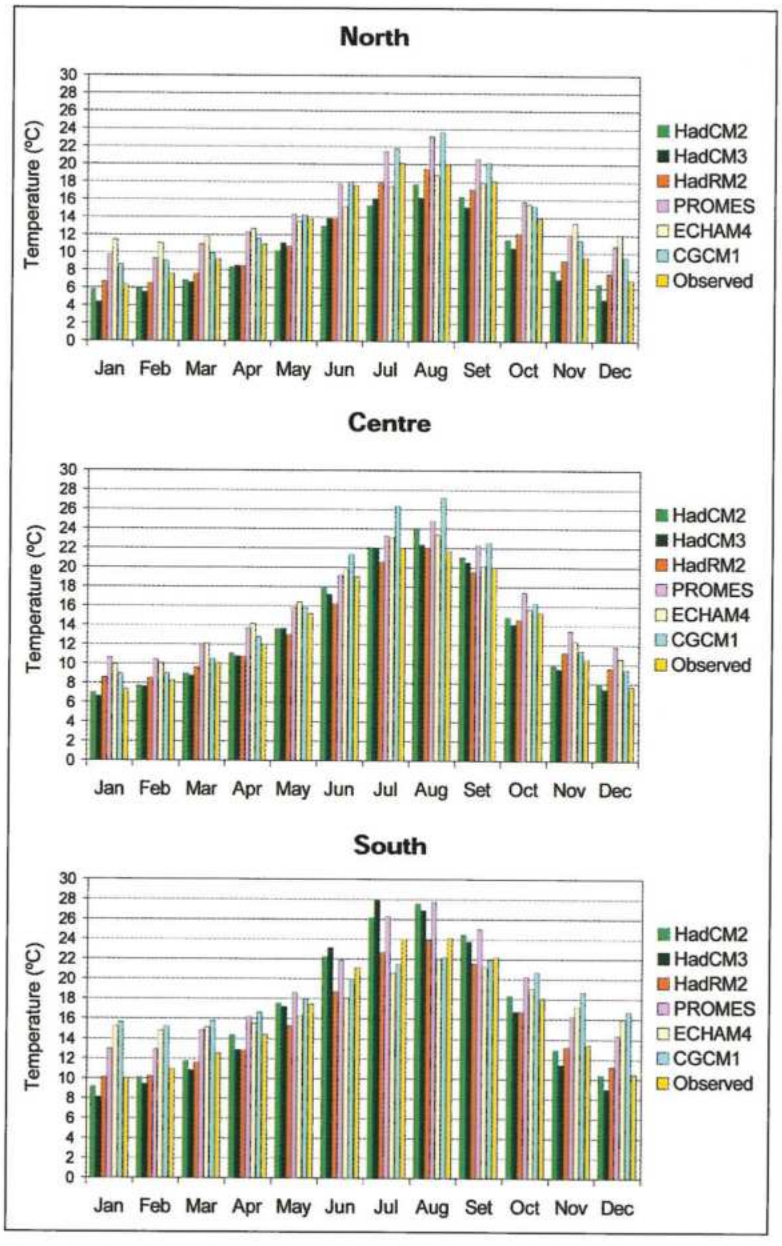

Figure 5.14 – Simulation of average monthly temperature according to the various models (1960-1994 period)

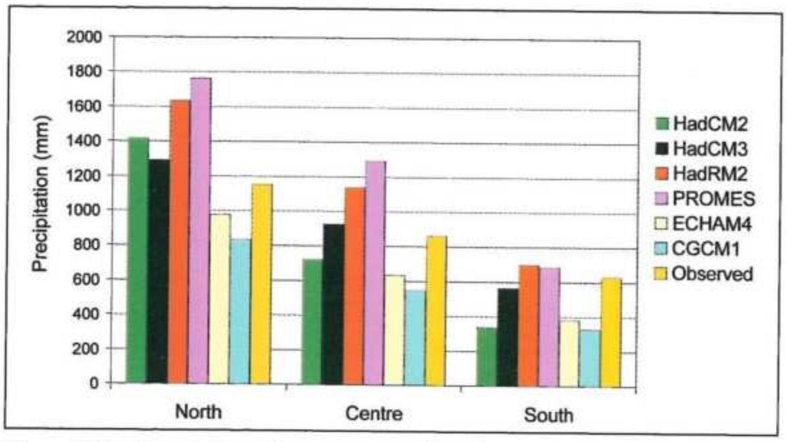

Figure 5.15 – Simulation of average annual precipitation according to the various models (1960-1994 period)

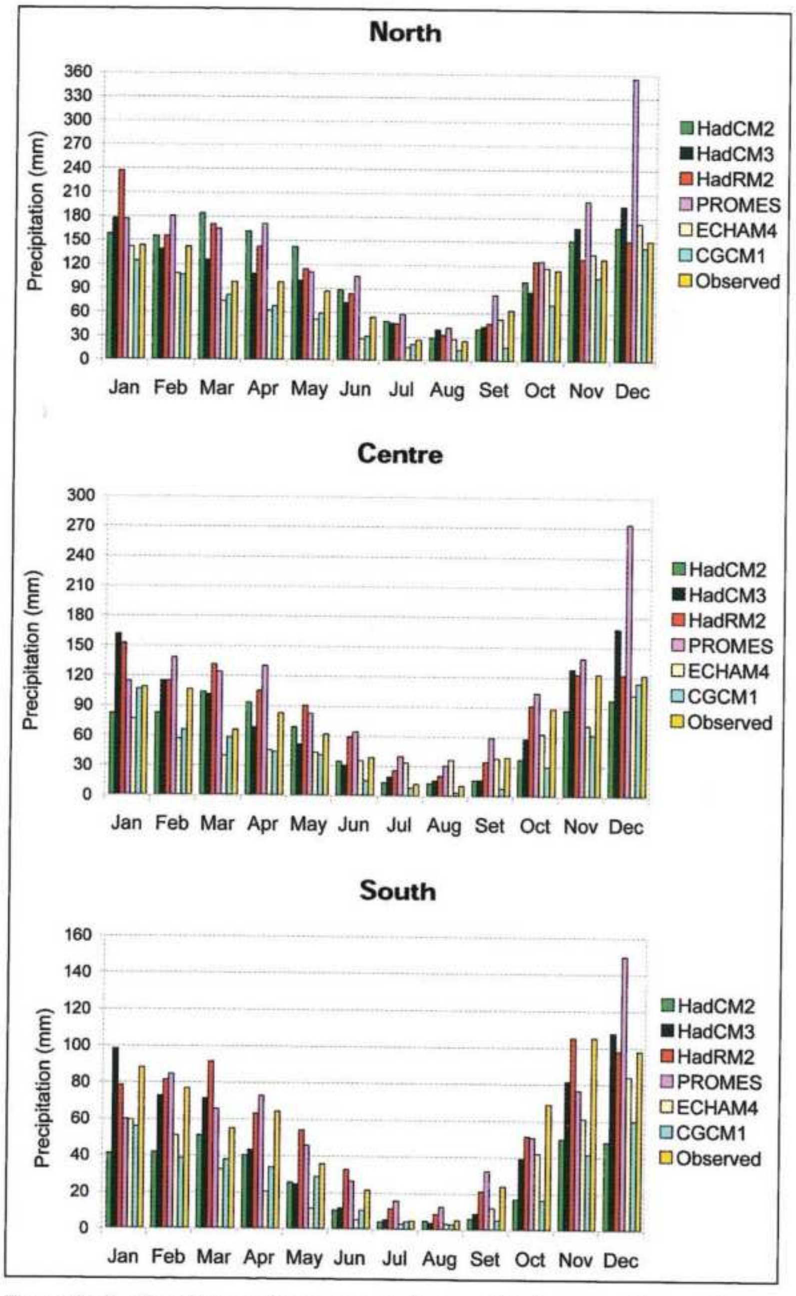

Figure 5.16 – Simulation of average monthly precipitation according to the various models (1960-1994 period)

It must be noted that the assessment presented in Figure 5.13 to Figure 5.16 is biased towards the HadCM models, as the observed historical average values were computed over the HadCM cells. A more accurate assessment is shown in Table 5.9, where the column 'observed' corresponds to the annual average estimated within each respective model cell and not the HadCM cell.

Table 5.9 again shows that HadCM3 performs better than other global models in what concerns precipitation. Regarding annual temperature values, CGCM1 is slightly better than previously concluded, as its estimates fall within 1°C of the historical values instead of 2°C. This precipitation scenario is however outperformed by the Hadley Centre predictions. The blank spaces correspond to the cells that are considered as ocean cells and not as land cells by the respective model.

Figure 5.17 and Figure 5.18 present the spatial distribution of the HadRM2 results. A similar analysis was not performed for the PROMES results, as this model was not adopted due to its poor performance (Figure 5.16).

Figure 5.17 shows the computed precipitation surface and a surface computed as the ratio between the model prediction and the historical annual average precipitation. The HadRM2 regional model results show a rather accurate annual precipitation surface including the effects of some local orography like the Alentejo plains (between Lisbon and Algarve latitudes) or the mountains of Gerês (northern border), Estrela (centre region) and Espinhaço de Cão (Algarve). The second surface presented on Figure 5.17 clearly shows that the regional model produces higher values than the historical values, particularly in the Douro (north) and Mira (southwest) river basins. The model fails to simulate the climatic barrier produced by the NW-SE mountainous range, responsible for the drier conditions of the eastern part of the Douro river basin.

Figure 5.18 shows the computed temperature surface and the differences between the observed and the computed surface. The

**Table 5.9 – Global climate models performance assessment**

| | North cell | | Centre cell | | South cell | |
|---|---|---|---|---|---|---|
| **Temperature (°C)** | **Modelled** | **Observed** | **Modelled** | **Observed** | **Modelled** | **Observed** |
| HadCM2 | 10.4 | 13.0 | 13.8 | 14.2 | 17.1 | 16.7 |
| HadCM3 | 10.0 | 13.0 | 13.4 | 14.2 | 16.5 | 16.7 |
| ECHAM4 | | 15.7 | 14.1 | | | |
| CGCM1 | 14.4 | 13.4 | 16.0 | 15.4 | | |
| **Precipitation (mm)** | | | | | | |
| HadCM2 | 1416 | 1152 | 722 | 864 | 335 | 636 |
| HadCM3 | 1293 | 1152 | 927 | 864 | 563 | 636 |
| ECHAM4 | | 635 | 1200 | | | |
| CGCM1 | 832 | 1352 | 549 | 833 | | |

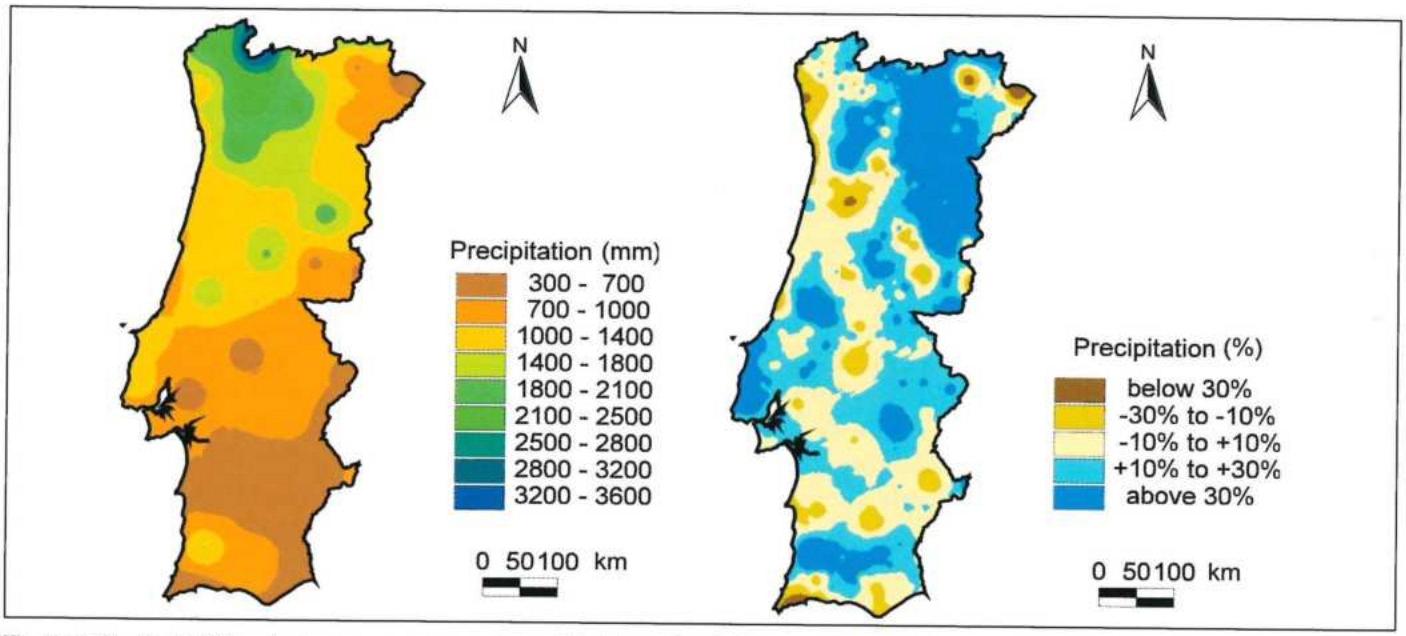

Figure 5.17 – HadRM2 control run average annual precipitation and ratio between the control run and the historical observations (1941/42-1990/91 period)

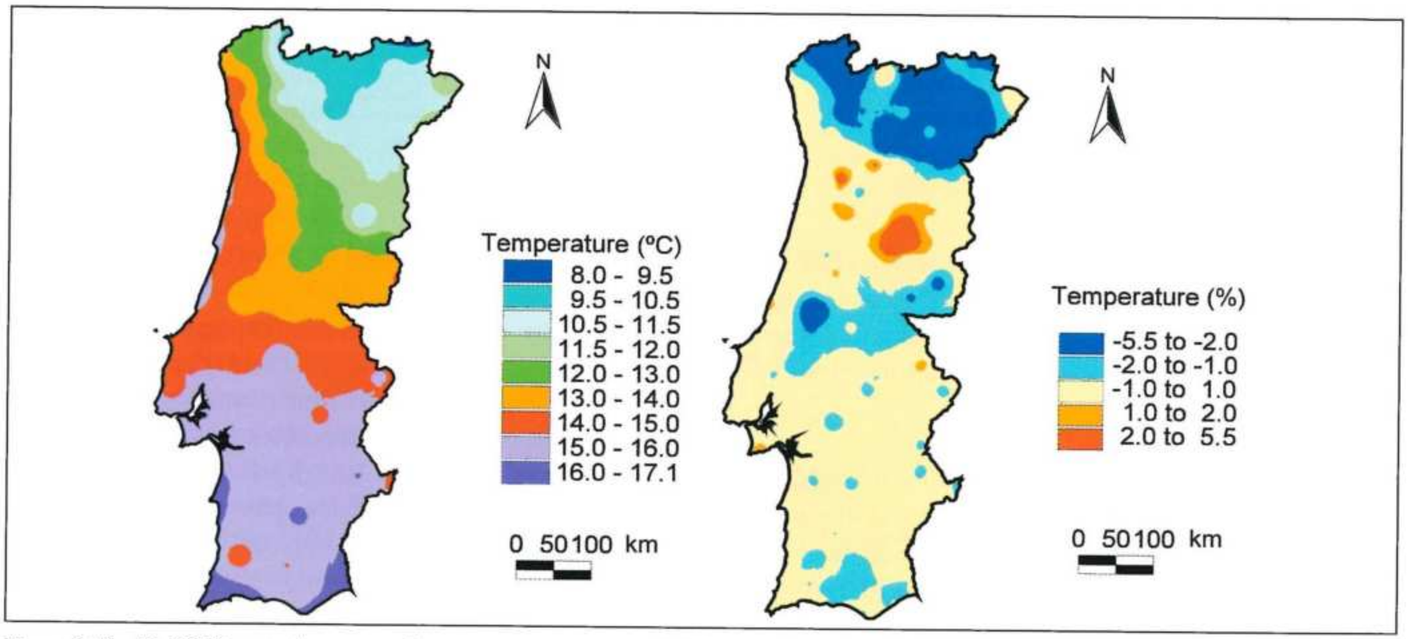

Figure 5.18 – HadRM2 control run annual average temperature and differences from historical observations (1961-1990 period)

model results are quite accurate for most of the country, with the difference falling within the ±1°C range. The Douro basin is again poorly simulated with the results showing a cooler scenario than the reality. Around the Serra da Estrela peak with an altitude of 1,990 m, the model assumes warmer values up to 5.0°C.

Both global and regional models show a good precipitation simulation in terms of precipitation probability, particularly in southern Portugal (Figure 5.19).

### 5.3.3.3 Implications for Impact Analysis

In conclusion, the results have shown that the HadCM3 and HadRM2 models from the Hadley Centre provide the most accurate results. They were therefore, selected to serve as the basis of the future climate scenarios adopted in this chapter.

These future climate scenarios were solely based on temperature and precipitation changes, given by the models. It is assumed that all other variables remain unchanged. Monthly time series were used in the hydrological model for the simulation of runoff conditions and daily time series were used in assessing extreme changes, namely extreme rainfall events and variations in the precipitation intensity.

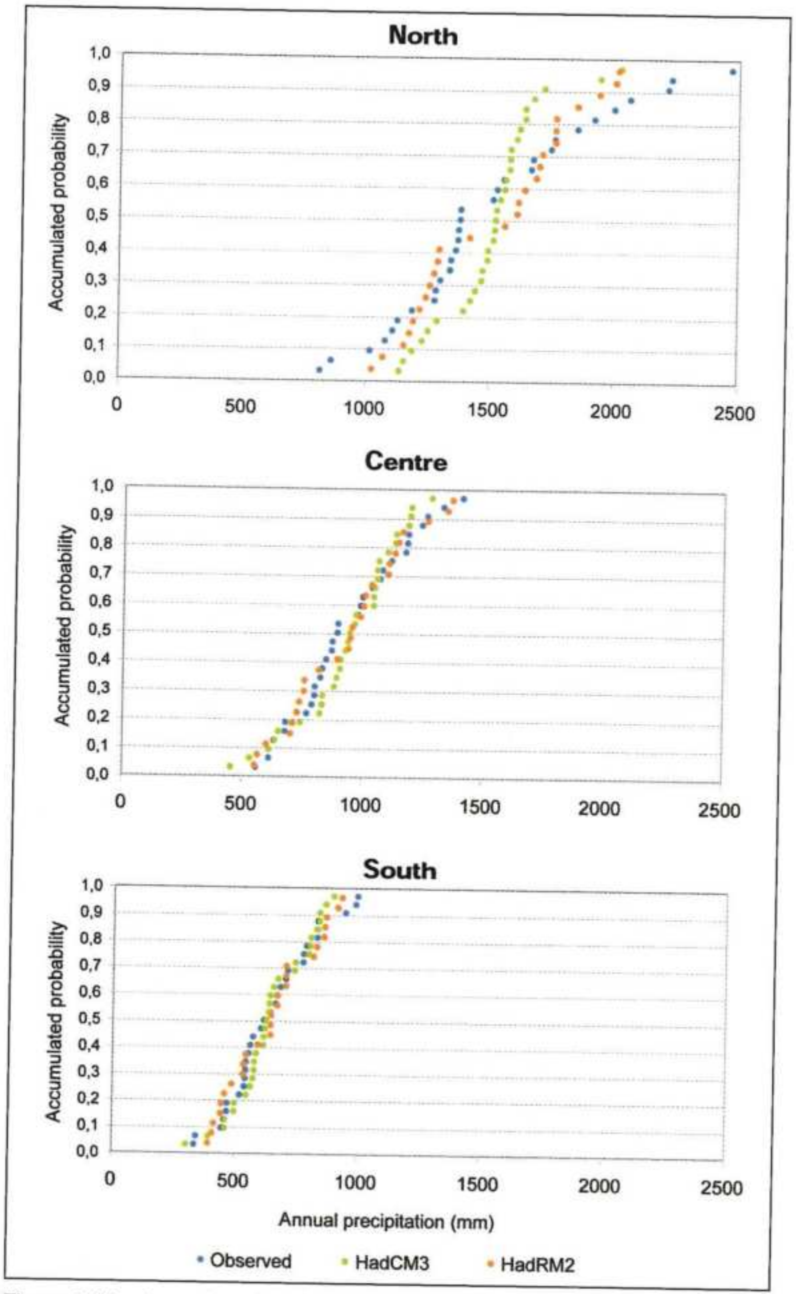

Figure 5.19 – Annual probability curve

## 5.4 IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

### 5.4.1 INTRODUCTION

The impacts of climate change on water resources have been studied by a number of international groups, who have put forward the global and regional scale scenarios briefly discussed in Section 5.1 (IPCC, 2001; Parry, 2000).

Given the working scale of these studies, its results do not have the needed detail to evaluate the impacts of climate change on water resources at a national level or river basin level. This section attempts to overcome such handicap by presenting predictions of runoff change for various regions of Portugal.

### 5.4.2 FUTURE CLIMATE SCENARIOS

Despite the sound simulation capability of current climatic models, there is still difficulty in modelling all climate phenomena and one cannot disregard the fact that some climatic variables are not accurately reproduced. In Section 5.3, the comparison between the observed historical records and some model results has shown that there is still some uncertainty that cannot be disregarded. In this context, it is recommended to use more than one model to assess the possible range of change for each climate variable.

**Table 5.10 - Annual average precipitation and temperature changes from 1960-1994 predicted by climate models**

| | Temperature (°C) | | Precipitation (%) | |
|---|---|---|---|---|
| | 2050 | 2100 | 2050 | 2100 |
| **North** | | | | |
| HadCM2 (I to IV) | +2.3 to +2.7 | +3.6 to +4.1 | -8.3 to -0.9 | -8.8 to -1.3 |
| HadCM3 | +2.5 | +3.9 | -5.7 | -9.4 |
| HadCM3+S | +1.8 | +3.7 | +1.3 | -1.5 |
| HadRM2 | +5.8 | -6.6 | | |
| ECHAM4 | +2.5 | +3.7 | -19.7 | -21.7 |
| CGCM1 | +2.6 | +4.7 | -10.2 | -16.6 |
| PROMES | +3.2 | +11.8 | | |
| **Centre** | | | | |
| HadCM2 (I to IV) | +2.5 to +3.2 | +4.1 to +4.7 | -7.5 to +6.6 | -5.1 to +4.4 |
| HadCM3 | +2.9 | +4.3 | -8.4 | -13.7 |
| HadCM3+S | +2.3 | +4.4 | +6.1 | -7.6 |
| HadRM2 | +5.9 | -8.2 | | |
| ECHAM4 | +3.1 | +4.7 | -23.6 | -31.4 |
| CGCM1 | +3.1 | +5.5 | -19.9 | -35.6 |
| PROMES | +3.3 | +7.4 | | |
| **South** | | | | |
| HadCM2 (I to IV) | +2.6 to +3.2 | +4.1 to +4.7 | -14.7 to -11.0 | -7.4 to +3.8 |
| HadCM3 | +2.7 | +4.0 | -16.8 | -25.8 |
| HadCM3+S | +2.3 | +4.3 | +2.5 | -23.4 |
| HadRM2 | +5.9 | -12.2 | | |
| ECHAM4 | +2.7 | +3.9 | -29.1 | -26.9 |
| CGCM1 | +2.5 | +4.6 | -23.2 | -33.9 |
| PROMES | +3.3 | +12.1 | | |

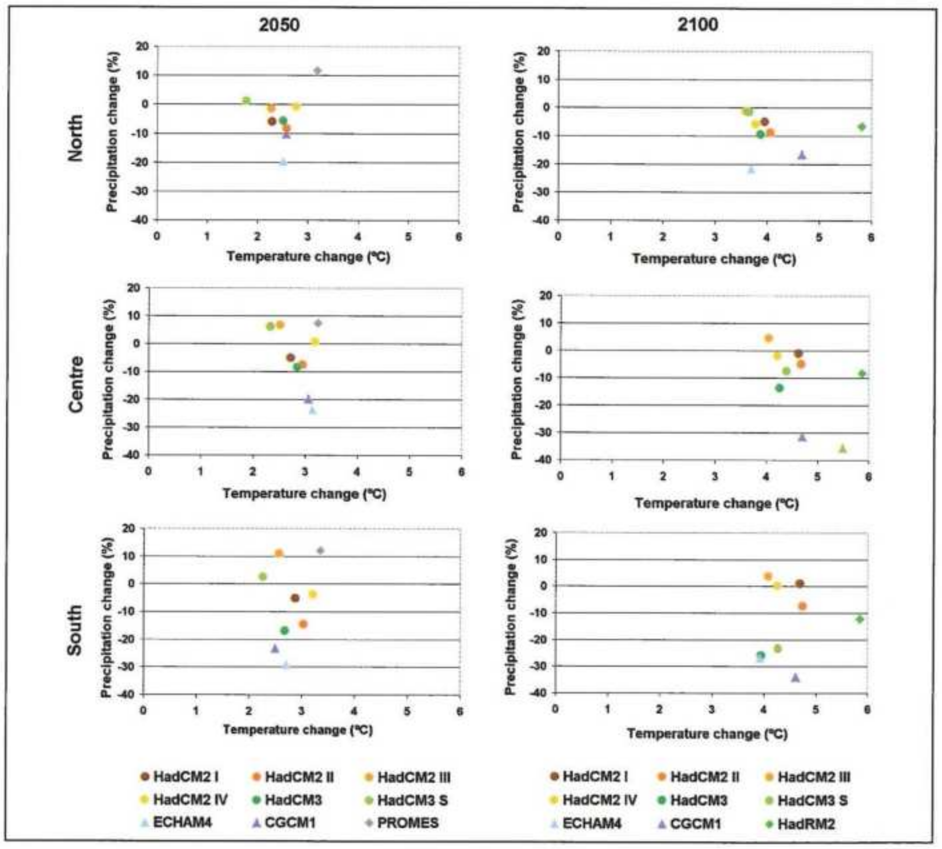

Figure 5.20 – Temperature and precipitation annual change for 2050 and 2100 in northern, central and southern Portugal

Figure 5.20 and Table 5.10 summarise the changes put forward by several climatic models for the northern, central and southern regions of Portugal. Four sets of results are presented from the HadCM2 model corresponding to four different runs of the same model, which assume slightly different initial conditions. Two sets are presented for the HadCM3 model, with the HadCM3+S run corresponding to a HadCM3 run that includes the effect of aerosols. The temperature change values for the 2050 scenario were computed as the difference between the average values for the 2030-2064 period of the perturbed run and the average values for 1960-1994 period of the perturbed run. Similarly, the temperature change values for the 2100 scenario were

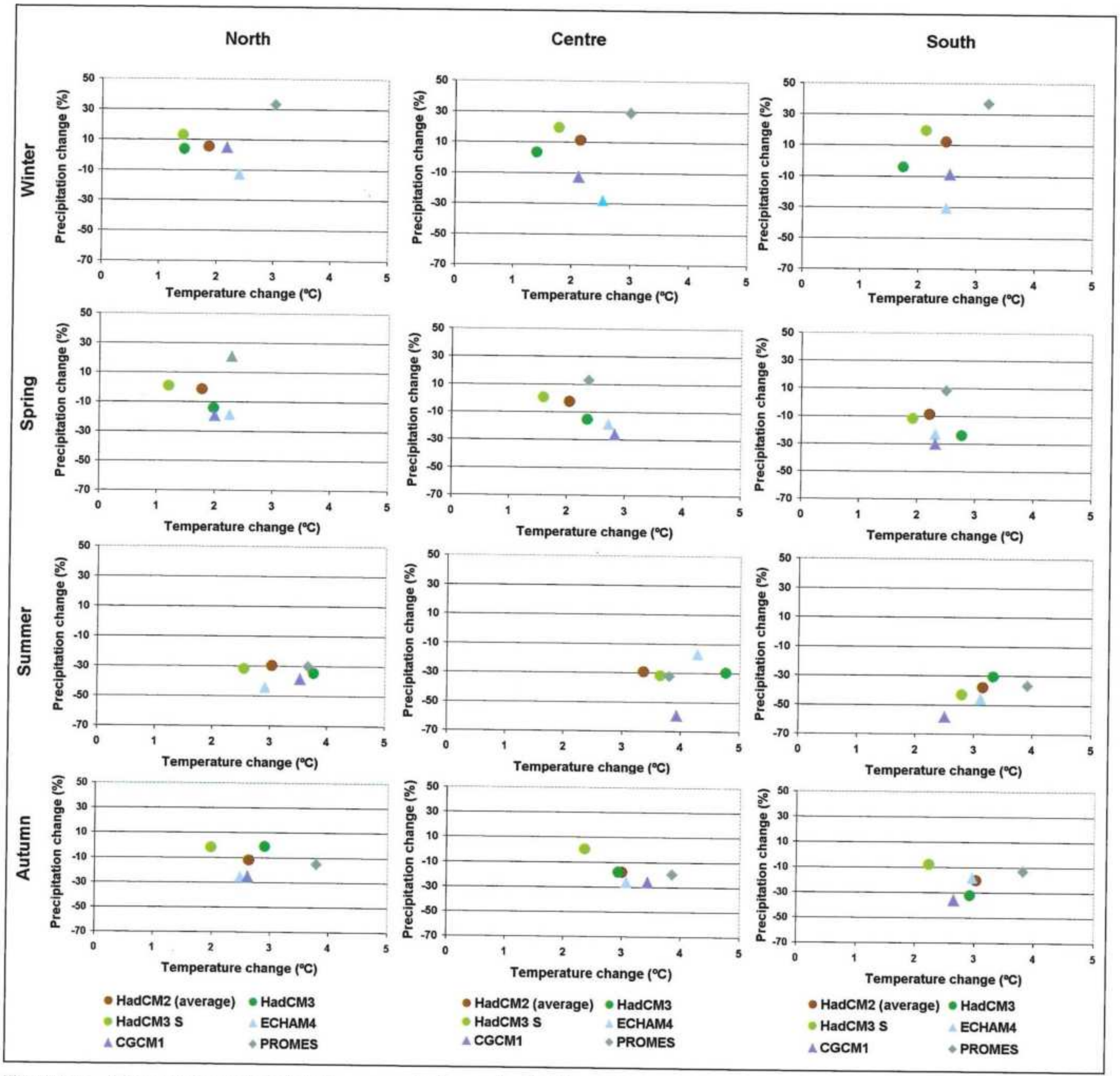

Figure 5.21 – Temperature and precipitation seasonal changes for 2050 in northern, central and southern Portugal

computed as the difference between the average values for the 2065-2099 period of the perturbed run and the average values for 1960-1994 period of the perturbed run. The precipitation change values were computed as the ratio between the average values of the same future periods of the perturbed run and the average values for 1960-1994 period of the perturbed run.

The first conclusion to be drawn is the highly consistent results indicating an increase of the annual mean temperature mostly between 2.0 °C and 3.0°C by 2050, and between 3.5°C and 5.0°C by 2100. The results for the central and southern regions are approximately 0.5°C higher than for the northern region.

The precipitation results show a lower agreement, but the general trend indicates an annual decrease up to 10% in the northern region, which could go as far as 30% in the southern region. Some results indicate a small increase in precipitation by 2050. These positive values almost disappear by 2100.

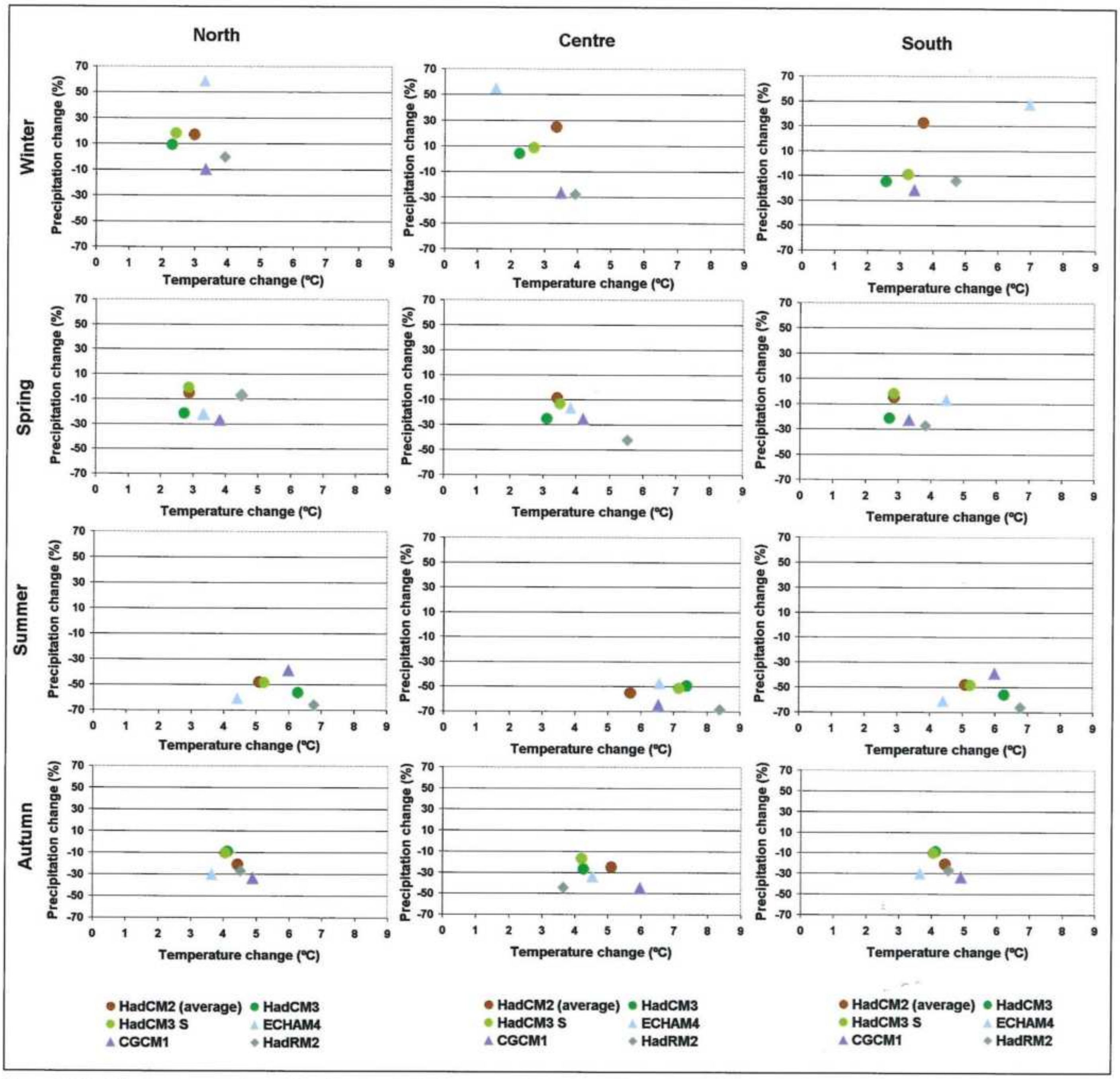

Figure 5.22 – Temperature and precipitation seasonal changes for 2100 in northern, central and southern Portugal

At the seasonally scale, trends are not so explicit, namely in the case of precipitation. Figure 5.21 and Figure 5.22 show the seasonal precipitation and temperature change for 2050 and 2100 on northern, central and southern Portugal. Again, the precipitation change is computed as the ratio between the average computed value for the 2030-2064 period and the average computed value for the 1960-1990 period. The results presented in Figure 5.21 show an increase in winter precipitation up to 10% in the northern region, along with a general decrease for the remaining seasons that could reach 20% to 30% in summer and autumn. In the south, winter precipitation results are not consistent. In the summer a monthly precipitation decrease above 30% is expected. Figure 5.22 presents the results for 2100, where a further aggravation of the 2050 scenario is observed. Winter precipitation may continue to increase up to 30% whereas precipitation continues to decrease during the rest of the year. Particularly in summer, reductions around 50% are observed for all regions.

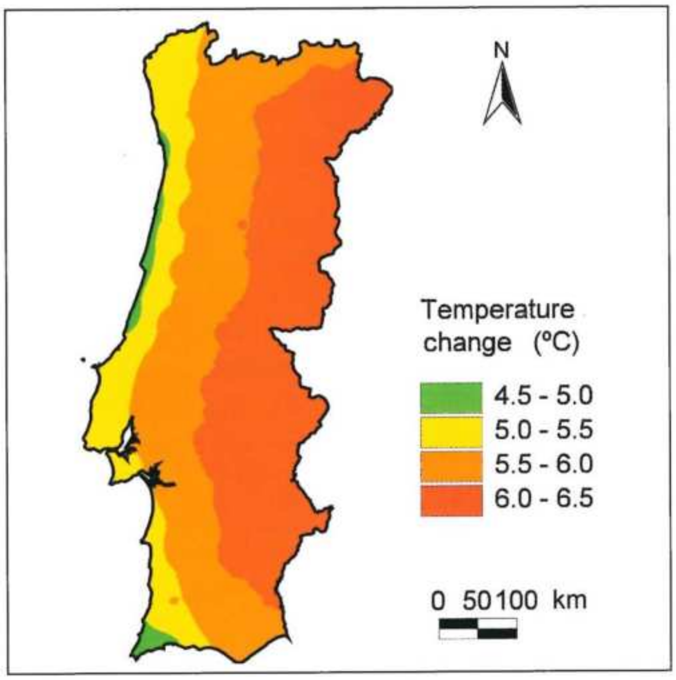

Figure 5.23 – Change in annual average temperature by 2100 predicted by the HadRM2 model

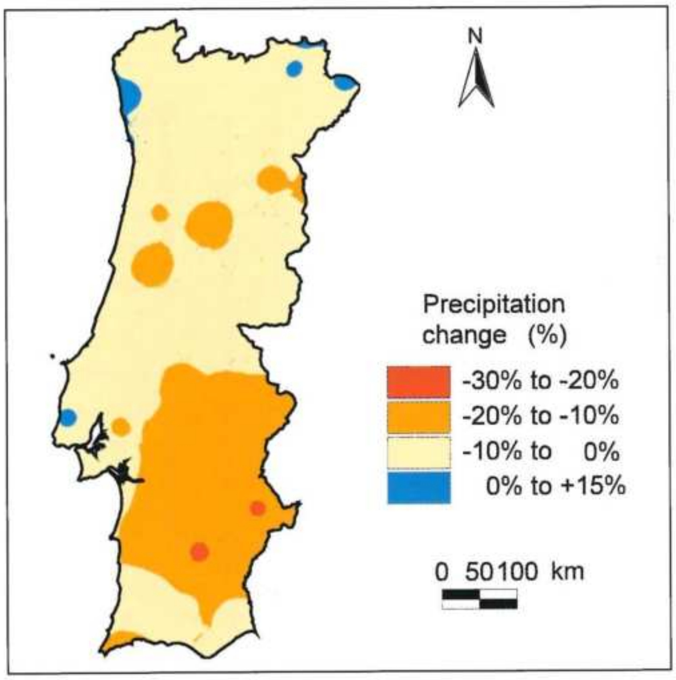

Figure 5.24 – Change in annual average precipitation by 2100 predicted by the HadRM2 model

Temperature is likely to increase all year round, pushed by a strong increase of summer temperatures of 3.0°C to 5.0°C and a more gentle increase of about 2.0°C, by 2050, in the winter. Summer temperatures are expected to increase between 5.0°C and 7.0°C by 2100.

Figure 5.23 shows the spatial distribution of the change in annual average temperature by 2100 predicted by the HadRM2 model. The expected change presents a clear west to east gradient with values fitting in the 5.0°C to 6.5°C range for all regions. This figure demonstrates the attenuating role of the ocean, with the inland area expected to warm at a much faster pace than costal areas.

In what concerns precipitation, the HadRM2 model results do not indicate any major change in annual values for most of the country north of river Tejo (Figure 5.24 and Table 5.11). The results of the models indicate reductions in annual average precipitation between 10% and 30% for the Sado and Guadiana river basins.

More importantly, the HadRM2 model predicts a strong change in the seasonally distribution of precipitation that will definitely have a profound impact on water resources (Figure 5.25). Results indicate an increase of above 45% in winter precipitation by 2100, which may reach 60% in the northern region, and a decrease in the summer precipitation between 65% and 75%.

Figure 5.26 show the evolution in annual average precipitation and temperature during the 21st century, according to the HadCM3 results. Both variables present a clear steady and uniform trend throughout the whole century for the three regions.

The existence of large river basins shared by both Portugal and Spain mean that Spanish climate also affects the Portuguese hydrological regime. Figure 5.27 presents the scenarios put forward by HadCM3 for Spain and Figure 5.28 compares the climate scenarios put forward by the HadRM2 model for both countries. Temperature changes are expected to be similar in both sides of the border with differences below one degree Celsius.

**Table 5.11 – Annual average precipitation and temperature changes from 1960-1994 predicted by HadCM3 and HadRM2**

| Scenario | North | | Centre | | South | |
|---|---|---|---|---|---|---|
| | Prec. | Temp. | Prec. | Temp. | Prec. | Temp. |
| HadCM3 2050 | - 6% | + 2.5°C | - 8% | + 2.9°C | - 17% | + 2.7°C |
| HadCM3 2100 | - 9% | + 3.9°C | - 14% | + 4.3°C | - 26% | + 4.0°C |
| HadRM2 2100 | + 7% | + 5.8°C | - 2% | + 5.9°C | - 11% | + 5.9°C |

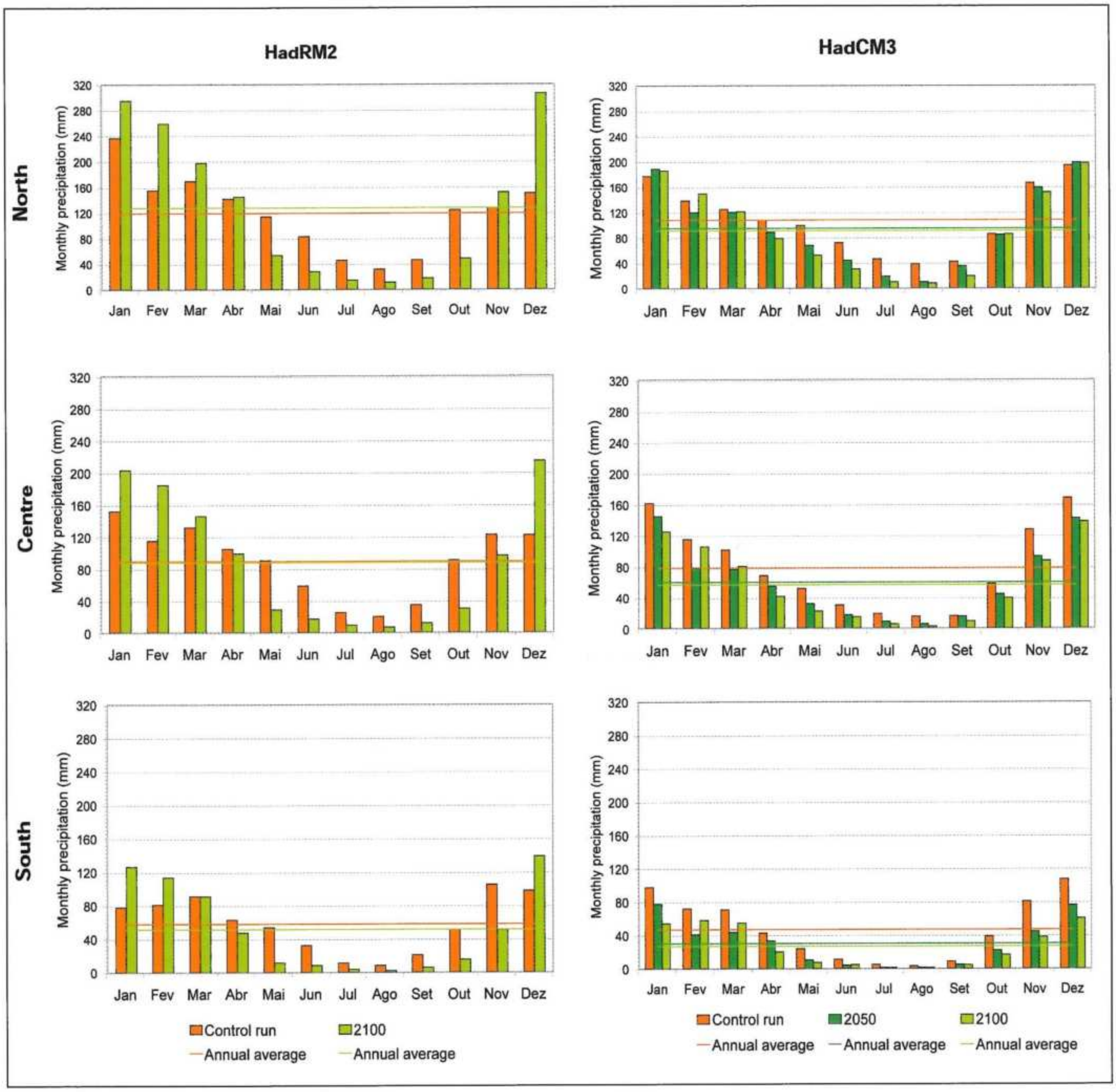

Figure 5.25 – Monthly precipitation scenarios predicted by HadRM2 and HadCM3

The precipitation scenario is also very similar with the precipitation forecasts falling mostly within 5% of each other.

The likely decrease of precipitation will lead to a reduction of the runoff generated in both sides of the border. The results presented in Figure 5.27 and Figure 5.28 indicate that the changes in runoff regime are likely to be affected by similar trends in both sides of the border. This will accentuate even further the expected decrease of water availability in the Portuguese part of the transboundary river basins. Section 5.5 reviews the results of two studies on the impact of climate change on Spanish water resources.

Figure 5.29 to Figure 5.31 present the monthly climatic scenarios predicted by HadCM3 and HadRM2 for 2050 and 2100. The results are presented for five regions that were established based on a compromise between the major Portuguese river basins and the three Hadley Centre modelling cells. Given the significant inter-monthly variability of the monthly differences between present and future scenarios in both the precipitation and temperature model records, it was decided to produce three sets of twelve monthly values, and therefore three scenarios of seasonal variation, for each climatic model output. One set of the monthly values corresponds to the exact model's anomalies while the other two were obtained by smoothing the inter-monthly differences. The use of these three scenarios allows for a sensibility analysis of the model's runoff results.

### 5.4.3 WATER AVAILABILITY

#### 5.4.3.1 Runoff Scenarios

With diminished precipitation and increased potential evapotranspiration, directly linked to a temperature increase, water availability is likely to decrease in annual terms. Nonetheless, the predicted seasonal change in precipitation and temperature

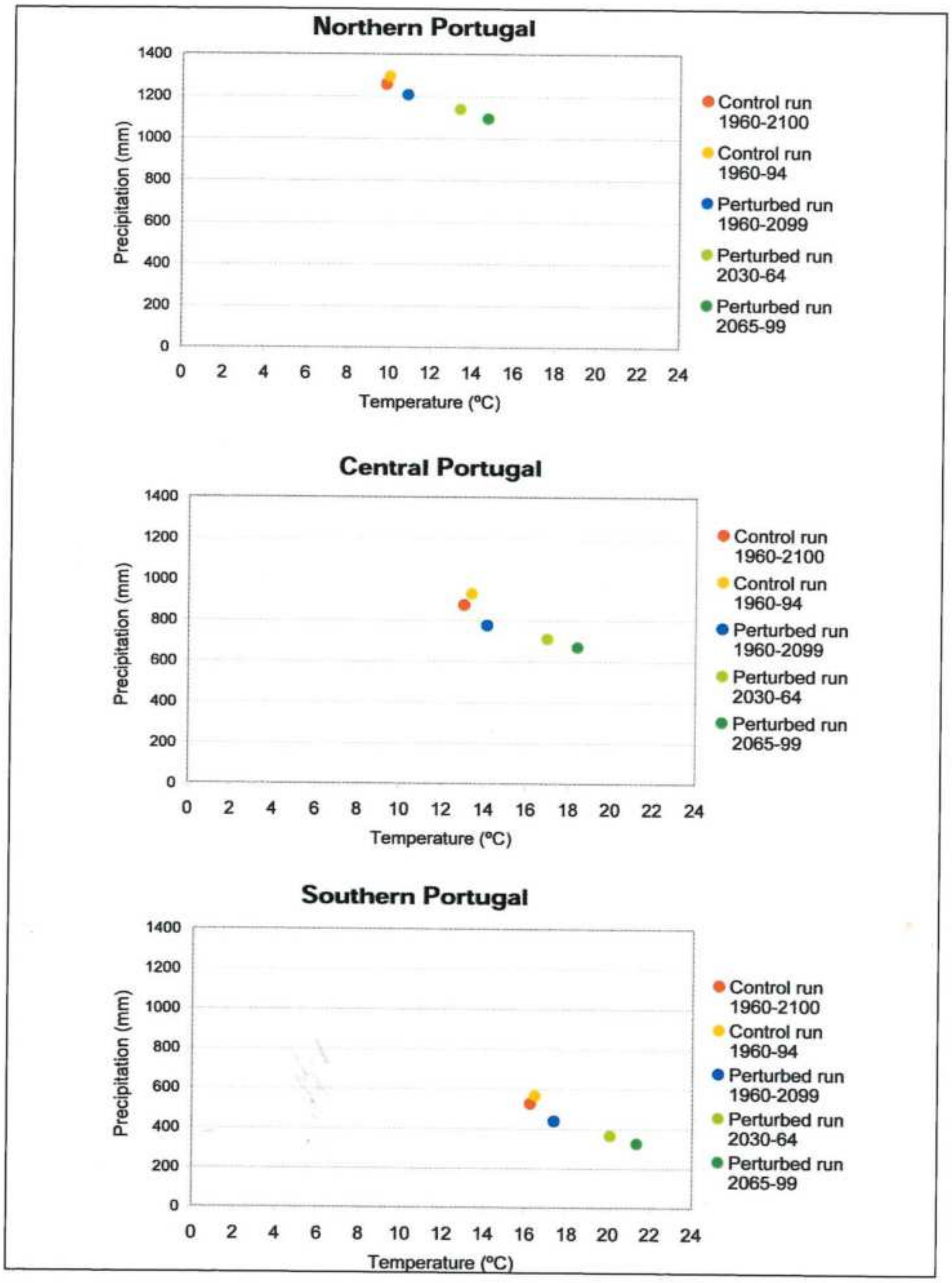

Figure 5.26 – Average annual temperature and precipitation evolution predicted by HadCM3

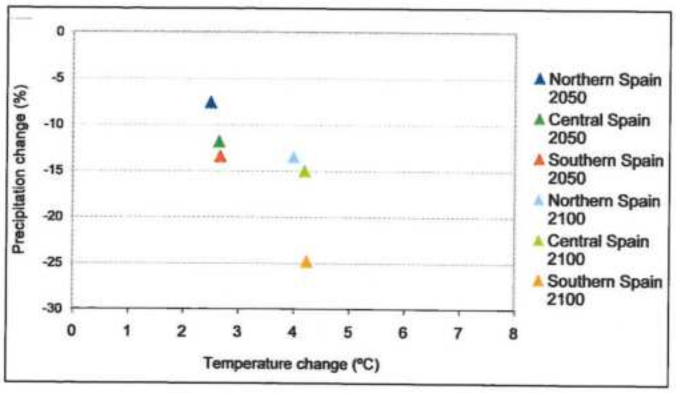

Figure 5.27 – Temperature and precipitation annual changes predicted for Spain by HadCM3

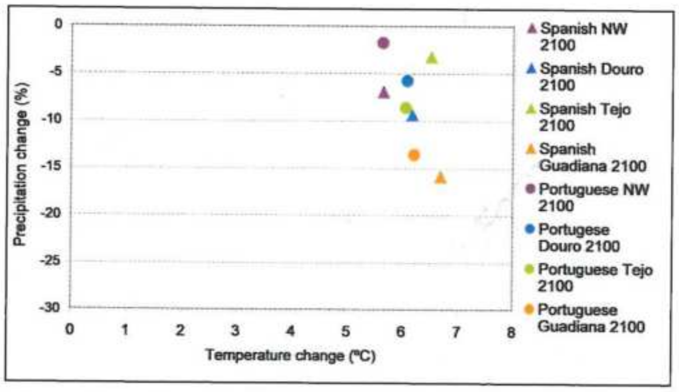

Figure 5.28 – Temperature and precipitation annual changes predicted for Spain by HadRM2

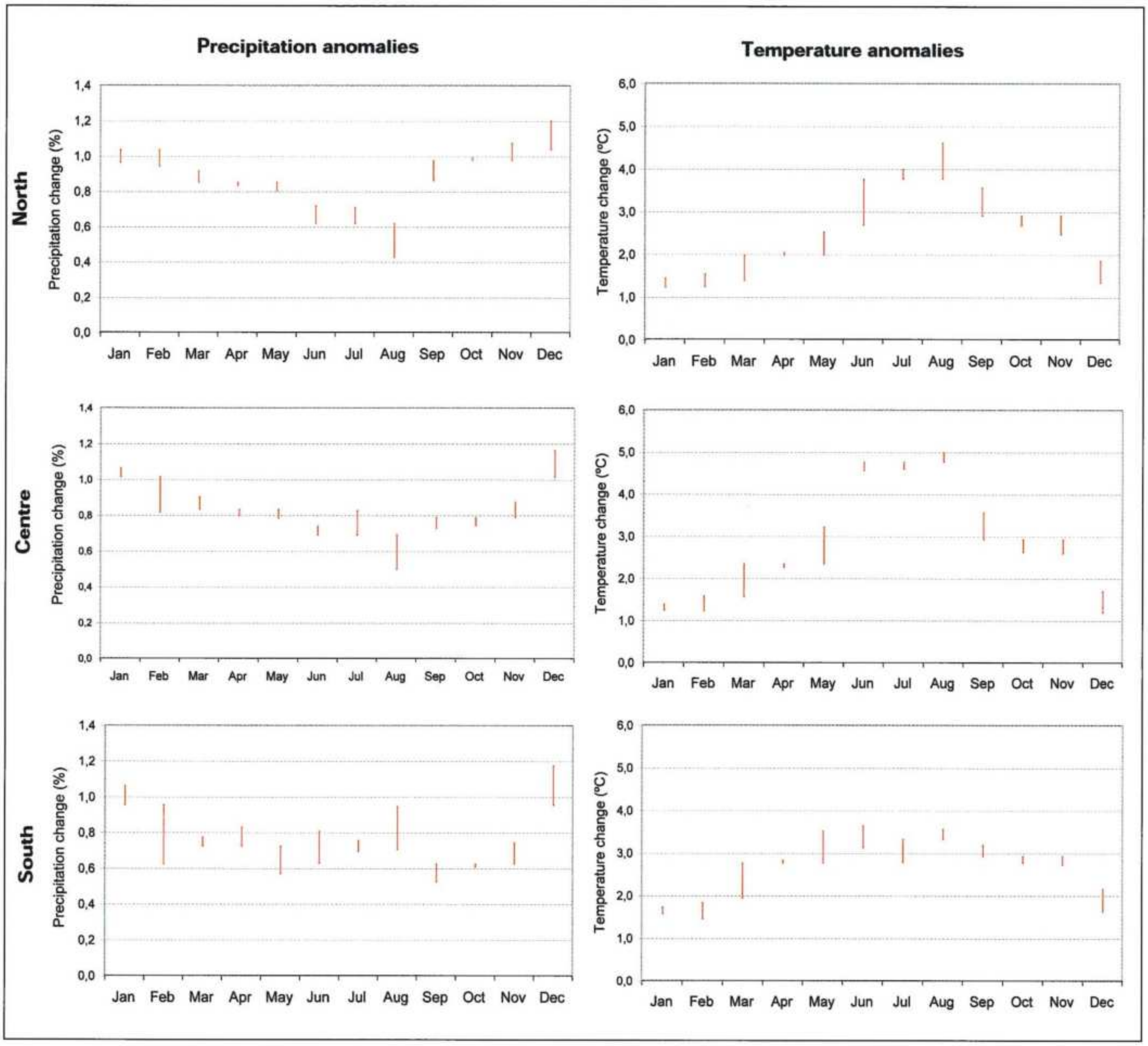

Figure 5.29 – Precipitation and temperature seasonal change for 2050 predicted by HadCM3

may constitute a much more severe constraint to water management.

River runoff was simulated for 62 river basins (Figure 5.9) using an hydrological model. The results obtained from these basins are expected to represent the variety of runoff regimes existing in Portugal (Figure 5.32 and Figure 5.33).

The HadCM3 scenarios for the various river basins were obtained with three sets of anomalies computed from the model's results of the three cells covering Portugal. All the river basins located in the same region were perturbed with the same precipitation / temperature scenario. The HadRM2 scenario was computed with different anomalies, each corresponding to the main Portuguese river basins.

Three major scenarios are presented in this section. HadCM3 results include values for 2050 and 2100, whereas the HadRM2 results only include values for 2100. Despite indicating similar general trends, the results for 2100 from both models do not fully agree with each other. Both models predict a

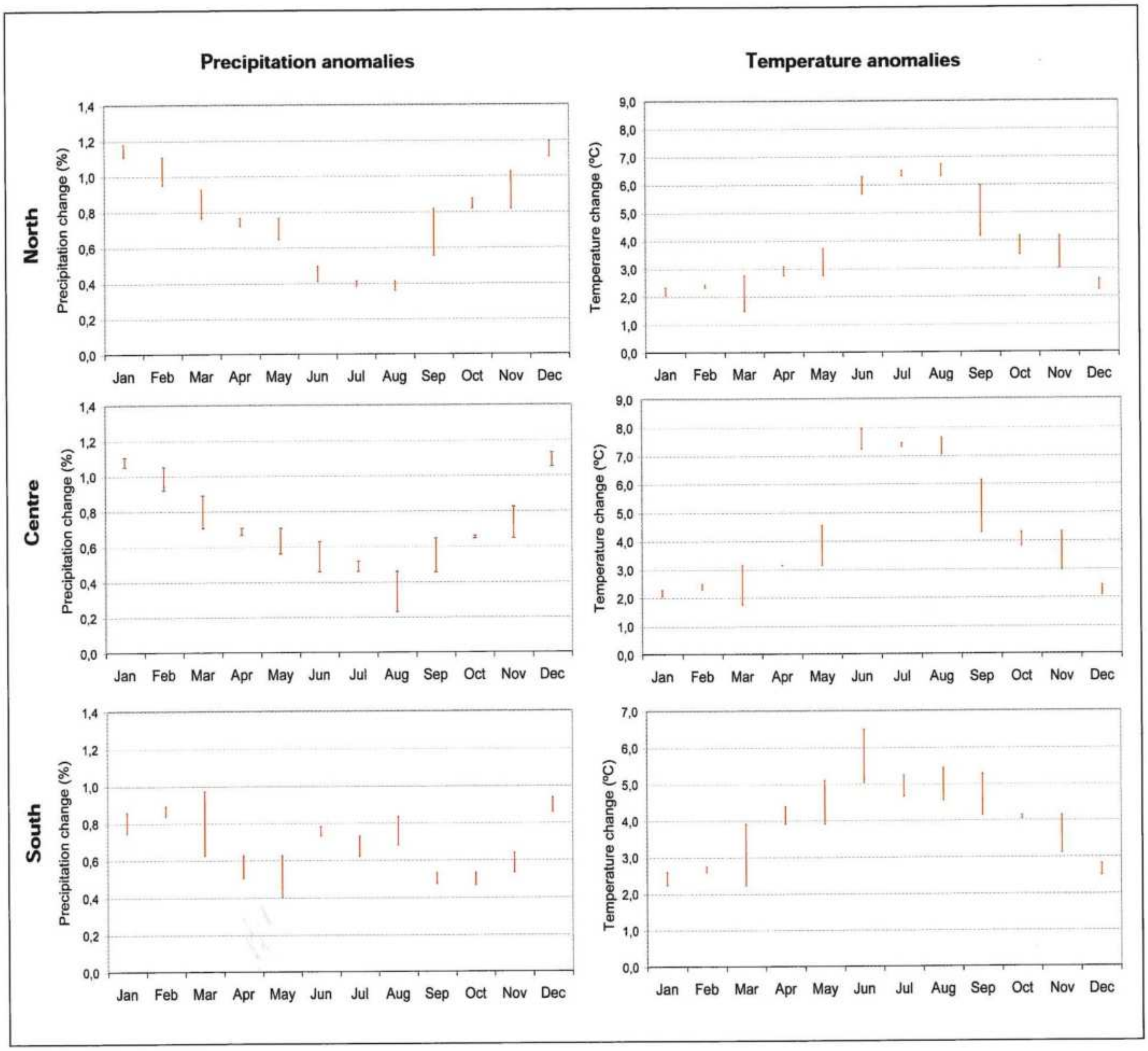

Figure 5.30 – Precipitation and temperature seasonal change for 2100 predicted by HadCM3

decrease in runoff for spring, summer and autumn. For winter, HadCM3 predicts a runoff decrease whereas HadRM2 predicts an increase. Nonetheless, both models predict an increase in the runoff spatial and seasonal asymmetry.

The next two sections discuss in further detail these runoff scenarios by presenting the general trends of annual and seasonal change in runoff. The values referred in the text are broad intervals within which most of the model results are included.

#### 5.4.3.2 Analysis of HadCM3 Scenario Results

*River basins north of river Douro*

According to the HadCM3 results, the annual runoff reduction in the river basins located north of river Douro should be less than 10% by 2050, but such limit may reach 20% by 2100. The HadCM3 results also show an increase of river runoff in winter from 0% to 20% by 2100. In spring, runoff may be reduced from 15% to 20% by 2050, and from 15% to 30% by 2100. Summer could become the most affected

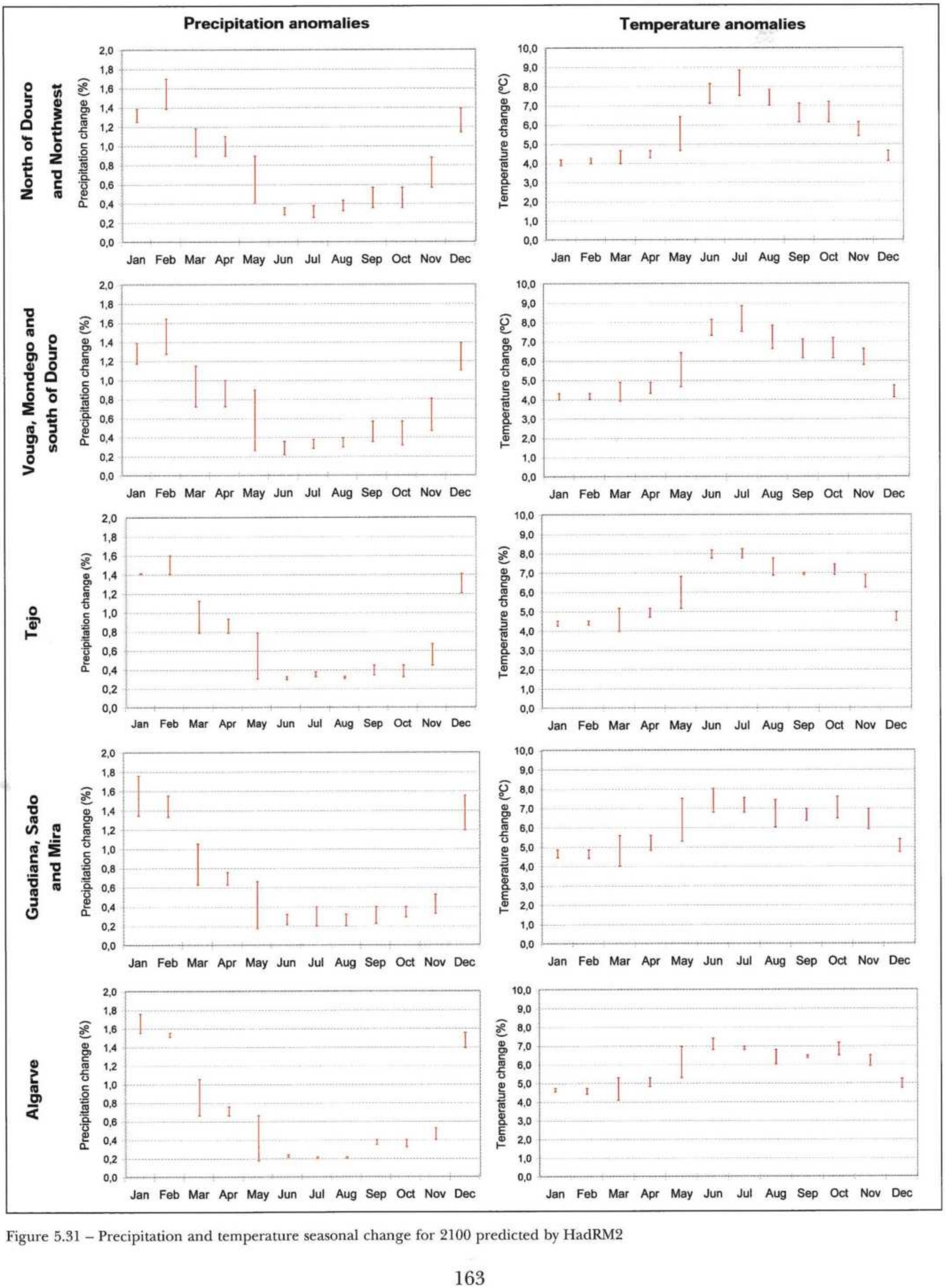

Figure 5.31 – Precipitation and temperature seasonal change for 2100 predicted by HadRM2

season, as the results point to a 20% to 40% reduction by 2050, and a further reduction by 2100. Autumn is also likely to observe reductions in its average runoff, ranging from 0% to 20% by 2050, and from 20% to 50% by 2100.

***River basins south of river Douro, Vouga, Mondego and Tejo***

According to the HadCM3 results, an annual runoff reduction is expected for this region. Values are likely to range from 15% to 20% by 2050, and from 15% to 30% by 2100. The winter runoff can decrease from 0% to 20% by 2100, whereas spring and summer may be progressively reduced from 20% to 80%. The runoff decrease could reach its maximum in autumn with values varying between 30% to 60% by 2050, and 40% to 80% by 2100.

***River basins of Sado, Mira, Guadiana and the Algarve region***

These four river basins stand as the most vulnerable ones to climate change. Results indicate annual runoff reductions from 20% to 50% by 2050, which could become 40% to 75% by 2100. The HadCM3 results also show a winter runoff reduction of 0% to 40% by 2050, and of 20% to 60% by 2100. In spring the estimated reduction ranges from 30% to 60% by 2050 and from 40% to 80% by 2100. These estimates may reach 50% to 90% in autumn after 2050.

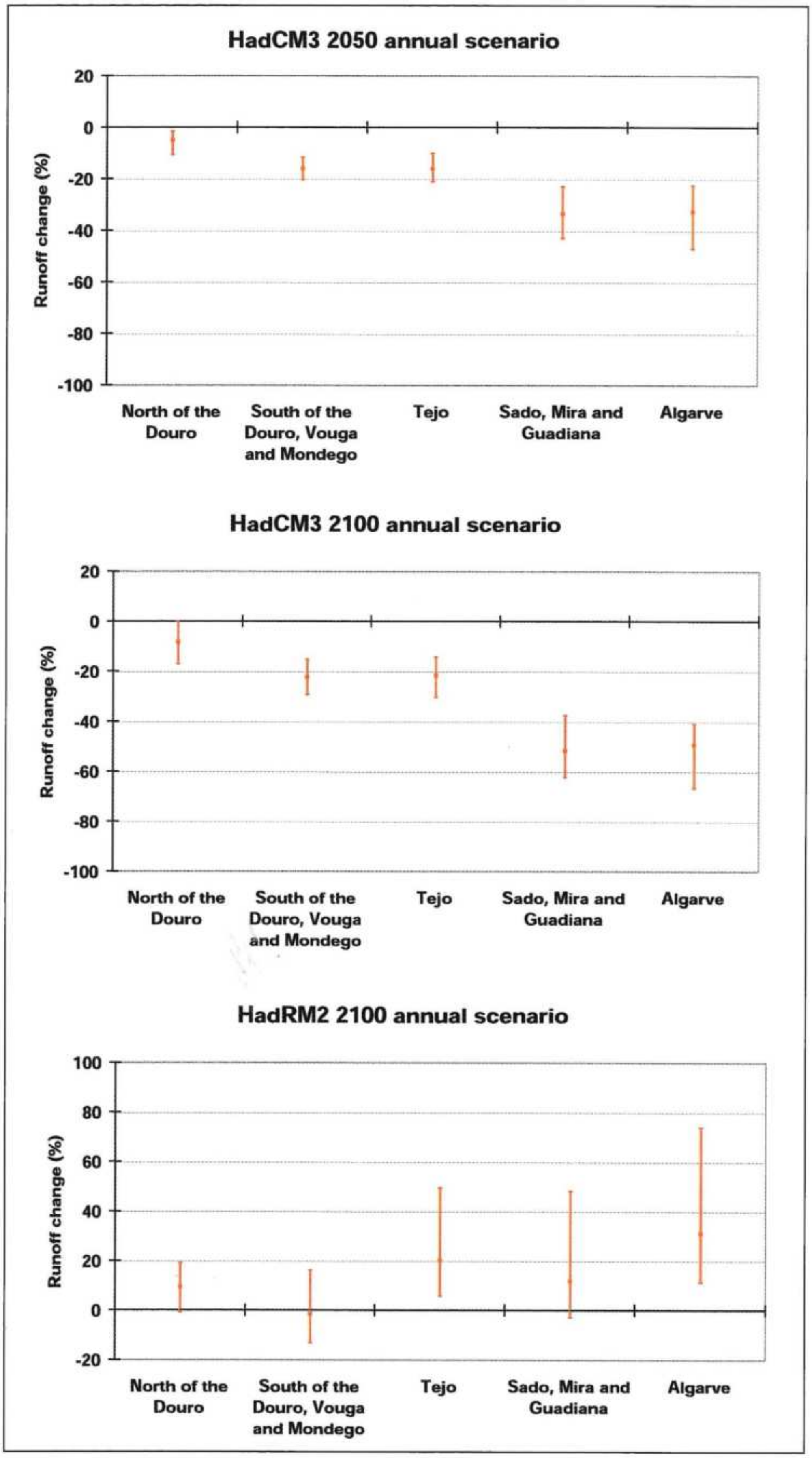

Figure 5.32 – Annual runoff changes predicted by HadCM3 and HadRM2

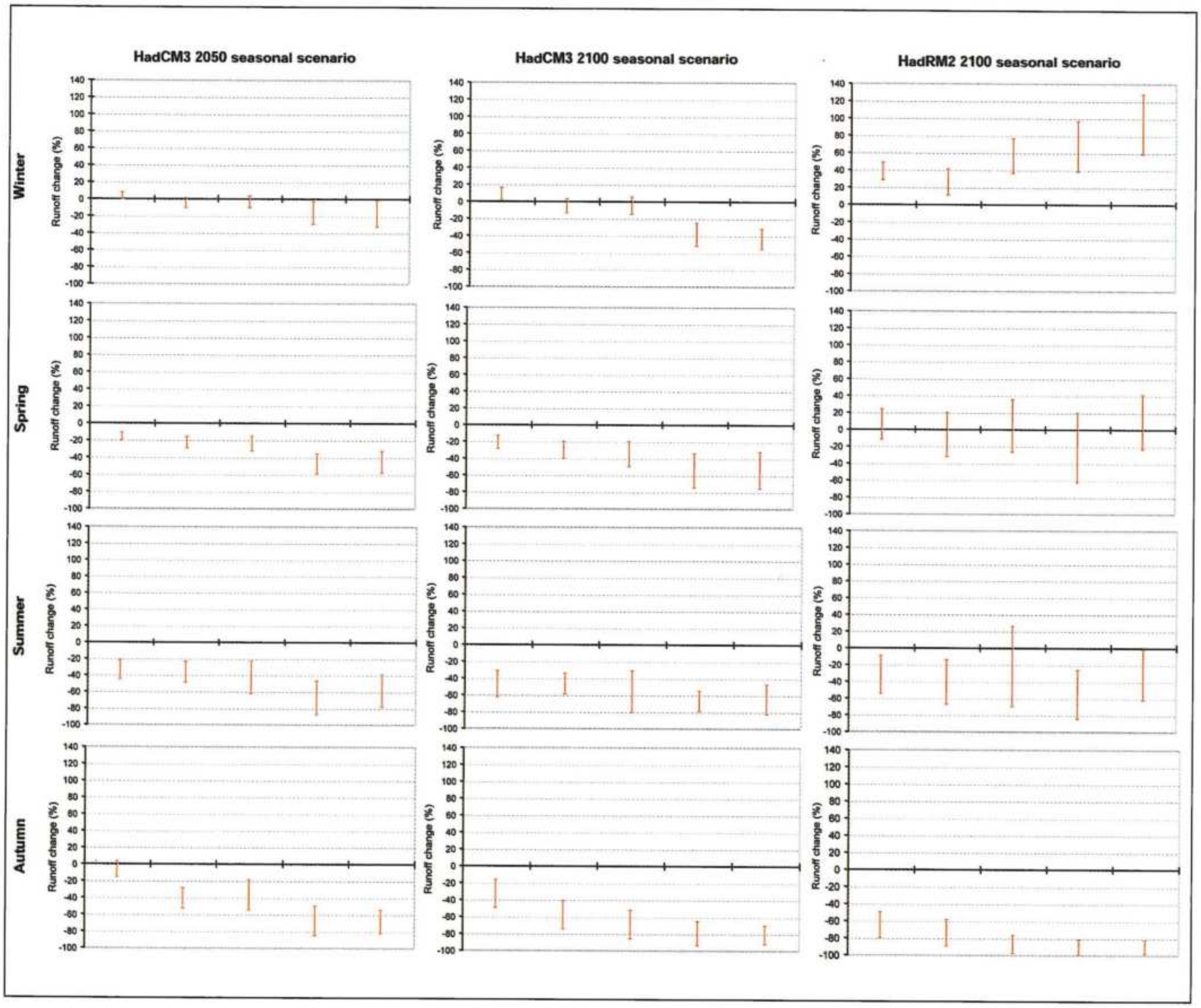

Figure 5.33 – Seasonal runoff changes predicted by HadCM3 and HadRM2

### 5.4.3.3 Analysis of HadRM2 Scenario Results

*River basins north of river Douro*

According to the HadRM2 results, the average annual runoff in the river basins north of river Douro may increase up to 20% by 2100, strongly promoted by a 25% to 50% increase in the winter runoff. In spring, results show a significant variability about the direction of change, while in summer and autumn runoff should be reduced between 10% to 60% and between 50% to 80%, respectively for the two seasons.

*River basins south of river Douro, Vouga, Mondego*

The trend in the annual runoff change predicted by HadRM2 is not clear as the model results point out to a +20% to –10% change, by 2100. Winter runoff is expected to increase from 10% to 40% and there is not a clear indication as for the direction of runoff change in spring. This season is likely to constitute the transition to the drier summer and autumn, when the reduction may range from 10% to 90%.

*River basins of Tejo, Sado, Mira and Guadiana*

The predicted annual runoff changes for these river basins are rather variable, with the estimates falling between a 0% and +50%. The trend towards an annual runoff increase is however clear, according to this model. Winter runoff increase should vary from 40% to 100%, while autumn may observe runoff reductions from 80% to 100%. The periods separating these two seasons serve as transitions and, therefore, the direction and magnitude of runoff change is unclear.

***River basins in Algarve region***

Estimates for the Algarve river basins are not only highly variable from season to season but also within the same season. The HadRM2 results for the Algarve region include the most extreme predictions, namely the most significant winter runoff increase and autumn runoff decrease. These results are therefore prone to different conclusions and should be validated by further studies.

The HadRM2 results for the Algarve indicate a winter runoff increase from 60% to 130% by 2100. In the months of spring and summer estimates vary largely and no explicit trend is observed. Estimates for the autumn months indicate monthly runoff reductions from 80% to 100%. The annual balance of such results is likely a fall within the 10% to 75% interval by 2100.

## 5.5 RESEARCH NEEDS

### 5.5.1 CLIMATE CHANGE IMPACTS ON WATER RESOURCES IN SPAIN

A number of impact studies have already been performed for the Spanish river basins. Ayala-Carcedo (1996) estimated variations in the annual water availability for 2060 based on climate models presented by IPCC. The main results concerning the river basins shared with Portugal indicate a 13% runoff reduction for the Northwest, 22% for the Douro, 17% for the Tejo and 23% for the Guadiana. These results agree with more recent studies such as the Spanish White Book on Water (MIMAM, 1998) and the Spanish Hydrological Plan (PHN, 2000). Ayala-Carcedo (1996) also found a trend for an intensification of extreme events in both floods and droughts. Moreover, a 5% to 10% increase in crop water demand is expected by 2060, when assuming the continuation of current crops.

A more detailed study used different scenarios based on monthly output of global and regional climate models (Fernández-Carrasco, 2000). The results are dependent on a wide variety of climatic scenarios and assessment methodologies, which hinders a clear quantitative conclusion. The approaches that only consider the change in the average annual values of precipitation and temperature lead to an average annual runoff reduction that reaches 65% in the Guadiana river basin for some scenarios. The scenarios that predict an increase of the average annual runoff assume a strong increase of winter precipitation. The main conclusions of this study suggest a change in the average annual runoff ranging from a small increase to a strong decrease. Precipitation events will likely be concentrated in wintertime leading to a strong decrease in water availability during the remaining seasons of the year.

The results mentioned above are very similar with the ones predicted for Portugal referred in Section 5.4. Such findings will only contribute to a worsening of the negative impacts estimated for the Portuguese water resources and underline the importance of bilateral cooperation, namely in the continuing analysis of climate change impacts on water resources.

### 5.5.2 GROUNDWATER RECHARGE

Groundwater provides an important fraction of the fresh water needs. Groundwater resources are normally used on a daily basis for supplying small towns and farms, namely in the most arid regions of the country, and play a crucial role in providing water during drought periods.

There is a limited knowledge on how aquifers levels will react to climate change, although aquifer recharge is expected to largely follow precipitation trends. Uncertainty however exists on how aquifers may react to changes in seasonal and interannual precipitation pattern, as the response depends on its geomorphologic and hydrodynamic characteristics. Aquifers with a large storage capacity can compensate water deficits during the summer months, if additional winter precipitations lead to greater groundwater recharge. Smaller aquifers cannot profit from the additional winter rain and may fail to compensate the summer rain deficit. This means that shallow aquifers are more likely to be affected by changes in the seasonal rainfall pattern.

The expected sea level rise also threats groundwater resources with saline intrusion. The coastal aquifers in the Aveiro and the Algarve region may be the most threatened ones. Higher temperatures and higher evapotranspiration levels may also lead to an accumulation of salt on the soil surface that, with time, could be leached into the groundwater reservoirs.

### 5.5.3 FLOOD RISK

The climatic scenarios put forward by the global and the regional models show a clear trend towards a concentration of precipitation in winter. This evidence is particularly clear for northern Portugal.

The increase of monthly precipitation does not, necessarily, lead to an increase in flood risk. To assess this question, the daily precipitation values from the HadCM3 and HadRM2 models were analysed. Although daily runoff simulations were not performed, precipitation patterns show a high correlation with runoff patterns.

A trend for an aggravation of extreme precipitation events is observed in northern Portugal. According to HadCM3 and HadRM2, northern Portugal may suffer an increase on both the daily maximum precipitation as well as in the number of days with higher than normal precipitation. The trend is not so explicit for the other regions, but according to HadRM2 central and southern Portugal may register an increase of the number of days with precipitation above 50 mm, by 2100 (Figure 5.34).

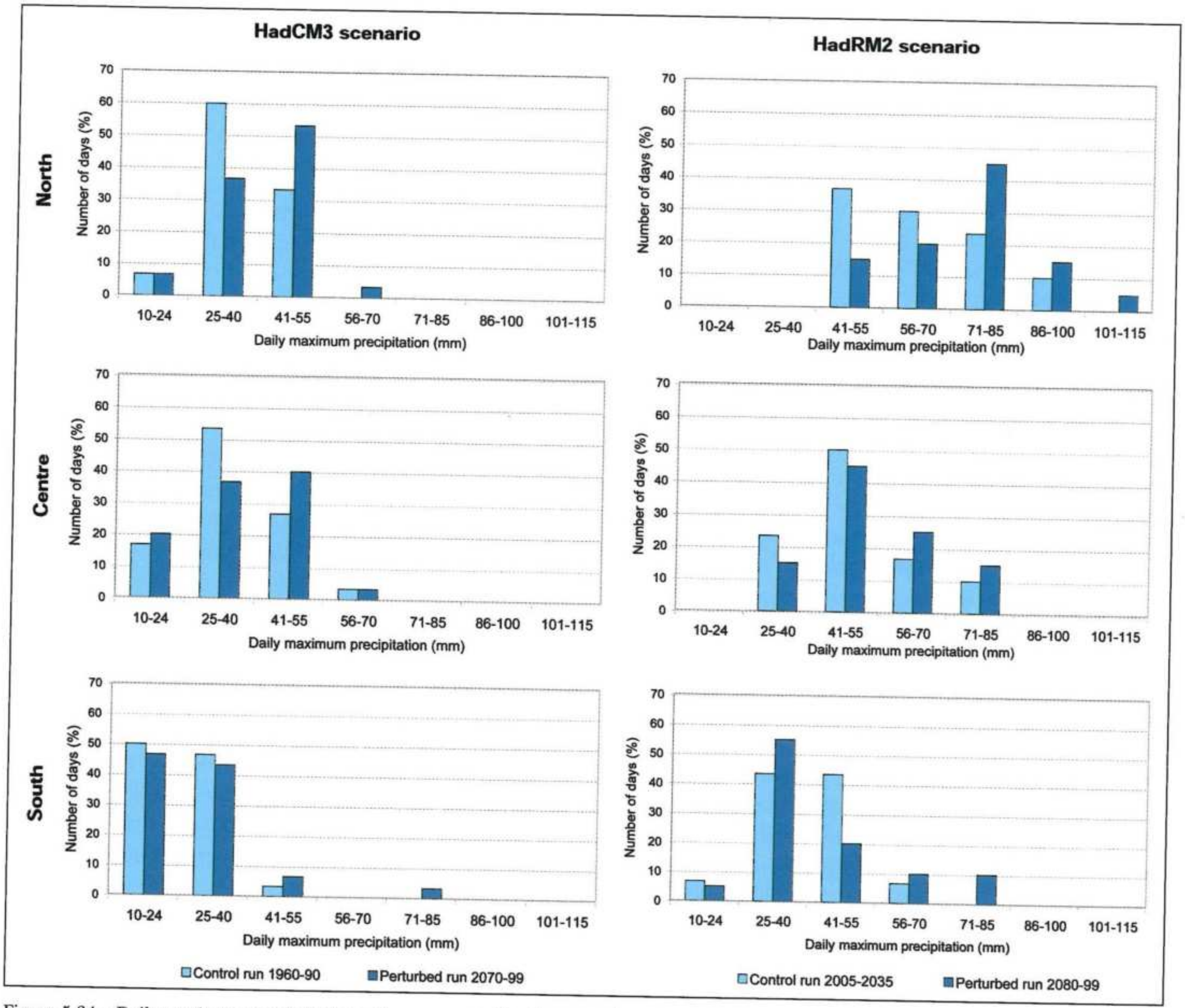

Figure 5.34 – Daily maximum precipitation values computed in the control run (2005-2035) and perturbed run (2080-2099) of HadCM3 and HadRM2

The rise of sea level may also contribute to an increase of flood risk as it decreases the discharge capacity of larger rivers near its outlet. Consequently, downstream riverine areas such as the lower part of Porto or the lower Tejo valley may suffer an increase in flood risk.

In conclusion, there is a strong indication that flood risk will be maintained or may even become higher, particularly north of river Douro.

### 5.5.4 WATER QUALITY

Climate change is very likely to affect water quality through changes in precipitation and runoff regime, as well as through the increase of air and water temperature.

The inflow rate of pollutants to river streams flow is expected to change through changes in precipitation patterns and its erosive potential, and through land and water use changes. A change in the rainfall erosive role and the sediment transport has impacts in the overall pollutants inflow balance, but it is not however clear the direction of this change given that the effects of a decrease of precipitation oppose the impacts of intense rainfall events that are responsible for conveying a larger fraction of sediments.

The main impacts over water quality will be originated by runoff decrease, as well as by an increase in the runoff seasonally asymmetry. The diminished dilution capacity of river streams, mainly in the dry periods of the year, will constitute the most severe problem. Furthermore, the increase of air and water temperature will lead to a decrease in the oxygen concentration in water and to an increase of reaction rates. Such increase in the biological productivity may increase the eutrophication problems already existing in Portugal.

Without adaptation measures water quality problems are likely to increase, although a proper quantification of the problem is still needed. Such negative impacts should be more significant in the south where higher temperatures and lower precipitation is predicted.

## 5.6 CONCLUSIONS

Based on the analysis presented in this chapter, the impacts of climate change on the Portuguese water resources can be summarised in the following way:

- The current simulations indicate a progressive reduction in the annual river runoff during the 21st century.
- This runoff reduction appears to be small in the northern region of Portugal, but increases progressively towards the south. If confirmed, this trend will increase the current spatial asymmetry of water availability in Portugal.
- There seems to be a systematic trend towards a concentration of the river runoff in winter, induced by a similar pattern of change in the precipitation distribution. If confirmed, this trend will increase the current seasonal asymmetry of water availability in Portugal.
- The comparison of the simulations using the HadRM2 and HadCM3 climate scenarios shows that the former leads to a wider range of runoff change predictions due to larger anomalies in precipitation and temperature, namely a strong increase precipitation in winter and a strong decrease during the rest of the year.
- By 2100, the average annual runoff in the region north of river Douro is estimated to decrease between 0% and 10% according to the HadCM3 model and to increase from 0% to 10% according to the HadRM2 model. Both models predict a reduction in the summer and autumn runoff between 10% and 80%.
- Also by 2100, the annual mean runoff in the Vouga and Mondego basins may be reduced from 15% to 30% according to HadCM3. HadRM2 estimates are uncertain as regards the direction of change. Both models predict a runoff reduction in summer and autumn ranging from 20% to 90%.
- The average annual runoff reduction in the Tejo river basin is estimated to be between 15% and 30% by 2100 according to the HadCM3 scenario. HadRM2 estimates a 40% to 80% increase in annual runoff, related to a strong increase in winter precipitation. Both models predict a runoff reduction in autumn between 60% and 100%.

- Sado, Mira and Guadiana rivers basins, as well as Algarve, stand out as the regions more vulnerable to climate change. HadCM3 estimates a 40% to 60% decrease in annual runoff by 2100. Again, HadRM2 results suggest a 0% to 50% increase in annual runoff related to a strong increase in winter precipitation, but both models predict a reduction, between 20% and 100%, in summer and autumn runoff.

- River runoff projections for the Algarve river basins are particularly uncertain because of a strong spatial variability of precipitation, mainly due to the mountainous range that separates the Algarve basins from the adjacent basins. The impacts are likely to be negative, namely in the drier months.

- The concentration of precipitation in winter and the estimated general increase in the frequency of heavy precipitation events is likely to increase the flood magnitude and frequency, particularly in the northern part of the country.

- It is expected that water quality will be degraded by higher water temperatures and by river flow reduction in the summer, particularly in the southern region.

In summary, it should be expected a general decrease in the water availability, an increase of seasonal and spatial asymmetries, an increase of flood risk and an increase of water quality problems. The decreased runoff in the Spanish part of the transboundary river basins is likely to accentuate even further the expected decrease of water availability in the Portuguese territory. The impacts of climate change on sea level may also affect the groundwater levels and the groundwater quality, thus influencing the water resources availability.

In order to fully evaluate the impacts of climate change on the water resources, it is necessary to estimate not only the impacts on the water availability but also the impacts on water demand, by considering the impacts on the various water uses. This is a difficult task because it depends on social and economic reactions to a modified situation. However, since 75% of all water needs are associated with the agriculture sector, it should be expected an increase in water demand due to higher temperatures.

To conclude it seems adequate to discuss some aspects, which appear to be important regarding the future water management policies are needed to cope with climate change impacts on water resources.

The challenge of climate change must be addressed with an increased attention on water resources management strategies and policies. The argument that the impacts of climate change are not yet fully known and that many uncertainties still exist is not a reason to postpone action. The results of different studies have already identified some trends with a high probability of occurrence, which should be considered in water management strategies and policies.

Furthermore, a sound water management policy has always required a capacity to decide under uncertainty. Policy makers and water managers routinely forecast both the hydrological regime and act upon these forecasts. They try to plan in advance the response to future scenarios, usually selecting flexible and adaptable policies to be able to quickly react to specific situations.

In this perspective, climate change does not require any drastic change in water management thinking, as it only constitutes an additional source of uncertainty that will influence future values of both the water demand and availability. The main conceptual change is the rejection of the traditional engineering assumption that considers the historical climate as a reliable indicator of future conditions. Water management authorities must start considering the climate change as a decision variable.

If climate change will not impose profound changes in how water resources are managed, it will be likely that the task of managing the Portuguese water resources will become even more challenging. The potential decrease of water availability and the increase of the hydrological seasonal asymmetries, together with more stressing conditions in terms of water quality and flood risk, underline just how important it is to have water management policies based on a solid and in depth knowledge of the Portuguese water resources. This stresses the need for further water resources assessment studies and climatic change research in order include the climate change information in water management practices.

According to IPCC (2001), such knowledge must include an explicit consideration of all the potential supply-side and demand-side actions. Furthermore, reactive or proactive adaptation measures have to be taken on a basinscale, accounting all the local users that directly or indirectly interact.

In addition to the issues discussed above, which are particularly relevant for water managers, other more general issues related to economic and social planning, development, land use, wealth enhancement or hazard insurance must be considered, in order to reduce, as much as possible, the vulnerability of the water sector to climate change.

Given the importance of the transboundary river basins for the Portuguese water resources it is of paramount importance to develop joint projects in cooperation between Portugal and Spain on this topic. This question should be considered with particular relevance in the general framework of bilateral scientific and technological cooperation.

The predicted decrease of river flow in southern Portugal towards the end of the century, if confirmed, may have dramatic consequences, and therefore, be a cause of significant concern. Thus, it does not seem wise to ignore the impacts of climate change in water resources planning and management in Portugal.

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# 6

# Coastal Zones

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## CONTENTS

## EXECUTIVE SUMMARY

The coast of mainland Portugal has an extension of approximately 950 km and is quite diverse in morphology and vulnerability, dominated by beaches and low cliffs, which correspond to 60% and 35% of its length. A number of barred estuaries and lagoons retain most of the wetland expansions. The coast is high-mesotidal and wave-dominated, energy decreasing in sheltered W-E trending sections, including the south-facing littoral of the Algarve.

About 3/4 of the population inhabits the coastal zone, which houses most of the country's largest cities (Oporto, Aveiro, Lisbon, Setúbal, Faro), trading facilities and employment opportunities, and accounts for about 85% of the Gross Domestic Product. The population living at the coast and related economical activities – with relevance for tourism – continues to increase, together with demands for coastal and marine resources. These demands generated conflict with environmental awareness and preservation of both biodiversity and scenic values, leading to the recent implementation of regulative and protective legislation.

The most relevant consequences of climate change upon the Portuguese mainland coast are sea level rise and changes in both direction and power of waves and storm surges, towards higher energy input and shorter return period of extreme events of flooding. External sediment sources to the coastal system are not expected to intensify, despite the forecasted changes in precipitation and run-off. The anticipated increase of sediment demand is likely to settle within the coastal system, which is at present starving and vulnerable in significant extensions.

The most important impacts of climate change upon the coastal system are likely to be: a) increased levels of inundation and displacement of wetlands and lowlands; b) accelerated coastal erosion; c) increased storm surge and flooding and d) encroachment of tidal waters into coastal basins (estuaries, lagoons) accompanied by changes of the tidal regime and of the sediment budget.

The Mean Sea Level has already risen by *circa* 15 cm during the 20th century along the Portuguese mainland coast and thermal expansion of the ocean has been indicated as the prime responsible for this rise, which is however likely to account for no more than 15% of the erosion observed after the 1950s. The exhausting of sediment supply with wave-driven longshore drift are essential causes for the already widespread erosion problem that affects more than 1/4 of the coastal ribbon. The management of Iberian river basins since the 1940s has reduced by one order of magnitude their solid input to the coast and this constraint is likely to exacerbate the coastal vulnerability to climate change, in general, and particularly to sea level rise. Erosion has had significant impact, both on developed and undeveloped coastal sections and a shoreline retreat of the order of 1 $myr^{-1}$ has been reported in considerable extensions of the coast (especially from 1900 onwards) affecting cliffed and sandy ribbons, and unchained the multiplication of protection works: at present, about 15% of the coastal length is either protected or hardened.

In contrast, the majority of Portuguese marshes and tidal flats appear not to have been significantly affected by inundation and flooding due to the rise in sea level because of high vertical accretion rates. The effects of future changes in both the rates of sea-level rise and tidal amplitude in eventual departures from this situation remain to be evaluated at a local scale and the general rule indicates widespreading and enhancement of erosion, flooding (including overwash of barriers) and squeeze of wetlands due to the degree of artificialization of their landward boundaries.

From 1990 to 2100 the full range of the Third Assessment Report IPCC scenarios project an absolute sea level rise of 0.11 to 0.77 m with a central value of 0.40 m. In the absence of objective data on vertical land movements and regional sea-level changes, it seems wise to adopt the high scenario of the IPCC projection as a cautious approach that encompasses the likely relative change along the coast of Portugal.

The longshore distribution of risk is quite variable at small spatial scales. The coast north of Lisbon, together with the Algarve ribbon of Portimão – Olhos d'Água, are characterized, in general, by a predominance of medium-high risk, the most delicate situation (high and very high risk) being associated with the Algarve barrier coast of the central and eastern Algarve. In contrast, the coast south of Lisbon to Cape S. Vicente and to Portimão consistently displays medium to medium-low risk values.

Protective action to minimize the impacts of sea level rise has been recommended in 24% of the coastal length and encompasses port upgrading (1.2%), construction of seawalls (8.9%) and groins (0.5%) together with combined solutions of soft and hard protection, including beach nourishment (9.2%). Retreat and relocation is recommended in 4.3% of the coast. In the present study it was not possible to yield quantitative evaluation on the effectiveness and costs of these actions.

Adaptation strategies for coastal zones should shift their emphasis away from hard protection structures to soft protection, such as beach nourishment, and retreat and relocation as a general rule. Nevertheless, hard protection is likely to be unavoidable in areas of high development and high population density and it also appears as a necessary complement to beach nourishment in the case of Portugal.

The actual impacts of climate change and, in particular, sea level rise, will be strongly site-specific and depend on our degree of preparedness to choose and implement, in due time, the most adequate adaptation to that change. In Portugal, there is clearly a need to increase the capacity to manage the coast, especially in the medium and long time scales, and include adaptation to climate change into long-term coastal planning. In addition, there is a weak general awareness of society about the expected future climate change scenarios and associated impacts upon the coast and this awareness must be changed rather urgently in order to minimize the social unrest and economical stress resulting from the inevitable adaptation measures. Continued research on the potential impacts and adaptation measures to climate change on the Portuguese coastal zones is clearly required at seasonal to century scales and at high resolution spatial scale. Particular attention should be given to increasing flood-frequency probabilities, flood risk and damage, erosion effects, and encroachment of tidal waters into estuaries and to their impacts on specific coastal and marine ecosystems and socioeconomic sectors.

# 6. Coastal Zones

## 6.1 INTRODUCTION

### 6.1.1 OVERVIEW

#### 6.1.1.1 Concept and importance

The concept of coastal zone and the wording defining its character and extension depends on military, political, scientific and/or economic criteria as illustrated by the following examples:

"The Coastal Zone is the part of the land affected by its proximity to the sea, and that part of the sea affected by its proximity to the land as the extent to which man's land-based activities have a measurable influence on water chemistry and marine ecology" (US Commission on Marine Science, Engineering and Resources 1969 [IR 1]).

"The Coastal Zone is the part of the land and waters extending inland for one kilometre from high-water mark on the foreshore and extending seaward to the thirty metre depth contour line, and so including the waters, beds and banks of all rivers, estuaries, inlets, creeks, bays or lakes subject to the ebb and flow of the tide" (adopted by Western Australian States – cf. Beer 1983).

"The Coastal Zone is considered to be the biophysical and geochemical interface area of interaction between the ocean, the land and the biosphere, being a dynamic area with biological, chemical, physical and geological characteristics constantly changing. Being one of the most dynamic areas on the Earth's surface, the coastal zone experiences large energy inputs from waves, tides and winds and changes in sea level at a range of time scales" (Parry 2000).

"The Coastal Zone is considered to be the ribbon extending along the marine coast whose width is limited by the maximum High-water Spring contour and the line located further inland 2 km apart" (Portuguese legislation – DL 302/90, 26 September – physical definition adopted to establish occupation, use and transformation criteria).

In this chapter, the coastal zone is considered as an interface area, extending from a seaward boundary, at the limiting depth of significant bottom disturbance by waves, into the terrestrial margin, up to the maximum penetration distance and ability of waves, tides and offshore winds to shape geomorphology and control sediment dynamics. In mainland Portugal the landward limit is extremely varied according to the local physiographic content but the seaward boundary stands at about 6-7 m depth in the southern Algarve coast and 10-12 m along the western littoral (Andrade 1998).

The importance of the coastal zone is widely recognized. It contains highly diverse and specific ecosystems, some of which are nurseries and refugees of varied marine species and birds. Coastal wetlands correspond to the most productive zones of the biosphere, their productivity being by far greater than that found on dry land, natural or cultivated. Beyond their intrinsic value as records of past environmental changes, wetlands are most efficient water depurators, trapping pollutants (nitrogen, phosphorus, heavy metals, radioisotopes) from sewage effluent and surface water. Specific contents of the coast, like beaches and dunes, as well as marshes and tidal flats in estuaries and lagoons, are vital self-reorganizing physical barriers against floods and storms. They integrate the complex of interconnected elements of the sediment budget of the coast, which also includes cliffs and fluvial discharge (Carter 1988; Eisma 1995; [IR 2]).

In spite of occupying less than 15% of the Earth's land surface, being only some 500,000 km in length, the coastal area is highly populated, with more than two-thirds of the world's population living within a narrow belt directly landward from the ocean's edge (Komar 1998). This narrow ribbon houses most of the political and technical decision-making centres of different countries and the majority of industry and most profitable economic facilities and activities, including tourism. These facts maintain the population migratory tendencies, overloading the coast. If this trend continues, up to 75% of the world's population could be living in coastal areas by 2025 (EEA 1999; [IR 2]).

The increasing occupation of the coast intensifies the conflict of interests between the human activities (tourism, fisheries, commercial and recreational navigation, sewage dumping, industry, housing, etc.) and both the preservation of biodiversity and natural mobility and functioning of coastal ecosystems.

### 6.1.1.2 The Portuguese coast

#### *6.1.1.2.1 Population and Development*

The coastline of Portugal extends through 1,846 km, distributed by the mainland (943 km), the archipelago of Azores (691 km) and the archipelago of Madeira (212 km) (Dias 2000). The Portuguese Exclusive Economic Zone (EEZ) has a total surface of 1 million and 700,000 km$^2$, which makes almost half of the European Union's EEZ (DGA 2000).

The occupation patterns of the Portuguese coast have changed in the last few decades due to fast development accompanied by changing political and economical constraints (Fig. 6.1).

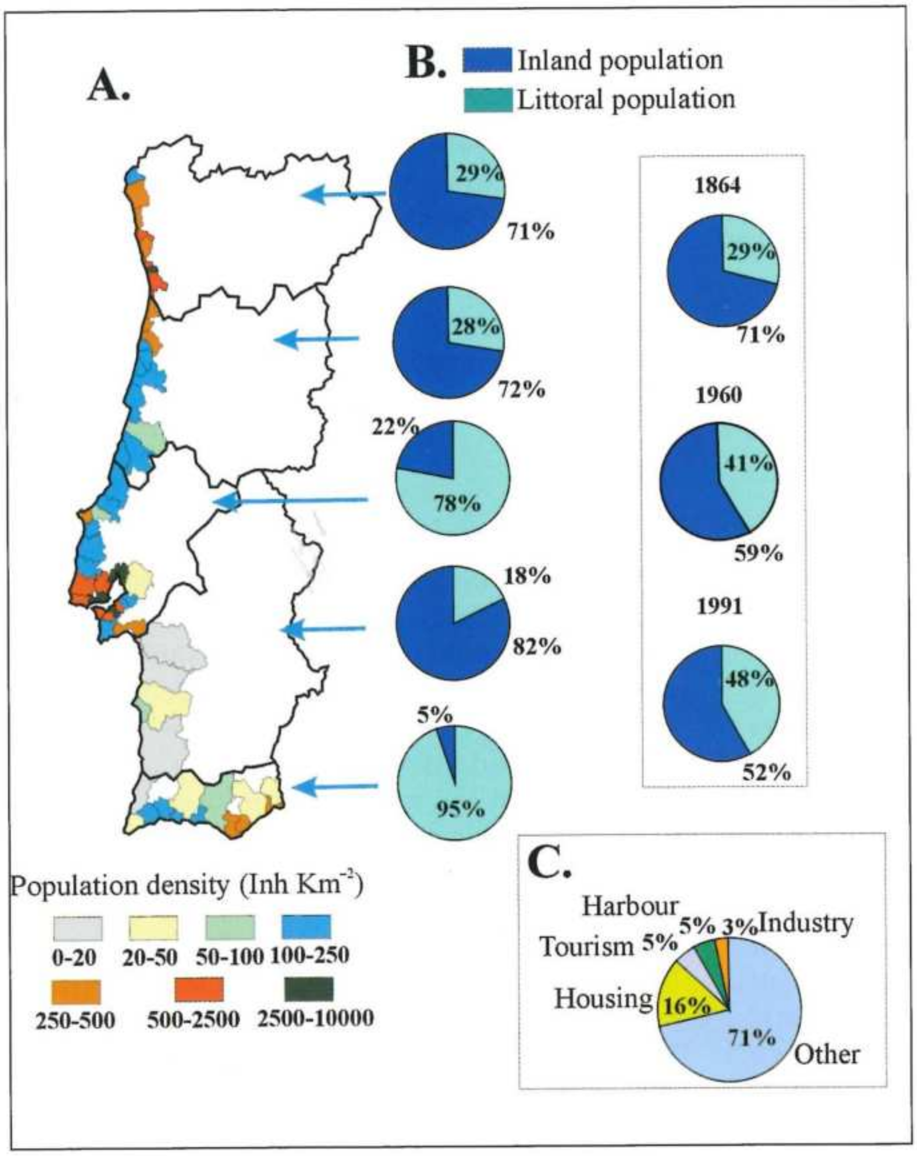

Figure 6.1 – The Portuguese coast. A – Population density of littoral municipalities. B – Inland population *versus* littoral population and its evolution since 1864. C – Occupation of the coast (adapted from INAG 1994).

The shift of Portuguese economy towards the secondary and tertiary, more profitable, sectors – to which tourism is a relevant contributor – made the coast a powerful attractor; in 1997, the total income from tourism represented 4.2% of the national Gross Domestic Product (GDP) – and increased to 8% in 2000 [IR 3] – against 2.3% of average in Europe and 1.5% in the world; it is also estimated that about 9% of the employment opportunities are connected to tourism (Albuquerque and Godinho 2001).

At present, 65% of the population lives within 60 km of the coast [IR4], which shows a population density of circa 215 inh km$^{-2}$ (compared with the national average of 125 inh km$^{-2}$) and where around 85% of the GDP is generated (INAG 1994); the coast also houses the country's largest cities (e.g. Lisbon, Oporto, Setúbal, Aveiro, Faro) and the principal trading facilities – ports and harbours. The morphological diversity of the coast, combined with a mild climate, explains its advertisement as one of the most attractive natural areas in Europe and the exponential growth of second-housing and tourism activities since the 1950s. The increased use of the coast for tourism and recreational activities presently generates seasonal migrations to the littoral fringe (INAG 1994), which are difficult to manage in terms of resources optimisation and of adverse impacts mitigation. The example of some well-known Algarve resorts is striking, with short-lived peaks of tourist inflow increasing the resident population density by a factor > 10 once or several times every year. Recent studies indicate that approximately 30% of the Portuguese mainland coast is at present significantly altered by housing (urban settling and expansion, second habitation), harbour and industrial facilities and tourism infrastructures (Fig. 6.1C), although the distribution of occupation patterns and density is quite variable along the shore.

#### *6.1.1.2.2 Protection and Management Policies*

Portugal is one of the few European countries that developed legislation regarding the ownership of the coast in the late 19th century, introducing the concept of Public Maritime Domain (PMD), which limits the property of land in the coastal zone to the State and restricts its use to specific permits. The primary consequences of this law is that lengthy sections of the coast have been spared from occupation for a long time but in reverse, the State is responsible for supplying and paying for protection if erosion affects or damages property landward of that zone. Since the 1950s increasing pressure for tourist development of the coast lead to the unaffectment of several parcels from the PMD (e.g. Tróia spit, Faro beach) and only in the late 1970s this trend has been opposed through a number of laws aiming to protect the coast from uncontrolled and hazardous occupation. At present, the coastal area is overlapped by the protection perimeter of the National Ecological Reserve Law (Reserva Ecológica Nacional – Law 93/90, 19 March; Law 213/92, 12 October; Law 79/95, 20 April), which defines the areas crucial to maintain the ecological stability and sustainable use of natural resources – e.g. beaches, dunes, wetlands, nearshore – and by the Public Hydric Domain (Domínio Público Hídrico – Law 468/71, 5 November), which includes the whole of the Portuguese coast within a protected strip ranging between 50 and 500m width; in addition, all restrictions approved within the scope of the European Union also apply to the Portuguese coast.

Several encased management plans have been developed since the 1980s, dependent of the central Government and of Local and Port authorities which include the coastal area. The PROT- Planos Regionais de Ordenamento do Território – are regional-scope instruments of management, which zoom into Municipality-scaled management plans (PDM – Planos Directores Municipais) and Special Management Plans, such as the Coastal Management Plans (POOCS – Planos de Ordenamento da Orla Costeira) with specific objectives on the coastal area; nevertheless, these instruments exclude land under jurisdiction of the Port Authorities. In addition, 35% of the coastline is classified as protected for environmental values (Bettencourt 1997) – e.g. Natural Park, Natural Reserve, Protected Landscape Area, and it constitutes a means to achieve promotion and conservation of the Natural Heritage.

Despite the effort devoted to articulate and enhance coherence and effectiveness to the legal instruments, the present-day status of the coast is still far from the adequate and desirable planning and management needs in a context of sustainable development.

#### *6.1.1.2.3 Geology and Geomorphology*

The large scale geotectonic context encompassing the Portuguese margin and its location concerning the mid-Atlantic ridge indicates that its littoral is of Afro- or Amero-trailing edge type, under the first-order tectonic and morphologic classification of Inman and Nordstrom (1971). The maturity and solid load of the outleting rivers and the large scale morphologic arrangement of the hinterland as well as the predominantly prograding character of the continental shelf are compatible with this classification; yet, the narrow breath and high slope of the shelf, the predominantly linear trend of the coast and abundance of raised terraces and cliffs, the important seismicity and tsunami activity, the absence of well developed coastal plains and rarity of true barrier-island chains, added by strong similarity in the wave climate, makes it quite comparable to Collision coasts, such as the Americas' Pacific coast in terms of a few first-order and many second- and higher-order features. The reasons that make the Portuguese coast exceptional in terms of classification are debatable; they possibly associate with large scale tectonic constrains and with the sea level oscillations related with the last Glaciation and the Flandrian transgression, which imposed the final characteristics to the littoral fringe and justify its wide morphological, evolutionary and dynamic diversity.

The coast develops in a wide range of lithologies (cf. Ribeiro et al. 1979 and SGP 1992 for a summary of the geology of Portugal) that group in four main tectono-stratigraphical terranes (Fig. 6.2) and to a large extent adapts to the major structural controls found inland.

Under the morphological point of view, the littoral of Portugal shows great diversity, including sandy shores backed by dunes or cliffs, rocky coasts with low to high and plunging cliffs, shore platforms, pocket beaches, bays/headlands, estuaries and lagoons and associated tidal flats and salt marshes, tombolos, sand spits and barrier islands. According to the prevailing geomorphological content, the Portuguese coast may be divided in eight stretches (Fig. 6.2):

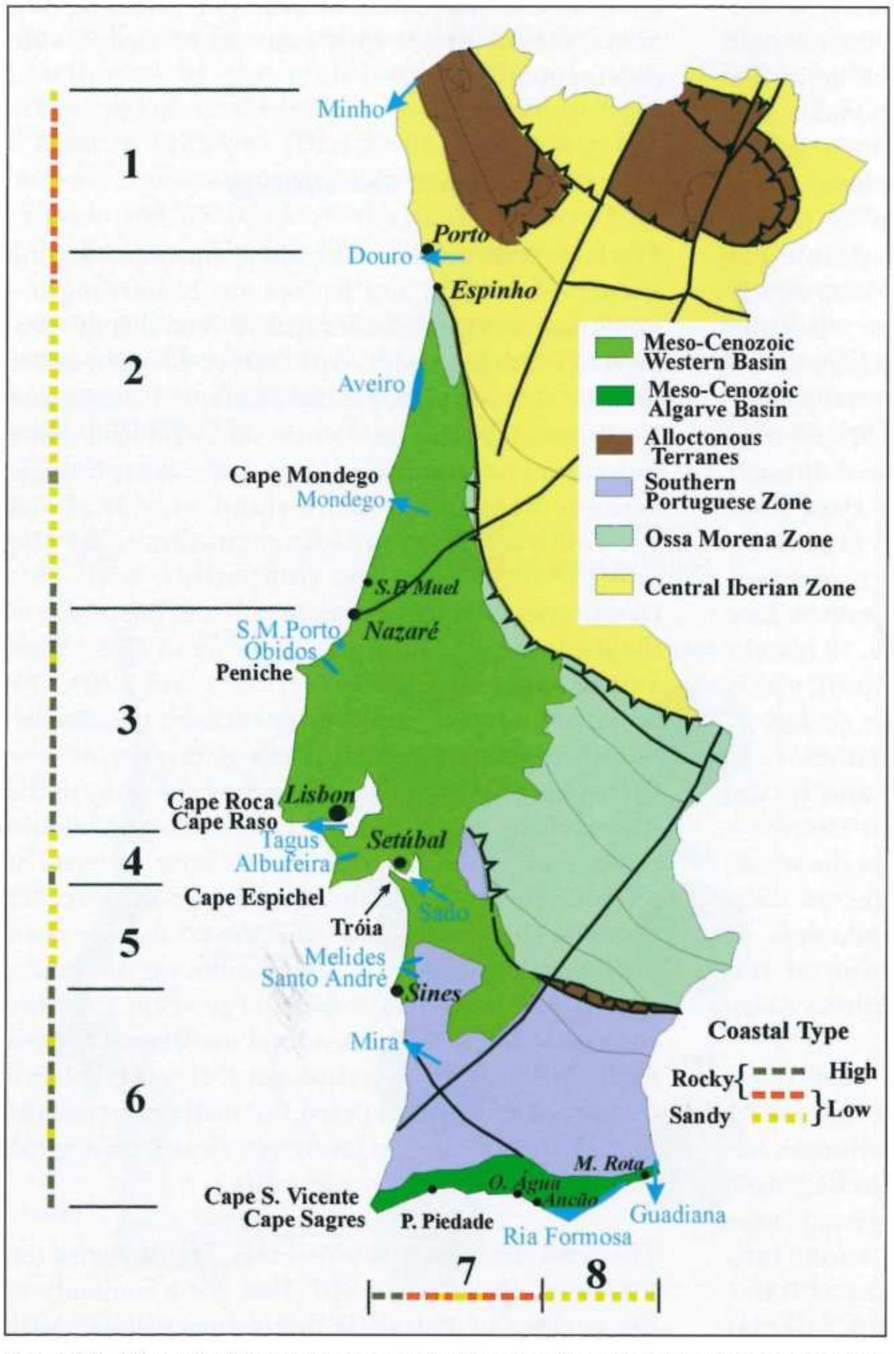

Figure 6.2 – The major Portuguese coastal stretches (1 to 8), coastal types and main tectonostratigraphical terranes. The latter were adapted from SGP (1992).

1 – From the Minho until the Douro estuary – this stretch, essentially directed NNW-SSE, develops in the Central-Iberian terrane, mostly in crystalline basement and early Palaeozoic metamorphic rocks. It corresponds to circa 80 km of a low irregular rocky coast, broken by beaches and containing numerous sea stacks and rocky shoals. Beaches depend on local sheltering and are usually small with the exception of larger systems occurring southward of estuaries (e.g. Minho, Âncora, Lima, Cávado, Ave, Douro), where local reversal of net drift direction allowed northward growing of spits. In places, the sea stacks and rocky shoals define the external boundary of a raised Pleisto-Holocene sedimentary coastal plain, contained between the hinterland basement and the present-day beach and dunes.

2 – From the Douro estuary until Nazaré – this stretch, essentially directed NNE-SSW, corresponds to 160 km of linear low sandy coast, with the exception of: (1) its extremities – Douro estuary to Espinho (low rocky coast developed in crystalline basement) and S. Pedro de Muel to Nazaré (cliffed, cut in Meso-Cenozoic sediments) and (2) the singularity of Cape Mondego (high cliffs defined in Jurassic limestones), which offsets the southern 60 km to the east without disturbing the general coastal trend, and shelters the estuarine lowlands of the Mondego estuary. It contains reflective to intermediate-dissipative sandy beaches backed by single or multiple foredunes which extend inland through wide vegetated dune fields. In its northern section the beach is interrupted by the artificial inlet of the Aveiro lagoon; this is the widest barrier-lagoon structure of the Portuguese coast and its evolution was characterized since the 11th century by extremely rapid siltation of a former gulf which has been isolated from the open sea by several fast growing spits (Teixeira, 1994).

3 – From Nazaré until the Tagus estuary – this coastal stretch, essentially directed NE-SW until Peniche, NNE-SSW until Cape Raso (110 km) and E-W till the Tagus outer estuary (15 km), is once again rocky, with active cliffs cut in limestones, marls and sandstones of the Meso-Cenozoic western basin, hanging directly to the sea. The coast displays an

irregular contour, with several headlands (e.g. the Peniche tombolo) and bays, the latter accommodating small coastal lagoons (S. Martinho do Porto and Óbidos) or reflective pocket beaches. The northern boundary of this section corresponds to the Nazaré canyon, an important morphological feature of the continental shelf with 60 km length whose head nibbles the coastal strip and connects it to the deep ocean floor. Óbidos and S. Martinho do Porto are relicts of vast lagoonal systems formed in the diapiric basin of Caldas da Rainha following its drowning by the Flandrian trangression and the establishment of detrital barriers, determined by the deceleration of the sea level rise rate in the Middle Holocene. Their intense silting up, especially after the Roman period, has progressively reduced both the water depth and wet surface of these lowlands. This evolutionary pattern is similar in other small coastal lagoons of the Portuguese coast (Freitas 1989;1995; Freitas and Andrade 1997; 1998; Bao et al. 1999; Freitas et al. 2002; Freitas et al. in press a; b). The E-W stretch corresponds mainly to an artificialized and developed coast with starved pocket beaches encased into low cliffs cut in Cretaceous limestones. This section forms a geomorphological singularity due to the pronounced coastal offset north of the Tagus estuary up to the Capes Raso and Roca (the latter associated with the subvolcanic intrusion of Sintra) and to the drowned large sand bulge that includes the river's paleodelta, forming most of its outer estuary. The Tagus has the largest European estuary, which is peculiar in morphology and sedimentation; instead of the typical funnel shape, it strangles downstream forming a structurally controlled narrow gorge, which connects the inner shallow and tide-dominated basin with the outer wave-dominated domain.

4 – From the Tagus until the Sado estuary – this stretch forms the littoral of the Setúbal Peninsula, with a section trending N-S facing the Atlantic (35 km) and another limiting the Arrábida chain (30 km) extending E-W. The former corresponds to an arcuate equilibrium bay, and includes a southern (1/3) cliffed section hanging directly to the sea with pocket beaches, and a northern (2/3) beach, backed by a low-lying coastal plain, mantled by dunes and limited by a cliff, which is fossil until Fonte da Telha and becomes active and topped by vegetated dunes further south. The sand beach is only interrupted by the inlet of the Albufeira lagoon, when it is artificially breached. The latter consists essentially of high plunging cliffs defined along the southern façade of the calcareous Arrábida chain with rare structural controlled pocket beaches.

5 – From the Sado estuary until the Cape of Sines – this coastal section, essentially trending N-S, is almost homothetic of the former stretch in shape, geomorphological contents and limits: the northern boundary is a major estuary (Sado) that extends and offsets the coast westwards, until cape Espichel; the exposed segment facing the Atlantic is an equilibrium bay, developed in a southern cliffed section and a northern low-lying beach and dune section; the southern boundary corresponds to the cape of Sines and is imposed by the resistant outcrops of a subvolcanic intrusion. This stretch contains a 64 km long continuous reflective sand beach backed by cliffs or dunes; north of Carvalhal the beach detaches from mainland and forms a spit (Tróia spit) which shelters the Sado estuary and confines its inlet. The Sado has the second larger Portuguese estuary that, like the Tagus, contains vast intertidal areas of mud-, sand-flats and marshes. South of Carvalhal the beach is backed either by cliffs cut in soft detrital Plio-Pleistocene sediments that erode by sub-aerial processes, or by multiple spit complexes that represent barriers of the Melides and Santo André lagoons and of few barred-rivulets such as Rio de Moinhos.

6 – From Sines until Cape S. Vicente – this coastal stretch essentially develops in the Late Paleozoic turbidites of the Southern Portuguese Terrane and at its very southern tip in resistant Jurassic limestones and dolomites of the Algarve basin. The wacke and slate Flysch are intensively folded and fractured and define a series of active, structurally-controlled linear cliffs of variable height trending NNE-SSW for some 120 km. They are margined by shore platforms and interrupted by the estuaries and associated lowlands of the rivers Mira, Odeceixe and Aljezur. The latter, together with a few sheltered indentations in the cliffs, allowed rare pocket beaches of sand or shingle to accumulate. This coastal stretch also contains the most representative yet localized semi-vegetated and presently active dune fields of the Portuguese coast, namely close to S. Torpes (Sines) and Bordeira – Carrapateira. The S. Vicente – Sagres headlands, protruding to the SW, margined by plunging cliffs and made of hard

monoliths of dolomitized thick-layered limestones impose a resistant singularity, separating the westward facing coast of SW Portugal from the sheltered southern Algarve littoral.

7 – From Cape S. Vicente until Ancão – the coast develops essentially W–E for some 90 km along the Algarve Mesozoic terrane. This stretch is essentially rocky and cliffed, the height of the cliffs generally decreasing eastwards and showing large-scale crenulation imposed by a number of headlands and bays. The Jurassic limestones outcropping in its westernmost tip correspond to stable plunging cliffs, scarcely indented by occasional fault-controlled incised canyons or rivulets confining small pocket-beaches. Between Porto de Mós and Ponta da Piedade, the Cretaceous detrital and carbonate sediments give place to active linear low cliffs; further east, the Miocene calcarenites define an extremely crenulated, low-cliffed rocky coast, due to the combination of structural constraints with the recent exhumation and marine drowning of a paleokarst, containing numerous yet very small sand beaches. Drowned shore platforms, eroding sea stacks and shoals are abundant features along this section. The easternmost end of this stretch roughly trends NW-SE and corresponds to the fast eroding linear cliffs of Olhos d'Água – Ancão, cut in Tertiary poorly consolidated sandstones that nourish an adjacent starving reflective and narrow sand beach. The major exceptions to the rocky nature of the western Algarve littoral are the embayments of Lagos – Alvor and Armação de Pera, where beach and dunes develop along arcuate equilibrium bays, which margin choked or totally infilled estuaries or lagoons.

8 – From Ancão until the Guadiana estuary – in contrast, the eastern 70 km Algarve coast is linear, low lying and sandy. The major geomorphological feature is the roughly triangular barrier-lagoon system of Ria Formosa, a non-coastal plain barrier chain, that forms the widest lowland of the Algarve. Barriers and inlets are extremely active and the easternmost islands that formerly extended up to the Guadiana estuary were drowned by the AD 1755 tsunami, the coast having reorganized into a welded beach-dune complex that forms the present day coastal plain of Manta Rota, which confines the Guadiana marshes and flats (Andrade 1990; Andrade and Freitas 2000).

### 6.1.2 EFFECT OF CLIMATIC VARIABLES ON THE COASTAL ZONE

The principal factors of forcing upon the Portuguese coast are partly weather-dependent and short-term in time-scale of operation (e.g. waves, surges) while others correspond to the cumulative effect of macro- to micro scale forcing (e.g. tides, sea level changes). Both may trigger responses on their own or interact in some way and contribute to the present day coastal dynamics and shape.

#### 6.1.2.1 Inheritance

A significant fraction of the morphodynamic organization and contents of the Portuguese coast is an inheritance of the pre-Holocene low-stands of the mean sea level, which have been followed by deep incision of the fluvial network and sediment yield to the present-day shelf. The Flandrian rapid rise in sea level drowned a significant fraction of it as well as the lower grounds of the terrestrial margin. In consequence, the Portuguese coast was more irregular than today, the valleys and depressions were extensively flooded to form a Ria-like coast with headlands and deep embayments (Freitas et al. in press a). Circa 5,000 BP the deceleration of sea level rise combined with large sediment availability lead to the development of detrital barriers, which enclosed most estuaries and coastal bays. The barrier islands of Ria Formosa seem to have been formed also by this time and no significant roll-over across the shelf has occurred since then (Andrade 1990). After *circa* 5,000 BP the coastal sediment budget became more similar to the present-day; anthropic activity – especially after the Roman times – added by other local-scale factors, promoted rapid siltation of the newly formed barred lowlands and became predominant in determining the rate and pattern of sediment fluxes and morphological changes of a number of coastal cells. This Late Holocene inheritance explains the estuarine nature and extensive sediment choking of the vast majority of fluvial outlets, and allowed the expansion of wide intertidal flats and marshes in both estuaries and lagoons along the Portuguese coast, regardless of their size and location. Land-sourced sediment is thus largely entrapped before reaching the shore in estuarine/lagoonal basins and tributaries. With few exceptions, inlets, either estuarine or lagoonal, usually correspond to sinks regarding marine sands, due to flood-dominancy of the tidal currents and, to the best of our knowledge, the continental shelf beyond the limiting depth of the submarine beach is an irrelevant source of sediment to the Portuguese shore.

### 6.1.2.2 Sea level

The study of mesoscale changes of relative mean sea level along the Portuguese coast, deduced from tide-gauge records of Cascais and Lagos (118 and 92 years, respectively), indicates a transgressive trend, the linear regression of data corresponding to secular average elevation rates of 1.3±0.1 and 1.5±0.2 mmyr$^{-1}$ (Taborda and Dias 1989; Dias and Taborda 1988;1992; Kol et al. 2002) – Fig. 6.3. These figures are consistent with the observed eustatic global rise in mean sea level during the 20th century (e.g. Barnett 1984; Bird 1993; Church et al. 2001) and are curiously similar to the 50 year-average of 1.5 mmyr$^{-1}$ reported earlier by King (1959) using the Portuguese series available in 1954. The comparison of observed mean sea level changes in Portugal with the records of the North Atlantic sea-surface temperature suggests that the thermal expansion of the ocean is the prime responsible for the observed rise in Portugal (Figure 6.3B), the isostatic and neotectonic components being negligible.

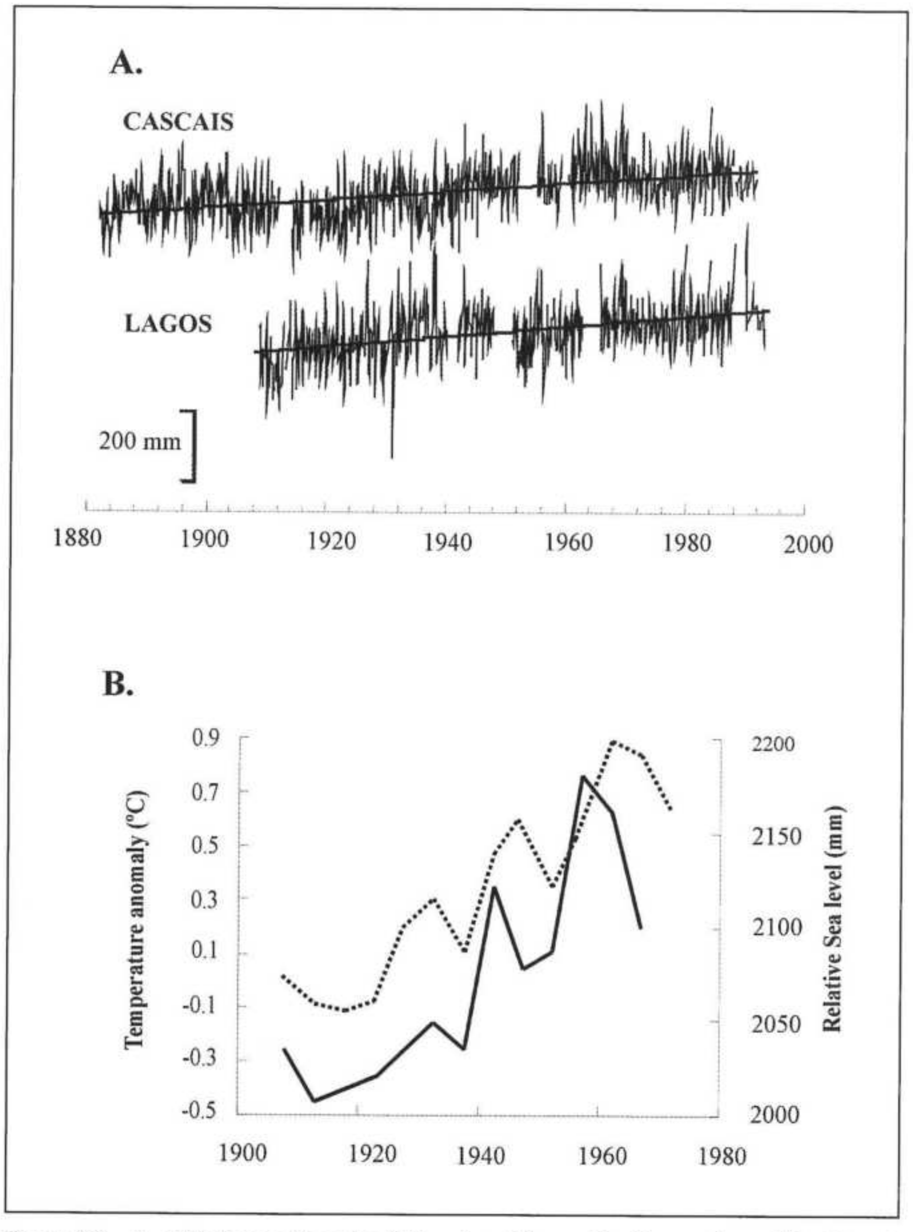

Figure 6.3 – A – Tide-Gauge Records of Cascais and Lagos. B – Comparison of the Cascais Tide-Gauge data with the North Atlantic Ocean Sea Surface Temperature (adapted from Ferreira et al. in press). Solid line – SST; dashed line – MSL.

The former conclusion may be challenged by the few (and controversial) available data on the vertical movement of the Portuguese margin throughout the Holocene. Neotectonics along the Portuguese coast result of stress fields developed in the Iberian microplate, which is postulated to have initiated incipient subduction along the western façade of Iberia (Cabral 1993; Ribeiro 1994) and induced downwarping. Yet, evidence of raised Holocene intertidal sediments exists north of Aveiro that associate with recent movement along active faults in the NW Portuguese region, which control the orientation and development of the coastal area in this zone (e.g. Cabral and Ribeiro 1989; Granja 1990; de Groot and Granja 1998; Granja 1999); in the southern Algarve coast, Andrade (1992) reported geomorphological evidence of co-seismic subsidence followed by marginal uplift in association with the AD 1755 earthquake.

The contribution of sea level rise to the erosion of the Portuguese shore experiencing interdecadal persistent retreat has been assessed in the NW low coast between the Aveiro inlet and Cape Mondego, along the Lisbon coast and in both cliffed and barrier coastal sectors of the southern Algarve, using Bruun's Rule (Bruun 1962; 1988). Results suggest that in all coastal stretches the rise in sea level observed in the 20th century accounts for only but a small fraction (10-15%) of the erosion observed after the 1950s (Andrade 1990; Teixeira 1990; Ferreira et al. 1990; Ferreira 1993); it follows that the amount of sediment eventually lost to the shelf and necessary to readjust the shape and dimensions of the littoral wedge in response to sea level rise is small when compared with the stock reworked in the shallow nearshore by wave-driven longshore transport; yet, in some linear coastal stretches of the Algarve coast trending perpendicular to the prevailing direction of wave approach, the measured secular rates of erosion match the predicted order of magnitude yielded by Bruun's rule (Andrade 1990). Sea level rise is therefore a secondary factor of coastal change at the time-scale typical of engineering and the shelf is not a relevant sediment sink at this scale of observation.

#### 6.1.2.3 Tides

Tides along the Portuguese coast are semidiurnal, the Spring tidal range averaging 2.8-2.9 m (High-mesotidal coast, according to the modified classification of Hayes 1979). By their own, tidal currents are unimportant to coastal processes except in the vicinity of inlets and across tide-dominated basins such as estuaries and lagoons, where they may become prime agents of sediment and morphological dynamics, and usually capture sand to build tidal deltas. However, the combined effects of tidal-generated and oscillatory wave-borne currents is known to produce synergetic enhancement of the sediment transport in the nearshore, this effect gaining relevance in sheltered coastal sectors, where the direct action of waves may be significantly reduced. The large tidal range that characterizes the whole Portuguese coast is of particular importance to processes shaping rocky cliffs and shore platforms, where recent studies on downwearing of hard to soft bedrock yielded surprisingly high rates ($10^0$ to $10^1$ mmyr$^{-1}$) which in places substantiate the existing theoretical relationships between mesoscale cliff retreat intensity and shore platform downwearing (cf. Marques 2002), modelled by Sunamura (1990).

#### 6.1.2.4 Waves

The Portuguese west coast and the southern-facing coast of Algarve are quite asymmetric in what relates the wave energy and wave climate, the latter sharing similarities with E-W trending sections occurring along the western littoral, such as the southern coast of the Setúbal Península or the Lisbon – Cascais littoral stretch.

The western coast is fully exposed to far-generated waves in the Atlantic and is a high energy, swell-dominated coast. The WERATLAS (1993) report indicates decreasing values of mean annual gross wave power density with latitude, ranging between 46 kW.m$^{-1}$ off shore Vigo to 39 kWm$^{-1}$ at the latitude of Lisbon and 33 kWm$^{-1}$ some 300 km SW Cape S. Vicente. The yearly mean significant wave height and peak period off shore the northwestern coast are of 2-2.5 m and 9-11 s and the modal height and period range between 1.5-3 m and 9-14 s; this wave regime corresponds with WNW to NNW swell generated in high latitudes in the North Atlantic, and prevails more than 3/4 of the year (Carvalho and Barceló 1966; Pires and Pessanha 1986; Pires 1989; Costa 1994; Teixeira 1994). The shore wave regime is somewhat reduced in height due to early breaking (cf. Carvalho and Barceló 1966; Teixeira 1994) Hs being of approximately 2 m in the north and decreasing to 1.5 – 2 m at the latitude of Sines (Pires 1989; Teixeira 1994).

In the W coast calm sea is exceptional and storms (defined by Hs exceeding 5 m off shore) are frequent between October and March. Typical storms raise 6 to 9 m-high waves in shallow waters along this coast (Pita and Santos 1989;1992; Carvalho and Capitão 1991); yet Hs exceeded 10 m during storms between 1956 and 1988 (Pita and Santos 1989) and the maximum Hs and Hmax reached 14 m and exceeded 21 m, respectively, in the same period (Pita and Santos 1992; Carvalho and Capitão 1991). Westerly storms approach from W (>50%) to WNW (*circa* 30%) typically last for 8 to 10 days and are extremely damaging, usually affecting the whole of the western coast; they are generated by fast moving wide and deep depressions in Winters characterized by pronounced southward shift of the Polar Front (Pires 1989; Carvalho and Capitão 1991). Southwesterly storms are usually short lived, and correspond to proximal source areas developed by Winter depressions moving across shore, which typically raise 4–7 m high waves with 9-10 s period.

Deep-water northwesterly waves account for most of the energy dissipated along sheltered sections of the western shore, such as the Cape Roca-Fonte da Telha or Cape Espichel-Carvalhal, where they approach the shore strongly affected by refraction (cf. Andrade and Barata 2002).

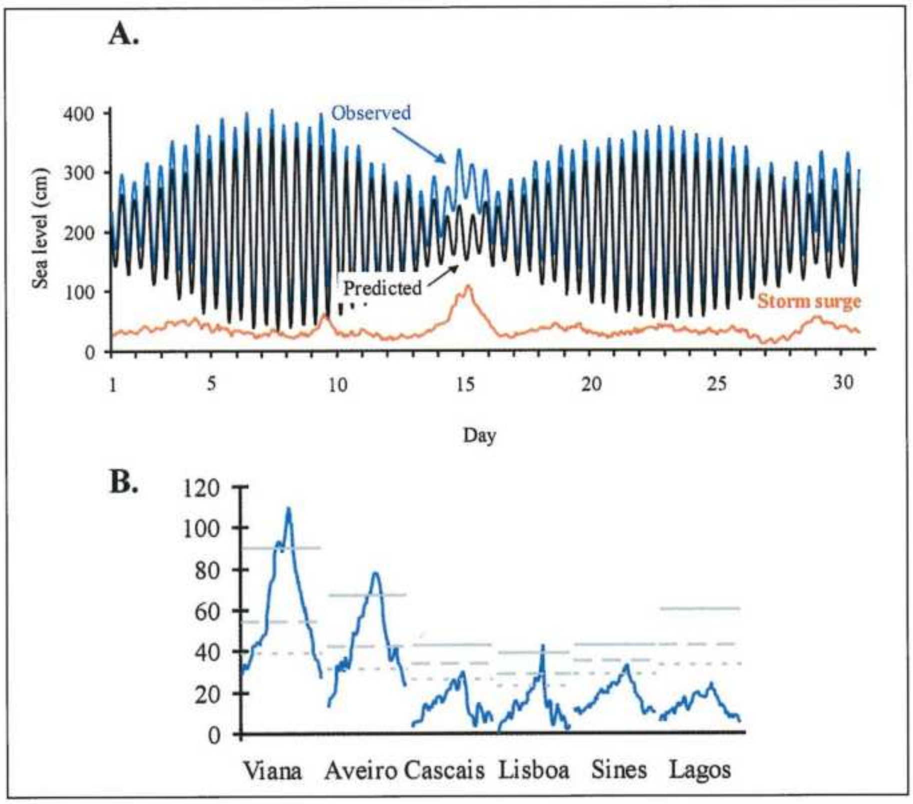

Figure 6.4 – A – Surge record, predicted and observed sea-levels during the 14-16 October 1987 storm at Viana do Castelo tide gauge. B – Storm surge levels observed in tide gauge stations during the 1987 storm. The heavy, dashed and dotted lines correspond to different ranking of storm surges – see table 1 (adapted from Gama et al. 1994a).

The southern Algarve coast is sheltered regarding waves approaching from the N-NW and the resultant regime is milder – 19 kWm$^{-1}$ mean annual gross wave power density off shore Cape Sagres, according to WERATLAS (1993). Calm sea (Hs< 0.5m) occurs during 30% of the year, the mean average Hs and period being 0.9 m and 6-11 s, respectively (Pires 1989; Andrade 1990; Costa 1994). Storms (defined as waves exceeding 2.5 m approaching this coast from the SW) never reach the intensity observed along the western coast; they typically rise 3 m, 8 s waves (the height of 5 m being exceptional) during 3 to 5 days, their intensity generally decreasing eastwards; storms from southeast ("levante") are usually weak, their duration varying between 1 day and one week, and occur when strong gales blow in the Gibraltar region; the resulting waves are usually 1–2 m and 6-7 s yet show high steepness and erosive potential.

### 6.1.2.5 Storm surge

Storm surge has been underestimated in maritime works and planning in Portugal until the pioneer works of Morais and Abecassis (1978) and Taborda and Dias (1992) which reported and characterized surge-induced vertical set up of the mean sea level of 0.5-1 m in locations of the west coast, developed during storms in 1973, 1978 and 1981. At present, storm surge and associated forcing of the Portuguese coast is still poorly characterized and known, the contributions of Gama et al. (1994a; b; 1995), Gama (1996) and Carvalho (1999) containing a summary of the current knowledge relying on both instrumented data and modelling. The results suggest that pressure-borne hydrostatic response of the near-shelf sea surface, and set-up resulting from both high onshore winds or Ekman-induced currents associated with strong alongshore south wind, pushing water ashore, are the main forcings of storm surge along the Portuguese coast. The statistical analyses of the frequency distribution of surge levels in five tide-gauge stations yielded the results presented in Table 6.1 and Figure 6.4. Care should be taken in extrapolating the return periods derived from this data due to the short length of the time-series used.

### 6.1.2.6 Synergies between surge and waves during storms

Relevant storm surges along the Portuguese coast associate with NW to SW high waves and intense rainfall. Their combined effects increase the washover, overtopping or breaching ability of both natural (beaches, barriers, dunes, cliffs) and artificial (jetties, breakwaters, bulkheads, sea-walls, dykes) barriers by incoming waves and may retard the natural outflow rate of fluvial and tidal currents during several

**Table 6.1 – Thresholds (cm) between storm-surge classes in different locations of the Portuguese coast (adapted from Gama et al. 1994a).**

| Storm surge | Tide gauge | | | | | | |
|---|---|---|---|---|---|---|---|
| | Viana | Aveiro | Cascais | Lisboa | Troia | Sines | Lagos |
| Significant | 39 | 31 | 26 | 23 | 28 | 29 | 33 |
| Very significant | 54 | 42 | 34 | 29 | 34 | 35 | 43 |
| Highly significant | 90 | 67 | 43 | 39 | 41 | 43 | 60 |
| Maximum observed | 110 | 78 | 52 | 48 | 51 | 47 | 75 |

Key: Significant > 95 percentile; Very significant > 99 percentile; Highly significant > 99.9 percentile

hours. Examples of extensive erosion, scarping and overwash of Portuguese low sandy coasts and soft cliffs and of barrier breaching associated with these circumstances have been reported in newspapers and scientific reports since the middle 1800s; the contributions of Perdigão (1931), Pereira (1937), Daveau et al. (1978), Feio and Almeida (1978), Feio (1980), Hidrotécnica Portuguesa (1980), Oliveira (1991), Reis et al. (1993) and Andrade et al. (1996) provide an extensive overview of the correspondent record and effects. The celebrated failure of the Sines breakwater in 1978, with many 42-tonne armour blocks being swept seaward or thrown above the jetty into the harbour illustrates the tremendous energy released upon the coast by these high-magnitude single events and their damaging potential. Under these circumstances, substantial amounts of sediment may be rapidly lost to the offshore but their return to the beach is certainly a slow process and sometimes may fail complete accomplishment. However, the exceptional erosive response of beaches (including the stripping off of the basal rock platforms, known to have been covered by beach sediment for more than 50 years), and pronounced retreat of the foredune toe observed along the whole of the Portuguese coast in the Winter of 2000/2001 did not associate with any particular single high magnitude event of coastal forcing; instead, it illustrates the accumulated effects of repetitive low-intensity storms which followed between December and March, separated by periods shorter than the time required for volumetric and morphologic recovery of the subaereal beach – estimated to exceed 3 months in the Algarve coast. An elucidative example of irreversible change of the sediment budget followed by steric and brittle response of the coast determined by the accumulated effects of both intense and short-term forcing with low-intensity but continuated depletion of a beach–dune system is described in Borges et al. (in press). Last but not least, many of the inundation events of downtown or low-lying developed areas of coastal towns, resorts and harbours (e.g. Lisbon, Porto, Oeiras, Cascais, Setúbal, Albufeira) reported since the 1960s (namely in 1967 and 1983), resulted from the unfortunate and infrequent – yet expectable – simultaneous occurrence of peak flow with Spring high tides and significant surge and were accompanied by the usual lot of damages, economic loss and, in cases, a distressing death toll.

### 6.1.2.7 Present-day dynamics

#### *6.1.2.7.1 Littoral Drift*

The high-energy wave regime of the Portuguese western coast, dominated by Northwesterlies, makes it one of the most active and susceptible of Europe. The huge amounts of energy released by breaking waves translate into exceptionally intense longshore drift, with a southward prevailing net residue of 1–2 million $m^3yr^{-1}$. Barata et al. (1996) demonstrated that most of this energy is conveyed by a relatively narrow spectrum of wave heights, slightly exceeding the yearly average and median Hs, the extremely high but infrequent storm waves contributing few to the longshore drift climate. The net longshore component of wave power and associated drift gradually subsides down to Cape S. Vicente, yet remaining within the same order of magnitude and direction in linear, exposed and N-S to NNE-SSW trending coastal ribbons; however, this potential easily falls of one or more orders of magnitude in linear sections slightly rotated clockwise, along equilibrium arcuate embayments and sections sheltered from the prevailing Northwesterlies, where the residual drift may be annulled or even reversed in direction. These contrasts are due to effects of shoaling, refraction, diffraction and sheltering, which range from regional to site-specific, in close dependence of the shelf, nearshore and coastal morphology, the whole lot interacting and feeding back with sediment supply and seasonal to mesoscale morphodyamical adjustment of the littoral wedge. This leads to the development of a number of encased coastal cell systems, whose dimensions decrease and whose physical boundaries change in position and permeability – both in space and time – with the increase of the spatial resolution and decreasing time-scale at which the sediment dynamics and morphological fluxes are to be understood, modelled or predicted.

Along the southern Algarve coast a similar reasoning may be applied, as most of the geological work performed by wave-borne processes associates with Southwesterlies, which predominate in terms of the longshore component of wave power. Net littoral drift is in general directed eastward in annual residue, typically ranges within $10^{3}$-$10^{4}$ $m^{3}yr^{-1}$ and locally reaches $10^{5}$ $m^{3}yr^{-1}$ along linear sections of the east coast; the exceptions are the linear NW-SW ribbons, which face the prevailing swell and display almost null residues of longshore power and drift, regardless the magnitude of the opposing components, wave energy being essentially dissipated by means of cross shore processes.

#### *6.1.2.7.2 Sediment Supply*

Sediment supply to the Portuguese shore is crucial to saturate the potential transport capacity of waves and maintain beach-dune systems, inlets, tidal deltas and the littoral drift conveying belt in balance.

Two major sediment sources nourish the Portuguese coast: stream sources and coastal erosion. Although the former constitute the largest suppliers of sediment to the shore at a worldwide scale, in Portugal only the basins located north of Espinho are relevant potential sources of bedload to the coast. This is due to the barred and estuarine nature of the vast majority of Portuguese river mouths, variable land use and soil erodibility, and strong asymmetry that characterizes the distribution of rainfall, evapotranspiration and consequent runoff in the watersheds. Fluvial networks have been extensively modified after the 1940s for water storage, energy production and flood control and include multiple dams and reservoirs (e.g. 140 dams along the Tagus river) which have dramatically reduced the actual sediment yield to the coast (cf. Hidrotécnica Portuguesa 1980; Oliveira et al. 1982; Oliveira 1990; Dias 1990 and Teixeira 1994 for a thorough review of the problem) – Fig. 6.5. At present the Tagus supplies less than 1/3 of its potential solid load to the inner estuary (Ramos and Reis 2001), and the bedload input of the Douro into the ocean (circa

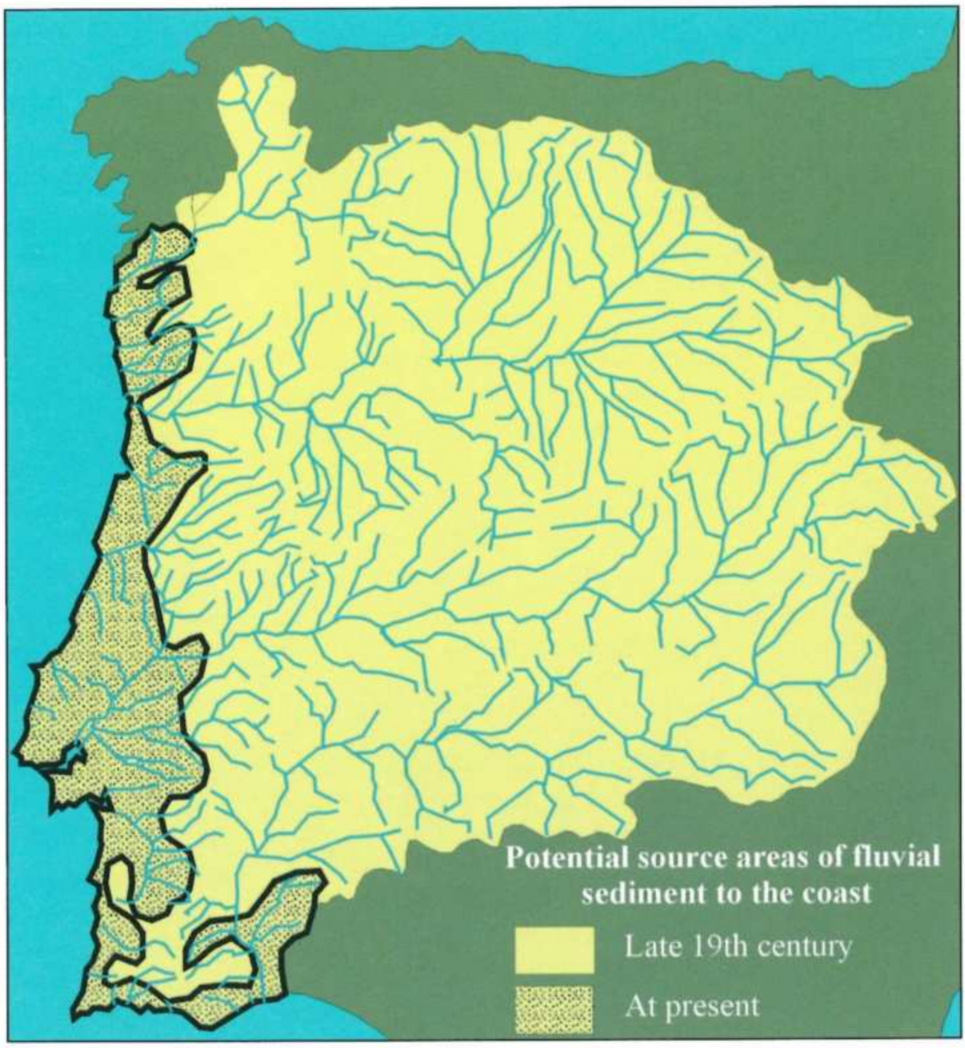

Figure 6.5 – Potential and effective source areas of sediment in Iberian watersheds resulting from dams (modified from Dias 1990).

2x10 $m^3yr^{-1}$) scarcely matches 1/7 of its potential transport rate (Oliveira et al. 1982; Ferreira 1993). Also, more sediment has been progressively retained due to the changes in land-use with relevance to reforestation programs and soil conservation practices in agriculture, which have been growing in importance since the last quarter of the 20th century. In addition, the mining of significant volumes of sand and shingle for construction and navigation, which has been steadily growing throughout the 20th century, contributed to the shortage of fluvial sediment input, leading to the undersaturation of the potential longshore drift and starvation of the coast.

Erosion of cliffs, beaches, dunes, strandplains, ebb-deltas and nearshore relict accumulations of sand is the present-day main source of sediment for the whole Portuguese coast and has been the most relevant process of supplying the amounts of sediment required to balance the littoral budget in several coastal cells. This erosion has been accomplished by a number of mechanisms, such as scarping of beaches and dunes, undercutting, mass movements and disintegration in cliffs, rill and gully incision of soft bedrock and flashfloods affecting small rivulets (Marques 1997a; b; Ramos and Reis 2001), that together determine shore recession at varied rates (Fig. 6.6).

Coastal erosion has been occasionally reported as hazardous or identified as a risk to the coast of Portugal in the late 1800s and the turn of the century marks a significant threshold in the widespreading and increasing intensity of this process (Teixeira 1990; Andrade et al. 1996). The reasons for this are still under discussion: some authors hypothesize relations with sea level fall contemporaneous of the Little Ice Age (e.g. Dias 1987), Granja (1990;1999) related climatic shift in the Little Ice Age to large-scale dune formation in NW Portugal and others privilege changes of both storm and wave climates (e.g. Andrade et al. 1996). Regardless the nature of causes, the setting up of erosion triggered a strong demand for coastal protection, which until very recently relied essentially upon hard defences, designed for mitigation and control of localized problems, and lead to the armouring of significant lengths of the coast (Alves et al. 1999), the artificial nourishment of the Praia da Rocha (Algarve) being a notable exception. Increasing anthropic disturbance enhanced the natural background stress upon the coast and coastal processes and increased erosion, favoured washover and flooding (Dias et al. 1994; Andrade 1998). Only after the 1980s the approach to littoral problems acquired a more integrated character, the concept of dynamic cell and the need to assess impacts beyond the strict physical boundaries of the site-specific problems became major concerns of authorities in coastal planning.

#### *6.1.2.7.3 Coastal Response*

The coastal section between the Minho estuary and Espinho is clearly undersaturated in sediment and starved, showing only but limited sand and shingle accumulations in thin pocket beaches and significant sand retention in estuarine mouths. The erosion rates of the rocky headlands and margin are negligible, yet they increase significantly in estuarine-spits or wider sand beaches, particularly downdrift of natural (headlands) or artificial (groins, jetties) barriers to longshore drift. This coast may be divided into a number of site specific cells sharing semi-permeable boundaries with the adjoining sections.

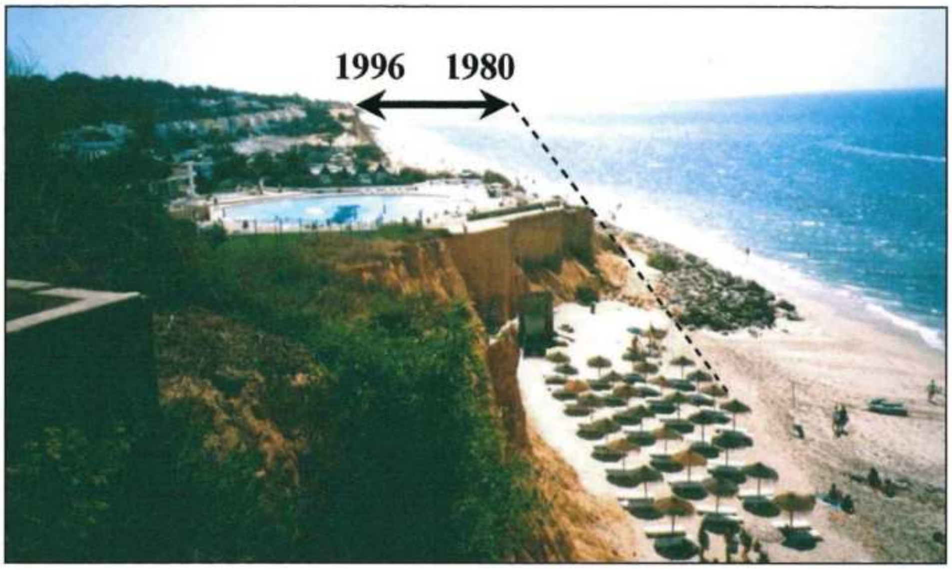

Figure 6.6 – Cliff retreat at Vale de Lobo (Algarve). Arrows indicate 16 years retreat of the cliff edge.

Between Espinho and Nazaré, the coastal dynamics is essentially dependent on longshore processes of sediment movement and the available sediment stocks in anamorphic littoral forms are huge. Natural barriers (such as Cape Mondego) are bypassed, but artificial structures (such as the jetties of the Aveiro inlet and the several existing groin fields and parallel defences) strongly disturb the sediment supply downdrift. Consequently, the beaches or barriers of Paramos, Cortegaça, Furadouro (south of Espinho), Costa Nova and Vagueira (downdrift of the Aveiro jetties) and south of Cova and Gala (downdrift of the south jetty of the harbour of Figueira da Foz) experienced very intensive erosion rates, in cases exceeding 8-10 $myr^{-1}$.

The Nazaré canyon conveys huge amounts of longshore-driven sediment into the continental shelf and slope and limited bypassing of this headland-canyon singularity still nourishes the littoral extending southward. Sediment is progressively entrapped in places of the rocky shore and longshore supply rapidly decreases southwards. In addition, the clockwise rotation of the linear coastal sectors south of Nazaré until the Peniche tombolo, such as the barrier of Óbidos, favours normal incidence of the prevailing waves, resulting in very small net littoral drift when compared with the high magnitude of seasonal components. This is a situation of very precarious equilibrium and extreme sensitivity of the coast to slight directional changes of both wave and storm climates. The average retreat rates of the cliffed coast are relatively small ($10^1$ to $10^{-1}$ $mmyr^{-1}$, according to Marques 1997a) and punctuated by infrequent localized large scale mass movements in high cliffs cut in marls. The Peniche tombolo defines an impermeable boundary to longshore drift and is margined by two wide equilibrium sandy bays with beaches and dunes, which rework a local sediment stock, steadily decreasing since the Middle Ages. South of Peniche the coast is starved, the same situation that characterizes the W-E section extending between Cape Roca and the Tagus estuary, which is inactive either as a sediment source or sink in what sand is concerned.

The coast extending further south until the Sines headland is nourished by erosion in the central region of the embayments (reaching 1 $myr^{-1}$ according to Marques et al. 1995; Marques1997a; 2000), which show divergent directions of the net drift departing from this location. Wave energy density increases in general southward along each of these arcuated sections, which show a complex pattern of sediment dynamics and circulation at both the seasonal and secular scales. The Arrábida coast is starved and corresponds to extremely stable plunging cliffs.

Between Sines and the S. Vicente-Sagres headlands, the coast is once more starved and rocky, the only relevant sources consisting of reduced sand inputs delivered by flash floods of small creeks and added by shingle to gritty contributions of localized cliff recession, which reaches an order of magnitude of $10^{-1}$-$10^{0}$ $cmyr^{-1}$ (Marques 1997b).

The southern Algarve coast repeats a similar morphodynamic and sediment dynamic context in its western section, until Olhos d'Água. Although limited in intensity, the potential transport ability of waves is clearly undersaturated and the coast is generally starved, the only relevant inputs resulting from localized gulling and failure of the Plio-Pleistocene sand units that top and outcrop along slowly retreating cliffs (Marques 1997b). Further east, the western barrier of Ria Formosa (Praia de Faro) replicates the delicate equilibrium condition previously described in Óbidos, this time in what regards the prevailing SW waves (Andrade 1995; LNEC 1997). The Faro inlet and jetties built an impermeable boundary to the longshore drift (Andrade 1990) and yet the eastern barriers respond and interact with moderately intense eastward longitudinal sand movement, of some 100,000 to 150,000 $m^3yr^{-1}$, which has been sourced at the expense of the Armona ebb delta, a situation that will soon come to an end.

## 6.2 METHODOLOGY

### 6.2.1 DESCRIPTION OF ASSESSMENT APPROACH

#### 6.2.1.1 State of the Art

Our current assessment of climate change impacts upon the coastal zone is still incomplete. In contrast with abundant literature linking economic activities to climate change, few studies exist that link climate change to impacts in sectors of economy dependent on the coast or coastal related processes, and virtually no comprehensive studies exist on non-market impacts (cf. Mendelsohn et al. 1999 for a literature review).

The early U.S. EPA Report (EPA 1986) on the effects of global climate change provided a worldwide-scoped pioneer document, the coastal zones being addressed under the sole theme of sea level rise and associated impacts in selected coastal locations. Within the IPCC, the Working Group III – Coastal Zone Management Subgroup (CZMS) – developed a common methodology (IPCC 1991) that uses a stepwise approach to cope with accelerated sea level rise (ASLR) impacts and include country-specific institutional, economic, technical and social implications. This dynamic view, shared by Yohe et al. (1999) among others, represents significant progress from the previous static approaches forwarded by Gibbs (1984), Kana et al. (1986) or Nordhaus (1991). One of the aims of the CZMS is to provide a worldwide estimate of socioeconomic and ecological implications of ASLR, this goal being prejudiced by the long time required to complete the necessary supporting studies. For this reason, the Global Vulnerability Assessment has focused on producing a first overview of the vulnerability of coastal regions on a global scale (Hoozemans and Hulsbergen 1995). Similar evaluations are being conducted in several countries, studies are being completed, in progress or planning stage; the present assessment is a pioneer contribution in Portugal.

Later assessments provide socioeconomic and ecological studies of global climate change implications upon the coast, which range in spatial scale from worldwide to regional and local, and use sectorial to partly-integrated methods of assessment, addressing single or multiple factors of forcing under dynamic views and including several scenarios of human feed-back (e.g. Nicholls et al. 1995; Klein and Nicholls 1998; Yohe et al. 1999; Downing et al. 1999; Field et al. 2001; IPCC 2001). Although there is a growing awareness that future climate-borne responses in a significant proportion of the world's coast will likely associate with impacts of forcing other than ASLR (e.g. changes in sediment supply resulting from weather or man-induced causes, shift of storm tracks, modification of the storminess patterns and increasing surge frequency – e.g. Bondesan et al. 1995; Viles and Spencer 1995; Plag et al. 2000; Jelgersma et al. 2000, SECRU 2002), impacts of anticipated sea level changes still form the core of concern in most scientific and technical literature, usually focusing on loss of dry land and wetland due to erosion or drowning and trying to associate a currency value to these effects.

Impact assessment upon the coast is in essence a multidisciplinary task that requires comprehensive understanding of causal-effect relationships within and between complicated systems of different nature: atmospheric, oceanic, geologic, biologic, environmental, social, economic, aesthetic and cultural, among others. Just as the advancement of scientific knowledge precludes the use of simple models of synchronous change of the world's oceans in response to global warming, achievements in coastal geology indicate that impacts and responses of the earth's crust to future climatic forcing are intrinsically complex; they vary in time scale, are frequently specific on regional to local spatial scales, and translate to different types and rates of geomorphological reaction (Carter 1988). Only very recently scientists granted relevance to a number of low frequency catastrophes (part of which are climate-triggered or feed back into the climate-driven component of coastal functioning) that have had profound impacts on country or larger spatial scales in shaping the coast (cf. de Groot and Granja 2001) and disrupted the established functioning of economy and society. This view is supported by recent work on the reconstruction of relations between forcing and coastal response throughout the Holocene in several Portuguese lowlands, which highlighted a number of brittle, catastrophic coastal responses, following a suite of impacts, which range between extreme events of flooding to continuated stress (e.g. Granja 1999; Andrade and Freitas 2000; 2001; de Groot and Granja 2001); in all cases, catastrophic behaviour corresponded to the exceedence of local levels of resilience, a subject that none of the afore mentioned studies includes in the scope of assessment. Our present knowledge of the coastal functioning is, unfortunately, very incomplete and is certainly insufficient to fulfil the requirements of deterministic approaches: in fact, a substantial part of this knowledge relies on empirical models and rests upon site-specific field data, usually acquired during short periods of observation. Also, in a large number of countries, including Portugal, one major impediment to impact assessment of forecasted rise in sea level is simply reduced to the lack of accurate data on ground elevations and poor spatial resolution of the available mapping. The scarcity of integrated studies relying upon long-term and regional to large scale data series has been bypassed by means of space-time substitution (cf. Brown and Quine 1999). In this approach, there is an implicit assumption of behavioural similarity among systems which presently respond to different levels of stress induced by the same factor of forcing regardless of their initial conditions. In addition, no validated methodologies exist that successively bridge the gap and establish some solution of continuity between the microscale approaches to coastal functioning, typical of engineering and usually supported by robust analogical or numerical models, and the meso to macroscale approaches commonly used by earth scientists, which heavily rely upon qualitative judgement and interpretation of the geological record.

The generalization of functioning models derived from specific contexts and limited data to coastal sections located elsewhere in the world and departing from different dynamic states is widespread in the scientific literature on coasts and coastal behaviour and yet it may lead to misunderstanding of local driving and response mechanisms, both present and future. However, these results, conclusions and models will eventually surface in the scientific literature, the latter serving as the essential foundation for technical assessment reports, which will absorb and perpetuate the original errors. These facts introduce additional elements of uncertainty when it comes to typify forecasted impacts of climate change upon the coast associated with one or multiple forcing, and stress the need to put greater emphasis on the development of methods for assessing vulnerability, especially at national and subnational scales where responses should be implemented (IPCC 2001).

#### 6.2.1.2 Options for Assessing Impacts on the Coastal Zones

Coastal systems can be affected in a variety of ways by climate change, the increasing of flood-frequency probability, erosion, inundation, rising water tables and saltwater intrusion being the most important geophysical effects. Owing to the great diversity and variation of natural coastal systems and to the local and regional differences in forcing factors, the occurrence of and response to these effects will not be uniform around the globe (Klein et al. 1999). Therefore, assessment of climate change impacts on coastal zone should draw on multidisciplinary studies and consequently employ an enormous variety of methods and tools (IPCC 2001).

An Integrated Assessment must be, ideally, interdisciplinary and iterative, in order to interpret and communicate knowledge from diverse scientific disciplines in the fields of natural and social sciences, to investigate and understand causal relationships within and between complicated systems (IPCC 2001). Methodological approaches employed in such assessments include computer-aided modelling, scenario analyses, simulation gaming and participatory integrated and qualitative assessments that are based on existing experience and expertise (IPCC 2001) and yield both qualitative and quantitative results. The assessment of impacts on human or natural systems that already have occurred as a result of recent climate changes is an important complement to model projections of future impacts (IPCC 2001).

##### *6.2.1.2.1 Data acquisition*

The starting point for any assessment study is the acquisition of the underlying data that characterize the problem and area under concern. The choice of adequate descriptors will to a large extent determine the quality of the final output and given the complexity inherent to the coastal zone it is difficult to forward a standard list of variables. Nevertheless, relevant characteristics of any natural coastal system with significance in assessment of impacts resulting from climate change include the following (Feenstra et al. 1998): coastal geology, geomorphology and topography; trends in sediment supply; erosion/stability/accretion trends; historical rates of relative sea level change and climatic data (wave and storm regimes, tides, floods). In addition, data on relevant socioeconomic characteristics of the area should be gathered if risk associated with the studied impacts must be evaluated: land use and value, demographic development, coastal protection and other economic, cultural and aesthetic values.

Several methods exist to obtain the required morphologic data, ranging from computer aided processing of both satellite and aerial photography imagery, to traditional photogrammetric processing, to field surveying. The choice of the most adequate data source must take into consideration the resolution of the available data and the length of coastline to be assessed within the available budget.

Satellite imagery processing is a promising method, yet somewhat expensive and currently does not match the adequate levels of accuracy in altimetry. In contrast, photogrammetric processing may be pushed to any desired level of resolution but is always time consuming and costly. Both methods rest upon the existence of a reasonably dense and high quality number of benchmarks, which are, in many countries, not readily available; in many cases both methods demand for specific technologies and expertise skills that must be searched outside the assessment team, therefore increasing the costs in time and money.

Geographical Information Systems (GIS) are an important technology for spatial analysis of the basic data. A very tempting application of GIS would be to overlay scenarios of sea level rise, storm surge, river flooding, tidal ranges and other forecasted effects of climate change with natural and socioeconomic data, to map and evaluate impacts, vulnerability, hazard and risk. The major drawback of this approach is that it must rely on vast, updated and high-resolution data sets, including < 1 m altimetric and < 10 m planimetric data. GIS technology and its applications are evolving rapidly and will hopefully provide an excellent (if not the standard) support to the assessment of impacts in the near future and a relying tool for judgement and decision on adaptation; at present, only a limited number of countries will be able to use its full potential beyond a local spatial scale.

A rapid and low cost surveying technique has been developed to overcome data deficiencies in studies on coastal land-loss in relation with sea level rise – the Aerial Videotape-Assisted Vulnerability Analysis (AVVA) (Nicholls et al. 1995; Leatherman et al. 1995). Like other semi-quantitative and qualitative approaches to data collection, AVVA heavily relies on expertise and judgement of the staff, this aspect being the most severe limitation of its accuracy and reliability. These difficulties may be overcome if the first-order data set is validated or improved using topographic and geological maps and ground-truthing; the method is easily adaptable to collect useful data on related subjects, such as vulnerability to storms, erosion and flooding.

#### *6.2.1.2.2 Data analyses*

Scenarios of forecasted climate change are essential to establish the time and space boundaries containing the anticipated changes in forcing factors and to constrain impacts within limits of plausibility. In general, the study of impacts of future rise in sea level upon the coast are attached to one or multiple scenarios of climate change and the improvement of GCMs achieved throughout the last decades translated into more realistic guesses of future changes in sea level.

Numerical models are extremely accurate and reliable instruments of prediction if dealing with short-term description of coastal functioning and forecast of impacts at detailed resolution scales. Otherwise, the summation of uncertainties inherent to the structure, functioning and assumptions of numerical modelling, added by performance limitations of computing technology, usually conduct to unrealistic results, which are of no use for management or adaptation purposes.

It is therefore preferable in early stages of assessment studies to rely on more simple models of coastal functioning of both qualitative and quantitative nature. This approach improves the chance of obtaining useful outputs within a reasonable time and to encompass larger sections of the coastal zone, but at cost of two drawbacks. First, the loss of spatial resolution and concomitant increase of the uncertainty; second, but equally important, the increased risk of non-expert end-users taking for granted a number of predictions which, in fact, represent only but best guesses within several choices. Figure 6.7 summarizes a practical approach to decide what appropriate land-loss model should be chosen to assess the two more important impacts of sea level changes (flooding and erosion) in contrasting coastal environments (cf. Nichols et al. 1995; Feenstra et al. 1998).

The empirical model of Bruun (Bruun 1962; 1988) and derivations from this model have been widely applied to assess erosive responses of the shore to anticipated sea level rise (e.g. Andrade 1990; Leatherman 1991), in spite of the discussion around the physical soundness of the underlying assumptions (cf. Carter and Woodroffe 1994, for a discussion on this matter and on the adequacy of the concept of equilibrium profile of the nearshore). Prediction of simple inundation of coastal lowlands resulting from ASLR have been addressed using

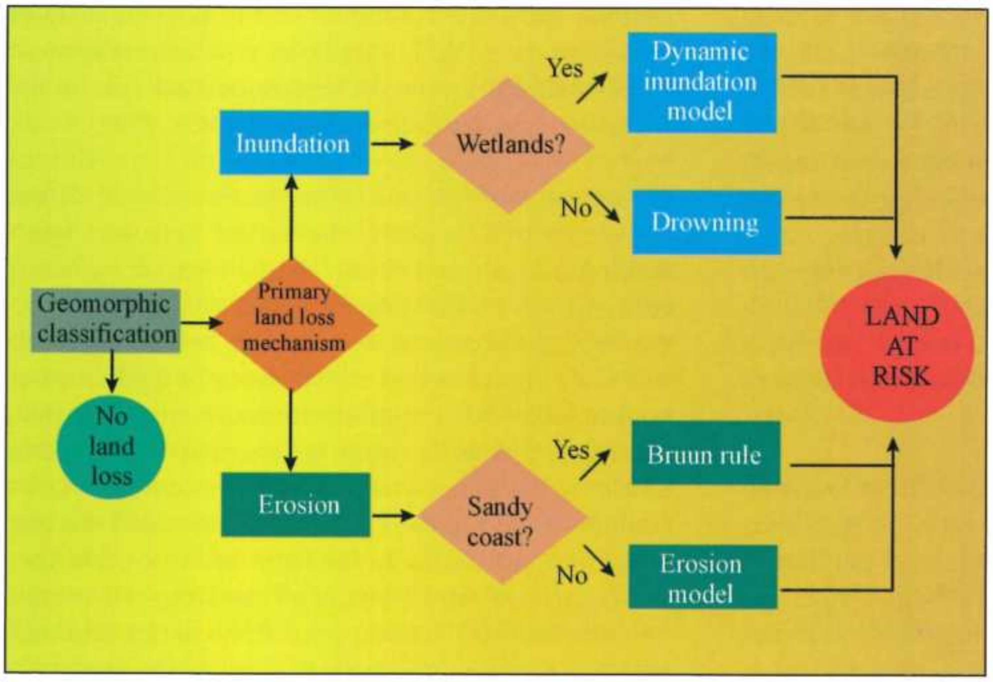

Figure 6.7 – Flow-diagram to determine the appropriate method to assess land at risk resulting from inundation and erosion (after Nicholls et al. 1995).

static linear models, relating the amount of land loss to surface slope, or weighting the simple inundation-slope relationships with filters determined from data on flood elevations and flood-preventive defences (Nicholls et al. 1995). Wetlands, such as lagoons, estuaries, tidal flats and marshes respond to sea level rise and changes in storms by means of vertical and horizontal accretion or erosion, and this response complicates the modelling of flooding impacts. The rates and patterns at which wetlands react to inundation are poorly defined and site-specific. Therefore, models of impacts of sea level rise upon these areas should include thresholds, dependent on the forecasting scenario and on present day rates of marsh accretion and on local sea level change (Nicholls et al. 1995).

When data are scarce impacts may be assessed using indices that to a variable extent rely on expert judgement. These index-based methods often lack the level of detail required to draw firm conclusions and should therefore be taken as a first order assessment only (Feenstra et al. 1998). The advantages of this methodology are the widening of potential sources of information which may be used as proxies of the missing data and the low cost requirements that allow to deal with extensive ribbons of coast within a reasonable time.

### 6.2.1.3 Description of Used Methodologies

#### *6.2.1.3.1 Data acquisition*

Data on coastal geomorphology, land use and coastal protection along the Portuguese littoral has been collected by means of AVVA. This technique requires a combination of: (1) oblique aerial video-recording of the coast; (2) archival research; (3) limited ground truthing and (4) data analysis and processing (cf. Leatherman et al. 1995 for details). Videotaping the coastline from a small craft at low altitude captures the relative aspect of the land to the sea (e.g. geomorphology, land use, types of occupation, defences and building density along the coast).

The archival research includes iconography (e.g., maps, aerial photographs) and technical reports, scientific literature and all information of value to assist interpretation and quantification of socioeconomic or natural characteristics captured in images, including trends of coastal evolution, geomorphology and other relevant features.

Ground-truthing is of use to solve uncertainties remnant from the rapid observation on board of a flying craft and archival data analyses; it is essential to provide objective scaling of elevations of both natural and artificial features and, in addition, the length and depth of relevant planimetric objects (e.g. city blocks, seawalls, jetties) can be obtained as well as updates of existing documents performed.

The 1:1,000,000 sheets of the CORINE Coastal Erosion Atlas (EC 1998) have been used as a source for information on stability of the coast. This information is categorised into seven classes that represent different states of shoreline evolution: (1) stable; (2) probable erosion trend; (3) confirmed erosion trend; (4) probable accretion trend; (5) confirmed accretion trend; (6) protection works; and (7) out of study or unknown.

The CORINE classification was aggregated and reduced to three classes of stability (Table 6.2): a) stable/accretion or stabilized by protection works which includes the former classes (1) and (4) to (6); b) tendency for erosion; and c) erosion confirmed. Classification (7) was replaced by extending the nature of the most vulnerable adjacent coastal strip. Information on coastal defences collected through AVVA overwhelmed the CORINE data in each individual cell classified as "hardened" or "with protection" (seawall, groin, jetty, bulkhead) and this cell was classified under a).

Other relevant variables were taken from existing documentary data, namely vertical aerial photography (1986-1988) and both topographic and geological maps surveyed by the Portuguese Army (Instituto Geográfico do Exército) and Geological Survey (Instituto Geológico e Mineiro). Complementary information was taken from existing Risk Maps (Monteiro and Lebreiro 1991; INAG and CEHIDRO 1999).

#### *6.2.1.3.2 Data processing*

Two methods of processing data acquired for the Portuguese coast have been applied for the purposes of this study, bearing in mind the available time and resolution constraints.

Assessment of Vulnerability and Risk – the Simple Multi-Attribute Rating Technique (SMART)

The assessment of vulnerability and risk of the coast using complex and limited information derived from indexes of qualitative and quantitative nature and describing processes-responses operating at different time-scales shares similarities with decision problems involving multiple objectives. One practical approach is to split the whole into small parts and focus on each part separately, instead of attempting a holistic view in early stages of the study. The results of the analyses of each part must be aggregated in a later stage of the work to achieve measurable results. The SMART approach is described in full in Goodwin and Wright (1991) and was adapted to assess impacts of forcing upon the Portuguese coast and to rank sections of this coast in terms of vulnerability and risk in relation to sea level rise and storms. The SMART is a simple and extremely flexible methodology that has proven to be of use in a wide scope of coastal problems in Portugal, ranging from the evaluation of the port capacity of estuaries (e.g. APL 1998) to the assessment of vulnerability to overwash and associated risk in the Algarve (e.g.. Andrade et al. 1998a; ICN 1998).

Having established lists of attributes relevant to the problems under study, the target area has been divided into a number of (ideally equal-dimension) cells, which in the present case, reduced to one-dimensional coastal sections. Each individual cell is therefore characterized by a number of qualitative or quantitative (discrete or continuous) attributes that, regardless its nature, must be assigned values within each cell. The quantification may not be straightforward in the case of qualitative and discrete (classified) attributes. In the latter two cases, arbitrary values can be assigned but, in all cases, the values must be rank-ordered making sure that correspondence with increasing vulnerability to the impact of a selected forcing varies in proportion with the selected ranking. An expert judgement should assist the processing at this stage of the problem and care should be taken to avoid redundancy. The next step is to remove bias resulting from different ranges between extreme values of each attribute, by means of some standardization procedure. In most cases, the number of coastal cells is sufficiently large to approach the empirical distribution of each attribute to the Normal Distribution and the usual standardization procedure consists in transforming the original data values into standard deviations from the mean of the population. The next step is aggregation, using additive or multiplicative procedures. In this way, an index combining multiple attributes is obtained, which is a proxy of the vulnerability or risk and may be used as a first-order quantitative descriptor, quite easy to translate into mapping or graphic representation. The major drawback of the method is that the aggregation operation is commutative, an obvious corollary of the underlying mathematics, which in cases does not have direct correspondence in the resultant of natural processes. In addition, the ranking of the output refers to deviations of the representative mean of the population and should not be taken as an absolute measure of vulnerability or risk.

Assessment of Risk of Land Loss – Nicholls' approach

When assessing the impacts of climate change upon the coastal zone, the most relevant concern is the spatial distribution and amount of land loss that can occur due to forecasted relative rise in sea level, increased storm surge and changing pattern of storminess, which potentially lead to erosion or inundation. Erosion stands for the physical removal of sediment by waves and currents, and inundation and drowning are hereby defined as the increased flooding or permanent submergence of low-lying coastal areas. The primary mechanism at any location depends on the geology and geomorphology of the coast, of its morphodynamics and sediment dynamics and of the boundary conditions at the initial time of the study. Despite other factors can play a part in determining land loss, it appears that sea level rise and consequent inundation – assuming no human response – will be a relevant cause for most of that impact at a worldwide scale (Feenstra et al. 1998; Nicholls et al. 1995); however, the dense human settlement and land value of many locations along the open coast mean that erosion will also have serious societal and economic implications. Because it is more simple and less expensive to control erosion or flooding at local and engineering time-scales than to devise and to frame solutions to cope with the elevation of mean sea level in a range of time horizons at a country-dimension, it looks quite probable that the no-response assumption is, at least, reducing, just as it is to forecast the response of a complex system to a varied suite of forcing factors using limited data, surveyed in a certain moment. Yet, at the intended level of analysis and given the available time and budget, it seems justified not to consider more sophisticated models, and to concentrate in the combined effects of all forcing agents contributing to potential land loss, regardless of the prime mechanism in each particular coastal location.

One simple approach to assess land loss, based on available data on the geomorphological features of the coast gathered using the AVVA technique, is described in Nicholls et al. (1995) and illustrated in figure 6.8.

The method heavily relies on expert judgement and yields a general picture of the distribution of the most hazardous spots on the costal ribbon in risk of land loss. Unlike SMART, this method does not include multiple variables, is manichaean in essence and jumps straightforward from evaluating the geomorphology into impact in terms of land loss which, if present, divides itself between inundation and erosion, once again in function of coastal contents. The concept of risk is taken in its widest sense since neither the rate of the coastal response is mapped, nor cross-correlation with land value or use is attempted, both items being necessary requisites to attach some value to land loss and to translate vulnerability or hazard into risk. The assumptions underlying the application of the flowchart in figures 6.7 and 6.8 are that on steep rocky coasts, no significant impacts will be felt; on wave-exposed sandy coasts and erodible cliffs, offshore transport of sand will be promoted and hence shoreline recession will be initiated or aggravated, implying land loss; on sheltered, low-lying coasts, including coastal wetlands, drowning is considered to be the primary land loss mechanism. Therefore, (1) by classifying the coastline by geomorphology, (2) the primary land loss mechanism can be defined and (3) an appropriate land loss model can be selected and applied (Figure 6.7). In the present case no further steps have been undertaken beyond step (2).

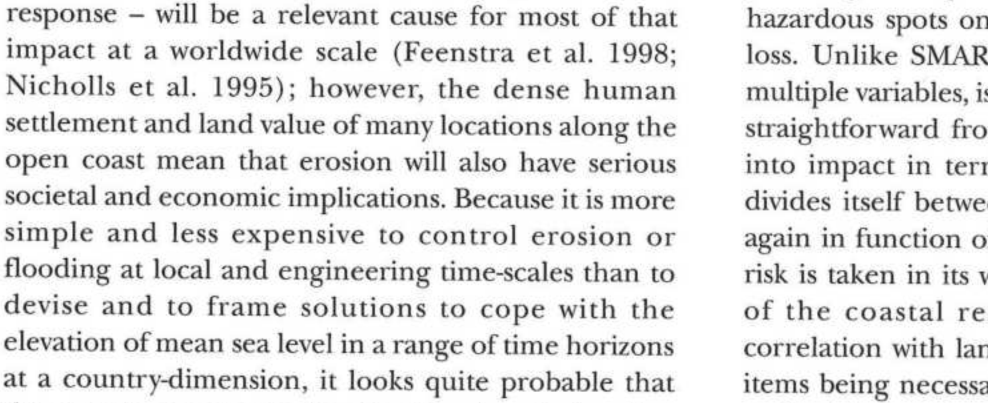

Figure 6.8 – Primary land loss response to sea-level rise by geomorphic type (adapted from Nicholls et al. 1995).

## 6.2.2 DESCRIPTION OF DATA USED

The videotape used as principal data source corresponds to a 1998 oblique aerial survey of the Portuguese coast, kindly supplied by INAG (Instituto da Água). The surveyed coastal strip was divided in 896 approximately 1.1 km-long cells, corresponding to a total length of 976 km, which includes limited upstream penetration in estuaries and inlets. The video failed to capture image in 67 cells and these have been characterized using replacement documents. The systematic observation and analyses of the videotape, assisted by complementary photographic and map information, yielded a varied and large amount of information that has been classified following a modification of the geomorphology and land-use system proposed in Leatherman et al. (1995). Some difficulties have arisen from the need to adjust a previously established classification system to the specificities of the Portuguese coast. Yet, given the time limitations and the general scope of this approach, changes restricted to indispensable modifications, keeping most of the original system untouched, thus ensuring comparability with similar studies carried out elsewhere.

### 6.2.2.1 Natural Attributes

Table 6.2 lists the classification of natural coastal attributes used in this approach. The system heavily weights the geomorphology of the coast, emphasizing the features of the fringe closer to the sea and within the expected elevation range of the mean sea level (coastal geomorphology) and includes explicit reference to the major geomorphic objects immediately backing the sea-front (inland geomorphology). The description of geological and structural features of rocks in cliffed sections reduces to an evaluation of resistance to erosion, and information on evolution trends in non-protected coastal ribbons has been added to the original system. Hardened sections are considered as a separate category of coastal geomorphology, the word was taken in its more restrictive scope, and assigned only when an artificial defence directly stands the impact of the sea. A consequence of the application of this system in coastal stretches characterized by geomorphological diversity at spatial scales matching the resolution of the analyses is an inevitable bias of the results towards

**Table 6.2 – AVVA – Natural attributes classification system (modified from Leatherman et al. 1995).**

| | | |
|---|---|---|
| **I. Coastal Geomorphology** | | |
| **A – Beaches** | | |
| 1. Barrier Beach | | |
| | *a. Type* | i) Bay barrier |
| | | ii) Barrier spit |
| | | iii) Barrier island |
| | *b. Morphology* | i) High (>5m), continuous foredune |
| | | ii) Extensive dune field |
| | | iii) Low, dunes with washovers |
| 2. Strandplain | | |
| | *a. Type* | i) Low coastal plain |
| | | ii) Flanked by erodible cliffs |
| | | iii) Flanked by hard rock cliffs |
| | *b. Morphology* | i) High (>5m), continuous foredune |
| | | ii) Extensive dune field |
| | | iii) Low, dunes with washovers |
| 3. Pocket Beach | | |
| | *a. Type* | i) Flanked by erodible headlands |
| | | ii) Flanked by rocky headlands |
| | *b. Morphology* | i) High (>5m), continuous foredune |
| | | ii) Extensive dune field |
| | | iii) Low, dunes with washovers |
| **B – Wetlands** | | |
| 1. Estuary | | a. Marsh (grass) |
| | | b. Marsh (scrub shrub) |
| 2. Backbarrier Areas | | a. Marsh (grass) |
| | | b. Marsh (scrub shrub) |
| | | c. Marsh (forested) |
| 3. Tidal Flats | | |
| **C – Cliffs (no beach)** | | |
| 1. Erodible | | a. Dunes on top of cliff |
| | | b. Flatland on the top of cliff |
| | | c. Hilly land on the top of cliff |
| | | d. Mountainous land on the top of cliff |
| 2. Rocky | | a. Dunes on top of cliff |
| | | b. Flatland on the top of cliff |
| | | c. Hilly land on the top of cliff |
| | | d. Mountainous land on the top of cliff |
| **D – Hardened (Protected) Shoreline** | | |
| | | a. Sand dunes behind protection |
| | | b. Flatland behind protection |
| | | c. Hilly land behind protection |
| | | d. Mountainous behind protection |
| | | e. Wetland behind protection |
| **II. Inland Geomorphology** | | |
| A. Flatland | | |
| B. Hilly land | | |
| C. Mountainous land | | |
| D. Wetlands | | |
| **III. Evolution Trend** | | |
| A. Stable/Acretion or stabilized by protection works | | |
| B. Tendency to erode | | |
| C. Erosion confirmed | | |

exaggeration of the importance of singular features, such as small pocket beaches or dunes of limited extension when embedded in prevailing contrasting contexts.

**Table 6.3 – Absolute and relative frequency distributions of major land forms and stability along the Portuguese coast.**

| | | Points observed | % | km |
|---|---|---|---|---|
| Coastal geomorphology | Beaches | 540 | 60.3 | 589 |
| | Wetlands | 4 | 0.4 | 4 |
| | Cliffs – no beach | 322 | 35.9 | 351 |
| | Hardened | 30 | 3.4 | 33 |
| Inland geomorphology | Flatland | 494 | 55.1 | 538 |
| | Hilly land | 217 | 24.2 | 236 |
| | Mountainous land | 63 | 7.1 | 69 |
| | Wetlands | 122 | 13.6 | 133 |
| Evolution trend | Stable/Accretion or stabilized by protection works | 682 | 76.2 | 743 |
| | Tendency to erode | 208 | 23.2 | 226 |
| | Erosion confirmed | 6 | 0.6 | 6 |

The Portuguese coast is, to a large extent, not very high nor very steep and sand beaches are predominant features, exceeding half of its total length (Table 6.3 and Fig. 6.9). They occur as the ocean facing side of spits or barrier-islands and also fringing coastal plains and the toe of cliffs. Beaches are present in all stretches, being the single geomorphological feature east of Olhos d'Água but losing importance between Nazaré and Cape Raso (stretch 3) and Sines – Cape S. Vicente (stretch 6). Cliffs lacking beaches as toe-protection occupy a significant (about 1/3) extension of the coast and concentrate in the stretches 3, 4 and 6; plunging cliffs contribute with a small part to this total and occur in stretch 4 under the category of mountainous land along the Arrabida chain. Wetlands directly facing the ocean are virtually absent: they typically lean against, and extend landwards, of linear detrital barriers in close association with estuaries and lagoons. A large part of the wetlands expand oblique to the regional coastal trend and penetrate deep inland. In consequence, they are better represented by the inland geomorphology category and its presence is expressive in stretch 2 (Aveiro lagoon) and 8 (Ria Formosa).

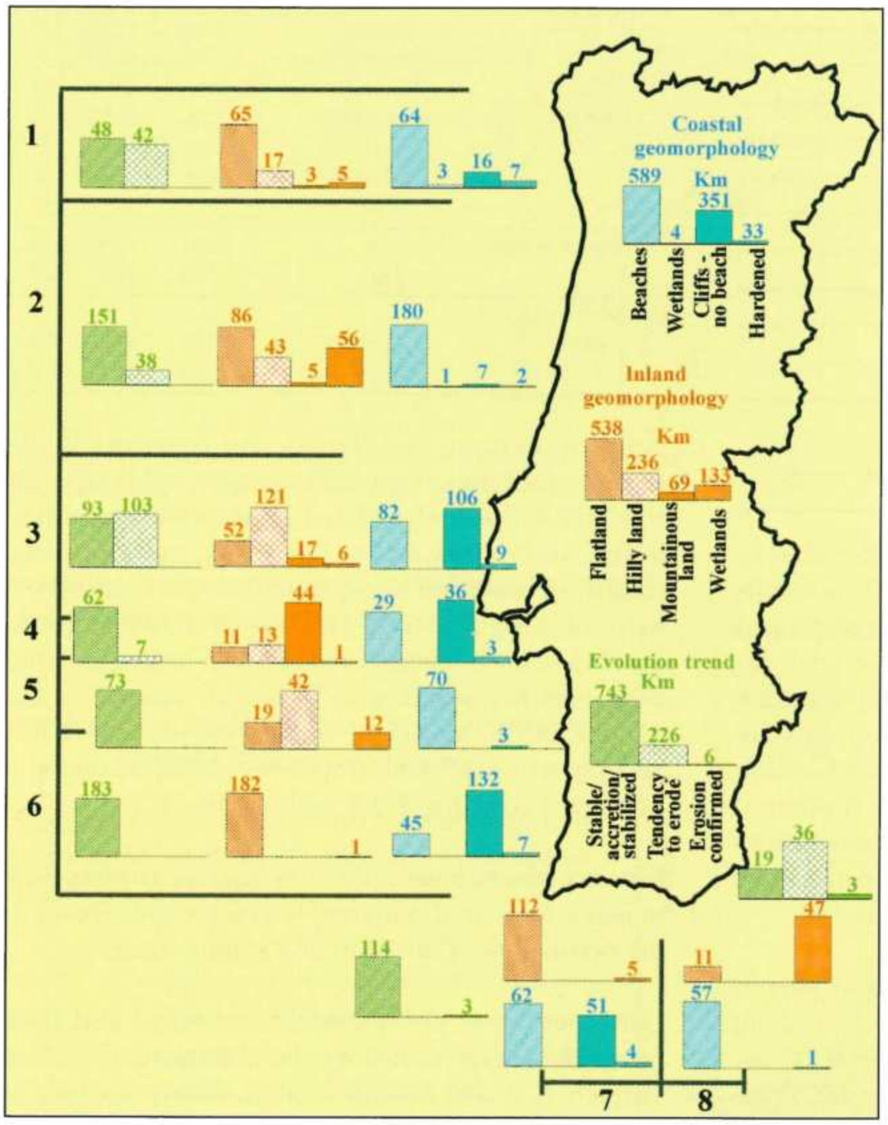

Figure 6.9 – Absolute frequency distribution of major land forms and stability attributes in different stretches of the Portuguese coast and summary data for all the country (inside map contour).

About 1/4 of the coast shows symptoms of instability, expressed by tendency to erode or erosion confirmed, in both cliffed and low-lying sections; this figure excludes coastal stretches armoured at the time of this study, within which erosion was halted. The pattern of confirmed erosion restricts to both Algarve stretches; this result underestimates the extension of the erosion problem along the Portuguese coast, namely in its central and NW façade.

### 6.2.2.2 Socioeconomic Attributes

Table 6.4 lists the classification of socioeconomic attributes considered relevant to the evaluation of risk which adds population density and coastal development to the original system.

**Table 6.4 – AVVA – Socioeconomic classification system (modified from Leatherman et al. 1995).**

| **I. Protection (if present)** |
|---|
| A. Seawall |
| B. Bulkhead |
| C. Groin |
| D. Jetty |
| E. Protected Harbour |
| **II. Land Use** |
| A. Urban/City |
| B. Residential |
| C. Industry |
| D. Tourism |
| E. Agriculture |
| F. Forest |
| G. Barren |
| H. Shrub land |
| **III. Population density** |
| A. High (>10 inhkm$^{-2}$) |
| B. Low (<10 inhkm$^{-2}$) |
| **IV. Coastal development** |
| A. High |
| B. Low |

Coastal protection has been traditionally undertaken by means of hard defences, among which seawalls predominate, to control marginal erosion of developed coastal areas, frequently at the cost of the adjacent beach tracts (Table 6.5 and Fig. 6.10). Jetties are inevitable complements of harbours and groins are increasing in number either to control localized erosion or to attempt sand retention seaward of revetment defences. Combination of different defence types ('more than one' in Fig. 6.10 and Table 6.5) occurs frequently, with relevance in stretches 2, 4 and 6.

The land-use categories of shrub land and barren correspond to about 2/3 and distribute evenly along the coast (Table 6.5 and Fig. 6.10); this reflects (1) the methodological constraint of retaining the use of the land lying at the water-front (bearing in mind the main concern of a less than 1 m rise in sea level); (2) historical inheritance in some stretches (e.g. stretch 6) and (3) legal constraints to the occupation of the seaward margin of the littoral fringe. Care must be taken when interpreting this information, which may give the erroneous image of a non-occupied coast.

**Table 6.5 – Absolute and relative frequency distribution of coastal protection works, land use, population density and coastal development along the Portuguese coast.**

| | | Points observed | % | Km |
|---|---|---|---|---|
| Protection | Seawall | 64 | 7.0 | 68 |
| | Bulkhead | 3 | 0.3 | 3 |
| | Groins | 14 | 1.5 | 15 |
| | Jetty | 10 | 1.1 | 11 |
| | Harbour | 11 | 1.2 | 12 |
| | More than one | 30 | 3.3 | 32 |
| | No protection | 764 | 85.5 | 8313 |
| Land use | Urban | 100 | 11.2 | 109 |
| | Residential/Tourism | 113 | 12.6 | 123 |
| | Industry | 18 | 2.1 | 20 |
| | Agriculture | 74 | 8.2 | 80 |
| | Shrub land | 550 | 61.3 | 599 |
| | Barren | 24 | 2.7 | 26 |
| | Forest | 18 | 2.1 | 20 |
| Population density | Low | 694 | 77.4 | 755 |
| | High | 202 | 22.6 | 220 |
| Coastal development density | Low | 698 | 77.9 | 759 |
| | High | 198 | 22.1 | 216 |

Housing (urban, residential and tourism) is the second more important land-use type and is typically concentrated in well defined clusters corresponding to the larger cities and to densely occupied sea side resorts, or scattered along the coast when associated with second housing and low density tourism development. In 2000 a total of 1,755 tourist facilities were legally operating in Portugal, mainly in the Algarve (40%) and close both to the Lisbon (27%) and Oporto (15%) metropolitan areas, involving a turnover exceeding € 1,2 million [IR 4].

Industry concentrates preferably in dense clusters close to major towns and ports and is a minor contributor to the occupation of the coast at a country scale.

Cultivated areas predominate over forest and both categories are relevant along the coast north of Lisbon (stretch 1, 2 and 3). Information on the density of population and coastal development was reduced to two categories (high/low), considered sufficient at the present level of this study. In both attributes the low

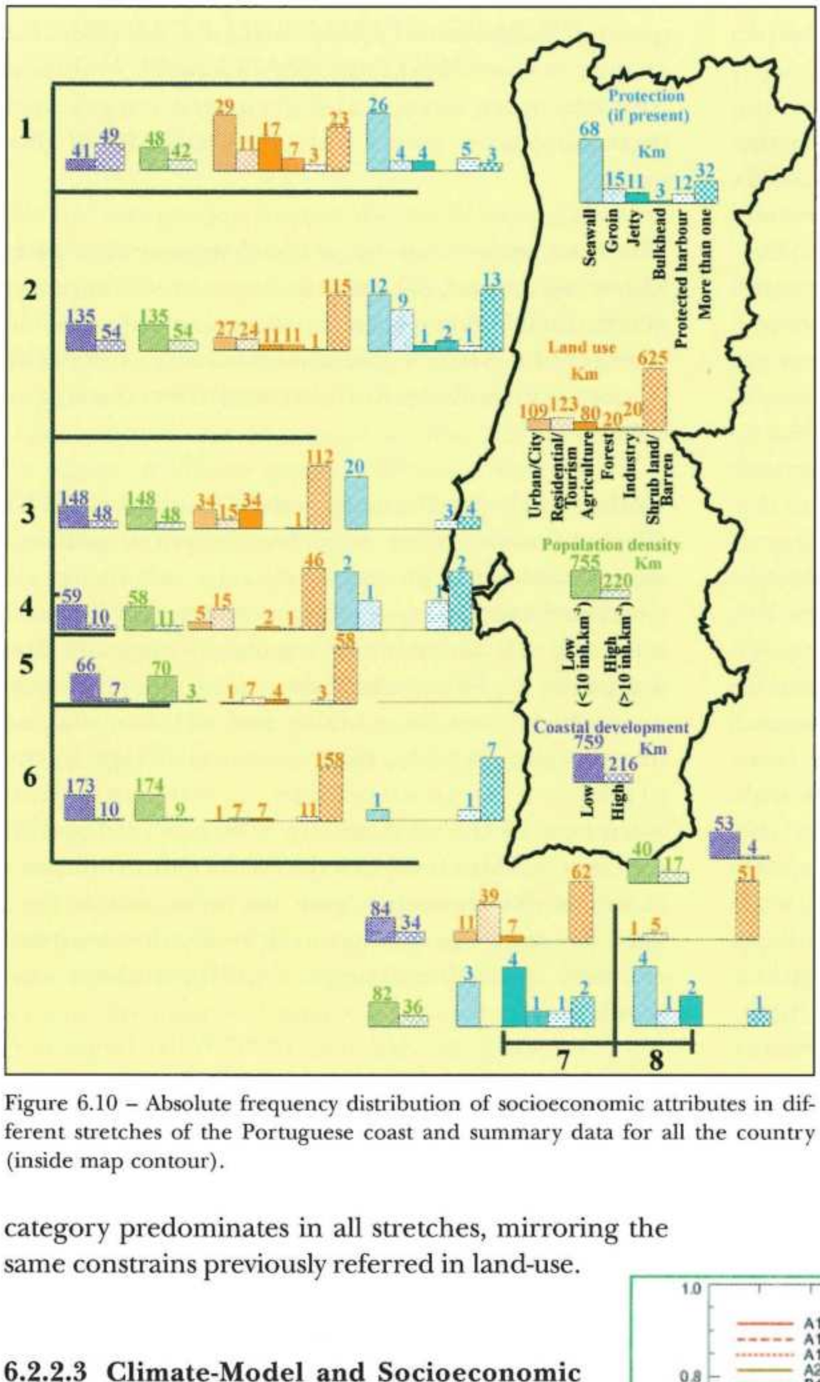

Figure 6.10 – Absolute frequency distribution of socioeconomic attributes in different stretches of the Portuguese coast and summary data for all the country (inside map contour).

category predominates in all stretches, mirroring the same constrains previously referred in land-use.

### 6.2.2.3 Climate-Model and Socioeconomic Scenario Generated Data

The scenario for relative sea level change in a given time horizon (t) can be expressed as (Feenstra et al. 1998):

$$S_{rt} = S_{g,t} + S_{o,t} + Vt = S_{g,t} + Vt$$

where, $S_{rt}$ = relative sea level rise in year t (m),
$S_{g,t}$ = global sea level rise in year t,
$S_{o,t}$ = regional sea level change induced by oceanic changes in year t (m)
$V$ = vertical land movement ($\mathrm{myr}^{-1}$), and
$t$ = number of years in the future (base year 1990).

The value of $S_{o,t}$ is considered zero, due to extreme uncertainty. Within the context of the discussion of mesoscale relative sea level rise in Portugal, and to the best of our knowledge it seems acceptable to assign also a zero value to V. This implies that, at the current level of approach, the future relative rise in sea level can be adequately described using estimates for global sea level rise at a given time horizon.

The IPCC (2001) projections of global average sea level rise from 1990 to 2100 (Fig. 6.11) using a range of AOGCMs and following IS 92a scenario (including the direct effect of aerosol emissions), lie in the range 0.11 – 0.77 m, the best guess being 0.3 – 0.5 m (cf. IPCC 2001 for further details). The projected sea level change rate in this interval is not uniform, a first period (1990-2040) being characterized by an average elevation rate of some 5 $\mathrm{mmyr}^{-1}$ which doubles in the second half of the century in the high scenario. Some studies predict more dramatic scenarios of relative sea level rise (e.g. Parry 2000) while others forward more optimistic estimates, such as of not more than 20 cm by the end of the 21st century (e.g. Mörner 2001).

In this study an elevation of mean sea level similar to the high IPCC 2001 scenario was assumed, in order to yield a first (cautious)

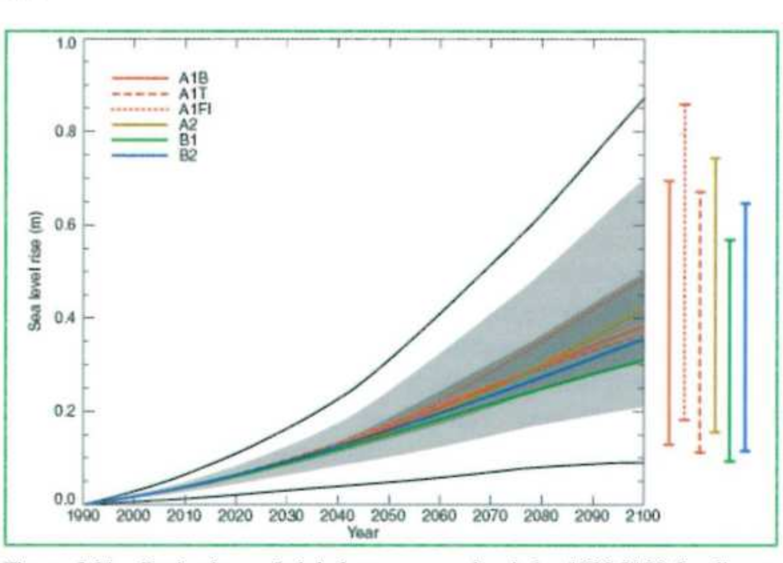

Figure 6.11 – Projections of global average sea level rise 1990-2100 for diverse emission scenarios (cf. IPCC 2001 for full details). Source: IPCC 2001.

approach that encompasses the likely relative change.

In the debate concerning climate change, the issue of possible intensification of extratropical storms in the North Atlantic, which include the ones affecting the Portuguese shores, is still controversial. The IPCC (1991) report is very cautious on this matter especially because of the lack of consistency between observed and modelled results. Langenberg et al. (1999) reported observed increases up to 10 cm in Winter Mean High Water Levels around the North Sea that were imputed to increased storminess and these results seem substantiated by the reports of the off shore oil industry on unprecedented storm intensity in that part of the world (Kaas et al. 2000). The results of Orford et al. (1996) and of the EU WASA Project (cf. Kaas et al. 2000 for further details) indicate that a tendency for increased storminess and higher than normal storm surges accompanied by increasing wave height characterised the later decades of the 20th century, in clear opposition with the results forwarded by Pirazzoli (2000) on the Atlantic coast of France. Yet, the former agree with the conclusions of the study of Bouws et al. (1996) undertaken in both margins of the North Atlantic at 50°-55° latitude, which suggest possible relations between the increasing height of swell and the NAO. Modelling of storm tracks under a 2x [$CO_2$] scenario suggests an increase of 10% in strength and a moderate northward shift of the modal paths (Kaas et al. 2000). An analysis of 127 years of storm data from the documentary record of the western Portuguese coast by Andrade et al. (1996) showed that there is a secular increase in storminess on that coast since the late 1800s despite strong interdecadal variability. Also, the work of Teixeira (1994) substantiates the hypothesis that the future wave and storm regime of the Portuguese shore will probably increase in frequency, intensity and duration of both average and extreme storms. The information is not sufficiently accurate to decide whether the shift in intensity of wave regime is related essentially to high magnitude single events, to modal wave regime or both. Clearly, this distinction is of prime importance in assessing impacts related with the consuming of energy released by breaking waves upon the coast. In addition, the available data on storm surge along the Portuguese coast is, at present, insufficient to substantiate forecasts of change in frequency, return periods and related impacts beyond the level of qualitative assessment. Given the context of plausible change in storminess and wave climate an evolution towards more severe and frequent surges and increasing wave power outcomes as a reasonable guess.

The four socioeconomic scenarios presented elsewhere in this book (Chapter Socio-economic impacts) may be analysed in qualitative terms to yield plausible changes of the future patterns of land-use and of the inherent pressure upon the coastal zone (local/global).

Under both A1 (Globalized Economy) and B1 (Global Sustainability) scenarios the population will rise, leading to an expansion in urban areas. Cultivated land is expected to decrease, while forest areas will remain stable or eventually increase. The tourism activities are also expected to bloom due to increasing desire for mobility and well-fare making that mobility possible; both scenarios diverge in the projection of amelioration of environmental awareness of the civil society, which is assumed in scenario A2. This is expected to reduce direct impacts of tourist developments upon the coast, due to feed back pressure towards nature-friendly development exerted by end-users upon policy-makers and developers.

Similarly, the A2 (National Interest) and B2 (Rural Sustainability) scenarios are to some extent identical in respect to projection of growth in population, agricultural areas and forests – they will remain stable or may slightly increase in consequence of limitations to urban concentration. Again, they diverge in tourism activity, which is expected to stabilize or decrease due to the lack of foreign investment (A2) or increased costs of real estate in the coastal areas (B2), resulting either from lower levels of economic activity or higher environmental awareness and restrictive policies aiming to reduce the pressure upon the coast.

The impacts of scenarios A and B upon the vulnerability of the coast are opposite in signal but no quantitative assessment is possible at the current level of knowledge. Given the present-day condition and structure of the country's economy and considering the principle of maximum precaution, the next chapter will consider the A1 or B1 socioeconomic scenarios as the most probable.

## 6.3 IMPACTS OF CLIMATE CHANGE ON THE COASTAL ZONE

### 6.3.1 INTRODUCTION

Climate change will impact the world's coastal areas in several ways. Sea level rise is regarded as one of the more certain consequences of climate change and is already taking place (Leatherman and Nicholls 1995; IPCC 2001). The rate of elevation of mean sea level is also a matter of importance and it is likely to increase, especially in the last part of the 21st century. Geological evidence recently obtained from the EU STORMS Project (1999), suggests that intervals of the Holocene characterized by increase of the sea level rise rate have been systematically accompanied by increases in flooding intensity and frequency resulting from changes in storms and storminess. These results agree with the mesoscale observation of increased storminess in the north Atlantic and substantiate scenarios of future increase in wave power.

The rapid elevation in mean sea level will eventually translate in land loss by extensive submergence of low-lying coastal areas. As the average depth of the nearshore increases, the highest tide level will also move upward and landward so that at least part of the present day intertidal area will become permanently submerged (Bird 1995); salt-tolerant species will try to invade farmland and the die-off of trees is expectable due to increased salinity (Leatherman 2001). Gently sloping coasts are likely to experience dramatic shift of the coastline even with small changes in water level; however, the gentle slope absorbs and dissipates the waves' energy along a broad front. In shallow meso to macrotidal basins, such as estuaries and lagoons, where frictional dissipation of tidal energy is depth-dependent, the tidal amplitude might be expected to increase with similar effects in mean tidal current velocities (Dyer 1995). The resulting enhancement of turbulence will tend to improve mixing and reduce stratification. Increasing tidal currents favor sediment movement and redistribution within the basin, leading to morphological adaptation of the bottom to the newly imposed dynamics. Given the existing relations between mean cross-sectional area of channels and both the tidal prism (Jarrett 1976; Bruun 1978; Hughes 2002) and distance upstream (Vincent and Corson 1980; Dyer 1995) and other factors remaining constant, the increase in tidal range is expected to cause the basin to deepen and to increase the estuarine breadth towards the mouth, which might potentially favor lateral expansion of marshland. The effects of tidal asymmetry in determining flood or ebb dominancy within a tidal basin are strongly site-specific and local within the same tidal basin and tidal asymmetry regulates a large fraction of the sediment dispersal and deposition patterns in estuaries and lagoons. It is therefore difficult to generalize the expectable change in the pattern of asymmetry determined by a rising sea level, but switch from one to the other mode of dominancy or towards a more symmetric pattern can be expected.

Regardless the departures from this first order approach, that depend on site-specific details, there will be loss of marshland and of tidal flats wherever physical barriers exist that inhibit the landward translation of the coastal ecosystem and whenever the rate of sea level rise exceeds the upper tolerance threshold of the salt marsh, which is primarily controlled by its rate of vertical accretion. In cases where the vertical accretion of flats and marsh matches or even exceeds the rate of sea level change, extensive choking of the basin is expectable and no appreciable land-loss will be felt in the intertidal areas. Most authors have concluded that wetlands could not keep pace with a significant acceleration in sea level rise (Kearney and Stevenson 1985), and thus the area of wetlands converted to open water will be much greater than the area of dry land converted to wetlands. Wave erosion usually concentrates along the leading edge of the tidal water level and a higher mean sea level will probably enhance marginal erosion of marshes but simultaneously increase the availability of re-suspended sediment to settle elsewhere within the tidal basin. The budget between opposing trends of marsh response – expansion, due to increased tidal range and retreat, resulting from enhanced wave activity – remains one other site-specific problem. The increase of tidal prism will enhance sediment retention in mesotidal ebb and flood-deltas therefore reducing the sediment supply to the adjacent shore and disturbing the present-day saturation level of wave-driven longshore currents. Along the open ocean coast a delicate balance exists between sediment supply, slope of the nearshore, wave power and sea level change rate that, apparently, modulate the response of clastic shorelines to sea level rise. The Holocene evolution of the Dutch coast typifies a progradational response under low sea level rise rate, while the eastern U.S. coast contains a varied suite of contemporary responses, ranging from progradation to drowning and to erosion. A response perceived as erosion of the ocean facing margin of a barrier might relate with the survival mechanism known as "roll-over", by which some of these features keep pace with rapid sea level rise and migrate landwards. This is not, however, the general case and a large number of coastal beaches and barriers will eventually erode and drown in place, if sea level rises at accelerated rates.

Erosion seems a widespread predicted response to accelerated near future sea level rise, either by intensification of existing trends or expansion of erosion to presently stable coastal tracts (Bird 1993;1995). An increase in sea level rise rate and in sea level will eventually force the nearshore sediment stock to move and redistribute across and along the shoreface (Wells 1995) resulting in net erosion of the subaereal section of the beach-dune system. Increasing wave heights and storminess will fuel up the power released at the coast, which translates into acceleration of sediment movement across and along the shore, therefore generating or enhancing erosion, with the exception of places where feed-back mechanisms of morphological compensation exist and are readily activated and where the external sediment input into the coastal system can counterbalance this increase of energy expenditure.

A rise in mean sea level will provide a higher base upon which storm surges can build and, in consequence, the return period of extreme storm surges will decrease and storm penetration inland will be favoured. Sea level rise could also increase flooding from rainstorms and river surges due to decreased drainage.

The potential socioeconomic impacts of climate change upon coastal areas have been categorised by Nicholls and Klein (2000 in Ferreira et al. in press) as follows: (1) direct loss of economic, ecological, cultural and subsistence values through loss of land, infrastructures and coastal habitats; (2) increased flood risk affecting people, land and infrastructures; and (3) changes in water resources, salinity and biological activity.

### 6.3.2 IMPACT OF CLIMATE CHANGE ON THE PORTUGUESE COAST

#### 6.3.2.1 Objective Assessment of Vulnerability

The basic data set obtained by the AVVA technique has been reorganized in four attributes, which are relevant to assess coastal vulnerability using the SMART approach: coastal contents (first and second order features), protection and evolution trend (Table 6.6). The 1st order features describe the seaward predominant contents of a littoral cell, with relevance to geomorphology. If protection is present (hardened – protected coast), it dominates the 1st order classification. The 2nd order features describe the predominant contents standing immediately landward of the 1st order feature. Several coastal cells display combinations of protection works. In these cases, the ranking was adjusted to 1.6, if two types of

**Table 6.6 – Attributes used to describe vulnerability of the coast to land loss and ranking of the performance of each attribute in relation to land loss. The ranking index grows with increasing vulnerability of the coast.**

| Attribute | 1st order features | | Rank | 2nd order features | Rank |
|---|---|---|---|---|---|
| **Coastal contents** | | | | Low dunes, washovers | 6 |
| | Sandy coast | Barriers (island, spit) | 5 | High dunes, extensive dune field | 5 |
| Natural | | Pocket beach | 4 | | |
| | | Opean beach, strandplain | 4 | | |
| | | | | Cliff (rocky) | 2 |
| | Cliffed coast | Rocky (hard) | 2 | Cliff (erodible) | 3 |
| | | Erodible (soft) | 3 | | |
| | | | | Coastal plain, flatland | 4 |
| | Wetland | | 5 | Wetland | 6 |
| Artificial | Hardened, protected (harbour, urban, residencial, industrial) | | 1 | Hardened, protected | 1 |
| | | | | Hilly, mountainous | 1 |
| **Protection works** | Jetty, Groin | | | | 3 |
| | Seawall, Bulkhead | | | | 2 |
| | Protected Harbour | | | | 1 |
| | No protection | | | | 4 |
| **Evolution trend** | Erosion confirmed | | | | 3 |
| | Erosion trend | | | | 2 |
| | Accretion, stable, stabilized (armoured) | | | | 1 |

protection coexisted, and to 1, if more than two types were present. The variables have been standardized and aggregated using an additive criterion to yield a vulnerability index for each coastal cell.

Figure 6.12 summarizes the performance of morphological attributes in relation to vulnerability. At a country scale the distribution of vulnerability of these attributes is bimodal with predominance of high vulnerability classes, which characterize, almost entirely, stretches 2, 5 and 8 in relation with their sandy and low-lying geomorphological contents. Stretches 4 and 6 and, to some extent, stretch 3, show opposite behaviour due to predominance of rocky and cliffed substrates.

In relation to coastal protection, the distribution is strongly unimodal and left tailed at both country and sectorial scales, stretches 1 and 2 concentrating most of the protection works (Fig. 6.13). South of Lisbon these features are rare and occur especially in the Algarve as a consequence of development associated with tourism. An asymmetry exists in the distribution of vulnerability as determined by the evolution trend: south of Lisbon low vulnerability is almost exclusive, with the exception of the eastern Algarve coast, which is more similar to stretches 1 to 3.

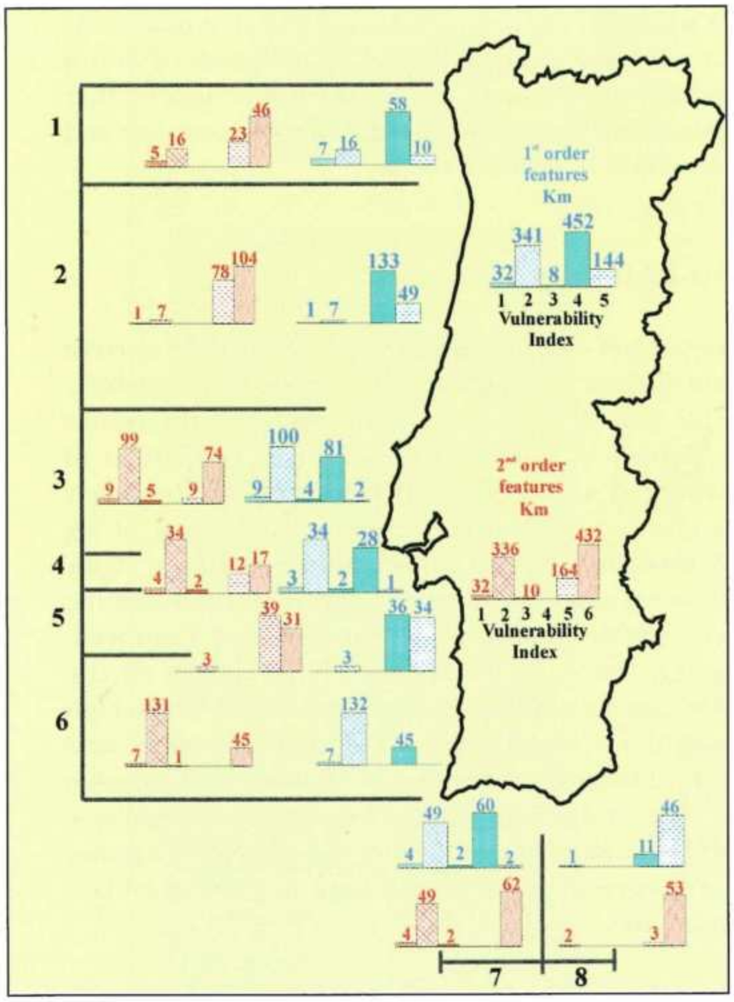

Figure 6.12 – Absolute frequency distribution of the performance of morphological attributes in relation to vulnerability in different stretches of the Portuguese coast and summary data for all the country (inside map contour).

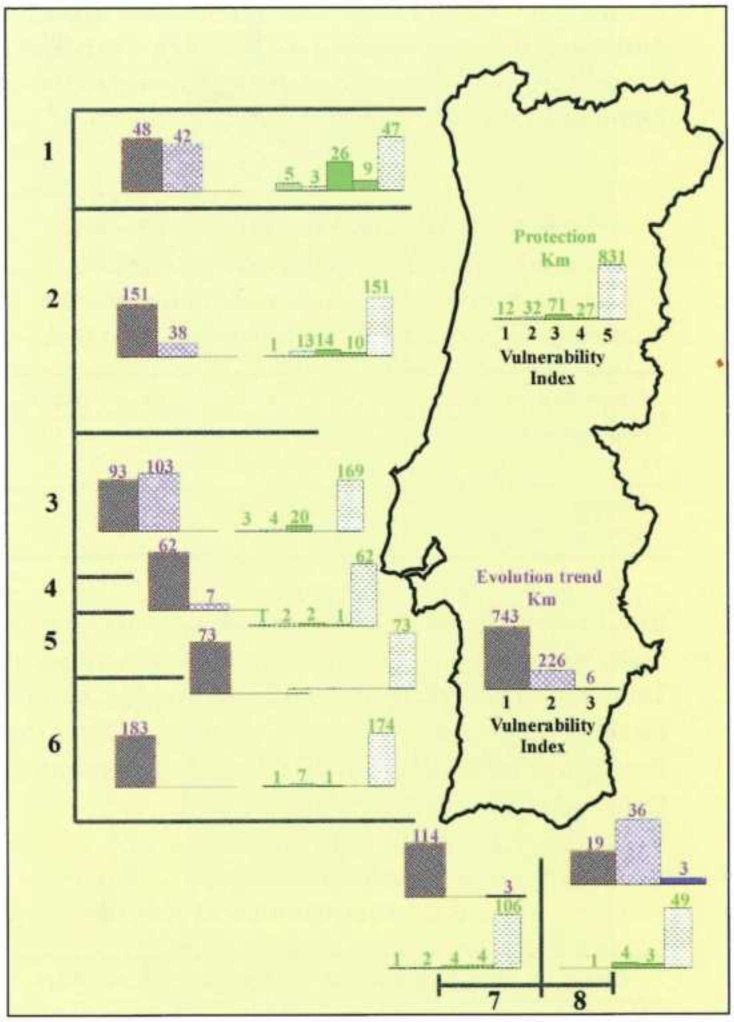

Figure 6.13 – Absolute frequency distribution of the performance of protection and evolution trend attributes in relation to vulnerability in different stretches of the Portuguese coast. Summary data for all the country inside map contour.

### 6.3.2.2 Objective Assessment of Risk

One approach to the evaluation of longshore distribution of risk to land loss has been undertaken using a SMART-borne index resulting from the additive aggregation of vulnerability with a proxy of coastal value (occupation value) – Table 6.7. The occupation value of each coastal cell resulted from the multiplicative aggregation of the ranked indexes describing population density and coastal development (Table 6.7).

**Table 6.7 – Attributes used to describe the occupation value of the coast in terms of socioeconomic features and rank index of each attribute's performance in relation to land loss.**

| Attribute | | Rank |
|---|---|---|
| **Population density** | High (>10 inh km$^{-2}$) | 2 |
| | Low (<10 inh km$^{-2}$) | 1 |
| **Coastal development** | High | 2 |
| | Low | 1 |

Risk has been ranked in five classes (very low to very high) using the criteria and boundaries described in Table 6.8. The information on risk yielded by this method is specific of the area under analyses (the Portuguese mainland coast) and given as departures from the national average.

**Table 6.8 – Classification of risk.**

| Class | Standard intervals | Standard values | Rank |
|---|---|---|---|
| Very low | $xi \leq x_{aveage} - 1.6\ \sigma$ | ]- ∞,- 4.05] | 1 |
| Low | $x_{aveage} - 1.6\ \sigma < x_i$<br>$x_{average} - 0.5\ \sigma \geq x_i$ | ]- 4.05, -1.28] | 2 |
| Medium | $x_{average} - 0.5\ \sigma < x_i$<br>$x_{average} + 0.5\ \sigma \geq x_i$ | ]-1.28, 1.26] | 3 |
| High | $x_{average} + 0.5\ \sigma < x_i$<br>$x_{average} + 1.6\ \sigma \geq x_i$ | ]1.26, 4.04] | 4 |
| Very high | $xi \geq x_{average} + 1.6\ \sigma$ | ] 4.04, ∞] | 5 |

The longshore distribution of values describing risk is generally quite variable at small spatial scales, stretches 4, 5 and 8 being unusually uniform and showing lateral persistence (Fig. 6.14 and 6.15). Stretches 1,2, 3 (north of Lisbon) and the eastern half of stretch 7 (Portimão – Olhos d'Água) are characterized by the predominance of medium-high risk, sector 8 displaying the most delicate situation (high and very high). In contrast, the coast south of Lisbon to Cape S. Vicente and to Portimão consistently displays medium to medium-low risk. The very extreme risk ranking, either very high or very low, usually corresponds to well defined and repetitive features. Very low risk sections are associated with armored ports, rocky headlands and resistant cliffs. The highest risk sections coincide with (1) highly valued land in different geodynamic contexts; and (2) fast eroding cliffs, spits/barriers sheltering wetlands and beaches, in association with different occupation values of the hinterland. In few, localized, cases (e.g. Praia da Cortegaça in stretch 1 and Praia de Faro in stretch 8) the method produces misleading results and underestimates risk. Actually, the low ranking of risk in these locations results from the existing protection structures which, however, are known to produce limited sheltering during storms.

The assessment of land at risk departing from Nicholls' method (Nicholls et al. 1995) provides an independent and complementary picture (Fig. 6.16), which yields absolute results and yet refers to only one dimension – the coastal length. The method foresees a risk of land loss in about 67% of the coastline. Land at risk concentrates specially in stretches 1, 2, 5 and 8, where the entire length of each ribbon is potentially at risk. At the present level of this study, it is not possible to evaluate the expression of loss further inland, nor to give an account of its importance and extension in terms of surface.

### 6.3.2.3 Impacts

Impacts of climate change along the Portuguese coast are difficult to generalize due to site specific variability and lack of basic data, as illustrated by the results obtained in this study. In addition, the effects of synergies and accumulation of impacts are poorly understood just as the temporal dimension of lag between forcing and impact. Also, our current ability to assess impacts of extreme weather events within the context of changes in climate must be improved, given the huge losses and importance to the functioning of the coastal system associated with high magnitude, single events. The following statements reflect these facts and should be taken as reasonable guesses and as first steps towards future investigations, which must proceed at higher resolution to maximize convergence between forecasted impacts and likely responses.

Inundation (the conversion of dry land to wetland) and drowning (the conversion of dry or wetland to open water) are likely to affect most low-lying areas along the coast corresponding with wetlands, in

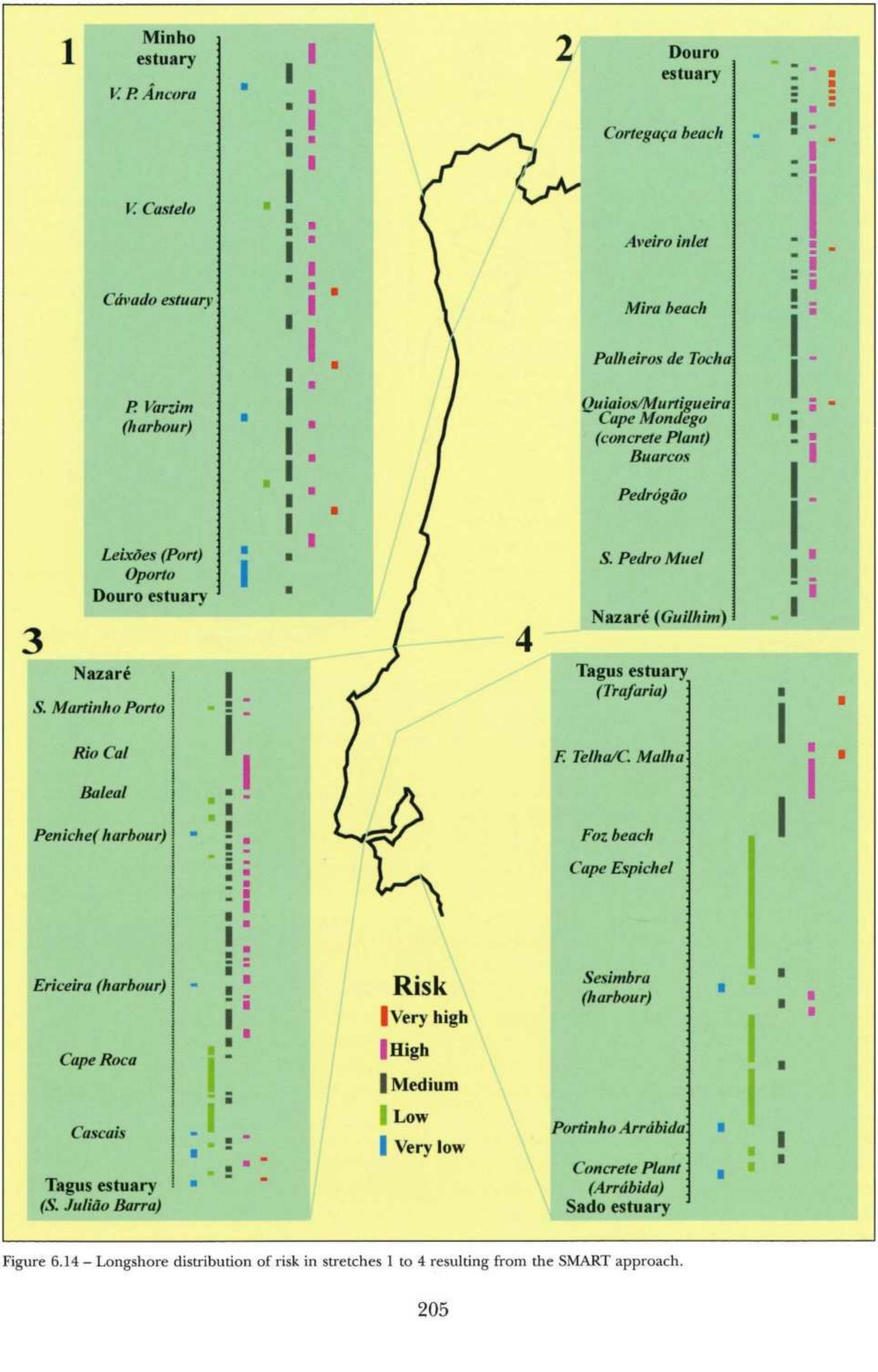

Figure 6.14 – Longshore distribution of risk in stretches 1 to 4 resulting from the SMART approach.

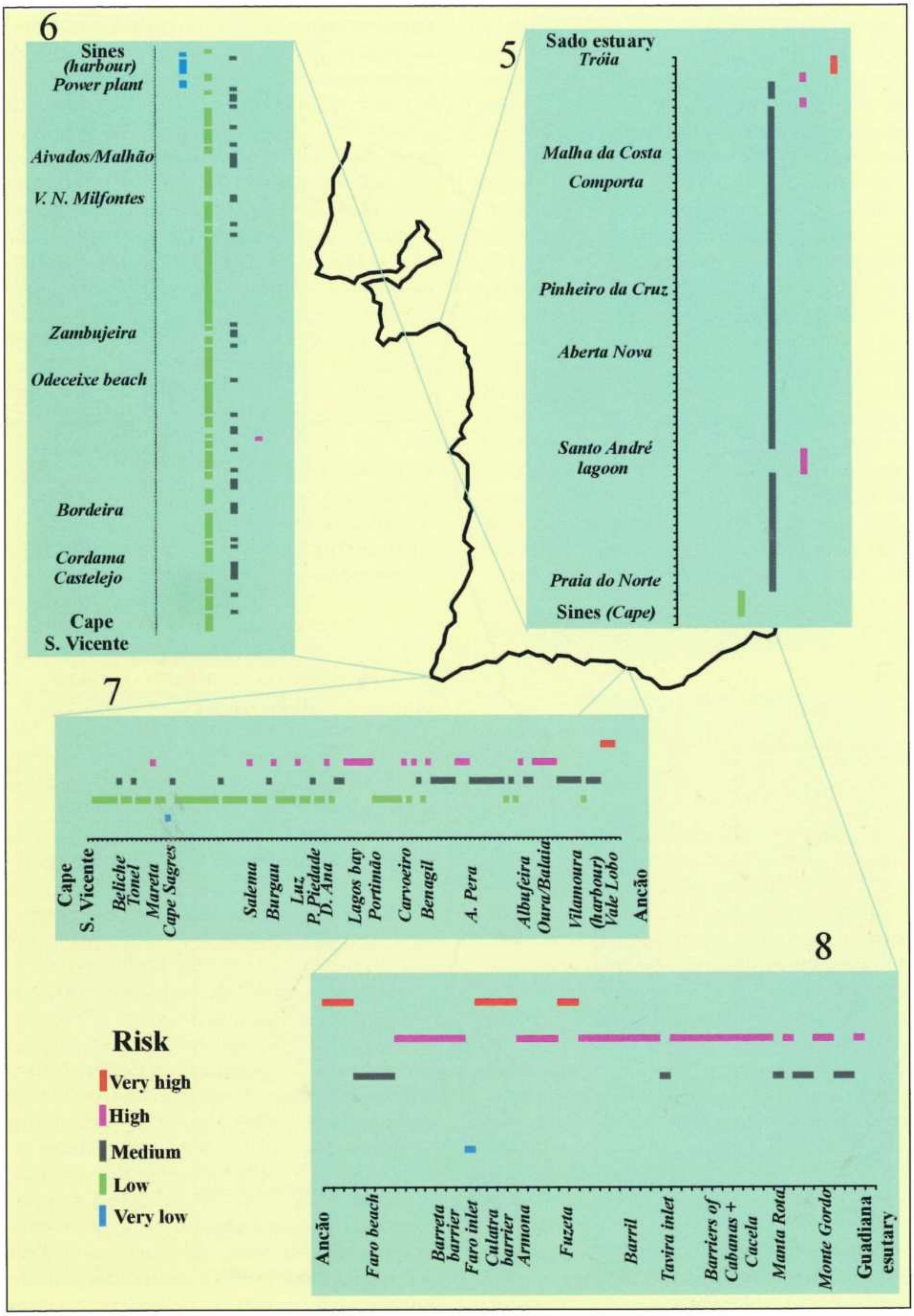

Figure 6.15 – Longshore distribution of risk in stretches 5 to 8 resulting from the SMART approach.

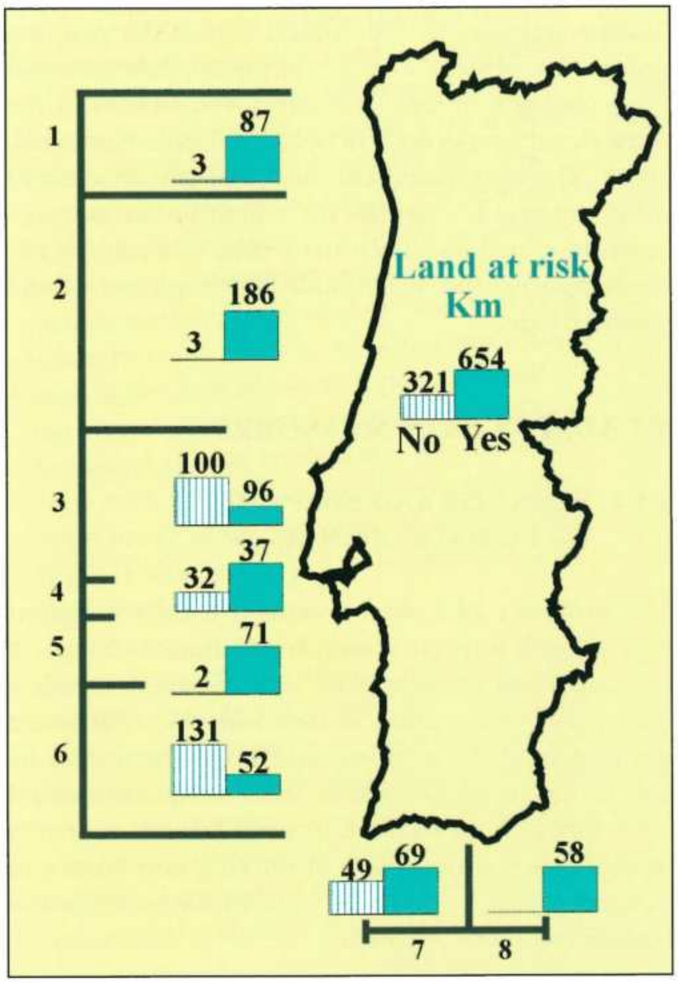

Figure 6.16 – Distribution of land at risk in different stretches of the Portuguese coast and summary data for all the country (inside map contour) using Nicholls' approach.

estuarine and lagoonal environments containing wide extensions of intertidal flats and marshes.

Should the resilience of the marsh cope with the disturbance induced by sea level change, no response of the ecosystem will be felt besides upward and landward displacement.

However, given that the boundaries of almost all Portuguese wetlands lean against dykes, walls and other rigid works designed to accommodate salt-works, fish farms and to control floods, this migration seems difficult and unlikely in a significant number of cases, leading to accelerated land loss. The assessment of the resilience of intertidal flats and marshes relies upon solid and accurate knowledge of the patterns and rates of sediment movement and this task is presently undone and should be conducted on a case to case basis. The sparse available data on micro to mesoscale sedimentation rates in Portuguese marshes indicates that a wide range of impacts are possible: in the Tagus estuary (e.g. Andrade et al. 1998b; Freire 1999) and in some coastal lagoons of the SW coast (e.g. Freitas 1995; Freitas et al. 2002; Freitas et al. in press b) the average accumulation rate presently exceeds 1 $\text{cmyr}^{-1}$ while in Algarve marshes of Ria Formosa it drops of one order of magnitude, scarcely matching the present-day sea level rise rate. Clearly, the impacts upon each of these marshes will be different. The pressure to displace present day depocenters further upstream in Portuguese estuaries is likely to enhance deposition of cohesive sediment deep inside the tidal basins, especially in those with low flushing times. This means added dredging effort and costs to keep navigation operational. The continuation or increasing of the present silting-up trend of coastal lagoons added by increased overwash ability will likely fasten the terrestrialization in some of these areas.

As nearshore waters deepen and in absence of a synchronous counterbalancing geomorphological response, larger and more destructive waves will break upon the coast, therefore enhancing erosion and inducing overwash of barriers. Thus, the general rule will be initiation of erosion in sectors which are stable at the moment, and acceleration of erosion where the coast is already receding.

The impacts of increasing wave-borne energy and northward shifting of the prevailing waves will vary in nature and consequences along the Portuguese coast. Resistant rocky sections are likely to be less impacted than soft, erodible, either cliffed or low-lying ribbons.

Increased wave power means increased geological work that will be spent in erosion, transport, reworking and deposition of sediment. Linear stretches of the coast trending NNE-SSW, such as the Espinho – Cabo Mondego, might experience increase of the net littoral drift and this will necessarily enhance recession of already starved systems, which feed their downdrift sections at the cost of updrift erosion. Linear sections trending NE-SW may disrupt the present-day delicate balance between longshore components of wave power and are likely to initiate a drift-dominated dynamics, similar to the one that governed the previously referred sections before significant human intervention; otherwise, the stress upon the system may trigger disproportionate responses of the coast to small scale disturbances and increase sensitivity to storms, even if of low-magnitude. Arcuate, equilibrium embayments appear to be the least impacted sections and an increase of the cross-shore sediment transfers may be foreseen; a case to case approach must be designed to support detailed assessment of impacts in these sections. Exceptions to this general statement are the small pocket beaches, corresponding to thin veneers of sediment resting upon rock or cobble basement and encased in cliffed coastal sections; the previsible impact of changing sea level and wave power is their vanishing, particularly where the supplying cliff has been reveted. In the southern coast of Algarve enhancement of the net residue of wave power and intensity of littoral drift are expectable; this will eventually increase starvation of western Algarve beaches and aggravate the incipient erosion along the low lying coast of Ria Formosa. The Faro peninsula is a functional equivalent of the Óbidos coast in what respects the anticipated shift of wave direction and no straightforward impact can be forecasted at present besides increasing overwash frequency.

The anticipated increase in temperature and aridity and reduction of mean annual rainfall (cf. Portela and Quintela 1998) will affect the fluvial network draining to the coast and carrying sediment into the littoral zone. This will have implications in river regime, and it is expectable that the reduction of river flow alters the circulation, mixing and flushing ability of estuaries and increase salt wedge penetration and retention of sediment; yet the impacts of these changes and the synergies with increasing flood intensity in what relates to the flushing time of estuaries have not been quantified, neither the feedbacks with the adjoining shore in terms of the sediment budget and sediment retention/release from tidal deltas (Bruun 1978; CERC 1984). Changes in the precipitation regime are likely to induce smaller impacts in the larger basins of Portugal because of the natural dumping associated with their extension, morphological maturity and number of dams. In contrast, the geological activity of flash floods in small catchments and of gulling of torrential channels in erodible cliffs might increase, with two opposing effects: increased delivery of sediment to the coastal system and enhancement of coastal retreat. At this stage, no reliable forecast can be forwarded on the effects of these contributions to the sediment budget, one of the most important controls determining coastal response.

The impacts of climate change upon the coast will also depend on socioeconomic factors, including future human activities in the coastal zones: the primary impacts are physical changes in the environment and these changes, in turn, will affect human uses of the coast (Leatherman and Nicholls 1995; Neumann et al. 2000). The anticipated knowledge of at least some of these impacts is essential for communities to make economic and social choices that can potentially contribute to the sustainable development of the coastal fringe.

## 6.4 ADAPTATION MEASURES

### 6.4.1 RESPONSE AND ADAPTATION TO CLIMATE CHANGE

The resilience of coastal systems is usually sufficient to cope with impacts arising from climate change, if they are given enough space and sediment to adjust their form. One option to deal with the anticipated impacts is to do nothing and let Nature take its course; however, given that the Portuguese coastal zone (just as most of the European littoral) is heavily used, an alternative option of working with Nature to sustain coastal ecosystems and minimise response costs seems more adequate.

Coastal adaptation to climate change can be considered a multi-stage and iterative process. Four basic steps recur in each of the case studies: (1) information collection and awareness raising; (2) planning and design; (3) implementation; and (4) monitoring and evaluation (Klein et al. 1999).

The assessment of adaptation exceeds the scope of technology (Capobianco 1999 in Klein et al. 2001) and must take into account appropriate and country specific economic, institutional, legal and socio-cultural contexts (Klein and Tol 1997 in Klein et al. 2001; Parry 2000) and should rely upon adequate scientific knowledge of the dynamical behaviour of the coastal system.

Several adaptation strategies exist, which are not mutually exclusive, being useful to distinguish emergency, reactive, from planned, anticipatory, adaptation. The former occurs after some impacts of climate change have become manifest and corresponds to interventions designed on a case to case basis to assist risk situations; the latter takes place before impacts are apparent and require more co-ordinated actions which must be concerted within the frame of a country-wide policy of coastal management. In Portugal, the first approach largely dominates and the country still lacks a clear definition of integrated options for coastal valuing and use. In addition, few relevant studies and very restricted public awareness exists on the potential impacts of climate change and, in particular, of sea level rise upon the coast (Ferreira et al. in press). This study is the first tentative approach to assess the extension of coastal vulnerability and risk to climate change impacts at a country scale. This makes it difficult to select the most appropriate strategy because of the multiple factors that condition the meaning of "appropriate".

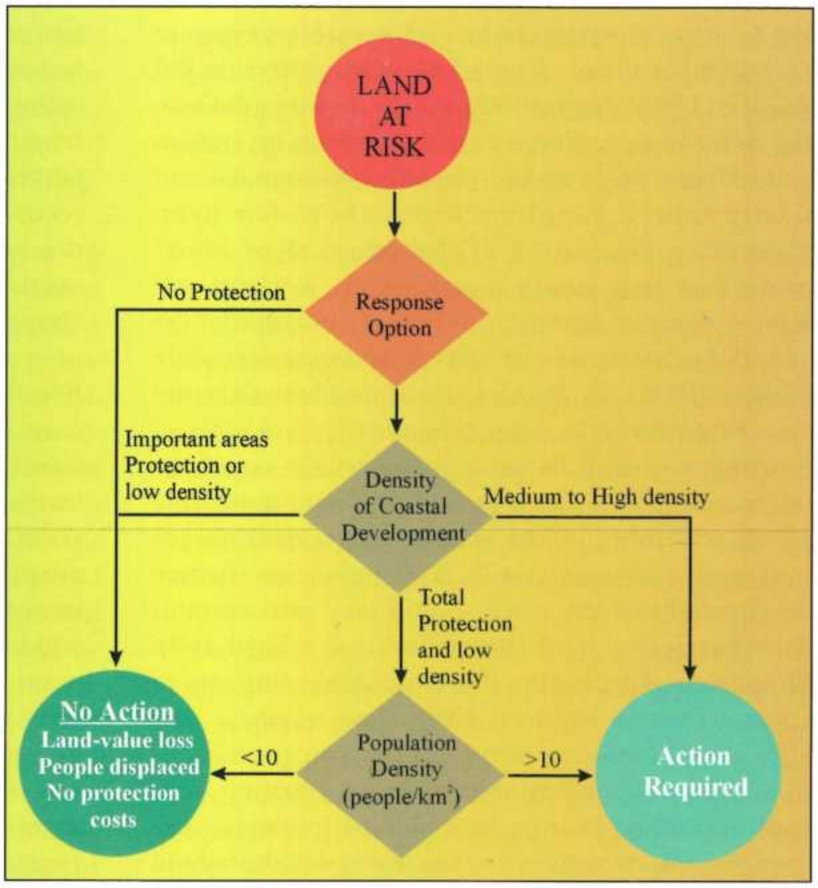

Figure 6.18 – Application of the response options (adapted from Nicholls et al. 1995).

Three broad adaptation strategies are usually considered, regardless the social, political, economic and scientific background available at a certain time and place: (1) to reduce the risk of the event by decreasing its probability of occurrence; (2) to reduce the risk of the event by limiting its potential effects; and (3) to increase society's ability to cope with the effects of the event.

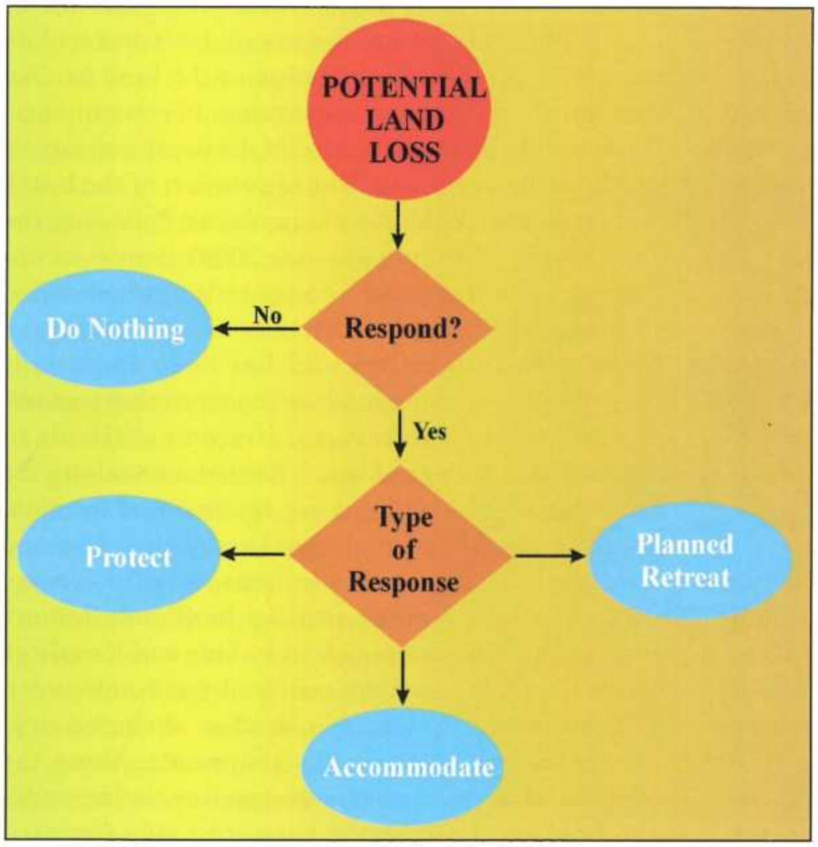

Figure 6.17 – Possible responses to land loss (adapted from Nicholls et al. 1995).

These strategies have been termed "Protect", "Retreat" and "Accommodate", respectively (Fig. 6.17 and 6.18).

### 6.4.2 STRATEGIES

Protection is usually associated with coastal squeeze and hence a decline in natural functions and values, although soft protection approaches may minimize this problem. Protection involving hard structures emphasizes the defence of vulnerable areas, population centres, economic activities and natural resources. Some hard structural options as response strategy involve construction of dikes, levees, floodwalls, seawalls, groins, breakwaters, jetties and eventually of floodgates, tidal and saltwater intrusion barriers (Feenstra et al. 1998).

Up to now, the assessment of possible response strategies has mainly focused on hard protection but this trend is changing towards alternative solutions; this is due to side effects of hard structures on erosion and sedimentation and to loss of environmental and scenic values; simultaneously, there has been increasing awareness of the benefits of "soft" protection (e.g. beach nourishment, wetland and dune restoration and creation, forestation) and of the adaptation strategies of retreat and accommodate (Komar 1998). It also has become clear that the massive construction and maintenance amounts of funding required to protect the whole coast are unbearable. This strategy is only recommendable where soft solutions or retreat and relocation are ineffective or not viable. Furthermore, future development of the coast should take into account this restriction and locate behind a land strip dimensioned to buffer the expectable impacts of climate change within a given time horizon. The upgrading of existing ports and harbour protections should be designed to include impacts arising from future climate change in order to minimize the dredging efforts required by the increasing draught of visiting vessels.

Soft protection also involves the defence of vulnerable areas, where population centres, economic activities and natural resources can be found (Feenstra et al. 1998). Past experiences suggest that the design of soft solutions is particularly important in determining the level of maintenance required and implies thorough knowledge of coastal dynamics (Klein et al. 2001). The most widely applied soft protection strategy is beach nourishment (Feenstra et al. 1998) which is a popular option in highly developed areas with heavily used beaches and valuable beachfront real estate, especially during the early onset of erosion (Neumann et al. 2000). This strategy is apparently simple in nature and has the added attractions of the minimizing of visual impacts and that of being Nature friendly. It involves the placement of large quantities of sediment in the littoral zone to advance the shoreline seaward or to halt beach erosion and implies the design of the entire active profile, including the dune, thus requiring the borough of vast amounts of compatible sediment. The simplicity on which it is based does not usually correspond to the aspects of its practical implementation: artificial nourishment is, of all the protection strategies, the most complex and expensive, and its success rate is also extremely variable. While many experts agree that beach nourishment with regular re-nourishment cycles is an appropriate response to sea level rise, it remains unclear when nourishment would cease to be cost-effective and another response strategy would be required. This strategy is a site-specific function of the rate of sea level rise, the availability and unit cost of sand, and the length of beach being nourished (Neumann et al. 2000).

Beach nourishment is not inedited in Portugal, the case of Praia da Rocha in the Algarve being a reference example of a cost-effective, successful and lasting protection (Castanho 1962; Gomes and Weinholtz 1971), designed to solve a complex adaptation problem. The artificial nourishment of localized coastal sections along the western Algarve and in the vicinity of Lisbon has been suggested in a number of coastal management plans and designed either to assist erosion problems, to increase the accommodation capacity of a number of sea side resorts, or to redistribute pressure likely to be exerted in the near future in other more sensitive places of the coast. So far, only a few interventions translated from documents into the field, namely along the Lisbon-Cascais coast. Dune restoration has been undertaken in the last 10 years along beach-dune systems of mainland Portugal on a case to case basis and seldom assisted by previous investigation of the local aeolian dynamics or followed by monitoring. In consequence, no comprehensive assessment of the degree of success can be made at present. The restoration of the beach and foredune of the Cacela peninsula following the 1987 storm-breaching (Matias 2000) is one recent example of soft approach to protection which failed to reach consensus in what concerns methods, impacts and objectives and has been essentially triggered by environmental and conservation reasons. Regardless the motivation, it seems difficult to consider the strategy of beach nourishment along the Portuguese coast without construction of terminal groins, given the general high-energy character and intensive longshore sediment transport of this coast; these, in effect, become artificial headlands, but are essential to minimize sediment leaking and longshore losses. The past examples required this combination and have been exclusively placed in sheltered, low-energy pocket beaches or embayments. Along the exposed western coast this strategy is possible under a technological perspective but its cost effectiveness is highly questionable. Widespreading of beach nourishment along the Portuguese coast will certainly raise the problem of finding adequate borough-areas for sand which, regardless their location, must contain vast amounts of compatible sediment required to supply the implementation and periodic refilling.

Planned retreat involves progressively giving up threatened land by strategic retreat from, or prevention of, future major developments in coastal areas that may be affected by climate change. Some possible encouraging response strategies involve no development in susceptible areas, conditional phased-out development, withdrawal of subsides or increased insurance costs. Relocation has been previously adopted in Portugal and driven by the multiplication of river dams since the 1940s. The populations, industrial facilities and goods located within the flooded perimeter of each reservoir have been relocated or owners made paid for abandonment of their property. Any country – scaled strategy of retreat from the coast and planned relocation regarding climate change will face an unprecedented dimension of the inherent social and economic costs. This may constitute the major drawback of the presently static concept of different legal instruments, with relevance to the Public Marine Domain, which transfers to the State the obligation of defending property located landwards. The owners may stand for their rights and despite the inexistence of objective forecasts, the costs resulting from relocation strategies will be extremely high in both monetary and social impacts, which remain to be evaluated.

Accommodation is a planned adaptation that involves continued but altered usage of the land, including responses such as elevation of buildings above flood levels, modification of drainage systems, and land-use changes. Accommodation gives emphasis on the conservation of ecosystems harmonised with the continued occupancy and use of vulnerable areas and adaptive management responses. Strategies involve: advanced planning to avoid worst impacts, modification of land use, change of buildings styles, protection of threatened ecosystems, strict regulation of hazard zones and hazard insurance to reinforce the effectiveness of regulation.

In Portugal, the strategy of accommodation should be viewed at present on a case to case basis and it seems an effective option to cope with climate change driven impacts in areas where the maintenance of the dynamic nature of coastal ecosystems is considered of vital importance. This can be the case of some Natural Parks, wetlands and other areas where development is directed towards environmental tourism, a profitable activity that has been growing side by side with education, welfare and environmental awareness.

The flow chart in figure 6.19 summarizes the application of the different protection methods within the response options.

One possible scenario of adaptation of mainland Portugal to the impacts of sea level rise and resulting types of action, based on Nichols et al. (1995), has been outlined by H. Monteiro (IGM) with the results presented in Table 6.9.

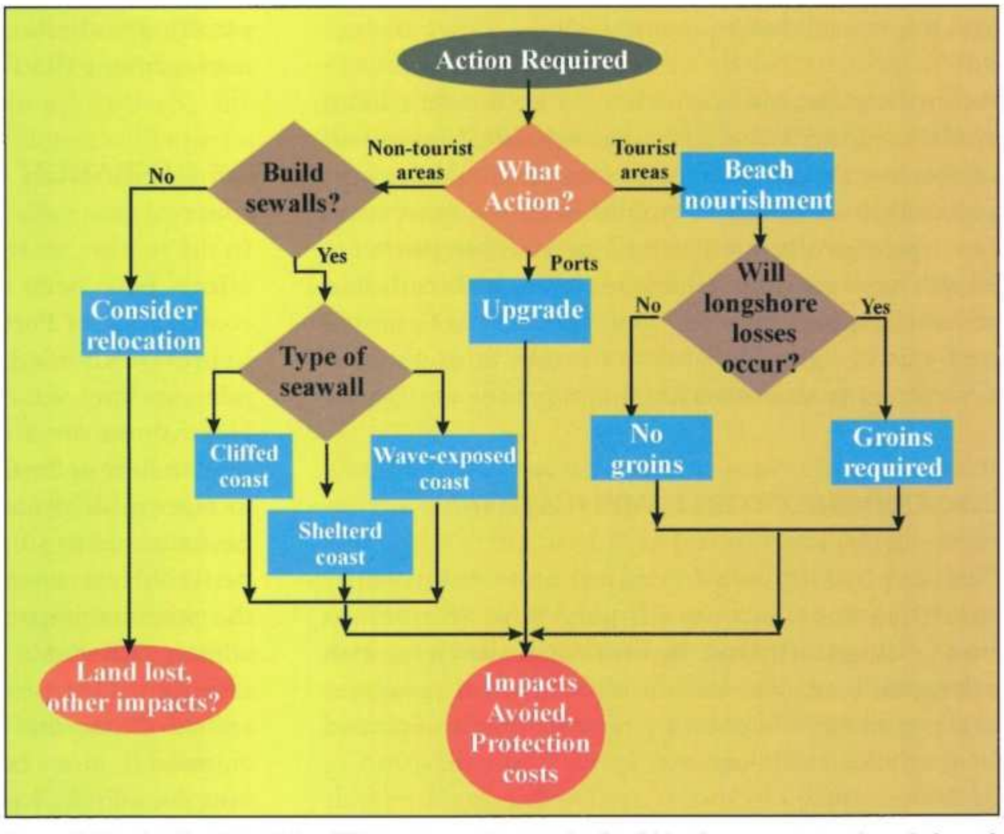

Figure 6.19 – Application of the different protection methods within the response options (adapted from Nicholls et al. 1995).

**Table 6.9 – Possible adaptation strategies to sea level rise in Portugal.**

| | | Points observed | % |
|---|---|---|---|
| Land at risk | Risk of land loss | 601 | 67.0 |
| | No risk of land loss | 295 | 33.0 |
| Stategies | Action | 217 | 24.2 |
| | No action | 679 | 75.8 |
| Type of action | Port upgrade | 11 | 1.2 |
| | Groins | 4 | 0.45 |
| | Seawalls | 80 | 8.9 |
| | Retreat | 39 | 4.3 |
| | More than one | 83 | 9.2 |

The assumptions backing these results were (1) a projected sea level rise of 1 m by 2100; (2) strategies to deal with risk of land loss include active (action) and passive (no action) responses; (3) the latter were assumed as appropriate in all non occupied and some poorly developed parcels of land at risk (e.g. schrub land, barren, some pocket beaches); the former have been assumed as appropriate in occupied or developed parcels of land at risk; (4) the type of action includes: (a) upgrading of almost all the existing fishing, recreational and commercial harbours and ports; (b) protection (groins, seawalls) if coastal development or population density are high; (c) retreat and relocation restricted to small localities with low population density and low coastal development.

According to this scenario, no action has been considered in 76% of the coast including almost half of the length in risk of land loss. In what concerns protection seawalls and combinations of more than one type of protection predominate. Within the latter, beach nourishment has been considered as a secondary protection measure, specially in Sesimbra and Cascais. Retreat and relocation strongly concentrate in coastal stretches 4 and 5.

### 6.4.3 CROSS-SECTORAL IMPLICATIONS

The impacts upon the coastal zone induced by modifications in climate may have important implications in many sectors of the society, with relevance to socioeconomic activities and resources and not all these impacts are necessarily accompanied by prejudicial implications.

Sea level rise in particular is likely to have significant implications for coastal ecosystems which are often already stressed by human activities; these implications translate directly into biodiversity and marine resources, the trends for the former being at present less clear at a country scale. Increased flooding, possible swamping of wetlands and incidence of hazardous agents, such as algae blooms, and others, may adversely affect human health and economy (Parry 2000).

Given the strong relation between tourism and coastline in Portugal, this economic activity is likely to be influenced by climate change impacts, if no action is taken; adaptation is necessary, either to avoid threatening of both the existing facilities and the natural features and values supporting tourism or to increase the country's ability to promptly react to the anticipated impacts in a sustainable way.

While many of these implications are negative, there will also be some beneficial changes.

The increased rate of coastal modification induced by climate change will provide additional opportunities for employment and work in coastal and civil engineering and construction industry and services. Particularly, sea level rise is likely to require substantial investment in these areas, and encourage strategic planning and efforts towards integrated coastal zone management (Parry 2000).

## 6.5 RESEARCH GAPS

In the recent past significant investments and scientific efforts have been directed towards research in the coastal zone of Portugal, the results translating in the improved knowledge of forcing factors (e.g. waves, tides, sea level, sediment supply) and coastal responses. However, we are at present still far from the required level to fully understand the present-day and past meso to macroscale dynamics of the littoral fringe, which is fundamental to support assessment of future impacts derived from climate change. Continued research on the potential impacts of, and adaptation measures to, climate change for Portuguese coastal zones is clearly required. One priority in future investigation is to consider case studies, previously identified as more vulnerable at a country-wide basis, using multi and interdisciplinary high resolution approaches, in order to improve the objectivity and quantification of impacts and adaptation measures.

In particular, additional efforts are required to fill gaps and improve knowledge on (1) sea level rise scenarios and expected changes in storms, storm surges and floods, that must become more local and specific; (2) the present day patterns and rates of morpho-sedimentary evolution of wetlands and dune systems, which should be studied on a case to case basis; (3) the mesoscale estuarine and lagoonal behaviour in terms of tidal propagation and flow at detailed spatial resolution, which must be approached by means of both numerical and empirical modelling relating morphology with dynamics and interaction with the adjoining coast; (4) the systematic assessment of the sediment budget in all Portuguese coastal cells and the exploration for sand sources other than the littoral zone; (5) the rates and patterns of cliff retreat and downwearing of shore platforms along the rocky coastal sections; (6) the direct change of economic, ecological, cultural and subsistence values through threatening of coastal land, infrastructure and habitats.

The success of these research lines depends on significant investments in (1) the construction and diffusion of several data bases (e.g. high resolution topo-hydrography, sedimentation/erosion rates, site-specific physico-chemical parameters) which are urgently needed to support reliable assessment of climate change impacts upon the coastal zone; (2) the training of young researchers and increase the man power dedicated to these problems and (3) the improvement of the institutional interaction between central and local administration authorities (including policy and decision makers), scientists, investors and users.

## 6.6 CONCLUSIONS

The coastline of Portugal houses the country's major political decision centres, cities and ports and is a powerful attractor for people and activities of both industrial and services sectors of economy, which contribute with a significant share to the Gross Domestic Product and employment opportunities of the country. This coast is extremely varied in natural contents, dynamics and vulnerability and its increasing and rapid occupation generated conflict with environmental awareness and value, leading to the recent implementation of specific protection legislation, which is still fragmentary and far from full effectiveness.

The anticipated changes in climate will certainly impact this coast (together with the associated social, economic and environmental values and activities) in distinct manners and with intensity that differ from place to place, according to physical and socioeconomic specific constraints.

Sea level has been rising since the 1900s at approximately 1.5 mmyr$^{-1}$ and this average trend is expected to increase non-linearly in the near future and especially in the last quarter of the 21st century. Storm frequency, duration and intensity will probably increase in the same time horizon together with the yearly average input of wave power and flood damage along the coast. Storm surges are likely to become more severe and the return period of extreme surges to decrease.

Given the starved character of large sections of the Portuguese coast, the qualitative assessment of climate change impacts upon this littoral include the drowning and flooding of lowlands, increased erosion of presently receding coastal ribbons and wide spreading of erosion in others. The behaviour of estuaries and lagoons is likely to shift towards increasing ability to capture sediment from both terrestrial and marine sources, therefore making the maintenance of navigation more hazardous and costier. Should the pattern of occupation of the inland boundary of marshes and tidal flats remain unchanged, the upward and landward shift of these ecosystems will be prejudiced and vast expansions of these wetlands may be lost to inundation, flooding and marginal erosion. The patterns of coastal reaction to future climate change will remain, to a large extent, site-specific therefore prejudicing the quantitative forecasting of responses and the design of standard adaptation strategies at a country scale.

The objective assessment of climate change impacts on the Portuguese mainland coast has been based primarily on the use of the reconnaissance technique "Aerial Videotape-Assisted Vulnerability Analysis" (AVVA). By combining the interpretation of a video record of the coastline, aerial photographs and truthing, it was possible to classify the Portuguese coastal environments in terms of geology and geomorphology, land-use, population density, development, protection, trends of erosion-accretion and infrastructures. With the use of appropriate models of forcing-response and using a simple multi-attribute rating technique, the assessment of vulnerability of the coast to the impacts of a rising sea level and of increased storminess has been indexed and mapped as departures from the national average. Coastal risk indexation followed, using a combination of vulnerability with a proxy of value, the latter reflecting essentially present-day socioeconomic uses of the coast. Simultaneously, and using criteria and assumptions tested elsewhere, a first approach to the risk of land loss along the Portuguese shoreline (especially associated with future sea level rise) has been completed, together with a recommendation scenario on the more appropriate measures of adaptation.

The results from evaluation of the longshore distribution of both coastal vulnerability and risk, in relative terms and at a country scale, and of risk of land loss, suggest that a significant proportion of the coastal land is characterized by relatively high indexes of vulnerability and risk and will, most probably, experience land-loss in the time horizon of 2100, should the sea level rise according to the high IPCC scenario and wave energy increase. The distribution of the most vulnerable and high-risk areas is, once again, complex; the littoral North of Lisbon and the Algarve (especially east of Olhos d'Água) are the most concerning areas. The very extreme risk ranking, either very low or very high, usually corresponds to well defined features: the first, associate with armored ports, rocky headlands and resistant cliffs while the latter coincide with (1) highly valued land in different geodynamic contexts; and (2) fast eroding cliffs, spits/barriers sheltering wetlands and beaches, in association with different occupation values of the hinterland. Indexes of higher than average consistently characterize starved beaches and fast eroding cliffs lacking protection and bearing high valued development, such as the majority of pocket beaches of the western and central Algarve and SW coast. Risk of land loss has been found along 67% of the coastal length in association with erodible bedrock or low lying coasts (beach-dunes, barriers, wetlands).

The assessment of risk and the most adequate adaptation solutions should be undertaken from regional to local spatial scales. Hard defences should be restricted as an adaptation strategy to sites only where high-density development or high values of specific occupations determine a protection policy at any cost. Soft protection (including nourishment) and retreat and relocation or accommodation are recommended as more adequate, the former more widespread and the latter in more specific conditions. These options must be taken on a site-to-site basis and yet they must be designed as parts of a nation-wide coherent strategy of adaptation that will necessarily interfere with present policies of coastal management and use, traditional economic activities and present general awareness of the threats, potential and value of the littoral zone.

Regardless the adaptation strategies that must be implemented, the study of scenarios of impacts, alternatives for adaptation and of related social and economic costs and benefits are urgent tasks that should be encouraged and focus on long-term (decades to century) time-scales. The quality of mesoscale prediction of coastal response will benefit from matching against past reactions of the littoral system to forcing, similar to the expected in the near future, archived in the geological record.

Continued research on the potential impacts of, and adaptation measures to, climate change for Portuguese coastal zones is required. Additional and continuated efforts should be placed in both collection of fundamental data-sets and in the investigation of case-studies, using multi and interdisciplinary high resolution approaches, aiming to quantify objective impacts and to design adequate adaptation measures.

There is a need to rise the awareness of the general public and especially of the people and institutions intervenient on, and dependent of, the coast, on the foreseen impacts of future climate change upon this sector, on coastal resources and conventional land-use practices. This task is necessary to achieve the best social and economical benefits from adequate adaptation strategies and to minimize the stress resulting from the implementation of the inevitable measures.

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# 7

# Agriculture

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## CONTENTS

## EXECUTIVE SUMMARY

- Weather and climate affect agriculture in many ways, from the biological productivity of agriculture crops, the possibility of executing agriculture operations, the incidence of pests and diseases, to the geographical distribution of crops in a region or country. In Europe the southern regions, including Portugal, are particularly sensitive to climate variability. The present crop distribution is conditioned by climate, availability of irrigation water, soil type. Social and economic influences strongly determine what crops grown if the other requirements are adequately met. Portuguese agriculture is dominated by the European Union Common Agricultural Policy, which seeks to integrate concerns for environmental protection and countryside likelihood. Although it is expected that the foreseeable climate changes will have important impacts on agriculture it is impossible to predict clear patterns of change in arable land use. Hence the present work focused on the estimation of climate change impacts on the biological performance of selected crops.

- The assessment of impacts of climate change on agricultural crops was based primarily on the use of crop simulation models of the series DSSAT (Decision Support Systems for Agrotechnology Transfer). Two sets of climate data were used: the baseline data set, simulating daily weather data from present conditions and a data set simulated by the HadRM2 model for the period spanning from 2080-2099. The crops chosen in the present study were wheat and maize since they are two of the most important field crops occupying 7% and 5% respectively, of the most overall area of the Portuguese arable land, which is $3.8 \times 10^6$ ha. Wheat is a typical dryland crop with a physiological behaviour very similar to the other crops grown in Portugal, namely, oats, barley and rye and maize is the main irrigated crop with a climatic range very similar to the majority of the irrigated annual crops grown during the warm and dry season. Furthermore they are representative in as regard to their response to increases in the atmospheric $CO_2$ concentration. Wheat is a $C_3$ plant that responds more positively to $CO_2$ increases than maize, which is a $C_4$ plant.

- The CERES WHEAT model was run for the baseline and for the period from 2080-2099 for a location situated at 38°16'N and 7°52'W (near Beja). There was an yield increased of 34% (from a present simulated yield average of 2,781 $kg.ha^{-1}$). A simple anticipation of two weeks in planting date (from November 1 to October 15), made possible by the absence of frosts during flowering. The effect of an increased atmospheric $CO_2$ concentration is responsible for most part of the yield increase. In fact, without the $CO_2$ increase, there is only an yield increase of 2%.

- The CERES MAIZE model was run for the baseline and for the period from 2080-2099 for a location situated at 39°17'N and 8°41'W (near Santarém). There was an yield increase of 12% (from a present simulated yield average of 12,237 $kg.ha^{-1}$). It was also possible to anticipate the plating date from April 1 to March 15 due to more favourable germination temperatures in the future scenario. The increase in atmospheric $CO_2$ concentration is partially responsible for this yield increase, but its effect is smaller than what was verified in the wheat crops, which is to be expected in a $C_4$ plant.

- The main adaptation measures to counteract the negative impacts of climate change are changes in planting and harvesting dates, choice and development through biotechnology of varieties better adapted to a warmer and drier climate and adaptation of cultural practices to a drier climate.

# 7. Agriculture

## 7.1 INTRODUCTION

Weather and climate affect agriculture in many ways, from the biological productivity of agricultural crops, the possibility of executing agricultural operations, the incidence of pests and diseases to the geographical distribution of crops in a region or country. The present crop distribution is conditioned by climate, availability of irrigation water, soil type, and social and economical influences strongly determine what crops to grow, if the other requirements are adequately met.

Therefore, although it is expected that the foreseeable climate changes will have important effects on agriculture, it is impossible to predict clear patterns of change in arable land use. As a result, this work focused on the estimation of the effect of climate change on the biological performance of selected crops – wheat and maize.

The assessment of impacts of climate change on agricultural crops was based primarily on the use of crop simulation models of the series DSSAT (Decision Support Systems for Agrotechnology Transfer).

### 7.1.1 THE AGRICULTURAL SECTOR IN PORTUGAL

The recent evolution of the Portuguese agriculture was affected by two major events that had major influences in the rate and direction of change.

In 1974, the change in political regime had a strong impact in agriculture, particularly in Alentejo, where the Agrarian Reform had its strongest expression. Its proclaimed goals were not attained and the gradual evolution from a traditional agriculture to a modern one was slowed down. During the period from 1974 to 1985 the agricultural sector under the influence of the Agrarian Reform – roughly half of the country – was decapitalized and disorganized; the production apparatus was dismantled, the farms' live capital was sold in huge amounts, the extensive systems of dryland farming were kept unchanged in spite of a large increase of the number farm workers per unit area (Pinheiro et al. 1999).

Portugal negotiated the adhesion to the European Economic Community with an agriculture lagging by far the agriculture of the northern countries of Europe and at the same time as Spain – a country that has similar environmental conditions and, therefore, producing agricultural commodities that are competitors with the Portuguese agricultural products. This context contributed to a long negotiating process that culminated with the signature of the Adhesion Treaty on June 12, 1985. Portugal became a full member of the European Community on January 1st, 1986 (Pinheiro et al. 1999).

If, on one hand the adhesion to the European Community allowed the financial resources to support the needed policies of markets and prices and social and structural policies, on the other hand the Portuguese Government lost autonomy in the definition of a national agricultural policy, being more and more dependent on community policies (Pinheiro et al. 1999).

As a result, as it might be seen from the following indices that characterize broadly the Portuguese agricultural sector, one cannot define clearly a steady state of Portuguese Agriculture since it is, by and large, changing rapidly.

#### 7.1.1.1 Farm structure

The size of the elemental unit of agriculture production – the farm – has almost doubled in thirty years. This also means that the number of farms is one half of what it was thirty years ago. Total agricultural land decreased by 5% from the maximum of $4x10^6$ ha during the Agrarian Reform period (Table 7.1).

**Table 7.1 – Portuguese farm structure (INE 1973, 1985, 1992, 1997 and 2000; FAO 2001).**

| | 1968 | 1983 | 1989 | 1993 | 1997 |
|---|---|---|---|---|---|
| **Agricultural land ($10^6$ ha)** | 3.91 | 3.99 | 4.01 | 3.95 | 3.82 |
| **Farm number (1,000)** | 812 | 794 | 594 | 488 | 416 |
| **Farm size (ha)** | 4.8 | 5.0 | 6.7 | 8.1 | 9.2 |

#### 7.1.1.2 Agricultural population

In the past forty years the fraction of economically active population in agriculture was reduced fivefold with a steepest decrease from the 60's. The average decrease rate nears thirty thousand people per year. Although it is a general and expected trend, the rate of change has

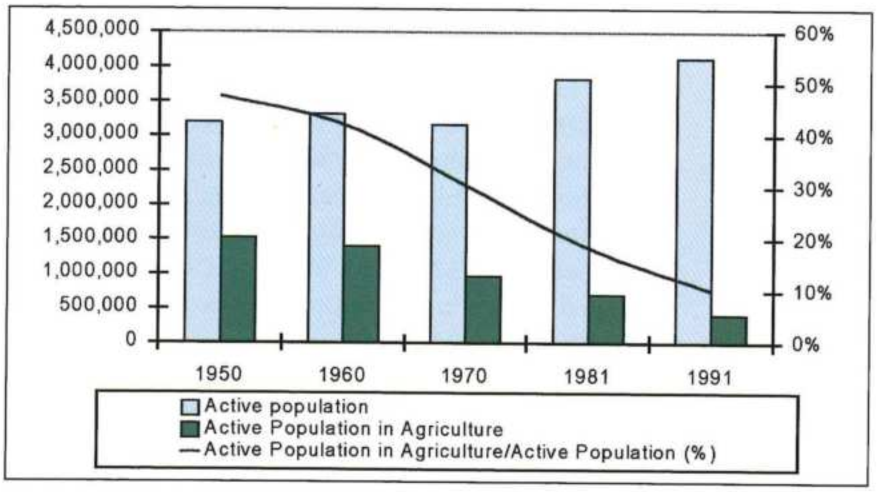

Figure 7.1 – Evolution of economically active population, economically active population in agriculture percent of agricultural population in economically active population (INE 2000).

been too fast and it has resulted in an increase in the average age of the agricultural population with a small rate of replacement with younger and better trained people (Figure 7.1).

### 7.1.1.3 Technological change

The increase in farm size as well as the influx of investment capital has allowed a degree of mechanization of farm operations that can be roughly measured by the number of tractors (Table 7.2).

**Table 7.2 – Degree of mechanization (INE 1973, 1997 and 2000).**

| | 1968 | 1993 | 1997 |
|---|---|---|---|
| **Tractors** | 130,161 | 146,589 | 154,393 |
| **Mechanization index (ha agricultural area/tractor)** | 30.1 | 26.9 | 24.8 |

The general trend in the increase in mechanization was strongly accelerated in recent years. Actually, the variation in the number of tractors per unit area between 1993 and 1997 was four times more than in the period between 1968 and 1993.

### 7.1.1.4 Land use

Agricultural land use topped 4×10⁶ ha around 1990, but decreased steeply thereafter. Although recent data on other land uses is not yet available, it is reasonable to think that the land lost to agriculture was mainly forested with new plantations. Nevertheless this represents an astonishing decrease of almost 10% in less than 10 years (Figure 7.2).

With such a variation it is only possible to have a point estimation of the partition of agricultural land into different categories, since the relative variation is not necessarily the same. Thus, the arable land (including, temporary crops, family horticulture and temporary uncultivated land) was slightly larger than one half of the total area of agricultural land (Figure 7.3).

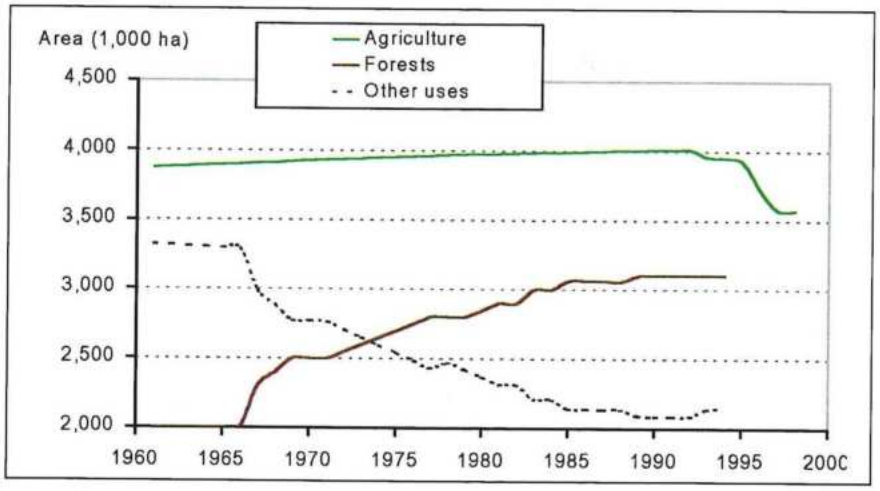

Figure 7.2 – Land use in Portugal (FAO 2001).

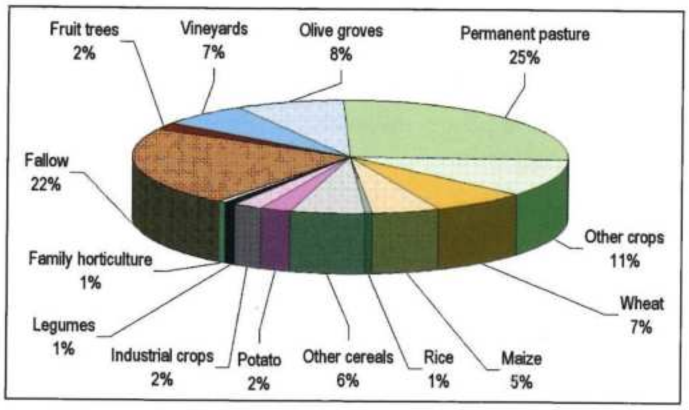

Figure 7.3 – Partition of Portuguese agricultural land in 1997 (INE 2000). Total agricultural land area: 3,820,000 ha.

### 7.1.1.5 Agricultural economy

The economic value of agricultural production as measured by the gross agriculture value added (GVA) has been relatively steady in recent years, although its relative importance as compared to the gross national added value has steeply decreased from a share of 5% in 1990 to almost 2% in 1997 (Figure 7.4).

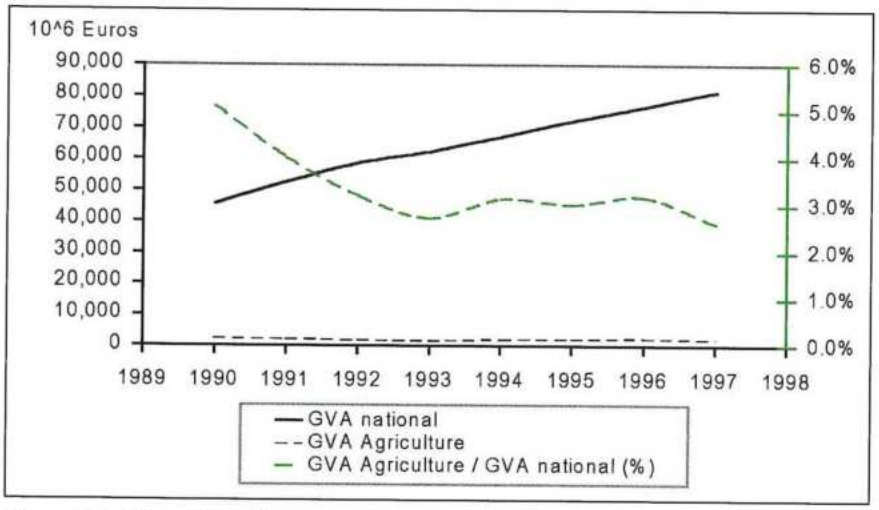

Figure 7.4 – Evolution of the gross agriculture added value (GVA agriculture) as compared to the gross national added value (GVA national) (INE 2001(1)).

In recent years the relative contribution of plant and animal production to the GVA was reversed: in 1990 the value of plant production was roughly 55% of total agricultural production, but in 1997, the value of animal production had the major contribution to the value of agricultural production (54%). After 1993 an important contribution comes from EC subsidies (Figure 7.5).

Although the value of agricultural production has remained reasonably steady in the 1990's (Figure 7.5) the agricultural trade balance deficit has more than doubled between 1990 and 1997, meaning that the ghost acreage (Odum 1989) is rapidly increasing. This term, firstly coined by Georg Borgstrom in The Hungry Planet (1967), denotes the unbounded area outside a country required to sustain the population within the boundary of that country.

The main conclusion that can be drawn from this synthetic overview of the Portuguese agriculture is that its importance in the Portuguese economy is decreasing very rapidly and this evolution is far from having reached the point of equilibrium.

It must also be said that in almost every country the importance of agriculture is not made of its contribution to the Gross National Product. Agriculture plays an important role in a country's competitiveness by creating a strategic food reserve and in the fixation of people in interior areas, maintaining agricultural jobs, creating new activities and promoting regional development (Pinheiro et al. 1999).

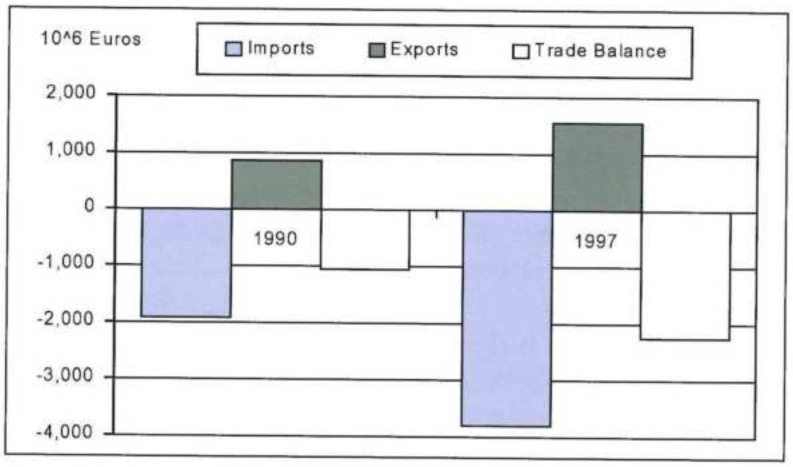

Figure 7.6 – Portuguese Agricultural Trade Balance (INE 2001b).

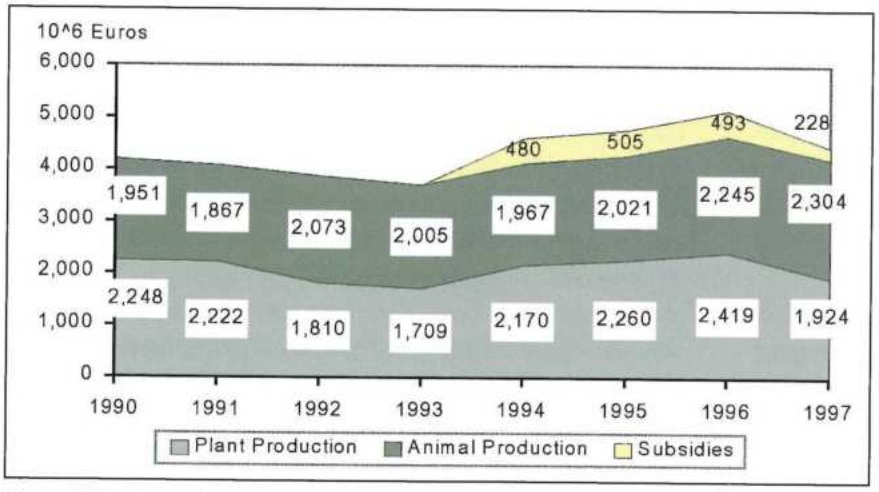

Figure 7.5 – Contributions of plant and animal production to the value of agricultural production (INE 1997, 2000 e 2001a – values in market prices).

## 7.1.2 CLIMATE AND AGRICULTURE

Weather and climate affect agriculture in various ways, from the biological productivity of agricultural crops, to the possibility of executing farm operations opportunely, to the incidence of pests, diseases and weeds and even to the geographical distribution of crops in a given region or country. In Europe, the Southern regions, including Portugal, are particularly vulnerable to climate variability. This vulnerability originates mainly from the lag between the rainy season and the growing season; as a result, in the absence of irrigation, agricultural yield depends heavily on the amount of rainfall in critical periods, namely during Spring.

Present crop distribution is conditioned by climate, soil type and the availability of irrigation water. Yet, the social and economic influences are the ones that more strongly determine the type of crops that are grown if all other conditions are met.

Portuguese Agriculture is dominated by the Common Agricultural Policy of the European Union which aims simultaneously to integrate concerns of environmental protection with regional agricultural potential, maintaining farmer's economic income and social well-being.

Although it is above all discussion that climate change will have important impacts in Agriculture – mainly attributable to its dependency on weather patterns – it is impossible to foresee clear change patterns in the use of arable land. As a result the present study is centered in the estimate of climate change impacts in the biological performance of selected crops.

Portuguese climate is classified as Mediterranean with some variation depending on orography and latitude. This type of climate presents several drawbacks to agriculture, the major one being the lack of rainfall during Summer and the insufficient rainfall in Spring.

The lack of coincidence between radiation and heat with soil water availability, limits the warmer and drier regions to dryland agriculture – agricultura de sequeiro, in Portuguese – in the absence of irrigation. This type of agriculture presents yield limitations since it depends on soil water stored during the rainy season.

When irrigation water is available, soil water storage can be replenished as needed and in this case the large solar radiation input during late Spring and Summer allows very high crop yields as well as a more diversified choice of crops. The possibility of irrigation is in most cases a pre-requisite of the intensification of agricultural systems (Coelho 1996).

**Table 7.3 – Fraction of the total agricultural area that can be irrigated (INE 2000).**

| | 1995 | 1997 |
|---|---|---|
| **Irrigated area (ha)** | 796,538 | 798,273 |
| **Agricultural area (ha)** | 3,924,623 | 3,822,127 |
| **Irrigated area (ha) / / Agricultural area (ha)** | 20% | 21% |

Irrigated agriculture represented in 1995/1997 around 20% of the total agricultural area (Table 7.3), although with an irregular distribution throughout the country – while in Northern Portugal, this fraction was 31%, in Southern Portugal it was near 8% (Avillez 1996).

Although it is outside the scope of this work at this moment, it can not be overlooked that within the timescale of the scenarios of climate change, the irrigated area in Southern Portugal will potentially increase by 100,000 ha with the conclusion of the artificial lake of Alqueva.

## 7.2 METHODOLOGY

In order to evaluate the impact of climate change in Agriculture and given the fact that so many crops are involved and that the baseline information is very difficult to ascertain – due to the rapid change that is still taking place in the sector – it was necessary to select representative crops on which to estimate the impacts of change.

Within the category of temporary crops, wheat and maize seemed to be the adequate choice because these crops are the ones that occupy the larger area (Figure 7.3) and at the same time each represents the two major types of agriculture in Portugal – dryland cereal crop system and irrigated spring crops. Wheat is a typical dryland crop with a very similar behavior to other dryland cereals such as oats, barley and rye. Maize is the main irrigated crop with climate requirements that are similar to a broad range of irrigated crops grown during Spring and Summer.

Another aspect that justifies this choice is their response to elevated $CO_2$ concentration. While wheat is a $C_3$ crop plant, with a C pathway strongly determined by $CO_2$ concentration, maize is a $C_4$ plant. A brief discussion on the effect of elevated $CO_2$ in plants with these different metabolic pathways is presented in section 7.2.1.4.

## 7.2.1 DESCRIPTION OF ASSESSMENT APPROACH

### 7.2.1.1 Methods used in impact evaluation

In the agriculture section of the IPCC – Intergovernmental Panel on Climate Change – (Feenstra et al. 1998) report several ways of approaching the question of climate change in regard to agriculture are proposed. The report mentions four types of effects: on crop productivity, on income equity between urban and rural areas, national and regional production, global production and prices.

The proposed methods of effect evaluation are growth chamber research, agroclimatic indices (degree-days, temperature ranges), statistical models, simulation models (CERES type models in the DSSAT – Decision Support System for Agrotechnology Transfer – series), analogy with real scenarios or economic models. The scale of analysis can be either at a global, national, regional or at the farm level.

In the final US report (National Assessment synthesis team 2000: 379-403) the Agriculture group used crop simulation models to forecast the effects of climate change. The input data used were the output of Hadley Centre climate simulation models and the output of Canadian Centre climate simulation models. For wheat, maize, soybean, sorghum, rice and tomato the DSSAT models were used; the model CENTURY (Parton et al. 1994) was used to simulate effects on pastures; and Ben Mechlia and Carrol (1989) model was used to foresee the effects in citrus crops. The models simulated agriculture production in 45 places in the US and in each location crops were selected according to its relative occupied area. The economic impacts are evaluated using a model of the US national agricultural sector (ASM) (Adams et al. 1990, 1997).

The European project ACACIA (Parry 2000:13-14) makes some generic considerations on the agricultural impacts of climate change, distinguishing between short-term (choice among cultivars, changes in planting and harvesting dates) and long-term (new cultivars that are heat and/or drought resistant) measures of adaptation.

The Kazakhstan study used the CERES-WHEAT model from the series DSSAT and a model developed by the Kaznimosk Institute for pastures (Forbes 1998).

In the Phillipines the models CERES-RICE and CERES-MAIZE were used (Forbes 1998).

The agriculture section of the third assessment report of the IPCC report (Mcarthy et al. 2001: 667-681) points as important characteristics of temperate crops that might be affected by climate change, future areas of production, crop duration, yield response to increased climate variability as well as the listing of adaptation measures. Using the Eurowheat model (for winter wheat) they estimate yield increases in Northern and Central Portugal and Spain and a decrease that can be as much as $3 \times 10^3$ kg.ha$^{-1}$ in Southern Portugal and Spain (Harrison and Butterfield 1996). It must be said that this expected decrease is largely exaggerated since average yields in these Southern climates are presently smaller than the expected decrease. The reason for this contradiction must be the use of a winter wheat model in regions were all wheat varieties used behave as Spring wheats. In the case of maize, using the model WOFOST, (World Food Studies) they suggest yield increases in the North and a decrease in the South (Wolf and Van Diepen 1995). In the case of root and tuber crops such as sugar beet and potato, given the longer growing season due to increased temperatures as well as increased sugar accumulation resulting from increased $CO_2$ concentration, there will be a probable yield increase.

Among permanent crops, there was a particular focus on vineyards and olive groves pointing to an increase in cropping area, although in the first case there are, at present, several restrictions due to Common Agricultural Policy.

In Spain, the model CERES-WHEAT was validated for seven locations in the most important wheat producing regions (Iglesias et al. 2000: 69-80). Using this model the authors conclude that the variables that better explained yield variations were the availability of water (rainfall and irrigation) and temperature during the developmental phase. Subsequently, a multiple linear regression model was developed in order to simulate the productivity response to their variations, in order to estimate climate change impacts in seven agro-climatic regions. The climatic models used were developed by the Hadley Centre and the Canadian Climate Centre.

The CLAIRE (Climate Change and Agriculture in Europe) project evaluated the effects of $CO_2$ concentration increase in vine plants under a controlled atmosphere environment and reported an increase in yield, an increase in leaf thickness, an increase in starch and sugar concentration and increase in berry acidity (European Commission 1997).

The European project CLIVARA (Climate Change, Climatic Variability and Agriculture in Europe) aims to increase the predictability of mechanistic models for wheat, soybean, vineyards and potato at a local, regional, country and European scale (CLIVARA 2001).

### 7.2.1.2 Characterization of the model used

Given the two crops previously selected (wheat and maize) it was decided to use the available CERES models included in the DSSAT series (Jones et al. 1998), in order to simulate crop behavior under a scenario of climate change and comparing to the simulation using an average of the current climate.

The required inputs are soil physical and chemical characteristics and daily climate data.

The model CERES-WHEAT was validated for the Alentejo region using historical yield data for the period 1986-98 and weather data for Beja for this period, during which the cropped area has been 203,348±±36,522 ha.

The model CERES-MAIZE was validated for the Ribatejo area with historical yield data for the *Ribatejo e Oeste* region and weather data for Santarém for this period during which the cropped area was 29,275±5,246 ha . It must be noted that the average maize area in the region has been increasing at a fast pace. Taking in consideration this average maize area for the 13 year period between 1986 and 1998, it is noticeable that in 1998 the cropped area was 42,500 ha.

The models CERES include a sub-routine that allows the simulation of the effect of variable $CO_2$ concentration on gross photosynthesis and therefore on yield.

### 7.2.1.3 Ecological and agronomic characteristics of wheat and maize

Wheat (*Triticum aestivum* and *Triticum durum*) is a crop adapted to a wide variety of environments being produced from the Artic Polar Circle to the Equator and from sea level to 3,000 m (Briggle and Curtis 1987; Gooding and Davies 1997) which is possible because there are a large number of cultivated varieties. This wide temperature range does not allow the definition of geographical limits based on temperature. The best crop areas are indicated by the yield obtained and they are located in Northern Europe. The varieties used in these regions are winter wheats, i.e., with a long cropping season – from October to August.

Cropping conditions are ideal, since the winter is cold and dry allowing vernalization and spring and summer have adequate rainfall for grain filling and long days that allow large daily photosynthesis rates.

The characteristics of the Mediterranean climate are not ideal for wheat growth and yield. In particular, in Portugal, winter rainfall exceeds soil water storage capacity which is a disadvantage in soils with difficult drainage and in Spring rainfall is irregular conditioning an adequate flowering and grain filling.

In Portugal wheat is traditionally cultivated under a dryland regime and therefore, water stress is always present, from April or May, thereon, depending on the amount and distribution of Spring rainfall. The varieties used are mainly spring varieties – without vernalization requirement –, sown from November to January and harvested from June to July. Late planting dates are necessary with short crop duration in order to avoid late frosts during flowering. Winter wheat needs cold winters in order to induce adequate flowering and therefore their use is restricted to Northern Portugal. It is considered that average monthly temperatures above 10°C during winter delay flowering and reduce flower fertility, resulting in a crop with a disproportionate leaf area and very low yields.

Even the high radiation inputs in Spring are not an advantage since the radiation saturation point is low, for wheat is a $C_3$ plant. Opposedly, at Northern latitudes, lower radiation inputs and longer days are more adequate for wheat net photosynthesis (Feio 1991).

Maize (*Zea mays*) is a subtropical crop that deals well with high heat and high humidity. Maize is a $C_4$ plant and therefore its productivity under comparable conditions is larger than the productivity attainable by wheat.

In the best natural production region – the Corn Belt, in the US – average temperature from May to September is 21°C and rainfall sums 500 mm (Feio 1991). The large number of recent varieties bred, pushed the northern limit of the crop to above 50°N, in France and in the United Kingdom. There is a wide choice of varieties ranging from short cycles corresponding to the accumulation of 1450 degree-days above 6°C to long cycles of more than 1900°C, therefore being adapted to a wide range of climatic situations. In Portuguese conditions, maize is a Summer crop being sown from March to May, depending on early Spring temperatures, and harvested in September or October. As a result, maize is almost always grown under irrigation, although the amount of water needed varies widely within the country (Feio 1991).

#### 7.2.1.4 Crop physiology of $C_3$ and $C_4$ plants

Higher plants may be divided in three categories according to their $CO_2$ assimilation pathway: $C_3$ plants, $C_4$ plants and CAM plants (Crassulacean Acid Metabolism).

The fixation of $CO_2$ in $C_3$ plants occurs in the presence of light, through the carboxilation of ribulose 1,5-bisphosphate, which is catalyzed by ribulose bisphosphate carboxylase originating a compound with 3 carbon atoms – phosphoglyceric acid. Yet, this enzyme also functions as an oxydase and some carbon just fixed is freed as $CO_2$ – photorespiration.

$CO_2$ fixation in $C_4$ plants follows the dicarboxilic acid pathway also known as HSK (Hattch-Slack-Kortscak) pathway: in the presence of light, phosphoenolpiruvate is carboxilated in a chemical reaction catalysed by the enzyme phosphoenolpiruvate carboxylase. The product is oxaloacetate (a 4C compound) that is rapidly converted into malate or aspartate (also 4C compounds). In a second step, these compounds are decarboxilated and $CO_2$ is freed an re-fixed into ribulose 1,5-bisphosphate. From this step on, the pathway is the same as in $C_3$ plants. $C_4$ plants have also a different anatomy that allows that the decarboxilation of malate and asparthate and the re-fixation into ribulose 1,5-bisphosphate takes place in a low oxygen environment inside the leaf tissue. As a result there is no photorespiration (Figure 7.7).

The productivity consequences of these physiological characteristics is that, in general, $C_3$ plants have a photorespiration loss that can be as high as 20 to 50% of gross photosynthesis rate – depending on temperature.

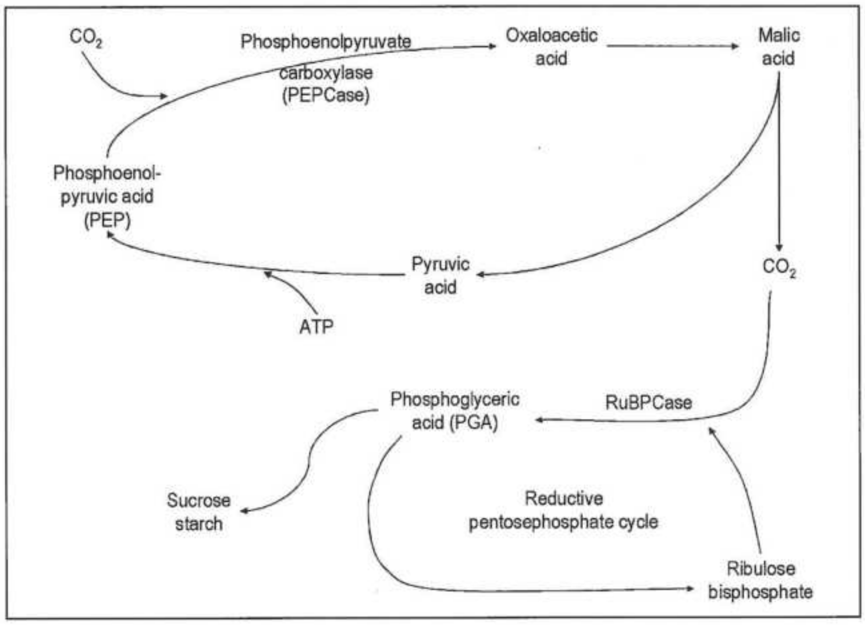

Figure 7.7 – The $C_4$-dicarboxylic acid pathway of $CO_2$ assimilation. Carbon dioxide reacts with phosphoenolpyruvic acid (PEP) in the presence of the enzime PEPCase to form oxaloacetic acid. The oxaloacetic acid is transformed to malic acid (in some $C_4$ plants to aspartic acid), which is decarboxylated to yield pyruvic acid and $CO_2$. Pyruvic acid is phosphorylated (ATP) to regenerate phosphoenolpyruvic acid and the $CO_2$ is further metabolized via RuBPCase in the reductive pentose phosphate pathway to sucrose, starch, and other products (Noggle and Fritz 1986).

Optimal temperatures for photosynthesis range from 10 to 25°C in $C_3$ plants while this range is 30 to 45°C in $C_4$ plants (Teixeira and Ricardo 1993).

### 7.2.2 DESCRIPTION OF DATA USED

#### 7.2.2.1 Historical climate data

For the validation of the models CERES WHEAT and MAIZE daily weather data from Beja (38°01'N, 7°52'W ) for the period from 1985 to 1995 and Santarém (39°15'N, 8°42'W ) from 1986 to 1994, respectively, were used. Weather variables used were maximum and minimum temperatures (°C), rainfall (mm) and solar radiation ($MJ.m^{-2}$).

#### 7.2.2.2 Simulated climate data

Two sets of weather data were used:

- a baseline, simulating present conditions and resulting in a 29 year series of weather data (Jones et al. 1995; 1997).
- a 19 year series of "future weather" resulting from

the predictions of the HadRM2 model (Jones et al. 1995; 1997) for a period between 2080 and 2099.

These simulated data series are geographically distributed in a rectangular grid that covers the national territory as depicted in Figure 2.1.

In both cases the simulated data used refer to cell 78 (located between Beja and Castro Verde: 38°16'N, 7°52' W) used in wheat simulations for Alentejo and cell 60 (located between Vila Franca de Xira and Leiria: 39°17'N, 8°41'W) used in maize simulations for Ribatejo.

The effect of a double concentration of carbon dioxide, used in the assumptions of the HadRM2 was also tested with both CERES models.

#### 7.2.2.3 Soil data

The requirements of CERES models include soil characteristics. Since cell weather data correspond to point estimates of simulated weather it was necessary to use the same rationale for soil characteristics, in spite of a broader spatial variability on soil characteristics. Thus, two "characteristic" soil profiles were used, corresponding to a common type of soil in each agricultural region, represented by the "weather data cell".

**Table 7.4 – Soil characteristics used in the simulations with CERES-WHEAT and CERES-MAIZE.**

| | Alentejo | Ribatejo |
|---|---|---|
| Soil type | Lithosols | Fluvisols |
| Depth (cm) | 64 | 130 |
| Texture | Fine sandy loam | Silty clay loam |

## 7.3 ESTIMATION OF IMPACTS

A first general estimate of global change on "agricultural climate" might be obtained using a general agroclimatic index followed by more quantitative evaluations of impacts on crop productivity using crop growth models.

### 7.3.1 AGROCLIMATIC CHANGE

Papadakis (1975) climate classification categorizes Winter and Summer seasons according to the possibility of growing specific "indicator" crops. This classification divides the world in five belts according to winter severity: "tropical", "citrus", "oats", "wheat" and "spring crops". Otherwise, in agreement with summer heat the earth may be divided into several zones according to the possibility of growing each of these crops, "cotton", "rice", "maize", "wheat warmer", "wheat cooler", "Taiga", "Alpine", "Tundra" and "Frigid".

For eight grid points, regularly distributed in order to cover the entire country (41°32'N, 8°43'W; 41°18'N, 7°04'W; 40°10'N, 8°29'W; 40°00'N , 7°25'W; 39°17'N, 8°41'W; 39°03'N, 7°07'W; 37°55'N, 8°29'W; 37°45'N,

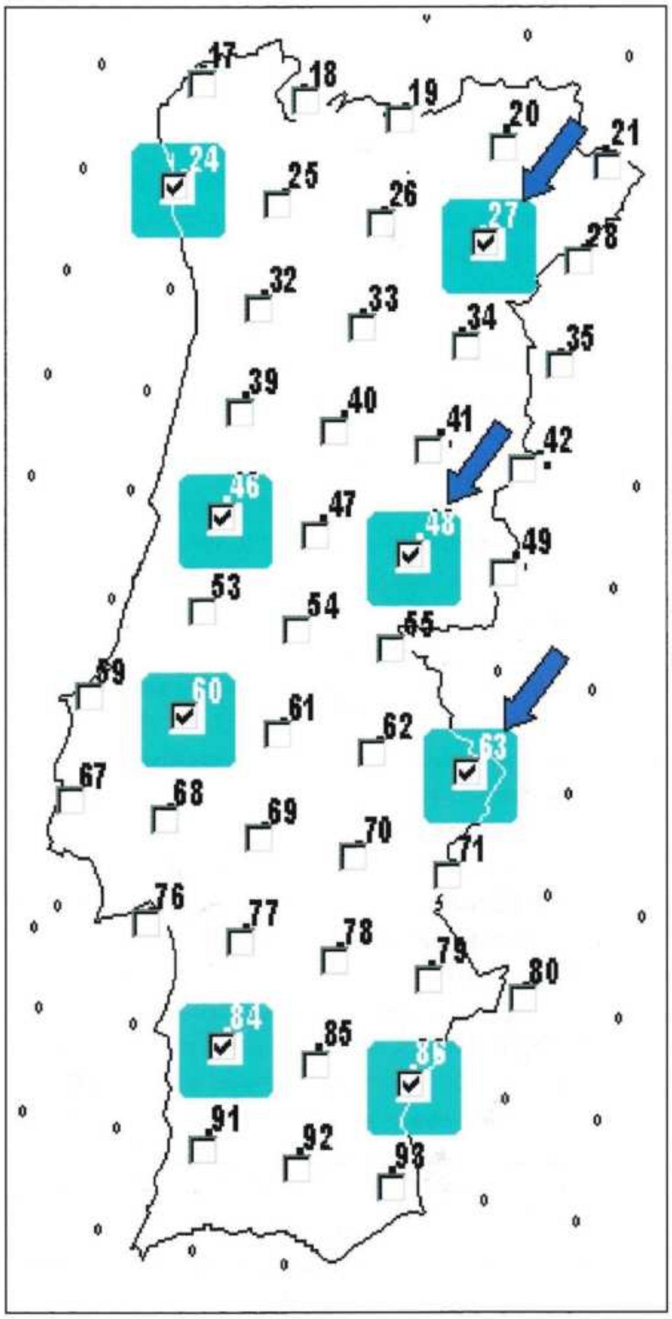

Figure 7.8 – The eight grid points selected. Arrow indicates the locations where there was a shift from Winter-oat to Winter-citrus.

7°28'W ), the present and future Papadakis classification indices, using weather information from the two data sets described above, were compared. In three cases, the winter classification changed from "oat" to "citrus", meaning that winter becomes sufficiently temperate to allow the citrus crop (Figure 7.8). In Summer there was a more general change: the two most southern latitudes remained Summer-cotton, while all the others, presently classified as cooler summers changed from Summer-wheat-cold or Summer-rice to Summer-cotton.

### 7.3.2 IMPACT ON CROP PRODUCTIVITY

### 7.3.2.1 Wheat

The effect of climate change in the productivity of wheat was simulated using the CERES-WHEAT model.

The model was run with the weather data previously described, corresponding to the Alentejo region. The baseline scenario consisted of 19 years chosen randomly from the 29 years series of present weather and the future scenario consisted of a series of 19 years starting in 2080.

Cultural characteristics used for each set of 18 runs are depicted in Table 7.5 (each run depends on weather data of two years because of planting and harvesting date).

The results obtained are presented in Table 7.6.

It is satisfying to record that the average simulated yield for the baseline is quite in accordance with the average productivity of wheat in a region such as Alentejo. Yield must be adjusted to 14% moisture which corresponds roughly to a wheat yield of 3,200 kg.ha$^{-1}$.

The future scenario reveals a negative impact of climate change in wheat yield with a decrease of 25% and a much larger variability. Yet, an adjustment of 2 weeks in planting date results in a yield increase of 34%. This yield increase is largely due to the simulated effect of increased $CO_2$ (32%), the remaining being the direct result of climate change.

**Table 7.6 – Simulated wheat yield (grain dry weight kg.ha$^{-1}$) in present and future scenarios.**

Future 1 – Future scenario incorporating model response to 2x[$CO_2$]; Future 2 – Future scenario with a slight adjustment in planting date; "Baseline" – Present scenario.

| | Future 1 (kg.ha$^{-1}$) | Future 2 (kg.ha$^{-1}$) | "Baseline" (kg.ha$^{-1}$) |
|---|---|---|---|
| 1 | 104 | 412 | 457 |
| 2 | 549 | 493 | 1,309 |
| 3 | 49 | 604 | 1,420 |
| 4 | 77 | 2,459 | 1,701 |
| 5 | 3,432 | 2,599 | 2,017 |
| 6 | 5,103 | 3,290 | 2,230 |
| 7 | 453 | 3,517 | 2,363 |
| 8 | 86 | 3,570 | 2,412 |
| 9 | 3,759 | 4,289 | 2,626 |
| 10 | 5,777 | 4,698 | 2,715 |
| 11 | 2,206 | 4,825 | 3,355 |
| 12 | 2,080 | 4,880 | 3,621 |
| 13 | 3,069 | 4,912 | 3,665 |
| 14 | 1,415 | 4,919 | 3,689 |
| 15 | 2,029 | 4,934 | 4,331 |
| 16 | 1,218 | 5,051 | 4,370 |
| 17 | 2,022 | 5,367 | 5,028 |
| 18 | 4,053 | 6,134 | 5,353 |
| Average | 2,082 | 3,720 | 2,781 |
| Standard deviation | 1,791 | 1,760 | 1,266 |
| Coef. of variation | 0.86 | 0.47 | 0.46 |

Usually, wheat is planted between November 1st to the end of December, in order to avoid frost damage during the flowering period.

The first future scenario maintains this same planting date which results in an increased water stress during flowering and grain filling. The increased yield variability shown in Figure 7.9 reflects the increased frequency of dry Spring seasons.

Yet, it is not reasonable to maintain all agronomic decisions without adjusting to the new conditions. Since in the future scenario the frost danger decreases, it is possible to anticipate the planting date by

**Table 7.5 – Cultural practices used in the wheat simulation for present and future scenarios.**

| | | "Baseline" | Future 1 | Future 2 |
|---|---|---|---|---|
| **Planting** | Cultivar | MARIS FUNDIN | M ARIS FUNDIN FUT | M ARIS FUNDIN FUT |
| | Planting date | November 1 | November 1 | October 15 |
| | Date of emergence | November 11 | November11 | October 25 |
| | Planting density | 120 seeds/m$^2$ | 120 seeds/m$^2$ | 120 seeds/m$^2$ |
| **N fertilization** | Total applied (kg N/ha) | 114 | 114 | 114 |

two weeks, thus avoiding partially water stress in the reproductive period.

Those are the conditions in scenario Future 2 that presents a variability that is similar to the baseline and an increase in productivity that is mainly due to the doubling of the $CO_2$ concentration.

The yield increase due to increased $CO_2$ concentration must be looked at with caution.

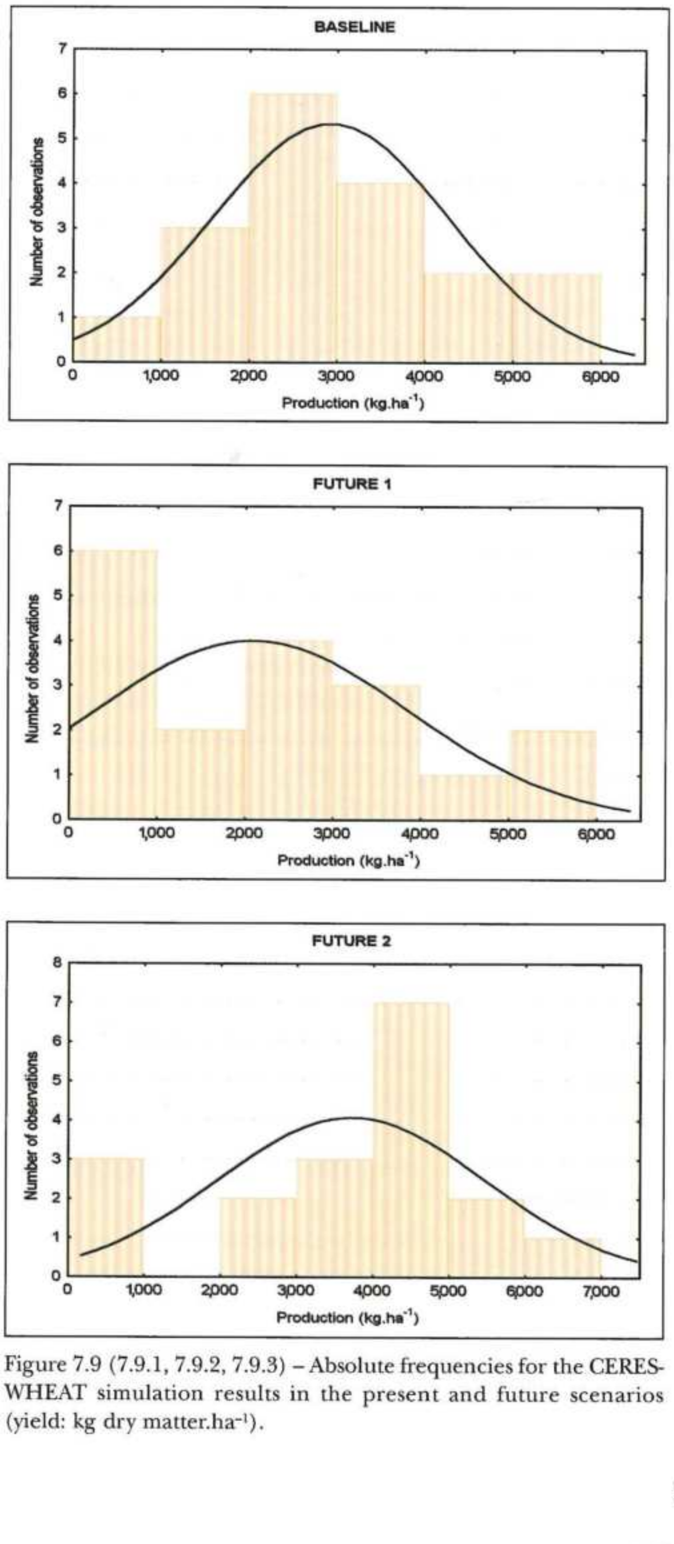

Figure 7.9 (7.9.1, 7.9.2, 7.9.3) – Absolute frequencies for the CERES-WHEAT simulation results in the present and future scenarios (yield: kg dry matter.$ha^{-1}$).

Experiments in single leaves or single plants confirm that an increase in the atmospheric $CO_2$ content increases net photosynthesis rate if light intensity is not the limiting factor.

That can be explained by the specificity of the $C_3$ pathway explained earlier. Yet, within the plant community this effect is much more complex, since it depends on rates of gas exchange, interference among plants and leaves that modify the light environment within the plant community and also the limiting effects of other factors, such as water or nitrogen.

In any case, photorespiration will certainly be depressed what contributes positively to the crop Carbon balance (Teixeira and Ricardo 1993).

### 7.3.2.2 Maize

The effect of climate change in the productivity of maize was simulated using the CERES-MAIZE model.

The model was run with the weather data previously described, corresponding to the Ribatejo region. The baseline scenario consisted of 19 years chosen randomly from the 29 year series of present weather and the future scenario consisted of a series of 19 years starting in 2080.

Cultural characteristics used for each set of 19 runs are depicted in Table 7.7.

The results obtained are shown in Table 7.8.

As in the case of wheat, the first future scenario, used exactly the same cropping conditions that were used in the baseline scenario which resulted in a productivity decrease of 29%.

Yet, similarly, this is not a reasonable approach. Given different climatic conditions, any farmer tends to fit his crop to those conditions.

Therefore, the reduction in frost risk in early spring (frost-free period is 295 days in the future scenario versus 174 days at present) allows the anticipation of sowing date and the use of a cultivar with a much longer growth cycle. The future scenario that incorporates this changes is simulation Future 2.

In the Future 1 scenario, yield is 29% less than in the baseline scenario. We can also see that the frequency

### Table 7.7 – Cultural practices used in the maize simulation for present and future scenarios.

| | | "Baseline" | Future 1 | Future 2 |
|---|---|---|---|---|
| **Planting** | Cultivar | PIO 3541 | SUWAN-1 | SUWAN-1 |
| | Planting date | April 1 | April 1 | March 15 |
| | Emergency date | April 11 | April 11 | March 25 |
| | Planting density | 8.3 seeds/m$^2$ | 8.3 seeds/m$^2$ | 8.3 seeds/m$^2$ |
| **Irrigation** | Irrigation depth (cm) | 30 | 30 | 30 |
| | Irrigation method | Sprinkler irrigation | Sprinkler irrigation | Sprinkler irrigation |
| | Irrigation efficiency | 0.75 | 0.75 | 0.75 |

distribution of the Future 1 simulations is more irregular, which is due to the inadequacy of agronomic characteristics to the simulated environment.

In a scenario of increase temperatures, developmental rates are higher, resulting in a shorter crop duration and therefore in a shorter photosynthetic period which contributes to a smaller yield. The second Future scenario, the anticipation of sowing date – 15 days earlier – and a later cultivar increases crop duration by 41 days – from 132 to 173 days. Yields obtained in the adjusted Future scenario are 12% higher than in the present.

These results are partially due to the increase in $CO_2$ concentration (9%) and the remaining 3% is due to the possibility of a longer crop cycle.

### Table 7.8 – Simulated maize yield (grain dry weight kg.ha$^{-1}$) in present and future scenarios.

Future 1 – Future scenario incorporating model response to 2x[$CO_2$]; Future 2 – Future scenario with a slight adjustment in planting date; "Baseline" – Present scenario.

| | Future 1 (kg.ha$^{-1}$) | Future 2 (kg.ha$^{-1}$) | "Baseline" (kg.ha$^{-1}$) |
|---|---|---|---|
| 1 | 6,425 | 8,106 | 9,326 |
| 2 | 7,169 | 11,553 | 10,020 |
| 3 | 9,276 | 14,551 | 10,214 |
| 4 | 10,316 | 15,744 | 10,624 |
| 5 | 6,834 | 15,002 | 10,934 |
| 6 | 10,209 | 13,772 | 11,176 |
| 7 | 8,193 | 13,643 | 11,298 |
| 8 | 10,315 | 14,738 | 11,589 |
| 9 | 11,876 | 17,837 | 12,039 |
| 10 | 8,685 | 12,485 | 12,279 |
| 11 | 6,857 | 10,481 | 12,392 |
| 12 | 10,413 | 18,797 | 12,604 |
| 13 | 9,911 | 15,760 | 12,695 |
| 14 | 8,870 | 13,983 | 13,114 |
| 15 | 9,101 | 15,743 | 13,278 |
| 16 | 6,884 | 11,562 | 13,851 |
| 17 | 9,117 | 13,648 | 14,211 |
| 18 | 6,219 | 12,402 | 14,385 |
| 19 | 5,387 | 9,662 | 14,444 |
| Average | 8,704 | 13,656 | 12,237 |
| Standard deviation | 1,659 | 2,683 | 1,437 |
| Coef. of variation | 0.19 | 0.20 | 0.12 |

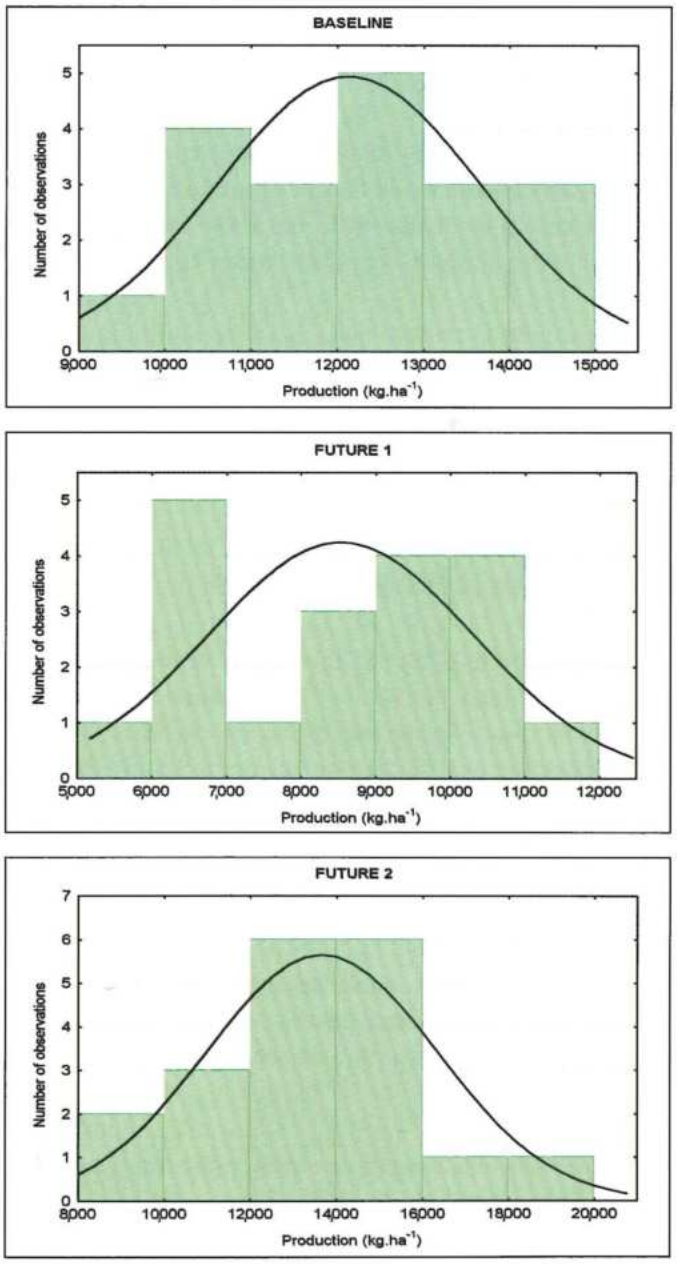

Figure 7.10 (7.10.1, 7.10.2, 7.10.3) – Absolute frequencies for the CERES-MAIZE simulation results in the present and future scenarios (yield: kg dry matter.ha$^{-1}$).

The coefficients of variation shown in Table 7.8 are, as expected, much smaller than those observed in the wheat simulations, since an irrigated crop is much less sensitive to climatic variability.

**Table 7.9 – Water and nitrogen applied in different simulation scenarios using the CERES-MAIZE model (mm e kg.ha$^{-1}$, respectively).**

| | Future 1 | Future 2 | "Baseline" |
|---|---|---|---|
| Irrigation (mm) | 756 | 972 | 707 |
| WUE – water use efficiency (kg/mm) | 12 | 15 | 17 |
| Total N aplied (kg/ha) | 411 | 521 | 335 |
| NUE – nitrogen use efficiency (kg/kg N) | 22 | 26 | 37 |

CERES-MAIZE also simulates the irrigation needs (on the basis of satisfaction of Crop Evapotranspiration) and, as expected, in the Future 2 scenario the water consumption for irrigation is about 37% more than at present.

Here, too, there must be said a word of caution. Since an increase in $CO_2$ is known to increase the water use efficiency and since this knowledge is not introduced in the model, the increase in water needs might not be as high as predicted.

## 7.4 ADAPTATION MEASURES

The main tools available to a farmer to reduce or control the negative impacts of climate change are the ones that he already uses when taking decisions on what crops to grow and when and where to grow them. Fortunately the majority of the cultivated species have a wide genetic variability which is translated in a large number of varieties that can be adjusted to almost any situation within the climatic range of the species.

Therefore, the farmer must define the adequate strategy to avoid stress, particularly heat and water stress, such as the ones followed in the future scenarios for wheat and maize.

Of course these strategies are only valid for temporary crops, since one can place them in a sliding location within the calendar.

A scenario of increase temperature with a longer growing season might be an opportunity to grow vegetable crops in regions where now it is too cold or too risky, due to frost hazard, to grow them.

Yet, the same reasoning can not be applied to permanent crops, such as vineyards and olive groves. In this cases, the major setback will be the increased water stress that can only be compensated by irrigation.

The increased demand for water in other human activities will place the problem of water use at the centre of discussion.

Yet, this is not new in Agriculture. Nowadays, the future of Portuguese agriculture competitiveness is already depending upon the availability of water for irrigation. In the absence of subsidies, the major part of dryland agricultural activities are not commercially profitable.

In a future scenario of increased temperatures and therefore, increased water demand adaptation measures will have to promote an increased efficiency in the use of water, either by more efficient varieties and more efficient systems of water distribution and application.

## 7.5 CONCLUSIONS

In the wheat crop the simulation using future weather data with a 15 days advance in sowing date (Future 2) managed to avoid water stress towards the end of Spring with a substantial increase in productivity (34%). In future weather conditions with a much longer frost-free season, the anticipation of sowing date is possible, since it is no longer necessary to condition the choice of sowing date in order to avoid late spring frosts during flowering. This yield increase is largely due to the effect on increased atmospheric $CO_2$, since the results of the simulation for the same future weather conditions without considering a raise in $CO_2$ concentration, point to an yield increase of only 2% above the baseline results.

In the maize crop simulation of future weather conditions, it is possible to obtain higher productivities than the present ones, by anticipating sowing date and using cultivars with longer developmental cycles, since the growing season is substantially longer. The earlier sowing date, allows the crop to be rain fed in its earlier stages of development and the longer crop duration counteracts the developmental acceleration caused by higher temperatures.

The increase in atmospheric $CO_2$ is the main reason for the increase in productivity (9%) while the climate change alone is responsible for a 3% increase in crop yield.

It is noticeable that this increase in obtainable productivity depends on irrigation water availability (+37%) and also demands an increase in nitrogen fertilizer .

Adaptation measures are needed to avoid the negative effects of climate change. To some extent, some adaptation measures are a common practice in today's agriculture. In fact, farmers have to choose the adequate crop for a given place and adjust sowing dates to local average weather conditions.

Facing a future weather scenario characterized by higher average temperatures and decreased rainfall it will be necessary to choose adequate crop varieties in order to maximize a strategy of stress avoidance, to select crop varieties better adapted to higher temperatures or more resistant to water stress. At the same time some opportunities raise from a general trend of milder winters, allowing the cultivation of some horticultural crops in regions where they are not possible today.

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# 8

# Human Health

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## CONTENTS

## EXECUTIVE SUMMARY

In this chapter, potential adverse health impacts of scenario-drived climatic changes in Portugal were assessed and adaptation measures to avoid/reduce these impacts were suggested. This study also reviews the existing literature on: the current health status in Portugal, populations most sensitive to changes in weather, health issues influenced by global climate change, recent global initiatives on climate change and human health assessment, and methods that are currently available to study climate change impacts on human health.

Following an extensive literature review, several health impacts were identified that may be adversely affected by climate change. Key findings regarding the impacts assessed are summarised below.

*Heat-related deaths* occur following heatwave periods in Portugal. Climate change scenarios for Lisbon indicate that heatwaves will become more frequent and more intense. Under these scenarios, heat-related deaths are expected to increase under all assumptions. For the 2020s, the most conservative approach (HadRM2 model results and assuming acclimatization) shows a 7% increase in heat-related deaths, compared to the present heat-related death rate of 6 deaths per 100,000 individuals per year. If the least conserative approach (PROMES model results and assuming no acclimatization) is used, heat-related deaths are expected to increase six-fold relative to the present. Planned adaptation measures such as a national early warning system, urban planning to reduce the "heat island" effect in urban areas, and the use of air conditioning are suggested to reduce population vulnerability to anticipated heatwaves.

Ambient *air quality* often reaches levels hazardous to public health. If the climate becomes warmer and more variable, as suggested by climate change models, ambient levels of tropospheric ozone and aeroallergens such as pollen may increase. Higher ambient air levels of these pollutants may exacerbate asthma and other respiratory diseases, which currently are significant public health concerns. Improved pollution control measures and a national air quality warning system are two of the adaptation measures required to reduce current and anticipated air pollution-related health outcomes.

*Flood and drought* are reccurring events in Portugal that result in significant economic and health outcomes. Climate change is likely to increase the frequency and intensity of both. Adaptation measures such as early warming systems and improved zoning and building codes are suggested in order to reduce population vulnerability.

Water quality and food-borne disease outbreaks are current significant public health concerns in Portugal. If precipitation variability and temperature increase as climate scenarios indicate, *water and food-borne disease* transmission risk may increase as these climatic changes favour pathogen survival and biotoxin production. Population vulnerability to water and food-borne disease transmission risk may be reduced if current water and waste management systems are improved and environmental and disease surveillance initiatives are strengthened. Deterioration of current public health infrastructures will undoubtedly lead to increased disease transmission risks, regardless of climatic changes.

Increases in temperature and precipitation variability may also increase the potential risks of *vector and rodent-borne diseases* such as Lyme disease, Leishmaniasis, and Leptospirosis. Insufficient information precluded any conclusions as to how climate change may affect Mediterranean spotted fever. Improved disease, vector, and pathogen monitoring and surveillance is necessary to better understand vector and rodent-borne disease transmission. In addition, improvements to current basic public health infrastructures were also suggested to reduce population vulnerability.

The scarcity of health and environmental data in Portugal and the significant number of knowledge gaps on the relationship between health and climate have resulted in many uncertainties being incorporated into the assessment. Consequently, no definite conclusions could be reached on the magnitude of change on potential climate change health impacts. These research gaps need to be urgently addressed in order to conduct more profound national assessments on public health vulnerabilities to anticipated climatic changes.

# 8. Human Health

## 8.1 INTRODUCTION

The World Health Organisation's (WHO) definition of human health (box 8.1) clearly indicates that human health incorporates many aspects of human welfare and encompasses much more than simply the absence of disease. Health can thus be regarded as an index that reflects the state of natural and socio-economic environments (box 8.1). Human health is therefore a particularly compelling reason to study the effects of environmental change.

BOX 8.1

> *Human health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity*
>
> (WHO definition of health)
>
> *Good health and well-being require a clean and harmonious environment in which physical, psychological, social and aesthetic factors are all given their due importance. The environment should be regarded as a resource for improving living conditions and increasing well-being*
>
> (European Charter for Environment and Health, 1989)

Historically, environmental health concerns centred on the adverse effects of exposure to specific physical and chemical agents in the local environment. In recent years, unprecedented changes to the global environment have begun to impinge upon human health (McMichael 1993). Global environmental changes that may adversely affect human health include:

- Global climate change
- Stratospheric ozone depletion
- Loss of biodiversity
- Desertification
- Chemical pollution

In this chapter we discuss the potential impacts of global climate change on human health in Portugal.

### 8.1.1 OVERVIEW OF CURRENT HEALTH STATUS

The past three decades have seen significant improvements in the overall population health. These improvements can be attributed to general improvements in economic and social conditions such as housing, education, sanitation, communication and transport infrastructures, and, to a lesser extent, increased human, material and financial resources devoted to health care. In this section, traditional health indicators are used to assess the current national health status in Portugal.

In 1998, the life expectancy for Portuguese males and females was 72 and 79 years respectively (WHO 1999a). By mid 1998 continental Portugal had a population of 9,474,070 with mortality and fertility rates of 10.7 and 11.4 per 1,000 individuals respectively (INE 1998a; INE 1998b).

Chronic diseases are the major causes of death, accounting for more than 60% of deaths. The leading causes of death are related to circulatory and respiratory disorders and cancer. Given the growing number of smokers (Azevedo et al. 1999), a decrease in chronic disease incidence rates is not likely in the near future.

Over the last two decades, the profile of infectious diseases has changed significantly. In the 1980's, the majority of the infectious disease cases reported were from measles, chicken pox, meningitis, pneumonia, tuberculosis (TB), gastro-enteritis, typhoid fever, rickettsial infections, tetanus, and hepatitis A. Children under the age of ten were the age group most affected by infectious diseases during this period (Lecour 1988). A more recent analysis of hospital admissions indicates that most infectious diseases in the late 1990's occurred in adults in the 21–35 age group. This is mostly due to an increased number of acquired immune deficiency syndrome (AIDS) cases and AIDS/HIV related infections observed during this period (Castro et al. 1996; Pereira et al. 1999). In 1998, infectious diseases contributed to 2% of deaths. AIDS, TB and septicaemia were the leading causes of deaths in this category (INE 1998b).

The current national health system (NHS) was created in 1979 with the idea that it would provide free, universal and comprehensive health cover to all citizens. Although universal coverage has been achived, a number of key challenges remain before an equitable, efficient and quality health service is attained. The public health care delivery system is composed of the traditional primary, secondary, and tertiary health care sectors. General practitioners (GP) in health centres provide primary health care services, while secondary and tertiary care is mainly provided by hospitals. Although the number of health centres and health posts have continued to grow over the last two decades, long waiting times for access to diagnostic facilities continue to be a problem. Inequitable distribution of health care resources and shortage of qualified staff in health centres are at the heart of this problem (EOHCS 1999). This problem is further aggravated by the lack of funding available for primary health care programmes and other preventative medicine initiatives (Calheiros 2001).

Accessibility to basic public health infrastructures such as water, sanitation and electricity contribute towards good public health. Despite significant improvements during the past two decades, data presented in table 8.1 shows that accessibility to these infrastructures vary between regions (INE 1998e).

### 8.1.2 EFFECT OF WEATHER ON HUMAN HEALTH IN PORTUGAL

Historical records indicate that the effects of weather on public health in Portugal have concerned scientists, medical doctors and politicians for more than three hundred years. As far back as the 19th century, scientists like Frazini, expressed concerns for public health during "extreme heat episodes". Some documented health outcomes linked to meteorological conditions in Portugal are briefly described below.

A study done on the monthly mortality in Lisbon from 1845–1997 shows changes in seasonal mortality patterns. These results show that during the mid 1800's most of the deaths occurred in August. The increased number of deaths in August and other summer months were attributed to gastrointestinal infections and malaria. By the late 1800's to mid 1900, distinct seasonal death patterns were not evident. During the last three decades of the 20th century, most deaths occurred in winter, and were mostly due to circulatory and respiratory illnesses. During the period of analysis, life expectancy and quality of life improved significantly (Alcoforado et al. 1999). This clear shift in seasonal mortality patterns may be attributed to society's adaptation to the underlying health hazards (warmer temperatures are more conducive to infectious disease transmissions) and adequate management of these hazards within the medical and technological capabilities of the period.

Analysis of unusually high ambient temperatures experienced in June 1981 established an excess of

**Table 8.1 – Household type and infrastructure accessibility in Portugal, 1997** (source INE 1998e)

| | Continental Portugal (%) | Northern Region (%) | Central Region (%) | LVT (%) | Alentejo (%) | Algarve (%) |
|---|---|---|---|---|---|---|
| **Household type** | | | | | | |
| House | 59.6 | 65.5 | 79.4 | 30.1 | 86.2 | 70.5 |
| Apartments | 38.7 | 32.2 | 19.7 | 68.1 | 13.7 | 27.9 |
| Others | 1.7 | 2.2 | 0.9 | 1.8 | 0.1 | 1.6 |
| **Households with** | | | | | | |
| Electricity | 99.3 | 99.4 | 99.4 | 99.7 | 98.6 | 98.2 |
| Tap water (indoors) | 92.7 | 93.0 | 92.0 | 94.4 | 90.8 | 89.6 |
| Tap water (outdoors) | 4.9 | 4.2 | 4.9 | 5.0 | 5.9 | 5.9 |
| Without tap water | 2.4 | 2.8 | 3.1 | 0.6 | 3.3 | 4.5 |
| Sewage connection to public grid | 62.8 | 44.9 | 41.2 | 88.4 | 83.4 | 65.7 |
| Septic tank | 33.5 | 52.0 | 52.4 | 10.6 | 10.6 | 26.4 |
| Without sewage removal | 3.7 | 3.1 | 6.4 | 1.0 | 6.0 | 7.9 |
| Air conditioners | 1.7 | 0.8 | 0.9 | 2.7 | 2.7 | 2.3 |

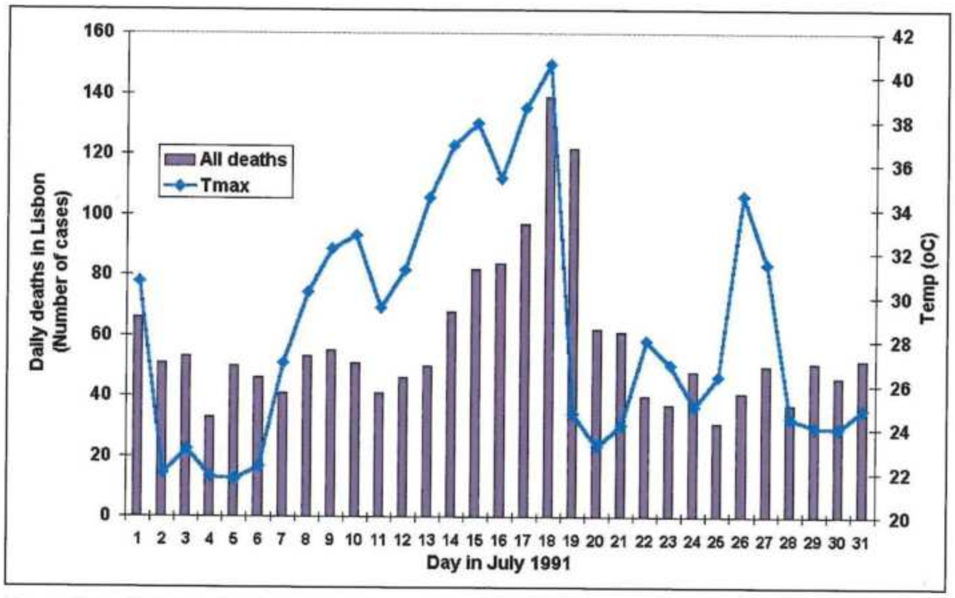

Figure 8.1 – Relationship between daily maximum temperature and mortality in Lisbon during the July 1991 heatwave (data from INE 2000 & IM 2000).

1,900 deaths during a period of nine days (Garcia et al. 1999). A decade later, another heatwave also resulted in unusally high daily mortalities (figure 8.1).

Though seasonal variations of infectious diseases are still evident, thanks to improved health care infrastructures, disease transmission is greatly reduced and fatalities are relatively low due to medical and technological advances. Infectious diseases that currently show seasonal patterns include; Mediterranean spotted fever (tick-bite fever), salmonellosis and other gastrointestinal disorders (DGS 1999; IGIF 2000). Although local transmission of cholera, malaria, and yellow fever no longer occur (DGS 1999), historical records demonstrated seasonal epidemics of these diseases (Calheiros 2001).

Studies have established a link between meteorological conditions and asthma and allergic disorders (Bastos et al. 1993; Pinto & de Almeida 1999). Relationships between air pollution levels and meteorological conditions in Lisbon have also been documented (Andrade 1996; Queiróz et al. 1998). Health outcomes such as premature death, asthma and other respiratory illness associated with air pollution are well documented in the international literature (WHO 2000).

Extreme weather episodes have also been associated with significant acute impacts on public health, perhaps the most noticeable of which are the health impacts of floods. Health effects known to be associated with flooding in Portugal include drowning, physical injuries, mental distress, and possible increases in rodent-borne diseases such as leptospirosis, as well as water and food borne diseases.

### 8.1.2.1 Population Vulnerability to Weather

Medical records indicate that the poor, the elderly, the very young, and people with compromised immune systems as more likely to develop illnesses due to exposure to environmental stresses. Immigrant populations were identified in this study as an additional population-subgroup whose health is likely to be adversely affected by global environmental changes.

#### *8.1.2.1.1 The poor*

The relationship between health and poverty is well established. People in low-income groups are more vulnerable to illness; this is particularity true for acute health risks such as infectious diseases, heat-stress, and the adverse health effects of poor air quality. Current and future trends in poverty in Portugal are discussed in chapter 3.

#### *8.1.2.1.2 The elderly*

The elderly are a vulnerable population group for various reasons. Firstly, ageing is often accompanied by multiple chronic illnesses that could lead to greater vulnerability to acute environmental stresses like heatwaves, air pollution and infections. Secondly, the economic status of the elderly generally declines with time. Financial resources available for help with housekeeping, nutrition, and personal hygiene are often reduced. Finally, social isolation endangers the mental health of elderly individuals living alone.

The number of individuals over 65 years of age has increased significantly. In 1998, 15.2% of the population was 65 years or older (INE 1998c). This number is expected to increase as life expectancy increases. Data presented in table 8.2 also shows that regional distribution of the elderly is not uniform.

**Table 8.2 – Population demographics for Portugal, 1998** (source INE 1998c)

| Region | Population size | Population <15 years (%) | Population 15-64 years (%) | Population 65 + years (%) |
|---|---|---|---|---|
| Portugal | 9 979 450 | 16.8 | 67.9 | 15.2 |
| North | 3 578 310 | 18.4 | 68.8 | 12.7 |
| Centre | 1 710 330 | 15.7 | 66.1 | 18.1 |
| LVT | 3 326 460 | 15.6 | 68.9 | 15.4 |
| Alentejo | 510 320 | 14.3 | 64.1 | 21.5 |
| Algarve | 348 650 | 16.0 | 65.3 | 18.6 |

The state is the major health care provider for the elderly. Some social services for the aged are provided in each region through the Ministry of Social Security. However, *Misericórdias,* which are independent charitable organisations, are the key providers of social services.

Residential care for the aged, provided by the public sector, is very limited and lacks sufficient resources. The majority of old age homes are privately owned and very expensive. Overcrowding and insufficient staff is a common problem in these establishments. It is thus not surprising that in Portugal the elderly often live alone in rural areas or with relatives in urban areas.

#### *8.1.2.1.3 The young*

Children are more vulnerable to contaminants than adults for various reasons. Firstly, they ingest more food and liquids relative to their body size than adults do. Secondly, they have higher breathing rates than adults, and thus breathe in more pollutants relative to their body size. Thirdly, they have behavioural patterns that expose them more to environmental contaminants (i.e. more soil exposure). And finally, their bodies are still developing and thus their organs are not as effective at metabolising and excreting contaminants (Landrigan et al. 1999).

In 1998, 16.8% of the population were under the age of 15 years (table 8.2). If the current national decline trend in fertility rate is assumed, the proportion of individuals in this age group is not expected to increase significantly in the next few decades.

Child health has improved significantly during the past four decades, dropping from an infant mortality rate of 77.5 in the 1960's to one of 6.0 (per 1,000 individuals) in 1998 (INE 1998c). Compliance with childhood vaccination is over 95% (WHO 1997). Current childhood public health concerns include asthma, acute gastric and respiratory infectious diseases, and accidents.

Recent epidemiological studies indicate a cumulative asthma prevalence of 10% and a general rhinitis of 27% in city children. Children between the ages of 13–14 reported a higher prevalence rate of both disorders (Allergonet 2000). Asthma and rhinitis sufferers are most vulnerable to pollen and other air pollutants.

#### *8.1.2.1.4 The immunocompromised*

Immmunocompromised individuals are more vulnerable to infectious agents, air and water pollutants, and thermal and physical stresses. These individuals are probably the most vulnerable to climate changes. AIDS/HIV individuals are not the only immunocompromised individuals within society; the elderly and people undergoing certain medical treatments (such as cancer therapy) are also in this population group.

The proportion of the population that is immunocompromised is difficult to determine correctly due to the lack of data. However, it is anticipated that the proportion of immunocompromised individuals is likely to increase in the future given the ageing population, increased cancer incidence, and longer survival rates of AIDS/HIV and cancer patients.

#### *8.1.2.1.5 Immigrant populations*

Immigrant populations are defined in this study as all groups of individuals that previously lived in a foreign country but now reside in Portugal. These individuals are vulnerable to health risks associated with both countries.

Since 1990, the growth of legal foreign residents present in Portugal has increased by an average annual rate of 7.2% (Baganha et al. 2000). By the end of 1998, there were 177,774 legally resident foreigners. This represents 1.78% of the total population in Portugal. The majority of which were from Africa (46.4%), followed by Europe (29.3%) and the Americas (19.7%). These individuals reside predominantly in the Lisbon, Faro, Setubal and Porto districts (INE 1998c). If the socio-economic scenarios described in chapter 3 are assumed, this population group is anticipated to increase by 7-13% per annum.

Most immigrants reside in the poorer areas of the larger cities. Such living conditions are often conducive to community diseases (Baganha et al. 2000). Some immigrants can have specific disease patterns and health needs due to genetic and behavioural factors and exposure to different environments in their countries of origin. Access to health care that can meet such specific needs is not always available. Illegal immigrants in particular may have restricted access to health care services.

## 8.2 METHODOLOGY

Few climate change assessments address the impacts on human health. This is mostly attributable to the fact that the field of climate change health impact assessment is yet in its infancy. Thus, it is particularly important to understand the particular methodology used in any given assessment. Here, various possible methodologies are reviewed.

### 8.2.1 DESCRIPTION OF ASSESSMENT APPROACH

Forecasting the potential impact of climate change on human health can not be determined using conventional human health risk assessment methodologies that focus on locally generated chemicals and physical exposures (NRC 1994). With climate change, the environmental "exposure" is complex and less immediate relative to conventional exposures. In addition, most of the climate change-induced "exposures" of concern lies in the future. This means that forecasting the potential impact of climate change on human health calls for the development of risk assessment methods based on scenarios rather than an estimation of risks based on past realities (McMichael & Kovats 1998). Recent developments in this field are described below.

#### 8.2.1.1 State of the Art

Concern for the potential health impacts of climate change have stimulated several investigations. The most comprehensive of which have been the reviews produced by; the United Nation's Intergovernmental Panel on Climate Change (IPCC) (McMichael 1996; McMichael & Githeko 2001), the World Health Organisation (WHO), World Meteorological Organisation (WMO) and United Nations Environmental Programme (UNEP) Task Group on health impacts of climate change (WHO/WMO/ /UNEP 1996), and several WHO communications (Kovats et al. 2000a; Kovats et al. 2000b).

The UNEP has produced a Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies. However, this handbook does not recommend any well-developed methodologies to assess human health impacts of climate change. Instead, a suggested approach to performing a qualitative impact assessment for human health is described. This approach focuses on identifying current national health problems that may intensify with predicted climate changes (Balbus et al. 1998).

The WHO, Health Canada and UNEP are currently involved in a joint project with the aim of producing a guideline document to assist countries assess the potential impacts of climate variability and change on human health (WHO/Health Canada/UNEP 2001).

To date, the most comprehensive national assessments on potential climate change impacts on human health have come from Canada (Duncan et al. 1999), the UK (DH 2001), and the USA (Patz et al. 2000). As the effect of climate change on a given population's health reflects the conditions of its ecological and social environments, health impacts will naturally differ between countries and regions. To our knowledge, the present study is the first national assessment done on the potential health impacts of climate change in any southern European country.

### 8.2.1.2 Options for Assessing Impacts on Human Health

The study of the impacts of climate on human health is an emerging research area. Most of the currently published work in this field has been review articles on probable health impacts based on expert judgement. Predictive modelling for health impacts of climate change are limited, firstly because most aspects of human systems are not readily amenable to modelling and, secondly, because of insufficient long-term data series on health outcomes. Conclusions regarding health outcomes in populations living in currently unknown circumstances many decades into the future are thus difficult to formulate and are subject to a considerable level of uncertainty.

Research methods by which climate-health interactions have been studied can be grouped into four general categories: expert judgement, analogue studies, direct studies of early effects, and predictive models (McMichael & Kovats 2000a). Ecological risk assessment is an additional approach that can be used to evaluate potential climate health impacts (Balbus et al. 1998; Bernard & Ebi 2001).

#### *8.2.1.2.1 Choice of assessment methodology*

The linkage of climate and health data offers considerable benefits but also poses many dangers if not carefully carried out. The choice of the most appropriate assessment method depends on several factors such as the purpose of the study and the type of data available.

Important issues that need careful consideration in detecting and quantifying the influences of climate change upon human health include (Kovats et al. 2000b):

- Most diseases have multiple causes,
- Great diversity in possible disease types, for example, acute and chronic, physical injury and mental health disorders,
- Many uncertainties regarding the biological and physical process by which climate affects health, as well as the many environmental assumptions,
- Long-term nature of the changes involved, and
- Most epidemiological studies have been done on a local basis, making application on a wider scale difficult.

The advantages and disadvantages of the assessment methods listed above are summarised in table 8.3. These facts have to be carefully considered so that the most suitable method is used. For example, while predictive modelling methods are the most desirable assessment methodology to study health impacts of climate change, the extensive resources and large amounts of additional data that these models require make them impractical when such requirements are limited. In practice, such requirements cannot always be met by most countries, including many developed countries, leaving researchers with no alternatives but to use less data intensive assessment methods. Results of the latter assessment types can still be accepted as a basis for action provided that they were conducted in a scientifically credible manner and the results obtained are consistent with those obtained from more detailed studies for which the statistical precision was established. Moreover, the results from these less complex assessment methodologies are useful in highlighting areas or issues requiring further, or more detailed investigation.

#### *8.2.1.2.2 Uncertainties inherent in climate change health impact assessments*

Assessments of the impacts of climate change have been overwhelmed by large uncertainties at each step of the process. The health impact assessment is no exception. Uncertainty accumulates throughout the process of climate change prediction and impact assessment creating a "cascade of uncertainty". This occurs due to the uncertainties of future emissions of greenhouse gases, modeling of the climate system, climate-health relationships. In our assessment we explored the uncertainty range of potential health outcomes through scenarios that represent plausible and internally consistent futures.

Broadly speaking, uncertainties arise from two different sources: 'incomplete' knowledge and 'unknowable' knowledge. Incomplete knowledge affects much of our model design whether they be climate models (e.g., poorly understood cloud

**Table 8.3 – Advantages and disadvantages of study methods**

| Study Method/Approach | Advantage | Disadvantage |
|---|---|---|
| Expert judgement | • Inexpensive & rapid<br>• Integration of multiple factors possible (very basic level)<br>• Stakeholder involvement possible<br>• Not very data intensive | • Only qualitative results possible<br>• Imprecise, may be subjective |
| Analogue studies | • Qualitative and quantitative assessments possible<br>• Relatively inexpensive & rapid<br>• Visual representation of important information possible<br>• Simpler computation than predictive modelling | • Dependent on secondary health and environment data availability and quality<br>• Unable to integrate numerous factors & dynamic interactions<br>• Limited applications to population with vulnerabilities different to historical reference population |
| Early effects | • Quantitative<br>• Visual representation of important information possible<br>• Rapid identification of disease endemic areas and new outbreaks, allowing for rapid intervention | • Relatively data intensive<br>• Dependent on health and environmental indicator trends<br>• Low predictive power<br>• Requires on going data collection |
| Predictive Modelling | • Quantitative<br>• Integration of numerous factors & dynamic interactions possible | • Very data intensive<br>• Complex with many uncertainties<br>• Most expensive and time consuming<br>• Resource intensive<br>• Dependent on secondary health and environment data availability and quality |
| Ecological risk assessment | • Draws on expertise from various study fields<br>• Qualitative & quantitative assessments possible<br>• Relatively rapid<br>• Assessment complexity flexible<br>• Uncertainties discussed<br>• End result useful for decision-makers & public. | • Dependent on secondary health and environment data availability and quality<br>• May be subjective<br>• Ecosystem health associations not always fully understood<br>• Integration of other health determinants (e.g. socio-economic factors) not always possible |

physics) or impact models (e.g., poorly known dose-response effect of thermal stress and cardiovascular health outcomes). Unknowable knowledge arises from the inherent indeterminacy of future human society and of the climate system (Hulme & Carter 1999). Examples include the cultural adjustments in time that may have an impact on the relationship between thermal stress and mortality rates, for example, improvements in housing conditions (Martens 1998); or the climate system, as a complex non-linear dynamic system, is indeterminate and even with perfect models and unlimited power, for a given forcing scenario a range of future climates will always be simulated.

### 8.2.1.3 Description of Assessment Methodology Used in Present Study

The assessment methodology used in the present study drew on the UNEP recommendations (Balbus et al. 1998) as well as several assessment techniques used in the Canadian, UK, and US national assessments (Duncan et al. 1999; DH 2001; Patz et al. 2000). The present assessment used the following approach:

1. Assessing current health status in Portugal

2. Identifying populations most vulnerable to climate change

3. Understaning the manner in which scenario-derived climate changes may affect human health

4. Assessing the manner in which potential climate change health impacts may be avoided/reduced.

5. Identifying knowledge gaps that need to be investigated further to fully understand the possible impacts of climate change on human health in Portugal.

Due to the difficulties in obtaining reliable and timely data, quantitative modelling of future impacts was not possible for most health outcomes assessed. Potential climate change health impact "projections" made in the present study are therefore mostly qualitative. Results of the work done on the first two points listed in the assessment approach above are presented in section 8.1, while the remaining three points are discussed in sections 8.3, 8.4, and 8.5 respectively. Assessment of all five points was based on expert judgement and national data collection. However, determination of the manner in which expected climate changes may affect human health in Portugal (point 3) required a more in-depth analysis. The methodology followed is briefly described below.

Following an extensive literature review, several health impacts were identified that may be adversely affected due to climate change in Portugal. The present study focused on the following health outcomes:

- Heat-related mortality,
- Air pollution-related health effects,
- Health effects associated with floods and drought,
- Water and food-borne diseases, and
- Vector and rodent-borne diseases.

Potential health outcomes that were not anticipated to be *adversely* affected due to climate change in Portugal were not assessed in depth. Health outcomes were assessed for continental Portugal only. Assessment of potential health outcomes due to international travel was not included in the present study.

During the assessment of each health outcome, the following points were considered:

- Is the health outcome currently a problem in Portugal?
- Are there historical records to indicate that the health outcome was a problem in Portugal in the past?
- What is the climate-health relationship for the health outcome?
- Assuming the above climate-health relationship is valid for all climate change scenarios for Portugal, what health changes are anticipated to occur?

The manner in which each potential climate change health outcome was studied is summarised below.

#### 8.2.1.3.1 Heat-related mortality

An empirical-statistical predictive modelling approach was used to assess the impacts of climate change on heat-related mortality in Lisbon. This modelling approach was based on a dose-response relationship derived from daily maximum temperature and excess mortality during the summer months of 1980-1998 observations.

The climate-mortality association was estimated using an observed-expected analysis similar to the method applied by Guest et al. (1999). Two approaches were used to calculate expected deaths during summer months in order to account for the uncertainty in estimating this variable:

- A fixed mean of daily mortality for each summer month for the entire period 1980-98 (these were: 50.5 in June, 49.9 in July and 47.6 in August);

- A 30-day running mean (from mid-May to mid-September) for the whole period, but selecting only the summer values (thus having a different value for each summer day).

In each case, daily excess deaths were calculated by subtracting the expected values by the observed daily values. In the fixed mean approach that meant subtracting every observed daily death of June by 50.5, every observed daily death of July by 49.9 and so on. In the 30-day running mean method each observed daily death was subtracted by its corresponding expected value. Heat-related deaths were defined as the number of deaths occurring in excess of the number that would have been expected for that population in the absence of stressful weather (McMichael 1996). Each summer day for the 1980-98 period had an excess death value and a corresponding maximum temperature. We then aggregated excess deaths into 1°C intervals and summed them up to determine at what temperatures the heat effect was more pronounced. Our analysis showed that heat-related deaths were not discernible below 29°C (Figure 8.2).

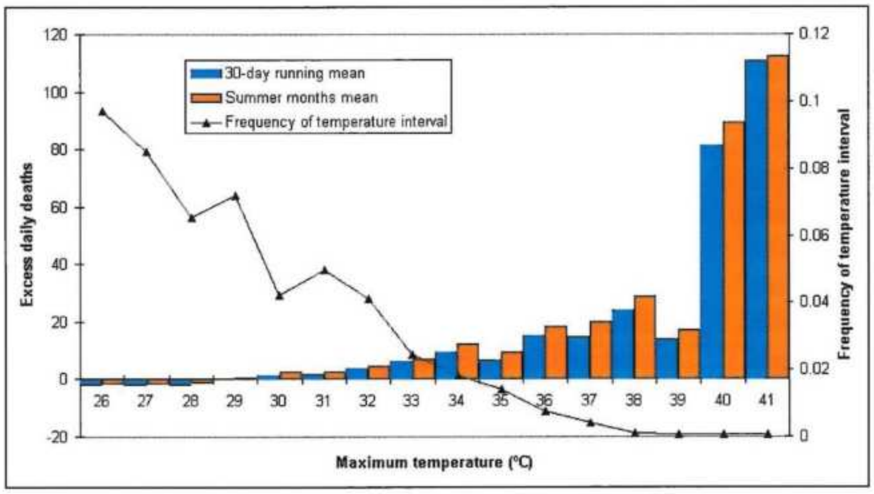

Figure 8.2 – Excess heat-related daily deaths in Lisbon during the summers of 1980-98. Added difference between observed and expected number of deaths, according to temperature intervals of 1°C, using a 30-day running mean and a summer months mean as expected values. The black line represents the frequency of occurrence of the temperature interval during the period. (data from INE 2000 & IM 2000).

A non-linear regression showed a strong relationship between maximum temperature and excess deaths (using two approaches to calculate expected deaths: a 30-day running mean and a fixed summer months mean) in Lisbon for the period in study (Dessai 2001).

**Table 8.4 – Observed and modelled mortality under two variants of the model (a summer months mean and a 30-day running mean approach). Mortality rates per year are given under brackets using the average population throughout the period**

| | Summer months mean | 30-day running mean |
|---|---|---|
| **Observed** | 2425 (6.2) | 1903 (4.9) |
| **Modelled** | 2338 (6.0) | 2108 (5.4) |

Observed and modelled mortality using these two variants is summarised in table 8.4. Under the fixed mean approach total annual heat-related mortality was around 6 per 100,000 or 128 deaths per year for the population of Lisbon, during the period 1980-98. This relationship (under the two approaches) was used to assess potential heat-related deaths in Lisbon under various climate change scenarios. These scenarios are described in section 8.2.2.

A climate impact assessment exercise entails many uncertainties either due to incomplete or unknowable knowledge. Due to this fact, many assumptions have to be made about the future because:

1. Temperatures above 29°C have a higher frequency that the period 1980-98, and often occur outside summer.

2. Temperatures will go well beyond previously experienced conditions where the dose-response relationship is no longer valid.

3. People will acclimatize/adapt to future climates.

To deal with these problems of epistemic uncertainty (i.e. incomplete knowledge of processes that influence events) a set of assumptions were made to provide, in our opinion, a wider picture of the possible impacts.

With respect to point one, the model used here (Dessai 2002) is only valid for summer months, but taking into account that heat waves could extend their period (outside summer) in the future we assumed the relationship holds outside summer (considered a high estimate and called hereafter *Year-round*). We also only selected future summer daily temperatures to calculate future mortality. This was considered a low estimate and designated *Summer (JJA)* hereafter.

As for the second point, we took two approaches. In the first approach, we allowed the extension of the dose-response curves into *unobserved temperatures* (i.e. temperature outside the demonstrated range of the model) assuming the association holds its characteristics for temperatures higher than those observed (considered a high estimate). However, we did set a limit to avoid unrealistic results. We only considered valid those results that contemplated less than 0.5 days per year of unobserved temperatures, which is roughly saying that the model holds an extra 2°C outside its proven-valid range.

In the second approach, which takes into account point three at the same time, we assume people will *acclimatize/adapt* with time. This approach is centred on the possibility that people may acclimatize over long periods. It is known that initial physiological acclimatisation to hot environments can occur over a few days but complete acclimatisation may take several years (McMichael 1996). "How many years" is still an unanswered question due to the lack of long-term studies on climate and human health. We assumed complete acclimatization to an extra 1°C (compared to the present) is reached after three decades, making the dose-response relationship work from 30-42°C in the 2020s, 31-43°C in the 2050s, and 32-44°C in the 2080s (as compared to 29-41°C in the present). This approach reduced considerably the number of unobserved temperatures because it artificially changed the range of the dose-response curves in the future.

#### *8.2.1.3.2 Air pollution-related health effects*

Recent studies on global climate change and air pollution-related health effects indicate that health effects of concern are most likely to be those associated to tropospheric ozone ($O_3$) and aeroallogens (i.e. pollen) exposures (Patz et al. 2000; Kovats et al. 2000a). Ambient air levels of these pollutants were obtained (DGA 2000a; EPI 2001) for Portugal and the health effects likely to be associated with these air pollutant levels assessed.

Since ambient levels of these pollutants are influenced by factors including pollutant emission sources and local weather conditions, information on these factors was compiled. Data on $O_3$ precursor emission trends for Portugal was thus collected (UNECE/CLRTAP 2000; DGA 2000b) as well as information on the plants responsible for most pollinosis in Portugal (EPI 2001).

Analogue studies were used to determine the effect of climate variables on the levels of nitrogen dioxide (NO2), $O_3$ and pollen in Lisbon. The climate-$NO_2$ relationship was established based on daily windspeeds and minimum temperature in Lisbon in relation to $NO_2$ levels (Andrade 1996). The climate-$O_3$ relationship was achieved based on daily windspeeds and maximum temperature in relation to $O_3$ levels. Airborne pollen levels in Lisbon were found to increase by increases in daily maximum temperatures during the flowering period, cumulative rain-free days, and windspeeds (Queiróz et al. 1998).

The climate-pollutant relationships established above were used to determine potential changes in the intensity and dispersion of these pollutants in Lisbon under different climate scenarios. Results from two regional climate models (see chapter 2), PROMES and HadRM2, were used to construct the climate scenarios. Potential changes in health effects of climate-related changes in air pollution were qualitatively assessed based on these scenarios. In-depth quantification of potential health outcomes was not possible, as reliable quantification data on future pollutant levels was not available.

#### *8.2.1.3.3 Health effects associated with floods and drought*

An international literature review was conducted in order to ascertain the health impact of natural disasters such as floods and drought. Results indicated that indirect health effects of floods and drought are far greater than direct health outcomes.

The indirect effects of potential climate change alterations in floods and droughts, such as waterborne diseases and vector and rodent-borne diseases were investigated as described in the three sections that follow.

#### *8.2.1.3.4 Water and food-borne diseases*

The available literature was reviewed to ascertain current and historical disease prevalence (and outbreaks) of water and foodborne diseases. Health outcomes associated with coastal and marine issues such as seafood poisonings were also included in the definition of water and food-borne diseases and thus also assessed in this section. Potential pathogen contamination routes of these diseases are discussed.

Since water quality has a critical role in the transmission of all diseases assessed in this section, data on drinking water, recreational freshwater and coastal water quality was studied based on official water quality records (DGA 2000c; INAG 1996; INAG 2000). Information on population accessibility to basic health infrastructures such as drinking water and sanitation were also compiled (INE 1998e). Collectively, this information was used to determine population groups currently most at risk of contracting water and foodborne diseases. Although climate change may affect water supplies in terms of quality, quantity and availablity, only potential health impacts associated with the former were assessed here.

Climate variables known to influence water and foodborne disease transmission were identified based on international studies (Rose et al., 2000; WHO 1999b; INAG 1996; Lacey 1993; Baird-Parker 1994). Changes in these climate variables in Portugal were assessed based on results from the HadRM2 climate model (see chapters 2 & 5). These facts allowed for a qualitative assessment of the potential changes in water and foodborne disease transmission. Quantification of risks in the transmission of these diseases was not possible because of limited health data availablity.

### *8.2.1.3.5 Vector-borne diseases*

Vector-borne diseases of possible public health concern due to climate change were identified based on expert judgement from review studies (Kovats et al. 2000a; Parry 2000; Patz et al. 2000) as well as consultations with key national vector biologists.

Information on current and historical data pertaining to disease, vector, and parasite prevalence was compiled. Where possible, disease prevalence was collected for various population sub-groups in order to identify populations most at risk. Information on each disease's clinical manifestations and transmission dynamics was obtained based on available literature. Special attention was given to temperature threshold limits required for pathogen and vector survival.

These temperature threshold limits were used together with results from the climate change models PROMES and HadRM2 in order to determine potential temperature favourable periods for pathogen and vector survival for five regions in Portugal. Two climate scenarios were used from each model, one representative of a $1xCO_2$ concentration (model-baseline climate scenario) and the other representative of a $2xCO_2$ concentration (model-future climate scenario).

Vector and pathogen survival potentials were used as indicators of vector abundance and pathogen prevalence potential. Potential disease risks were assessed based on vector abundance and pathogen prevalence potential relative to the scenarios listed in table 8.5. The qualitative risk levels used in this assessment were categorised as summarised in table 8.6.

**Table 8.5 – Scenarios used in vector-borne disease assessment**

| | Assuming current knowledge of vector & parasite prevalence in Portugal | Assuming the introduction of a small population of parasite infected vectors into Portugal |
|---|---|---|
| $1xCO_2$ (current) climatic conditions | Scenario 1 | Scenario 2 |
| $2xCO_2$ (future) climatic conditions | Scenario 3 | Scenario 4 |

**Table 8.6 – Potential vector-borne diseases risk level criteria**

| Parasite ⇒ / Vector ⇓ | None Present | Imported human cases only | Low prevalence in vectors/hosts | High prevalence in vectors/hosts |
|---|---|---|---|---|
| None Present | No Risk | No Risk | No Risk | No Risk |
| Focal Distribution | No Risk | Very low Risk | Low Risk | Low Risk |
| Regional distribution | No Risk | Very low Risk | Low Risk | Medium Risk |
| Widespread distribution | No Risk | Very low Risk | Medium Risk | High Risk |

### *8.2.1.3.6 Rodent-borne diseases*

Available literature was reviewed and key national experts consulted (Filipe 2000; Collares-Pereira 2001) in order to identify which rodent-borne diseases might cause public health concerns under climate change. National official records and other relevant scientific material were assessed to determine rodent and parasite prevalence and disease incidences.

The relationships between climatic factors and disease transmission dynamics were determined from the literature. These relationships were used to determine the changes in the potential risk of contracting rodent-borne diseases under HadRM2 climate change scenarios.

#### *8.2.1.3.7 Uncertainties*

Uncertainties most likely to affect the conclusion of each health impact studied are listed in table 8.7. Uncertainty level associated with each was ranked based on the current state of knowledge into four classes namely (Moss & Schneider 2000);

- *Well-established:* when models incorporate known processes; observations largely consistent with models for important variables; or multiple lines of evidence support the finding.

**Table 8.7 – Uncertainties incorporated in the assessment process**

| Uncertainty source | Evidence available to support finding |
|---|---|
| **Common to all health outcomes assessed** | |
| Observed climatic records for Portugal | Discussed in chapter 2 |
| Model-generated climatic results for Portugal | Discussed in chapter 2 |
| Use of current socio-economic conditions in future assessment scenarios | Speculative |
| Identification of climate change health outcomes of concern for Portugal | Established but incomplete |
| **Heat-related deaths assessment** | |
| Observed mortality data records for Portugal | Well-established |
| Establishment of heatwave definition for Lisbon | Competing explanations |
| Applicability of current heatwave definition to future populations in Lisbon | Competing explanations |
| **Air pollution-related health outcomes** | |
| Observed records of air pollution levels in Lisbon | Well-established |
| Establishment of climate-ozone relationship | Established but incomplete |
| Establishment of climate-pollen relationship | Established but incomplete |
| Health effects associated with air pollutants | Established but incomplete |
| Future pollution emission trends in Portugal | Speculative |
| Applicability of current climate-air pollutant relationship in future scenarios | Established but incomplete |
| **Health effects associated with floods and drought** | |
| Identification of health outcomes of concern | Speculative |
| **Water and Food-borne disease assessment** | |
| Identification of diseases of concern | Well-established |
| Observed disease incidence data for Portugal | Established but incomplete |
| Establishment of climate-disease transmission potential relationship | Well-established |
| Applicability of current climate-disease transmission relationship in future climate scenarios | Established but incomplete |
| **Vector-borne disease assessment** | |
| Identification of diseases of concern | Well-established |
| Observed disease incidence data for Portugal | Established but incomplete |
| Characterisation of disease transmission competent vector populations and pathogens in Portugal | Established but incomplete |
| Establishment of temperature-vector survival relationships | Well-established |
| Establishment of pathogen-vector survival relationships | Well-established |
| Applicability of favourable temperature ranges for vector and pathogen survival to assess period of days suitable of survival under different climate scenarios | Established but incomplete |
| Use of temperature as the only environmental factor of concern in disease transmission | Competing explanations |
| Assumption that vector survival can be an indicator of vector abundance and distribution | Speculative |
| Assumption that pathogen survival can be an indicator of pathogen prevalence in hosts and vectors | Speculative |
| Establishment of qualitative risk levels to assess potential disease transmission in Portugal | Speculative |
| **Rodent-borne disease assessment** | |
| Identification of diseases of concern | Well-established |
| Observed disease incidence data for Portugal | Established but incomplete |
| Determination of pathogen strain and infection status of hosts involved in disease transmission in Portugal | Established but incomplete |
| Establishment of climate-disease transmission relationship | Speculative |
| Applicability of above relationship to assess potential disease transmission under different climate scenarios | Speculative |

- *Established but incomplete:* if models incorporate most known processes, although some parameterizations may not be well tested; observations are somewhat consistent with theoretical or model results but incomplete; current empirical estimates are well founded, but the possibility of changes in governing processes over time is considerable; or only one or a few lines of evidence support the finding.

- *Competing explanations:* if different model representations account for different aspects of observations or evidence, or incorporate different aspects of key processes, leading to competing explanations.

- *Speculative:* conceptually plausible ideas that have not received much attention in the literature or that are laced with difficult to reduce uncertainties or have few available observational tests.

### 8.2.2 DESCRIPTION OF DATA USED

Data used throughout the assessment process was obtained from official sources in order to minimise data errors and biases.

#### 8.2.2.1 Climatic Data

##### *8.2.2.1.1 Observed data*

The Portuguese Institute of Meteorology supplied all the observed climate data used in all health impact assessments. Observed climatic variables used for each health impact assessment are listed in table 8.8.

##### *8.2.2.1.2 Climate-model generated data*

Climate change scenarios for Portugal used in health impacts assessed in this chapter were constructed based on results from the regional climate models (RCMs) PROMES and HadRM2. Climate variables used for each assessment are briefly described in table 8.8. Some health impacts made use of local (focal) model-climate data represented by a single model grid point. Others required regional climate variables that were composed by several model grid points. The latter was calculated as the mean of climate data from five regions in Portugal.

For the heat-related mortality study, future daily weather series were produced from the RCMs output.

**Table 8.8 – Climate data used in assessment process**

| Health outcome | Observed climate variables | Climate-model generated variables |
|---|---|---|
| Heat-related deaths | Daily maximum temperatures for Lisbon (1950-1999) | Daily maximum temperatures from PROMES grid point 1618 and HadRM2 grid point 68 |
| Air pollution-related health effects | Daily maximum temperatures for Lisbon (1998-1999) | Daily maximum and minimum temperatures, and windspeeds from PROMES grid point 1618 and HadRM2 grid point 68 |
| Health effects related to extreme weather events | None used | Flood and drought potential results from chapters 2 & 5 |
| Water and food-borne diseases | None used | Mean monthly temperature results from chapter 2<br>Precipitation, flood and drought potential results from chapters 2 & 5 |
| Vector-borne diseases | None used | Daily mean temperatures for five regions in Portugal from PROMES and HadRM2 models.<br>Precipitation, flood and drought potential results from chapters 2 & 5 |
| Rodent-borne diseases | None used | Mean monthly temperature results from chapter 2<br>Precipitation, flood and drought potential results from chapters 2 & 5 |

We added the baseline climate (1969-98) daily temperatures with the RCMs mean monthly temperature anomaly, which was linearly interpolated between months. After calculating the average monthly temperature anomalies for both models, these values were linearly disaggregated into days to construct a 365-day period of temperature anomalies in order to avoid step changes between months (Figure 8.3).

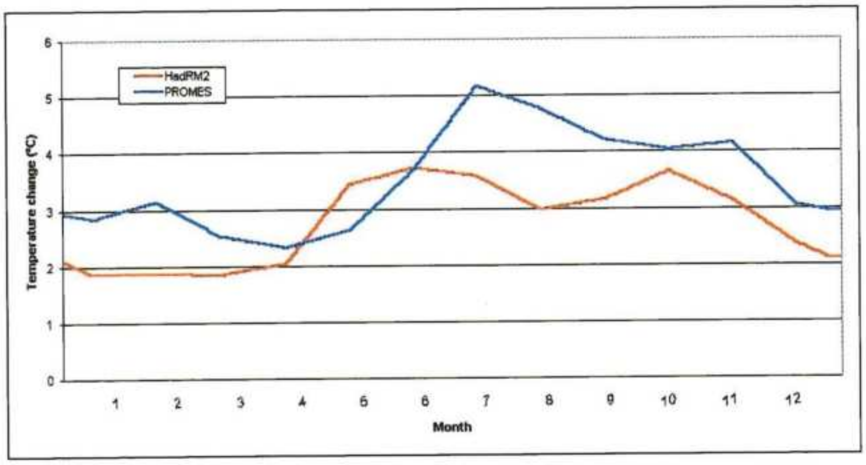

Figure 8.3 – Linear interpolation between mean monthly temperature change in HadRM2 and PROMES regional climate models for the 2040s.

A consistent increase in the number of days above the critical temperature in both RCMs was observed (Table 8.9). For the period 1980-98 these days constituted 52% of summer days, but in the future they increased dramatically. Acclimatization reduce days above the critical temperature in both RCMs and in HadRM2 the 2050s even have less days than the 2020s with no acclimatization. Substantial unobserved temperatures (above 0.5 days per year) are only reached by the 2080s. The RCMs are consistent in showing that unobserved temperatures only occur in summer before the 2050s, whereas in the 2080s some already occur outside summer.

### 8.2.2.2 Socio-economic Data

Portugal's administrative system comprises of 18 districts and 2 autonomous regions (the islands of Açores and Madeira). Health and socio-economic data collected from these districts are normally grouped and presented for seven regions; Northern region, Central region, Lisbon and Tagus Valley (LVT), Alentejo, Algarve, Madeira, and the Azores. The first mentioned five regions are for continental Portugal and the remaining two for each autonomous (non-continental) region. In the present study, the health and socio-economic data used were grouped into these five continental regions.

#### *8.2.2.2.1 Observed data*

Observed demographic, population mortality data, and information on accessibility to basic public health

**Table 8.9 – Days above critical temperature per year compared to baseline climate (1968-98) for year-round and summer months assuming no and full acclimatization. Critical temperature is 29°C under no acclimatization, and an extra 1°C is added for each time slice with full acclimatization. In brackets is the number of days of unobserved temperatures per year. The shaded blocks are periods with more than 0.5 days of unobserved temperatures per year, which were not used in the study.**

| | | Year-round | | | Summer (JJA) | | |
|---|---|---|---|---|---|---|---|
| | | *2020s* | *2050s* | *2080s* | *2020s* | *2050s* | *2080s* |
| **No acclimatization** | *HadRM2* | 19.5<br>(0.07) | 45.9<br>(0.17) | 106.6<br>(2.13) | 12.6<br>(0.07) | 28.1<br>(0.17) | 58.0<br>(1.73) |
| | *PROMES* | 26.3<br>(0.07) | 61.0<br>(0.40) | 117.5<br>(8.8) | 17.6<br>(0.07) | 39.9<br>(0.4) | 60.4<br>(7.97) |
| **Full acclimatization** | *HadRM2* | 7.1<br>(0.03) | 15.2<br>(0.03) | 51.4<br>(0.20) | 4.6<br>(0.03) | 9.6<br>(0.03) | 31.5<br>(0.20) |
| | *PROMES* | 13.5<br>(0.07) | 29.5<br>(0.10) | 76.9<br>(2.03) | 9.7<br>(0.07) | 21.0<br>(0.10) | 49.3<br>(1.83) |

**Table 8.10 – Observed health and socio-economic data used in assessment process**

| Data description | Data source |
|---|---|
| **Identification of vulnerable populations** | |
| Population demographics | INE 1998c |
| Poverty trends | Chapter 3 |
| Foreigners residing in Portugal | INE 1998c |
| Living conditions of immigrants in Portugal | Baganha et al. 2000 |
| Asthma and rhinitis prevalence in children in Lisbon | Allergone 2000 |
| **Heat-related deaths** | |
| Daily mortality data for Lisbon (1980-1999) | INE 2000 |
| Building characteristics in Portugal | INE 1998e |
| Urbanisation trends in Lisbon | Lucas 1991 |
| Old inner city buildings in Lisbon, quality & inhabitants | Ribeiro 1991 |
| **Air pollution-related health effects** | |
| Asthma hospital admission peak periods | Bastos et al. 1993 |
| Allergic rhinitis seasonality in Lisbon | Lopes da Mata 2001 |
| **Water and food-borne diseases** | |
| Foodborne outbreaks in Portugal (1987-1998) | WHO 1999c |
| Monthly incidences of notifiable diseases in Portugal (1994-1998) | DGS 1999 |
| Seafood biotoxin contamination in Portugal | Sampayo et al. 1997<br>Vale & Sampayo 1999; 2001a & b |
| Public accessibility to tap-water and sanitation facilities | INE 1998e |
| **Vector-borne diseases** | |
| Disease incidences of malaria, Mediterranean spotted fever & Leishmaniasis in Portugal (1994-1998) | DGS 1999 |
| Hospital admissions for dengue, yellow fever, West Nile fever, Lyme disease, TBE & Schistosomiasis in Portugal (1992-1998) | IGIF 2000 |
| **Rodent-borne diseases** | |
| Disease incidence of leptospirosis in Portugal (1994-1998) | DGS 1999 |

infrastructures were obtained from the Portuguese National Institute of Statistics. Additional observed health and socio-economic data used in each health impact assessment is summarised in table 8.10.

#### *8.2.2.2.2 Socio-economic scenario generated data*

Most of the potential health outcomes investigated in this study could only be assessed qualitatively. Therefore, socio-economic scenarios were rarely used. An exception was the heat-related mortality assessment. Future demographic changes were calculated in consistency with the IPCC Special Report on Emission Scenarios (SRES; Naki´cenovi´c et al. 2000). OECD population growth rates from each SRES scenario was applied to the 1990 Lisbon population to produce 10-year spaced population figures until 2100.

In terms of population, Lisbon was shown to grow in all scenarios, reaching a maximum of 3.6 million (in SRES A2 scenario) and a minimum of 2.2 (in SRES B2) by 2100. The middle range scenarios all converged around 2.6 million. This median value was used in this modelling exercise.

## 8.3 IMPACTS OF CLIMATE CHANGE UPON HUMAN HEALTH

### 8.3.1 INTRODUCTION

#### 8.3.1.1 Overview

Climate change is anticipated to affect human health through a variety of pathways (figure 8.4). Some are direct pathways such as extreme thermal exposure or floods. Others involve intermediate and multiple pathways such

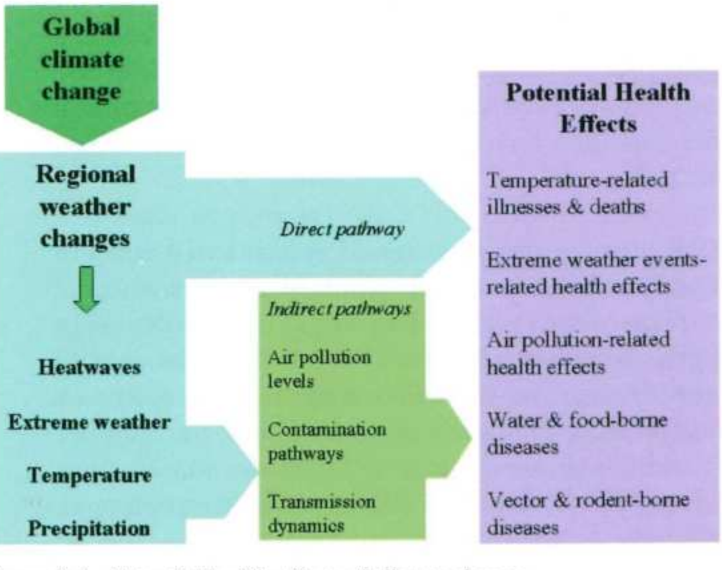

Figure 8.4 – Potential health effects of climate change.

as those affecting the transmission dynamics of vector-borne diseases.

#### *8.3.1.1.1 Direct effects of climate change*

Increased occurrences of extreme weather events and thermal extremes have direct impacts on human health. Exposure to thermal extremes may result in altered rates of heat and cold related illnesses and deaths (Kalkstein 1993).

Alterations in the frequencies and/or intensity of extreme weather events such as storms and floods may result in rapid increases in deaths, physical injuries, malnutrition, and psychological disorders. Additional health impacts can also result if these weather events damage public health infrastructures. An extreme weather event like drought may result in increased malnutrition, poverty and violence (McMichael & Haines 1997).

#### *8.3.1.1.2 Indirect climate change effects*

Health impacts due to indirect climate change effects such as those resulting from increased ambient air pollution levels and ecological disturbances are also possible.

Weather has a major influence on the dispersal and ambient concentrations of air pollutants. Increased ambient air levels of pollutants such as ozone, particulates, and aeroallergens will have a negative impact on respiratory and cardiovascular health outcomes. Higher air temperatures and altered precipitation patterns have the potential to increase the ambient concentration of tropospheric ozone and aeroallergens such as pollen (Wark et al. 1998; Patz et al. 2000).

Disturbances in ecological systems can lead to significant changes in the transmission dynamics of infectious diseases and regional changes in agricultural productivity. Infectious diseases of concern can be transmitted to humans either by vector organisms such as insects, ticks, and rats, or directly by human exposure to contaminated water and food (Epstein 2000). As a consequence to ecological disturbances, public health can also be affected by human population movements and by regional conflicts over shortages in food and water supplies (McMichael 1996).

Projections of the extent and direction of potential climate change health impacts are difficult as such assessments incorporate many confounding and poorly understood factors associated with potential health outcomes, population vulnerability and adaptation. Given the uncertainty regarding the potential climate change effects on human health, focusing on describing and reducing population vulnerability is essential. This section focuses on identifying and describing current national public health concerns that may intensify under climate change scenarios. Adaptation measures that may help reduce or eliminate these health impacts are discussed in section 8.4.

### 8.3.1.2 Detailed List of Impacts

#### *8.3.1.2.1 Identified*

Currently, there are very few published studies showing changes in the Portuguese population health status in response to the observed climatic changes. Identification of potential future health impacts of climate change in Portugal is thus difficult. Nevertheless, if potential global climate change health impacts (McMichael 1996) are considered in the context of climate change scenarios for Portugal, then the following potential health impacts are possible:

- Increased heat-related illnesses and deaths due to more frequent and more intense heatwaves,
- Decreased cold-related deaths due to milder winters,
- Increased prevalence of asthma and allergic disorders, as well as other respiratory disorders and deaths associated with poor air quality,
- Increased deaths, injuries, infectious disease risks, and mental disorders associated with floods and storms,
- Increased risks of infectious diseases and mental disorders associated with drought,
- Increased deaths, injuries, and cardiovascular and respiratory symptoms associated with forest and vegetation fires,

- Increased incidence of diarrhoea and other infectious water and food-borne diseases,
- Increased incidence of death-by-drowning and other water-related injuries as water recreational activities may become more frequent,
- Changed geographical ranges and incidence of vector-borne diseases,
- Increased risks of infectious diseases and mental disorders associated with population displacement and infrastructure damage due to sea-level rise, and
- Increased poverty, mental disorders and possibly malnutrition due to reduced agriculture yields and fishing.

Since current knowledge of future environmental and societal conditions is not complete, it is reasonable to conclude that additional, currently not identifiable, public health outcomes are possible due to future climatic and socio-economic changes in Portugal.

#### *8.3.1.2.2 Studied*

Several of the adverse potential health impacts identified above were assessed further in an attempt to avoid/reduce population vulnerability to climatic changes. Impacts, which, based upon available data, currently pose a public health threat in Portugal, were further assessed. These impacts were:

- Heat-related deaths,
- Air pollution-related health effects,
- Health effects associated with floods and drought,
- Water and food-borne diseases,
- Vector-borne diseases, and
- Rodent-borne diseases.

Potential health impacts due to heat-related illnesses, sea-level rise, and changed food yields were not further assessed due to insufficient available data and resources. Cold-related deaths were not studied further as the aim of the current investigation was to identify adverse impacts and recommend adaptation measures to reduce population vulnerability.

### 8.3.2 Heat-related deaths

Increased heat-related deaths are a typical direct health impact of climate change. Prolonged human exposure to elevated ambient temperatures can result in heat cramps, heat exhaustion, and heat stroke. The latter being the most common cause of death directly attributable to elevated temperatures. Elderly persons, individuals undergoing intense physical stress, and those with cardiovascular disease are most at risk (Lipscomb, 1992). Other causes of death observed following heat waves include ischemic heart disease, diabetes, and respiratory diseases (Ellis, 1972, Garcia et al., 1999).

Studies have shown that populations in urban areas are the most vulnerable to the adverse heat-related health effects largely due to the "urban heat island effect" (McGeehin & Mirabelli 2001). Heat-related deaths in Lisbon were assessed in the present study, since it is the urban region with the most population living in apartments, and hence more susceptible to the "urban heat island effect" (see table 8.1).

Future heat-related mortality in Lisbon was calculated based on its past relationship with temperature in conjunction with future socio-economic and climate change scenarios. Our analysis showed a consistent increase in death rates (Table 8.11). If we consider the possibility of heat-related deaths occurring year-round, considered a high estimate, a six-fold increase (compared to the present) in death rates is expected by the 2050s using PROMES and assuming no acclimatization. This is our most extreme scenario, which contrasts with only a 7% increase of heat-related mortality rates by the 2020s, under the HadRM2 assuming full acclimatization and only summer heat-related mortality; our most conservative approach.

From our analysis, it is clear that climate change will increase heat-related mortality in Lisbon. The magnitude of this increase depends on the assumptions made about acclimatization, excess death calculation method (summer months mean or 30-day running mean), seasonality (year-round or only summer heat waves). A preliminary uncertainty analysis (Dessai 2001) indicated that the greatest uncertainty arises in order of magnitude: from the RCMs, acclimatization/adaptation, seasonality, and lastly, excess deaths estimation method.

**Table 8.11 – Modelled mortality rates (per 100,000 population) for the different model variants (summer months and 30-day running means), climate scenarios (HadRM2, PROMES), and set of assumptions about seasonality (year-round and summer) and acclimatization.**

| | | | *Year-round* | | *Summer (JJA)* | |
|---|---|---|---|---|---|---|
| | | | *2020s* | *2050s* | *2020s* | *2050s* |
| **Summer months mean** | *No acclimatization* | HadRM2 | 11.6 | 21.5 | 9.1 | 16.6 |
| | | PROMES | 15.1 | 35.6 | 12.1 | 28.8 |
| | *Full acclimatization* | HadRM2 | 9.9 | 12.9 | 7.7 | 10.0 |
| | | PROMES | 12.8 | 21.4 | 10.3 | 17.3 |
| **30-day running mean** | *No acclimatization* | HadRM2 | 10.7 | 20.7 | 8.5 | 16.2 |
| | | PROMES | 14.2 | 35.9 | 11.5 | 29.5 |
| | *Full acclimatization* | HadRM2 | 7.3 | 9.5 | 5.8 | 7.3 |
| | | PROMES | 9.6 | 16.5 | 7.8 | 13.4 |

## 8.3.3 AIR POLLUTION-RELATED HEALTH EFFECTS

Pollutants in the air are transported through the airspace by wind. Their distribution and concentration in the air is therefore dependent on the prevailing weather conditions. This section investigates the potential human health effects caused by anticipated changes of air pollution exposures associated with climate change scenarios.

Recent studies indicate that the most convincing evidence of global climate change on air pollution-related health effects are likely to be those associated from tropospheric ozone and aeroallergens exposures (Patz et al. 2000; Kovats et al. 2000b). These air pollutants were thus identified as the pollutants of potential concern in this study. As nitrogen dioxide and volatile organic compounds are important precursors of tropospheric ozone, they are also discussed here.

### 8.3.3.1 Air Pollutant Sources and Health Effects

Detailed reviews of the adverse health effects associated with air pollutants of potential concern are widely available (WHO 1999d; CalEPA 2000a & b; Burge & Rogers 2000). In the present study only the most essential points of tropospheric ozone and aeroallogens are presented. Population exposure to these pollutants in Lisbon, the largest urban centre in Portugal, is also discussed.

#### *8.3.3.1.1 Tropospheric ozone*

Ozone is a secondary pollutant formed during photochemical reactions involving nitrogen oxides (NOx), volatile organic compounds (VOCs) and sunlight. During 1990–1998 NOx and VOC emissions for Portugal increased by 16% and 27% respectively. The transport sector contributed the most to these emission increases (UNECE/CLRTAP 2000), although natural vegetation and wild fires also contributed significantly to the observed increase in VOC emissions (DGA 2000b). Recent studies indicate large increases in air and road traffic fuel consumption in Portugal until 2010, potential increases in NOx and VOC emissions are thus anticipated in the near future from the transport sector (DCEA 2000).

Health effects associated with ground-level ozone ($O_3$) exposures arise primarily due to the fact that it is a powerful oxidant capable of damaging tissues of the respiratory tract and lungs. Ozone is also known to induce damage to vegetation and ecosystems.

Short-term health effects of $O_3$ exposures include;

- induced changes in lung function and airway inflammation,
- increased airway responsiveness to bronchoconstrictors,
- increased numbers of hospital admissions from respiratory diseases,

- aggravation of asthma and other chronic lung diseases.

Review studies also suggest small, but consistent decrements in lung function due to long-term $O_3$ exposures (WHO 1999d; CalEPA 2000b).

Population groups most vulnerable to $O_3$ exposures are, children, adults that are active outdoors, and people with respiratory diseases, such as asthma, emphysema and bronchitis (CalEPA 2000b). Quantification of the health impacts of $O_3$ exposures can be achieved using coefficients of +3% and +3.5% for a 50 mm/g$^3$ 8-hour mean $O_3$ increment for deaths and respiratory hospital admissions respectively (Touloumi et al. 1997; Spix et al. 1998).

Air quality monitoring stations situated in high traffic urban areas in the two largest cities in Portugal, Lisbon and Porto, indicate higher $NO_2$ levels in Lisbon. WHO guidelines are often exceeded in both cities (DGA 2000). At these high $NO_2$ concentrations, the risk of exaggerated responses to the cold and aeroallergens increases significantly in asthmatic individuals. Quantification of these health effects was not possible, as reliable exposure-response coefficients are currently not available.

Insufficient data and annual fluctuations in $O_3$ concentrations in Portugal prevent clear conclusions on time trends. Nevertheless, $O_3$ concentrations in Portugal seem to be lower than those reported in most Southern European countries (EEA 2000). Air quality data for Lisbon indicate highest $O_3$ levels at the Beato monitoring station. This station is within a residential zone in Lisbon. While data for 1999 show no exceedances above the EU 1-hour threshold, 8-hour exceedances of the WHO guideline and EU thresholds were recorded (DGA 2000a). Preliminary analysis indicate that these $O_3$ exposures may have contributed up to 1.6% of all deaths (± 350 cases) and 1.9% of respiratory hospital admissions in Lisbon during 1999 (Casimiro & Calheiros 2001).

#### *8.3.3.1.2 Aeroallergens*

Primary sources for outdoor allergens include vascular plants (pollen, fern spores, soy dust), and fungi (spores, hyphae). Floristic patterns thus have a fundamental role in the distribution of aeroallergens. Once airborne, aeroallergens follow the physical laws that apply to all airborne particles. Pollen and fungal spores are the main aeroallergens present in the ambient air.

Although pollen is known to play a significant role in allergic rhinitis, it is considered too large to penetrate the lower airways consequently, the mechanism whereby pollen exposure causes asthma remains speculative. Nevertheless, exposures to pollen, fungal spores and other airborne allergens such as soya have been reported to exacerbate asthma (Delfino et al. 1997; GINA 1996).

Short-term peaks of allergen exposure are sufficient to exacerbate allergic diseases such as hayfever and asthma. These result in increased use of medication, more medical treatment and more visits to hospital emergency rooms. In severe cases, an asthma attack can be fatal (GINA 1996).

The potency of aeroallergens is however simply not a matter of abundance, for example pollen from specific plant species such as; alder, birch, hazel, mugwort, ragweed, several grasses, and wall pellitory, are known to produce allergic symptoms more readily than pollen from other plants (EPI 2001). Furthermore, potency differences amongst the same species are not uncommon (reviewed in Burge & Rogers 2000).

Results from pollen monitoring studies in Lisbon indicate that the levels of pollen grains most likely to cause adverse health effects are highest in spring (Queiróz et al. 1998). Observational studies indicate peak hospital emergency admissions for asthma and consultations for allergic rhinitis in Lisbon both coincide with the onset and duration of the peak pollen season (Bastos et al. 1993; Lopes da Mata 2001).

A recent investigation on the concentration of airborne pollen from *Cupressaceae* species in Lisbon concluded that peak airborne pollen levels occur in February. This study also showed peak *Cupressaceae* pollen levels in Lisbon start and end sooner than in other Mediterranean cities (Ramos et al. 2000). Preliminary results indicate that 7% of the allergic population in Lisbon is sensitive to *Cupressaceae* pollen (Lopes da Mata 2001).

**Table 8.12 – Typical pollen distribution levels in Portugal (source EPI 2001)**

Blocks in white represent months with low pollen counts, those in green (G) months with moderate pollen counts, those in yellow (Y) months with high pollen counts, and those in red (R) months with very high pollen counts. Most allergic individuals will start to experience symptoms when count reaches the moderate category.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alder | Y | G | | | | | | | | | | G |
| Cypress family | G | Y | Y | G | | | | | | | | |
| Nettle/Pellitory | G | G | Y | Y | Y | G | G | | | | | |
| Birch | | | G | Y | G | | | | | | | |
| Olive tree | | | G | G | Y | Y | G | | | | | |
| Grasses | | | G | G | Y | R | Y | G | | | | |
| Platain tree | | | G | G | | | | | | | | |

Typical pollen distribution levels in Portugal are summarised in table 8.12 (EPI 2001). This table suggests that grasses are probably the most important cause of pollinosis in Portugal.

### 8.3.3.2 The Role of Climate on Air Pollution Levels

Local concentrations of air pollutants depend upon the strength of their sources and the efficiency of their dispersion. Daily variations in ambient concentrations of air pollutants are however more affected by meteorological conditions than by changes in source strengths. Climate may affect air pollution levels by (Bernard et al. 2001);

- affecting local and regional weather and thereby air pollution concentrations,
- affecting the distribution and types of aeroallergens in the air, and
- affecting natural and anthropogenic sources of air pollution emissions.

In this section, the effects of climate on the levels of pollutants of concern were examined based on past ambient air pollution levels and climate variables in order to establish a relationship between the two.

Analysis on $NO_2$ levels in Lisbon show a trend of higher $NO_2$ levels in the winter months as well as peak traffic hour periods. Previous studies on air quality in Lisbon revealed that days with highest nitrogen dioxide pollution levels were those with windspeeds below 2m/s and lower temperatures (Andrade 1996).

As the name implies, VOCs are volatile substances. Increased temperatures are therefore most likely to result in evaporation increases of these compounds from their solid and liquid states. Moreover, VOCs vegetation emissions are known to be greater at higher temperatures.

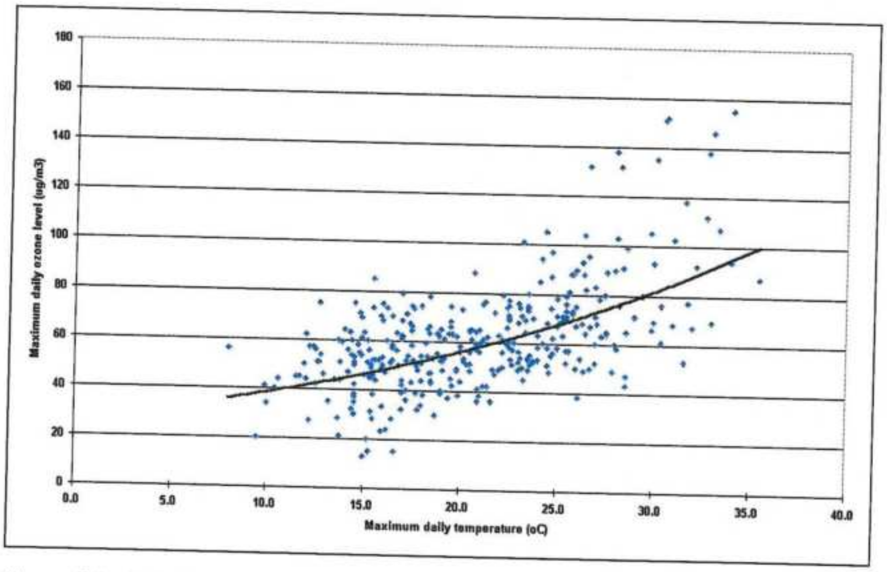

Figure 8.5 – Relationship between ozone and temperature in Lisbon in 1999

*(data from DGA 2000a & IM 2000)*

Ambient ozone levels in Lisbon are higher in the summer months. A direct correlation between temperature and ozone levels in Lisbon is observed in figure 8.5. Other studies have indicated that the simultaneous occurrence of daily maximum temperature above 25°C and low windspeeds favour the occurrence of summertime high ozone episodes (Anderson et al. 2001).

Aeroallergen particles are released from sources into the air by wind, rain, mechanical disturbance, or active discharge mechanisms. Information obtained from a study looking at daily levels of airborne pollen in Lisbon suggests that its concentration in the air increased with (Queiróz et al. 1998);

- increases in daily maximum temperatures during the flowering period,
- increases in cumulative rain-free days, and
- increases in windspeeds.

Results from studies conducted elsewhere have also indicated that grass pollen released during thunderstorms influence asthma epidemics significantly (Bellomo et al. 1992).

### 8.3.3.3 Climate Change Effect on Air Pollution-related Health Effects

Health effects associated with climate change impacts on air pollution will depend on future air pollution levels. However, determination of the direction of change at a particular location and the magnitude of the change in air quality that may be attributable to climate change cannot be determined with certainty. Potential health effects associated with climate change impacts on nitrogen dioxide, ozone and airborne pollen in Lisbon are thus *qualitatively* assessed relative to health effects associated with current air pollution levels.

PROMES and HadRM2 model results (table 8.13) both point to higher windspeeds during the cooler months in the future. Better dispersion of $NO_2$ during these months is thus anticipated. Consequently, if current air pollution emission levels are maintained, $NO_2$ levels in winter are likely to decrease. Reductions in health effects associated with acute ambient $NO_2$ exposures are thus likely to result.

Climate change is anticipated to increase the risk of forest and wild fires (see chapter 10) and consequently increase ambient air levels of VOCs and dust. Health effects associated with haze episodes such as respiratory illnesses and eye irritations are thus likely to increase.

Climate change scenarios also indicate (table 8.14) that meteorological conditions of low windspeeds and daily maximum temperatures above 25°C will occur more frequently. These conditions will thus be more conducive to higher ozone pollution episodes. Furthermore, global photochemical models also indicate increased ozone levels for Portugal (Anderson et al. 2001).

Human exposure levels are not only dependent on the pollutant concentration in the environment, but also the "contact time" in that environment. Days in which ozone levels are anticipated to be high will also have higher than normal ambient temperatures. Warmer days encourage people to spend more time out-of-doors and so increase exposure (contact time). It is therefore very likely that climate change will aggravate current ozone related health effects.

**Table 8.13 – Meteorological conditions conducive to high nitrogen dioxide levels in Lisbon**

| Meteorological Condition | Baseline climate scenario (% days per year) | | Climate change scenario (% days per year) | | % Change relative to baseline scenario | |
|---|---|---|---|---|---|---|
| | PROMES | HadRM2 | PROMES | HadRM2 | PROMES | HadRM2 |
| Days with windspeeds at or below 2 m/s | 7 | 2.5 | 6 | 1.5 | -1 | -1 |
| Days with windspeeds at or below 2.5 m/s | 14 | 5 | 13 | 4.5 | -1 | -0.5 |
| Days with windspeeds at or below 3 m/s | 25 | 10.5 | 20 | 11 | -5 | -0.5 |
| Days with windspeeds at or below 2m/s and temperature minima at or below 0°C | 0.4 | 1 | 0.1 | 0.5 | -0.3 | -0.5 |
| Days with windspeeds at or below 2m/s and temperature minima at or below 5°C | 2 | 2 | 0.5 | 1 | -1.5 | -1 |
| Days with windspeeds at or below 2m/s and temperature minima at or below 10°C | 3.5 | 0.1 | 1 | 0 | -2.5 | -0.1 |

**Table 8.14 – Meteorological conditions conducive to high ozone levels in Lisbon**

| Meteorological Condition | Baseline climate scenario (% days per year) | | Climate change scenario (% days per year) | | % Change relative to baseline scenario | |
|---|---|---|---|---|---|---|
| | PROMES | HadRM2 | PROMES | HadRM2 | PROMES | HadRM2 |
| Days with windspeeds at or below 2 m/s | 7 | 2.5 | 6 | 1.5 | -1 | -1 |
| Days with maximum temperatures at or above 25°C | 27 | 30 | 53 | 42 | 26 | 12 |
| Days with maximum temperatures at or above 25°C and windspeeds at or below 2m/s | 1 | 0.1 | 1.5 | 0.2 | 0.5 | 0.1 |
| Days with maximum temperatures at or above 25°C and windspeeds at or below 2.5m/s | 2 | 1 | 4 | 2 | 2 | 1 |
| Days with maximum temperatures at or above 25°C and windspeeds at or below 3m/s | 5 | 3 | 9 | 5 | 4 | 2 |

If current land-use patterns are assumed, as well as climate change scenarios that are warmer and drier, then it seems reasonable to anticipate that relative to current weather;

- the amount of pollen produced may increase, subsequent to temperature changes and increased atmospheric $CO_2$ concentrations (reviewed in Burge & Rogers 2000),
- airborne pollen levels may be higher due to higher pollen production as well as less rainy days,
- alterations in areas of favourable growth for allergen-producing plants may result in geographical shifts in species, and
- peak airborne pollen levels will most likely occur earlier in the year.

However, it is not clear whether this will result in pollen seasons with longer duration.

Higher pollen levels will inevitably lead to increases and possibly more severe incidences of allergic conditions and asthma. Land-use changes will however have the most significant impact in future aeroallergen levels.

### 8.3.4 HEALTH EFFECTS ASSOCIATED WITH FLOODS AND DROUGHT

Floods have the potential of affecting human health directly and indirectly. Direct effects are those caused by the floodwaters such as physical injuries and drowning, while indirect effects are those caused by other systems damaged by floods. The latter include mental disturbances, water-related diseases, and vector and rodent-borne diseases. Indirect health effects generally affect more individuals (Kovats et al. 2000a; International Federation of Red Cross and Red Crescent Societies 2001).

Drought conditions have been associated with widespread crop failure leading to famine in developing countries. This scale of malnutrition and starvation are not public health concerns in developed nations. However, drought associated crop failure, desertification, and wildfires have been observed in Portugal during the last few decades (see chapters 2, 5, 7, and 10). Such drought-related effects have obvious economic losses that may affect human health adversely. Potential health outcomes include mental disorders, fire-related illnesses and deaths, water-related diseases, and vector and rodent-borne diseases.

Potential climate change impacts on flood and drought associated waterborne diseases and appropriate vector and rodent-borne diseases in Portugal are assessed in sections 8.3.5–8.3.7.

### 8.3.5 WATER AND FOOD-BORNE DISEASES

Water and food-borne diseases are transmitted to humans when they come into contact with biotoxin and pathogen-contaminated water or foods. These infectious diseases are a serious public health problem in developing countries and to a lesser degree in developed nations. However, in recent years, concern about water and food-borne disease transmission has increased in developed countries (Rose et al. 2001; Stanwell-Smith 2001; Bentham 2001; Henrickson et al., 2001). Emergence of new, antibiotic-resistant strains, chlorine-resistant pathogens, and an ever-increasing susceptible population is likely to aggravate the situation in the near future.

Although gastro-enteritis is the most common health effect, other health outcomes such as respiratory, renal and hepatic disorders and even some cancer types may result due to pathogens transmitted by water and foods (table 8.15). Selected water and food-borne pathogens of concern are also listed.

Human exposure to water and food-borne pathogens can occur via many pathways, including:

- Drinking contaminated water,
- Eating foods prepared in/with contaminated water,
- Eating foods that were irrigated with or grown in contaminated water,
- Eating foods that were in contact with contaminated individuals,
- Breathing in water aerosols/mist that contain pathogens,
- Dermal contact with contaminated water.

Determination of the route of exposure of many water and food-borne diseases is however difficult as the pathogen is often found in both water and foods (table 8.15). This is complicated further by the fact that some diseases may be transmitted from person-to-person. Disease incidence rates for notified water and food-borne diseases of concern appear in table 8.16.

Water and food-borne disease transmission is influenced by climate directly and indirectly. In this section, potential climate change health impacts from

**Table 8.15 – Health outcomes associated with selected water and food-borne diseases**
(adapted from Rose et al 2001)

| Health outcome | Pathogen | Found in sewage sewage | Waterborne transmission | Food-borne transmission |
|---|---|---|---|---|
| Cancer, peptic ulcer | *Helicobacter pylori* | Possibly | Possibly in groundwater | Yes |
| Cholera | *Vibrio Cholerae* | Yes | Yes | Yes |
| Dermatitis/diarrhoea related to blue green algae | Toxins of *Cyanobacteria spp.* | No | Yes | Yes |
| Diarrhoea and gastro-enteritis | *Giardia, Cryptosporidium, Salmonella, Shigella, Campylobacter, Staphylococcus aureus, Escherichia coli,* & enteric viruses | Yes | Yes, most | Yes |
| Fascioliasis | *Fasciola hepatica* | Yes | Yes | Yes |
| Hepatitis | *Hepatitis A virus*<br>*Hepatitis E virus* | Yes<br>No | Yes<br>Yes | Yes<br>Potentially |
| Kidney failure | *Escherichia coli (0157), Microsporidia, Cyclospora, Vibrio vulnificus, Cyanobacteria* | Yes, most | Yes, most | Yes |
| Liver failure | *Hepatitis A virus*<br>*Hepatitis E virus*<br>*Cyanobacteria* | Yes<br>No<br>No | Yes<br>Yes<br>Yes | Yes<br>Potentially<br>Yes |
| Legionnaire's Disease | *Legionella* | No | Yes | No |
| Typhoid fever | *Salmonella typhi & paratyphi* | Yes | Yes | Yes |

**Table 8.16 – Incidence rates of selected water and food-borne diseases in Portugal for 1998** (source DGS 1999)

| Disease | Incidence rate (/100 000) |
|---|---|
| Typhoid fever | 3.0 |
| Nontyphoidal Salmonellosis | 3.4 |
| Shigellosis | 0.1 |
| Hepatitis A | 2.7 |
| Cholera | 0 |

two overlapping environmental health-related areas will be addressed. The areas studied include:

- Waterborne diseases associated with drinking water, recreational freshwater and coastal water.
- Food-borne diseases linked to fresh and seawater contamination.

### 8.3.5.1 Waterborne Diseases

Quantification of the present threat of waterborne diseases in Portugal is difficult due to lack of appropriate data and the fact that many waterborne diseases, notably gastrointestinal illness, are underreported. Recent studies linking waterborne pathogens and disease outbreaks in Portugal are few, while studies linking water quality or waterborne diseases to climate could not be found.

Results from an epidemiological investigation on water quality and acute diarrhoea showed a statistically significant association between acute diarrhoea and households using drinking water with high levels of microbiological indicators (Falcão et al. 1997). Other studies have reported clear seasonal occurrences in the incidence of acute gastroenteritis, with most cases being reported during the warmer months (Paulo et al. 1989; Lima et al. 1998).

Results from the 1998 water for human consuption national monitoring programme indicate that at least 1.5 million (about 15% of the total population) individuals are exposed to tap water with microbiological contamination above drinking water quality limits. The Northern and Central interior are the regions where less water disinfecting occurs and consequently, where microbiological contamination is the greatest (DGA 1999). Potential exposure to waterborne pathogens is thus greater in these regions.

Freshwater quality is influenced by changes in precipitation, temperatures, and wind. Several studies have shown that freshwater quality is negatively affected by drought, and by storm water drainage and raw-sewage run-off following precipitation events (Atherholt et al. 1998; Rose et al 2000; Rose et al. 2001), while other studies have indicted that pathogenic growth is favoured by warmer temperatures (table 8.17). Higher evaporation rates may also concentrate pathogen and chemical pollutants in freshwater bodies.

Water quality depends not only on weather events but also to a large extent on how water resources are managed and protected. Poor management and disposal of sewage and other wastes into fresh and seawater bodies has a negative impact on water quality. Extreme precipitation and increased urbanisation have the potential to exacerbate this further. Current monitoring results on surface freshwater indicate that less than 20% of monitored water is within national recommended recreational water quality limits (INAG 2000).

Climate change scenarios (see chapters 2 & 5) indicate warmer ambient temperatures and more

**Table 8.17 – Effect of temperature on pathogen survival**

| Pathogen | Temperature effect | Reference |
|---|---|---|
| *Salmonella* | Grow above 7°C,<br>Optimal growth at 37°C | Baird-Parker, 1994 |
| *Cryptosporidium* | Survive –20°C to 60°C | Fayer & Nerad, 1996<br>Fayer, 1994 |
| *Campylobacter* | Growth only above 30°C | Lacey, 1993 |
| *Cynobacteria* (in general) | Photosynthetic capacity, specific respiration rate and growth rate optimised at 25°C | Robarts & Zohary, 1987 |
| *Cynobacteria – Microcystis* | Sensitive below 15°C | Robarts & Zohary, 1987 |
| *Cynobacteria – Oscillatoria* | Optimal toxin production at 25°C. | Sivonen, 1990 |

frequent extreme precipitation events. Warmer ambient temperatures will most likely lead to warmer surface water temperatures. These climatic changes have the potential to exacerbate the already poor surface water quality. Thus, if current water management practises are maintained, climate change scenarios indicate that freshwater quality and consequently drinking water quality is likely to deteriorate even more. Deterioration of surface and drinking water quality is likely to increase the risk of waterborne disease transmission.

#### *8.3.5.1.1 Cyanobacteria issues*

The presence of blue-green algal (cyanobacteria) blooms in surface waters used for drinking water sources and recreation is common throughout Portugal. Approximately 60 % of these blooms produce toxins harmful to humans. During the last decade blooms have become more frequent. This has been attributed to high nutrient levels in the water, warmer climate and more droughts (Vasconcelos & Araújo 1997).

Blue-green algal blooms can have dramatic effects on the aquatic ecosystem and for public health. Human health outcomes associated with cyanobacteria biotoxins that have been detected in freshwaters in Portugal include; hepatic disorders, which could lead to death and cancer, neurological effects including paralysis of vital muscles (skeletal & respiratory) that may result in death, skin and eye irritations, allergies and hayfever, and gastrointestinal symptoms (INAG 1996; Ressom et al 1994). Moreover, deterioration in drinking water quality is also possible since water treatment is made difficult when freshwater is contaminated with algal blooms.

Cyanobacteria blooms appear in surface waters in Portugal from May to October, being more intense during the summer months (Vasconcelos & Araújo 1997). Environmental conditions known to favour blooms include (Ressom et al 1994):

- Increased temperatures (see table 8.17),
- Changes in nutrient levels,
- Increased stability of water bodies,
- Changes in light intensity,
- Air movement changes, and
- Increased UV irradiation.

As described in chapters 2 and 5, climate change scenarios point to warmer temperatures and more frequent extreme weather events. Since, these weather conditions favour bloom formation, which may have negative health impacts, climate change may increase the incidence of health problems related with cyanobacteria presence in freshwater bodies.

#### *8.3.5.1.2 Coastal issues*

Coastal-related activities are an important aspect of the Portuguese culture. Population exposure to seawater and other coastal related issues (beach sand, seashells etc.) is thus significant. Pathogen and chemical contamination of seawater may result in public health impacts of concern in exposed individuals.

Health outcomes associated with coastal water and other coastal related exposures include:

- Drownings and physical injuries,
- Skin & eye irritations and allergic reactions to seawater contaminants,
- Psychological and socio-economic effects of beach closures, and
- Microbiological infections due to pathogen ingestion or dermal contact with seawater.

Microbiological contamination of seawater occur mainly due to (WHO 1999b):

- Sewage and other waste discharges into sea, and
- Microbiological agents present in freshwaters that flow into the sea.

Results from the 1999 coastal water quality programme indicate that 20 % of the 274 beaches analysed did not meet recommended national water quality limits. Quantification of the present public health threat of the poor coastal water quality was not possible due to lack of appropriate health data.

Changes in precipitation are known to influence coastal water quality. As explained earlier, extreme precipitation events may increase the pathogen contamination in freshwater. Higher pathogen levels in freshwater are carried to coastal waters, reducing coastal water quality. In addition, increased freshwater flow into the sea reduces seawater salinity, which favours pathogenic survival in coastal water (WHO 1999b).

Temperature changes also affect coastal water quality, with warmer temperatures favouring pathogen survival. In addition, warmer months are accompanied by increased human exposures to coastal waters due to increased recreational activities during summer vacations. Moreover, as the population in coastal towns increase, so does the sewage volume, and hence the risk of exposure to higher levels of pathogens in coastal waters.

Climate change scenarios indicate (chapters 2 and 5) more frequent extreme precipitation events as well as warmer ambient temperatures. Consequently, coastal water quality may deteriorate even more with climate change. Potential health risks associated with coastal water and other coastal related exposures might thus increase due to climate change.

#### 8.3.5.2 Food-borne Diseases

Food-borne diseases are mostly caused by ingestion of foods that were contaminated with pathogens during their preparation (via contaminated water/person/animal) as well as foods that were irrigated or grown in water that was contaminated with pathogens or biotoxins. Official records of food-borne disease outbreaks indicate a rise in the number of disease outbreaks as well as cases (WHO 1999c). Similar findings have been reported in other developed nations (Kaferstein & Abdussalam 1999; Rose et al. 2001; Bentham 2001). Several factors are believed to have contributed to this increase, including:

- Better disease diagnosis and reporting,
- A growing susceptible population (elderly and immunocompromised),
- Increased importation of food from global markets,
- Changing food-processing technology,
- Changing food consumption patterns.

In 1998, food-borne diseases in Portugal were linked to at least 1,411 cases of illness, with 602 hospitalisations (WHO 1999c). Since many cases are not notified this is very likely to be a large underestimate of the real level of incidence. Although in most cases the infectious agents cannot be positively identified, the two pathogens most often associated with food-borne illnesses were *Salmonella spp.* and *Staphylococcus aureus* (WHO 1999c). Other investigations have however indicated that infections due to *Campylobacter, Shigella, Brucella, Clostridium,* Hepatitis A virus, Hepatitis E virus, *Helicobacter pylori, E.coli, Cryptosporidium, Giardia, Fasciola hepatica,* and *Yersinia* also occur (WHO 1990; Melo Cristino et al. 1988; DGS 1999; Novais 1990). Most infectious food-borne outbreaks have been attributed to poor hygiene practices during food preparation in public eating places such as canteens and restaurants. Foods of animal origin were the primary source of many food-borne cases (WHO, 1999c). Seafood poisonings due to various shellfish-associated toxins have also been reported (Silva 1980; Vale & Sampayo 1999).

Figure 8.6 shows that food-borne diseases such as Typhoid fever and Salmonellosis have higher incidence rates during the warmer months (DGS 1999). Laboratory results conclude that higher temperatures (see table 8.17) favour multiplication of many pathogens found in foods.

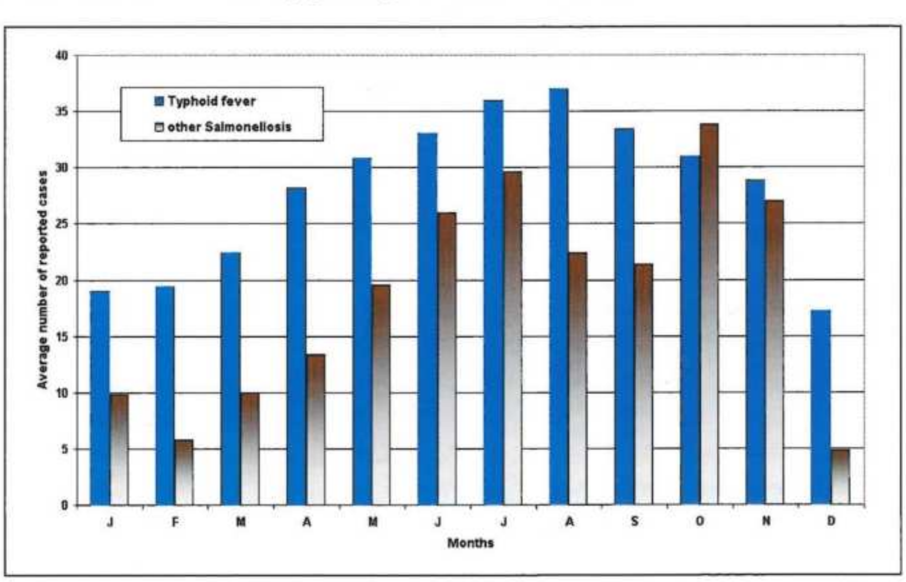

Figure 8.6 – Average monthly distribution of Salmonellosis incidence in Portugal from 1994-98 *(data from DGS 1999)*

Data presented in figure 8.6 also indicates that food poisoning cases where humans are the only reservoir and host such as Typhoid fever (caused by *Salmonella typhi*) peak in months with higher temperatures than those cases caused by *Salmonella* species that have animal reservoirs. The latter observation has also been reported by other researchers and has been attributed to food contamination during early stages of the food production process such as animal husbandry and slaughtering (Bentham & Langford 1999).

Since food-borne diseases are directly associated with warm weather, increases in temperatures have the potential to increase disease transmission risk. In conclusion higher future temperatures may exacerbate the food poisoning problem, which is already a significant threat to public health.

#### *8.3.5.2.1 Seafood poisoning*

Seafood poisoning is caused by a group of biotoxins produced by planktonic algae such as dinoflagellates and diatoms upon which zooplankton, shellfish and herbivorous fishes feed. These biotoxins accumulate in fishes and shellfish such as clams, oysters, and mussels; often reaching levels that may cause adverse health effects if ingested by humans. Potential health outcomes associated with consumption of seafood contaminated with algal biotoxins include acute gastrointestinal symptons within 30mins to 3hours after ingestion, followed by acute neurological effects in some cases. Fatalitiy rates can be as high as 15%. New evidence indicates that some biotoxins are also tumour promoters, cyctotoxic, and clastogenic and therefore potential carcinogens (Maynes et al. 2001; Traore et al. 2001).

These biotoxins are temperature stable, so cooking does not ameliorate toxicity in contaminated seafoods. Apart from the direct health effects of shellfish poisoning, marine algal blooms are responsible for extensive die-offs of fish and shellfish, which reduce quantities available for human consumption, which, in turn, may result in socioeconomic, nutritional, and psychological impacts (HEED 1998; Van Dolah 2000).

The first records of seafood poisoning in Portugal occurred in the late 1950s. These were traced to biotoxin contaminated seafood consumed from a coastal lagoon in Óbidos (situated mid-way along the Portuguese Atlantic coastline) (Silva 1980). More recently, in 1998, another significant seafood poisoning outbreak occurred, in which 18 individuals reported intoxication symptoms (Vale & Sampayo, 1999).

Global increases in the distribution and occurrences of algal biotoxins of human health concern have been reported since the 1970s. These global changes have been attributed to changes in several environmental factors such as (Van Dolah 2000; HEED 1998):

- World-wide increases in maritime transportation,
- Significant loss of marine life,
- Increased coastal eutrophication due to higher nutrient levels in seawater, and
- Sea surface temperature anomalies.

Since 1986, the Instituto de Investigação das Pescas e do Mar (IPIMAR) has been monitoring fish, shellfish, and coastal waters for harmful marine algal biotoxins.Results from this monitoring programme confirm the presence of algal biotoxins along the Portuguese coastline responsible for;

- Paralytic Shellfish Poisoning (PSP),
- Diarrhetic Shellfish Poisoning (DSP), and
- Amnesic Shellfish Poisoning (ASP).

Clear seasonal patterns in seafood biotoxin contamination have not emerged. Nevertheless, while summer blooms are frequent, highest levels seem to occur in spring and autumn months (Sampayo et al. 1997; Vale & Sampayo 2001b).

Similar observations have been reported along the American Atlantic coast (HEED 1998). In this study, the rapid changes in sea surface temperatures and precipitation regimes (leading to increased nutrient levels in seawater) associated with spring and autumn months were suggested to be a significant cause for the increased harmful marine algal biotoxins. Moreover, the observation that the incidence of marine algal blooms increase significantly during El Niño events, when sea surface temperatures are higher than normal, has lead to the speculation that climate change may be an underlying cause to the increased occurrences of marine algal blooms (HEED 1998).

Climate change scenarios for Portugal indicate future increases in extreme precipitation events that may potentially increase nutrient levels in fresh and seawaters. In addition, these scenarios also indicate higher ambient temperatures, which may result in warmer sea surface temperatures. Changes in climate and the possible relationship between climate and bitoxin production described above may favour the production of harmful marine algal biotoxins along the Portuguese coast, worsening the current public health threat of seafood poisoning. However, as climate is only one of the many environmental factors that may impact marine algal biotoxin levels, additional research and appropriate time series data are required in order to draw any definite conclusions on this topic.

### 8.3.6 VECTOR-BORNE DISEASES

Vector borne diseases are infectious diseases transmitted to humans and other vertebrates by pathogen-infected invertebrates (vectors) such as mosquitoes, ticks, and snails. These diseases often exhibit distinct seasonal patterns that clearly suggest that they are weather sensitive.

Disease transmission is influenced by the co-presence of reservoir hosts (normally warm-blooded creature), competent vector population, and pathogen at adequate numbers to maintain transmission. Transmission to humans requires human contact (exposure) with the parasite-infected vector. This exposure is influenced by a variety of factors including, human behaviour, socio-economic conditions, environmental management practices, and primary health care practices. Disease transmission only occurs if all of the above factors are favourable for transmission. A suitable climate is hence necessary, but not a sufficient condition for vector-borne disease transmission to humans.

Countries with a temperate climate, such as Portugal, are at risk of future climate conditions that may be more favourable to vector-borne diseases due to global warming. Potential changes in vector-borne disease risks in Portugal are discussed in this section.

#### 8.3.6.1 Mosquito-borne diseases

Diseases transmitted by mosquitoes such as malaria, dengue fever and yellow fever are of great public health concern.

Mosquitoes acquire the disease-causing parasite (pathogen) when they take a blood meal from an infected reservoir host (human or animal). Once inside the mosquito, the parasite reproduces several times so that when the mosquito takes its next blood meal it is capable of delivering disease-causing doses of the parasite to a previously disease-free person.

Mosquitoes are very sensitive to meteorological conditions. Cold weather kills many mosquito eggs, larvae and adults outright. On the other hand, excessive heat also kills mosquitoes (Epstein 2000). However, warmer temperatures affect disease transmission dynamics by (reviewed in Martens 1998a);

- increasing the mosquito biting rate,
- allowing mosquitoes to proliferate faster and
- increasing the parasite developmental rate inside the mosquito.

Mosquito survival is also dependent on other environmental factors, including suitable breeding sites, humidity, and mosquito predators. Floods and droughts can help trigger outbreaks by creating breeding grounds for insects whose desiccated eggs remain viable and hatch in still water. Moreover, extreme weather events such as drought may also reduce the number of natural mosquito predators such as frogs and ladybirds, resulting in elevated numbers of adult mosquitoes (Epstein 2000).

Portugal has a temperate climate favouring mosquito-borne disease transmission during several months. Field studies have indicated that there are about 40 mosquito species in Portugal, some of which are known to be capable vectors of agents that cause diseases in humans (Ribeiro et al., 1988). Over the past three decades, mosquito-borne disease epidemics have not been reported. This is largely due to the malaria eradication campaigns of the 1950's, and improved socio-economic conditions.

Recent studies have suggested that a global mean temperature increase of several degrees as indicated by the IPCC may result in a real risk of reintroduction of several mosquito-borne diseases into disease free areas such as Portugal (Epstein 2000; Martens et al. 1995). Potential risk of reintroduction of mosquito-borne diseases into Portugal was investigated further and the results are summarised below.

#### *8.3.6.1.1 Malaria*

On a global scale, malaria has been identified as the disease most likely to be affected by climate change (Kovats et al. 2000b). Malaria epidemics have re-emerged in Eastern Europe posing a serious public health concern to neighbouring countries and most of southern Europe (WHO 1999e).

Prior to the malaria eradication campaigns of the 1950's and 1960's, malaria was a common summer disease throughout Portugal. Currently, there are no local malaria cases reported, however, an average of 80 imported malaria cases per year are reported (DGS 1999). These are attributable to the strong cultural and economic ties with malaria endemic countries such as Angola, Guinea-Bissau, and Mozambique.

The first clinical signs of the malaria infection appear 10-14 days after the bite of a female mosquito that has been infected with the *Plasmodium* parasite. The infected person may experience headaches, pains in the arms and legs, backache, insomnia, nausea and vomiting. Severe attacks follow as the infected person's blood cells are destroyed and the toxins appear in the bloodstream. Infections involving *Plasmodium falciparum* are often associated with fatal complications such as anaemia and cerebral malaria.

Studies show that during the past two decades imported malaria cases in Portugal have invloved *Plasmodium falciparum, Plasmodium vivax, Plasmodium ovale, and Plasmodium malariae* parasite strains. Most cases (93%) have been due to *P. falciparum* followed by *P. vivax*. The same studies also indicate that malaria is often quickly diagnosed by medical professionals, resulting in favourable recoveries in most cases (Proença et al. 1996). Most cases are reported from the larger cities, with majority of the cases being reported in the LVT region (DGS 1999).

Six malaria-competent mosquito species are known to be present in Portugal. Of these *Anopheles atroparvus* is the mosquito that offers the most public health concern. Firstly this species is nationaly distributed, secondly it is the most abundant mosquito, and lastly it is capable of transmitting both the temperate and tropical strains of *P. vivax*. Moreover this was the species responsible for most malaria transmission prior to the eradication of the disease in the 1960's (Ribeiro et al. 1988).

The relationship between climate and malaria transmission is well documented. The two most climate sensitive parameters in malaria transmission are the relationship between temperature and the adult mosquito survival probability, and the relationship between temperature and the developmental rate of the parasite inside the adult mosquito. The latter seems to be the more sensitive parameter. *P. vivax* will not develop at temperatures below 14.5°C and *P. falciparum* below 16°C, while the proportion of either parasite surviving decreases rapidly at temperatures above 35°C. For most anopheline species, adult mosquito survival below 10°C and above 40°C is very limited (reviewed in Martens 1998a). In view of the above, it seems reasonable to conclude that disease transmission of *P. vivax* malaria occurs mostly when temperatures are between 14.5°C and 35°C, whereas *P. falciparum* malaria occurs mostly when temperatures are between 16°C and 35°C. However, as other abiotic factors such as water-breeding sites, humidity, and low altitudes are also known to favour disease transmission, interpretations of the results presented below should be made with caution.

The current Portuguese climate is already conducive to *P. vivax* malaria transmission, having several days with mean daily temperatures between 14.5°C and 35°C (tables 8.18 and 8.19). The fact that no local malaria cases are reported is an indication that the local mosquito population is not infected with malaria parasites. Thus the current (scenario 1 from table 8.5) potential risk of contracting *P. vivax* malaria is very low. However, if a population of *P. vivax* infected mosquitoes were to be introduced into Portugal and current environmental conditions are assumed (scenario 2), the potential risk of contracting malaria would increase from very low to low levels. Higher risk levels are not anticipated to be reached, as infected humans (hosts) would be treated for the disease reducing the parasitic prevalence rates.

## Table 8.18 – Mosquito-borne disease transmission favourable periods based on PROMES mean daily temperature results

| Region in Portugal/ Climate Scenario* | Percent days per year within favourable temperature range for parasite survival | | | Percent days per year within favourable temperature range for mosquito survival | |
|---|---|---|---|---|---|
| | **Plasmodium vivax (14.5-35°C)#** | **Plasmodium falciparum (16-35°C)#** | **Dengue virus (11.9-37°C)#** | **Aedes (6-40°C)#** | **Anopheles (10-40°C)#** |
| **Northern** | | | | | |
| **– $1xCO_2$** | 37 | 30 | 50 | 86 | 60 |
| **– $2xCO_2$** | 50 | 43 | 67 | 97 | 79 |
| **Central** | | | | | |
| **– $1xCO_2$** | 44 | 35 | 59 | 93 | 72 |
| **– $2xCO^2$** | 60 | 51 | 79 | 98 | 90 |
| **LVT** | | | | | |
| **– $1xCO_2$** | 54 | 43 | 74 | 99 | 89 |
| **– $2xCO_2$** | 75 | 62 | 94 | 99 | 99 |
| **Alentejo** | | | | | |
| **– $1xCO_2$** | 53 | 46 | 69 | 98 | 83 |
| **– $2xCO_2$** | 71 | 60 | 90 | 99 | 97 |
| **Algarve** | | | | | |
| **– $1xCO_2$** | 59 | 50 | 79 | 99 | 92 |
| **– $2xCO_2$** | 81 | 68 | 96 | 100 | 99 |

* $1xCO_2$ is representative of the current (baseline) climate scenario, where as $2xCO_2$ is representative of a future climate scenario.
# Temperature range used as favourable.

## Table 8.19 – Mosquito-borne disease transmission favourable periods based on HadRM2 mean daily temperature results

| Region in Portugal/ Climate Scenario* | Percent days per year within favourable temperature range for parasite survival | | | Percent days per year within favourable temperature range for mosquito survival | |
|---|---|---|---|---|---|
| | **Plasmodium vivax (14.5-35°C)#** | **Plasmodium falciparum (16-35°C)#** | **Dengue virus (11.9-37°C)#** | **Aedes (6-40°C)#** | **Anopheles (10-40°C)#** |
| **Northern** | | | | | |
| **– $1xCO_2$** | 28 | 23 | 42 | 85 | 55 |
| **– $2xCO_2$** | 57 | 49 | 76 | 99 | 87 |
| **Central** | | | | | |
| **– $1xCO_2$** | 37 | 30 | 54 | 93 | 69 |
| **– $2xCO^2$** | 68 | 58 | 87 | 99 | 94 |
| **LVT** | | | | | |
| **– $1xCO_2$** | 50 | 40 | 74 | 98 | 87 |
| **– $2xCO_2$** | 86 | 75 | 97 | 99 | 99 |
| **Alentejo** | | | | | |
| **– $1xCO_2$** | 51 | 43 | 70 | 97 | 83 |
| **– $2xCO_2$** | 81 | 71 | 95 | 99 | 98 |
| **Algarve** | | | | | |
| **– $1xCO_2$** | 50 | 40 | 71 | 98 | 85 |
| **– $2xCO_2$** | 86 | 75 | 97 | 99 | 99 |

* $1xCO_2$ is representative of the current (baseline) climate scenario, where as $2xCO_2$ is representative of a future climate scenario.
# Temperature range used as favourable.

Climate change scenarios used in this study indicate that the number of days with mean temperatures between 14.5°C - 35°C will increase by more than 30% (tables 8.18 and 8.19), indicating a more favourable climate for *P. vivax* malaria transmission. However, if no infected vectors are present (scenario 3), the potential risk of contracting *P. vivax* malaria should remain very low, but increase to a medium risk level if a population of *P. vivax* infected mosquitoes were to be introduced (scenario 4) as oulined in table 8.20.

The potential risks of contracting *P. falciparum* malaria assuming the four scenarios appearing in table 8.5 are lower than those for *P. vivax* malaria (see table 8.20) due to two overriding reasons. Firstly the *An. atroparvus* population currently present in Portugal seems to be refractory to tropical African strains of *P. falciparum* (Ribeiro et al. 1989), and secondly because current and future climatic conditions for *P. falciparum* malaria transmission are less favourable (tables 8.18 and 8.19).

**Table 8.20 – Potential risks of mosquito-borne diseases in Portugal**

| Disease | Scenario * | Suitable Vector | Parasite | Risk level # |
|---|---|---|---|---|
| Vivax malaria | 1 | Widespread distribution | Imported cases only | Very low |
| | 2 | Focal distribution (new vector) | Low → High prevalence | Low |
| | 3 | Widespread distribution | Imported cases only | Very low |
| | 4 | Focal → potentially regional distribution (new vector) | High focal prevalence → Low prevalence, regional distribution | Low-Medium |
| Falciparum malaria | 1 | None present | Imported cases only | None |
| | 2 | Focal distribution | Low → High prevalence | Low |
| | 3 | None present | Imported cases only | None |
| | 4 | Focal v potentially regional distribution | High focal prevalence → High prevalence, regional distribution | Low-medium |
| Dengue | 1 | None present | Imported cases only | None |
| | 2 | Focal distribution | Low → High prevalence | Low |
| | 3 | None present | Imported cases only | None |
| | 4 | Focal → potentially regional distribution | High focal prevalence → High prevalence, regional distribution | Low-medium |
| Yellow fever | 1 | Widespread distribution | Imported cases only (very few) | Very low – none |
| | 2 | Focal distribution (new vector) | Low → High prevalence, focally distributed | Low |
| | 3 | Widespread distribution | Imported cases only | Very low |
| | 4 | Focal → potentially regional | High focal prevalence → | |
| | | distribution (new vector) | Low prevalence, widespread distribution | Low-medium |
| West Nile fever | 1 | Widespread distribution | Low prevalence, focally distributed | Low |
| | 2 | Focal distribution (new vector) | Low → High prevalence, focally distributed | Low |
| | 3 | Widespread distribution | Low → High prevalence, regional distributed | Low – medium |
| | 4 | Focal distribution (new vector) | Low → High prevalence, focally distributed | Low |

** listed in table 8.5*

*# described in table 8.6*

#### *8.3.6.1.2 Dengue*

Dengue is the most important viral vector-borne disease and an increasing global problem. During the past three decades, dengue outbreaks have occurred in the Americas, Africa, Southeast Asia, the Western Pacific region, and in several Eastern Mediterranean countries (WHO 1997c). Distinct seasonal patterns and disease outbreaks are evident in most dengue outbreaks (Hales et al. 1999).

The disease is currently not present in Portugal and has caused minimal public health concern in the past. During 1992-1999, official hospital admission records indicate a single imported case of the disease in continental Portugal (IGIF 2000). Dengue infections cause various clinical symptoms, ranging from no clinical observations to severe and fatal haemorrhagic disease. Disease transmission to humans is similar to that of malaria. The dengue parasite is a virus of the family Flaviviridae. There are four dengue serotypes: DEN-1, DEN-2, DEN-3, and DEN-4 (WHO 1997c).

Of the 40 mosquito species currently present in Portugal, none are known dengue vectors. Records do however indicate that prior to 1956 *Aedes aegypti,* the most problematic dengue vector, was in fact present in Portugal (Ribeiro et al. 1988). In recent years the appearance of another dengue vector, *Aedes albopictus,* in some regions in southern Europe has prompted environmental health concerns that this species may also infest Portugal (Filipe 1993; Schaffer & Karch 2000). Several investigations are currently being undertaken in Portugal to investigate the possibility of the latter occurrence. Preliminary results show no indication of the presence of either *Aedes aegypti* or *Aedes albopictus* in Portugal currently (Almeida 2000). However, the possibility that dengue infected *Aedes* mosquitoes could be introduced in the future cannot be completely ruled out.

Dengue viruses require a minimum temperature of 11.9°C to develop. Viral development decreases dramatically above 37°C. As *Aedes* mosquitoes often occupy human dwellings they are generally less responsive to ambient temperatures than *Anopheline* mosquitoes. However, survival of *Aedes* mosquitoes below 6°C and above 40°C declines rapidly (reviewed in Martens 1998a). A temperature range of 11.9°C to 37°C, thus favours dengue transmission dynamics.

The current climate is already conducive to dengue transmission (tables 8.18 and 8.19), however, as no suitable vector is known to be present, the potential risk of contracting dengue is non-existent (scenario 1 from table 8.5). If however, a dengue-infected vector population was to be focally introduced (scenario 2), the potential disease risk would become low.

Future climate change scenarios point to increased numbers of days with mean temperatures within the favourable disease transmission range (tables 8.18 and 8.19). However, if no competent vector is present (scenario 3), potential disease risk will remain non-existent. In the presence of a focal infected mosquito population (scenario 4), the disease risk may increase from low to medium, as the vector widens its geographical distribution as indictaed in table 8.20.

#### *8.3.6.1.3 Yellow fever*

Yellow fever is a hemorrhagic fever also caused by a virus of the Flaviviridae family. The disease is transmitted to humans and monkeys by the bite of several different species of mosquitoes of the genus Aedes and other genera.

The most significant European yellow fever outbreak occurred in Lisbon during the autumn of 1857. During this period, 6000 deaths by yellow fever were reported in Lisbon. The outbreak came to an end at the start of winter, when it is belived that the cold weather made survival of the *Aedes aegypti* mosquito population unfavourable (Filipe 1993). Official records indicate that locally contracted cases have not been reported for several decades. Nevertheless, a single imported yellow fever case was hospitalised in Portugal during 1992–1999. (IGIF 2000).

Presently, neither *Aedes aegypti* nor *Aedes albopictus* are present in Portugal. However, another potential vector, *Aedes vittatus* is present in Portugal (Ribeiro et al. 1988). As no local cases of yellow fever have been reported in Portugal for several decades, it seems reasonable to assume that this local *Aedes* species is not infected with the virus.

Studies have shown that the survival of *Aedes* mosquitoes below 6°C and above 40°C declines rapidly (reviewed in Martens 1998a). Temperature threshold survival values for the yellow fever virus development inside the mosquito could not be obtained in the available literature. The former temperature range was thus used as an indicator of favourable disease transmission periods in the present study. Future climate scenarios (table 8.18 & 8.19) indicate increases in the number of days per year with mean daily temperatures within this favourable range.

In the abscence of the parasite, the current potential risk of contracting yellow fever is thus very low to none (scenario 1). Potential changes in disease transmission for the remaining scenarios are summarised in table 8.20.

#### *8.3.6.1.4 West Nile fever*

Since its initial isolation in Uganda in 1937, West Nile fever soon became recognised as the most widespread of the flaviviruses, with a geographic distribution that includes Africa, Asia, Europe, and recently North America. Bird-feeding mosquito species seem to be the principle vectors of the virus. Migratory birds are therefore instrumental in the introduction of the virus worldwide. Although the incidence of West Nile fever in Europe is largely unknown, recent disease outbreaks in France (Valenciano 2000), Italy, Romania and Poland have prompted concerns that the disease may be re-emerging in Europe (Hubalek & Halouzka 1999).

Four human clinical cases of West Nile fever were hospitalised in Portugal during 1992-1999. Three in the summer of 1995 and the other in July 1997 (IGIF 2000). Between 1967 and 1970, the presence of West Nile virus infections was detected in humans, cattle, sheep, horses, and wild birds (Filipe et al. 1990). On a global scale, the virus has been isolated from 43 mosquito species, predominately of the genus Culex.

Competent mosquito vectors present in Portugal include *Anopheles atroparvus, Aedes caspius, Culex modestus, Culex molestus, Culex theileri,* and *Culex univittatus* (Ribeiro et al. 1988). In 1996, the West Nile virus was isolated from an *Anopheles atroparvus* population around the Tagus estuary (LVT region). Mosquitoes from other parts of Portugal were not infected (Fernandes et al. 1998). Two decades prior to the latter study, mosquitoes in Aljustrel (southern Portugal) were found to be positive for the virus (Filipe 1972). Studies are currently being conducted to determine if the virus is still present in the mosquito populations or in suitable animal hosts (Almeida 2000).

Studies have shown that *Aedes spp.* and *Anopheles spp.* mosquitoes require temperatures between 6°-40°C and 10°-40°C respectively for adult survival (reviewed in Martens 1998a). These vector survival temperature ranges were thus used as indicators of favourable disease transmission periods in the present study, as temperature threshold values for West Nile virus developmental survival inside the mosquito could not be obtained in the available literature.

Tables 8.18 and 8.19 show that the current temperatures in Portugal are conducive to *Aedes* and *Anopheles* survival. Although suitable *Aedes* species have not been reported to be present in the last few decades, several suitable *Anopheles* species, notably An. *atroparvus*, currently enjoy an abundant and widespread distribution (Ribeiro et al. 1988). Moreover, the virus has been known to be present in vectors, animals and humans at selected locations. In view of these findings it is reasonable to conclude that the current risk (scenario 1) of contracting West Nile fever in Portugal is low.

Mosquito survival periods are likely to increase under future climate scenarios (tables 8.18 and 8.19). Higher parasite prevalence rates are thus possible as infected hosts extend their distrubution range and increase in numbers. Hence, the potential risk of contracting West Nile fever assuming such climatic changes (scenario 3 of table 8.5) might increase from low to a medium level.

### 8.3.6.2 Tick-borne diseases

Ticks are vectors of more kinds of micro-organisms than any other single arthropod, including mosquitoes. As some of these micro-organisms can cause pathological conditions in humans, the ability of ticks to transmit pathogenic organisms to humans is thus of great public health concern.

The infectious agent is transmitted to humans when ticks infected with the pathogen acquire a blood meal. Ticks require blood meals once per life cycle stage, as a larva, a nymph and an adult, between which they spend long developmental and host-seeking periods on the ground. Although transmission can occur during any of these life stages, the nymphal stage is regarded as the most significant stage for disease transmission in humans. This is because infection prevalence in nymphs is usually higher than in larvae, and nymphs are more abundant and smaller (less noticeable) than adults.

Tick-borne disease transmission dynamics is complex and in some cases not well understood. Factors that are known to affect the transmission include biological risk parameters as well as human and host (birds and mammals) activities. Biological parameters such as tick distribution, abundance, pathogen presence, and the pattern of seasonal activity are fundamental in the transmission of tick-borne infections. Climatic conditions such as temperature and precipitation patterns, as well as environmental management practices pertaining to land-use and water management can have significant influences in these biological risk factors (Filipe 1969). Human activities, such as farming, hunting, and various outdoor leisure pursuits are additional risk factors in disease transmission.

The Iberian Peninsula has climatic, botanical and faunal conditions that are favourable for tick fauna. Studies have indicated that there are 36 tick species in the Iberian Peninsula, 24 of which are known to occur in Portugal (Caeiro 1999). Of the latter, 10 tick species are known to be capable vectors of agents that cause diseases in humans (Dias 1994). Lyme disease and Mediterranean spotted fever are currently the tick-borne infections that cause greatest public health concerns in Portugal (Filipe 2000).

#### *8.3.6.2.1 Lyme disease*

Lyme disease has emerged as the leading arthropod-borne disease in Europe. The disease is caused by a spirochete (bacterium) named initially *Borrelia burgdorferi*. In Europe, the European sheep tick (*Ixodes ricinus*) is the principle vector involved in Lyme disease transmission (EUCALB 2000).

In Portugal, the first clinical case of Lyme disease was reported in 1989 (de Morais et al. 1989), disease presence was however suspected years prior to this case (Filipe et al. 1990). Subsequent serological studies confirmed the prevalence of antibodies for *Borrelia burgdorferi* in the human population. In a study done in the Alentejo region, 9.7% of the population tested sero-positive for the antibodies against *Borrelia burgdorferi* (Núncio, et al. 1992). In the same region, 14 cases of Lyme disease were hospitalised during 1988-1991 (de Morais et al. 1992). Official records indicate that during 1994-1999 an average of 20 cases per year were hospitalised in continental Portugal (IGIF 2000). The disease was declared as compulsory notifiable in 1999.

The disease affects the skin, nervous and musculoskeletal systems and rarely the heart. It has a good recovery rate and low lethality. A few weeks following infection, a characteristic skin rash, erythema migrans, appears near the bite in most patients. Not all individuals exposed to the bacteria develop the disease (O'Connell 1995).

During the last decade several strains of *B. burgdorferi* have been isolated, not all of which are pathogenic to humans. Recent studies have identified *B. lusitaniae, B. garinii, B. valaisiana* and *B. afzelli* in ticks obtained from sylvatic habitats in Portugal (de Michelis et al. 2000; Baptista et al. 2000). However, the local human pathogenic strain has not been isolated as yet (Collares-Pereira & da Franca 2000).

*I. ricinus* ticks are present throughout continental Portugal (Caeiro 1999). In 1992 *Borrelia burgdorferi* was isolated from male *I. ricinus* collected in the Alentejo region (Núncio et al. 1993; de Michelis et al., 2000). *I. ricinus* have a wide host range, however, birds and small mammals seem to be commonly parasitised by larvae and nymphs whereas adult ticks tend to feed on larger animals such as sheep, and cattle (Caeiro 1999). Humans are incidental hosts for the tick at any life cycle stage (O'Connell 1995). People living or working in forest or rural areas are at higher risks of exposure to infected ticks (Núncio et al. 1992).

*I. ricinus* collected from sylvatic habitats were reported to have high (up to 75%) infection prevalence, but most infections are however of the non-pathogenic strain, B. *lusitaniae* (de Michelis et al. 2000, Baptista et al. 2000). To date, ticks infected with human pathogenic strains such as *B. garinii* and *B. afezlli* have only been observed in one of the natural parks. Overwintering birds from Northern Europe have been suggested as the reservoir hosts responsible for the focal introduction of the pathogenic strain in this natural park (Baptista et al. 2000). The present focal distribution of the pathogenic *Borrelia* strains leads one to conclude that current (scenario 1) potential risk of contracting Lyme disease in Portugal is low.

As mentioned, disease transmission to humans is dependent on tick distribution, tick abundance, and human exposure to the tick. Climate change can have a significant influence in some of these disease transmission factors. The most noticeable of which is probably the observation that disease transmission below 7°C is extremely rare (Sonenshine 1993) and that the tick requires temperatures of 15-30°C in order to advance into the next life-cycle stage (Caeiro 1992). A temperature range of 7-30°C thus favours disease transmission. As tick distribution is more influenced by suitable host availability, land-use and agricultural practices than by climatic conditions alone (Filipe 1969 and Mawby & Lovett 1998), it is not possible to determine if the present tick distribution will change using only climate change scenarios. On the other hand, the well-documented seasonal changes in tick activity patterns are an excellent example of how tick abundance is influenced by climatic conditions (Caeiro 1992).

*I. ricinus* ticks are found throughout Portugal, but with less abundance in the drier and warmer southern regions of Portugal. In contrast to Northern Europe, the tick is found throughout the year in the Iberian Peninsula, being more abundant during the cooler months (Caeiro 1999). This is to be expected, as this tick is sensitive to prolonged heat and low soil moisture. Climate change scenario data appearing in tables 8.21 and 8.22 indicate that climatic conditions will become less favourable for disease transmission in Southern Portugal, but more favourable in the Central and Northern regions. Keeping in mind that the human population in the southern regions is much smaller than that of the rest of the country, and that no pathogenic strains have been isolated in ticks in Southern Portugal, it is reasonable to conclude that the national prevalence rate of Lyme disease is not likely to decrease given future climatic conditions (scenario 3). In fact, it is anticipated that disease risk may potentially change to a medium level as focally

**Table 8.21 – Vector-borne disease (except mosquito-borne disease) transmission favourable periods based on PROMES mean daily temperature results**

| Region in Portugal/Climate Scenario* | Percent days per year within favourable temperature range for parasite survival | Percent days per year within favourable temperature range for vector survival | | Percent days per year within favourable temperature range for vector activity | |
|---|---|---|---|---|---|
| | *Schistosoma* (15-39°C)# | *Phlebotomus papatasi* (10-40°C)# | *Phlebotomus ariasi* (5-30°C)# | *Phlebotomus perniciosus* (15-28°C)# | *Ixodes ricinus* (7-30°C)# |
| **Northern** | | | | | |
| **– 1xCO$_2$** | 34 | 60 | 91 | 34 | 81 |
| **– 2xCO$_2$** | 48 | 79 | 96 | 41 | 92 |
| **Central** | | | | | |
| **– 1xCO$_2$** | 41 | 71 | 95 | 39 | 89 |
| **– 2xCO$^2$** | 58 | 90 | 94 | 47 | 92 |
| **LVT** | | | | | |
| **– 1xCO$_2$** | 51 | 89 | 99 | 47 | 97 |
| **– 2xCO$_2$** | 71 | 99 | 92 | 58 | 92 |
| **Alentejo** | | | | | |
| **– 1xCO$_2$** | 51 | 84 | 98 | 47 | 95 |
| **– 2xCO$_2$** | 68 | 97 | 90 | 52 | 90 |
| **Algarve** | | | | | |
| **– 1xCO$_2$** | 56 | 92 | 98 | 51 | 97 |
| **– 2xCO$_2$** | 77 | 99 | 89 | 60 | 89 |

* 1xCO$_2$ is representative of the current (baseline) climate scenario, where as 2xCO$_2$ is representative of a future climate scenario.

# Temperature range used as favourable.

**Table 8.22 – Vector-borne disease (except mosquito-borne disease) transmission favourable periods based on HadRM2 mean daily temperature results**

| Region in Portugal/Climate Scenario* | Percent days per year within favourable temperature range for parasite survival | Percent days per year within favourable temperature range for vector survival | | Percent days per year within favourable temperature range for vector activity | |
|---|---|---|---|---|---|
| | *Schistosoma* (15-39°C)# | *Phlebotomus papatasi* (10-40°C)# | *Phlebotomus ariasi* (5-30°C)# | *Phlebotomus perniciosus* (15-28°C)# | *Ixodes ricinus* (7-30°C)# |
| **Northern** | | | | | |
| **– $1xCO_2$** | 26 | 55 | 90 | 26 | 79 |
| **– $2xCO_2$** | 55 | 87 | 92 | 43 | 90 |
| **Central** | | | | | |
| **– $1xCO_2$** | 35 | 69 | 95 | 34 | 89 |
| **– $2xCO^2$** | 66 | 94 | 89 | 50 | 88 |
| **LVT** | | | | | |
| **– $1xCO_2$** | 46 | 87 | 99 | 45 | 97 |
| **– $2xCO_2$** | 84 | 99 | 91 | 69 | 91 |
| **Alentejo** | | | | | |
| **– $1xCO_2$** | 48 | 83 | 98 | 45 | 94 |
| **– $2xCO_2$** | 82 | 98 | 82 | 57 | 81 |
| **Algarve** | | | | | |
| **– $1xCO_2$** | 46 | 85 | 99 | 45 | 97 |
| **– $2xCO_2$** | 83 | 99 | 89 | 65 | 89 |

* $1xCO_2$ is representative of the current (baseline) climate scenario, where as $2xCO_2$ is representative of a future climate scenario.
# Temperature range used as favourable.

infected ticks and hosts widen their geographical distribution. Table 8.23 suggests that focal introduction of additional human pathogenic infected ticks are not likely to change the potential disease risk levels for current (scenario 2) and future climate conditions (scenario 4).

### *8.3.6.2.2 Mediterranean spotted fever*

Mediterranean spotted fever (MSF), commonly referred to as "tick bite fever" or "Boutenneuse fever", is probably the most important human tick-borne disease in Portugal. Clinical signs of the infection appear 5-7 days following the tick bite. These include chills, fever, lymphadenitis, and persistent headaches. A distinctive small ulcer with a dark brown, centre, the primary eschar (*tache noire*) frequently appears, near the tick bite. Untreated cases usually recover (Sonenshine, 1993). Individuals that are most vulnerable to the disease include the immuno compromised, the aged, and sufferers of diabetes mellitus, cardiac diseases, chronic alcoholism, and glucose-6 phosphate dehydrogenase deficiency (Walker & Fishbein 1991).

Disease is transmitted to humans by the bite of the brown dog tick (*Rhipicephalus sanguineus*) infected with a rickettsia (pathogen) called *R. conorii*. This tick is by far the most abundant tick species in Portugal, found countrywide in both rural and urban settings. In rural settings the tick is associated with farm and wild animals, whereas in urban settings it is associated with domestic dogs. In contrast with other tick-borne diseases, human exposure to ticks infected with *R. conorii* is not limited to outdoor activities. *R. sanguineus* has a remarkable capacity to adjust to most environmental conditions, completing 2-3 life cycles per year. Studies in Portugal and Spain have show that *R. sanguineus* is not the only tick capable of carrying rickettsiae (Bacellar 1999 & Oteo et al. 1996). Future investigation is however needed to ascertain the public health relevance of these findings.

Portugal has a high prevalence rate of MSF, with official health statistics indicating 800 –1,000 cases per

**Table 8.23 – Potential risks of vector-borne diseases in Portugal (excluding mosquito-borne diseases)**

| Disease | Scenario * | Suitable Vector | Parasite | Risk level # |
|---|---|---|---|---|
| Lyme Disease | 1 | Widespread distribution | Low prevalence, focally distributed | Low |
| | 2 | Focal distribution (new vector) | Low → high prevalence, focally distributed | Low |
| | 3 | Widespread distribution | Low prevalence, focal distribution → High prevalence, regional distribution. | Medium |
| | 4 | Focal → potentially regional distribution (new vector) | High prevalence, focal distribution → High prevalence, regional distribution. | Medium |
| TBE | 1 | Widespread distribution | None present | None |
| | 2 | Widespread distribution | Low prevalence, focally distributed | Low |
| | 3 | Widespread distribution | None present | None |
| | 4 | Widespread distribution | Low prevalence, focally distributed | Low |
| Mediterranean spotted fever | 1 | Widespread distribution | High prevalence, Widespread distribution | High |
| | 2 | Widespread distribution | High prevalence, Widespread distribution | High |
| | 3 | Widespread distribution | High prevalence, Widespread distribution | High |
| | 4 | Widespread distribution | High prevalence, Widespread distribution | High |
| Leishmaniasis | 1 | Widespread distribution | High prevalence, regional distribution → Low prevalence, widespread distribution. | Medium |
| | 2 | Widespread distribution | High prevalence, regional distribution → Low prevalence, widespread distribution. | Medium |
| | 3 | Widespread distribution | High prevalence, Widespread distribution | High |
| | 4 | Widespread distribution | High prevalence, Widespread distribution | High |
| Schistosomiasis | 1 | Widespread distribution | Imported cases only | Very low |
| | 2 | Focal distribution (new vector) | Low → high prevalence, focally distributed | Low |
| | 3 | Widespread distribution | Imported cases only | Very low |
| | 4 | Focal → potentially regional distribution (new vector) | High prevalence, focal distribution → High prevalence, regional distribution. | Medium |

** listed in table 8.5*
*# described in table 8.6*

annum. The incidence rate for 1998 was 7.21 per 10,000 individuals. The actual disease prevalence is, however, anticipated to be much higher due to under reporting, self-treatment, and undiagnosed cases. Official health statistics reveal that the Alentejo region is the area with the highest incidence rates, followed by the Central region, the Algarve, the Northern region and lastly the LVT region. The young (1-14 years) and the aged (+65 years) are the population groups reporting most disease cases. Cases are reported throughout the year, but maximum amount of cases are reported during July, August, and September (DGS 1999). Serological studies have indicated that in Southern Portugal 7.6% of the human population tested positive to antibodies of *R. conorii* (Bacellar et al. 1991). In a separate study in the same region, 85.5% of stray dogs were serological positive (Bacellar et al. 1995).

Summer is the period of maximum activity of *R. sanguineus* (Caeiro 1992). Disease transmission is thus favoured during the warmer months. Predicting changes in disease transmission is very difficult as there is no simple statistical correlation between temperature and incidence of disease. An assessment of the factors known to affect tick-borne disease transmission, such as tick distribution and abundance provides useful insight to this end. As *R. sanguineus* has a remarkable ability to adapt to its environment, its distribution is not likely to change solely due to climatic changes. *R. conorii* infected *R. sanguineus* already have an abundant and widespread distribution consequently, current (scenario 1) potential risk of contracting MSF in Portugal is high. The potential risk level is not expected to decrease for the remaining three scenarios investigated in the study (table 8.23).

#### *8.3.6.2.3 Tick-borne encephalitis*

Tick-borne Encephalitis (TBE) is a viral infection of the central nervous system, which often results in fatalities. *Ixodes persuleatus* and *Ixodes ricinus* are the ticks involved in Tick-borne Encephalitis (TBE) in Europe. The latter tick is present throughout Portugal, but are not known to be infected with the TBE virus at present, consequently, there are no reported cases of locally transmitted TBE in Portugal (Filipe 2000). During 1992-1999 no TBE cases (imported or local) were hospitalised (IGIF 2000). The potential risk of contracting TBE in Portugal is thus non-existing at present (scenario 1).

TBE viral survival seems to be influenced not only by the tick's geographical range but also by climatic conditions, preferring continental climatic conditions to oceanic or tropical climatic conditions (Randolph et al. 2000). This is probably why TBE is not currently endemic in Portugal. Predictive statistical modelling study results do not indicate that Portugal will be threatened by the TBE virus under future climate change scenarios (Randolph & Rogers 2000).

#### *8.3.6.2.4 Other tick-borne diseases*

During the last decade, serological surveys have revealed at least three individuals in Portugal that had antibodies for the Crimean-Congo hemorrhagic fever (CGHF) virus. The CGHF virus is transmitted by the bite of the tick *Hyalomma marginatum* (Filipe 1993). This tick is present throughout Portugal, being most active during the warmer months of the year (Caeiro 1999).

In the winter of 1991, the first and only case of local human ehrlichiosis was reported in the Alentejo region of Portugal. Serological examination confirmed that the individual was serum-positive for *Ehrlichia chaffeensis*. The fact that this case was reported in the middle of winter is interesting. Attempts to determine which tick was the possible vector were inconclusive (de Morais et al. 1992).

### 8.3.6.3 Leishmaniasis

Leishmaniasis is a disease caused by protozoa of the genus *Leishmania*. The disease occurs mostly in two clinical forms, cutaneous and visceral leishmaniasis. It is prevalent in tropical, sub-tropical and Mediterranean regions, affecting some 12 million people world-wide. The parasites are transmitted from animal reservoirs to humans by the bite of female sandflies.

Visceral leishmaniasis (VL), also known as Kala-azar, is currently endemic in Portugal.

Clinical symptoms vary between individuals and geographic region. In countries bordering the Mediterranean basin, the most common symptoms include high fever, chills, fatigue, abdominal pain and diarrhoea. Anaemia and enlargement of spleen and liver are typical clinical manifestations. If untreated VL has high fatality rates. The disease is often complicated by serious secondary bacterial infections such as pneumonia and pulmonary tuberculosis. Clinical manifestations of the disease vary from a few weeks to several years after a person becomes infected. Children and the immuno-compromised are most vulnerable to VL. The number of VL cases among patients with human immuno-deficiency virus (HIV) infection has increased rapidly in recent years. *Leishmania*/HIV co-infection is currently considered to be a real "emerging disease" in southern Europe, with intravenous drug users being the population group most at risk (WHO 1999f).

There are three well-known VL foci: the Alto Douro zone in the Northern region, the Algarve region, and the Lisbon Metropolitan area in the LVT (Pires 2000). It has been a notifiable disease for several decades. This database indicates a steady decline in reported cases, from an average of 53 cases per year in the 1970's to 16 cases per year during the last five years. However, the actual disease incidence rate is believed to be much higher due to underreporting (Vicente 1990). The majority of notified cases are of children, although there has been a steady increase in cases from the 25-35 years group during the last decade (DGS 1992; DGS 1999). The latter is anticipated to be due to the increasing number of cases of *Leishmania*/HIV co-infections (Romão et al. 1995).

Domestic dogs are the principal reservoir hosts of *Leishmania infantum,* the protozoa involved in VL transmission. Studies conducted in Portugal revealed that the *L. infantum* infection prevalence in domestic dogs to vary from 11.4% to 7% (Campino et al. 1995; Sampaio-Silva et al. 1993; Abranches et al. 1987) whereas the infection prevalence in sandflies is below 3% (Pires 2000).

Sandflies of the genus *Phlebotomus* are involved in leishmaniasis transmission in Europe. These are flies having 2-3 mm body lengths, are known to breed in warm, humid micro-climates and are typically found in rodent burrows, forest areas, and rotting organic matter. The female sandflies require blood for egg production (Killick-Kendrick 1999). Typically, they have blood meals every 6-8 days during their adult life. The adult female becomes infected with the parasite during blood meals from infected reservoir hosts. Eggs from infected females are not infected. The entire life cycle is typically about two months.

In Portugal, there are four *Phlebotomus* species that are competent *Leishmania* vectors. The most widespread and abundant is *Phlebotomus perniciosus.* This sandfly is a known vector for *L. infantum,* and parasite-infected sandflies have been reported throughout Portugal. It is without doubt the most important vector in the transmission of VL in Portugal. *Phlebotomus ariasi,* another competent vector for *L. infantum,* is the second most abundant *Phlebotomus* in Portugal. Although this species also enjoys a widespread distribution, it is more abundant in the cooler and more humid regions in Northern Portugal. The third most abundant sandfly is *Phlebotomus sergenti,* a vector of *L. tropica* and thus important in the transmission of human cutaneous leishmaniasis. In Portugal, *Ph. sergenti* is currently known to be present in the Alentejo and Algarve regions. By far the least abundant *Phlebotomus* found in Portugal is *Phlebotomus papatasi,* this species has only been found in the Algarve. *Leishmania* infected *Ph. sergenti* and *Ph. papatasi* have not been captured in Portugal (Pires 2000).

Field studies in Portugal indicate that adult sandflies are found from May to November. These studies also show that the maximum activity periods of the flies to be at night when humidity is greatest (Pires 2000).

Distribution of *Phlebotomus* species is known to be highly dependent on environmental conditions. Laboratory studies show that adult sandflies are sensitive to high temperatures and low humidity. These studies indicate that *Ph. ariasi* are most sensitive to high temperatures while *Ph. papatasi* the most tolerant of high temperatures. Assuming humidity levels are not too low, survival of the former is best between 5-30°C (Rioux et al. 1985), while temperatures between 10-40°C ensure *Ph. papatasi* survival (Theodor 1936). It is thus no surprise that *Ph. ariasi* are found predominantly in the cooler and more humid northern regions of Portugal and *Ph. papatasi* in the warmer southern most regions. Laboratory studies have also shown that *Ph. perniciosus* develop relatively fast at 28°C and that development is stopped at 15°C (Tesh 1992). The maximum temperature tolerable for *Ph. perniciosus* survival is unclear.

Laboratory studies show that *L. infantum* development in the vector was achieved at all ambient temperatures suitable for vector survival, however, an optimum temperature for development was observed at 25°C (Rioux et al. 1985). These findings suggest that vector survival is more sensitive than parasite development to climate change. The former was thus used as an indicator for leishmaniasis transmission in the present study.

Unlike mosquitoes, sandflies do not need water pools for breeding, precipitation is thus not as important in the sandflies's life cycle as ambient temperature and humidity. Sandfiles adjust their behaviour to reduce their exposure to low humidity environments. For example, they are known to breed and inhabit microclimates (rodent burrows, wall cracks etc.) that are relatively high in humidity and adult flies are active at night when humidity is higher. These behaviours thus protect the flies from unfavourable ambient air humidity levels. Nevertheless, they remain very sensitive to ambient temperatures.

Current ambient temperature is conducive to *Phlebotomus* survival for several months. Field studies also show that parasitic prevalence is relatively high in reservoir hosts (dogs) in several regions in Portugal, resulting in a current (scenario 1 as per table 8.5) medium disease potential risk. Focal introductions of additional infected vectors (scenario 2) are not likely to change the disease potential risk level.

Tables 8.21 and 8.22 indicate that the number of days suitable for *Ph. ariasi* survival are likely to decrease in the future throughout Portugal except in the Northern region. Since this sandfly species is currently predominate in the Northern region, potential disease risk levels are not anticipated due to *Ph. ariasi* transmission dynamic changes. Data listed in these tables also indicate significant increases in days with favourable temperatures for *Ph. pernicious* activity for the whole of Portugal. If the latter is assumed as well as the fact that parasitic prevalence in Portugal remains high in both humans and reservoir hosts, it seems reasonable to conclude that the potential risk of contracting Leishmaniasis in Portugal may become high (scenario 3). Introduction of additional infected sandflies (scenario 4) is not anticipated to change the latter risk level.

#### 8.3.6.4 Schistosomiasis

Schistosomiasis, also known as bilharziasis, is a disease caused by parasitic worms of the genus *Schistosoma.* Disease prevalence has increased worldwide owing to the expansion of irrigation systems in hot climates, enabling snail populations to survive and the parasite to find human carriers. The disease currently affects more than 200 million people and contributes to a million premature deaths each year (WHO 1998). Humans become infected with the parasite by dermal contact to free-swimming parasitic larvae (cercaria) in fresh water. Freshwater snails are the intermediate hosts in the schistosome life cycle.

Disease clinical manifestations are dependent on the schistosome species a person is infected with. Individuals infected with *S. haematobium* suffer from urinary and bladder signs and symptoms, of which haematuria (blood in urine) is the most frequent. *S. intercalatum, S. mansoni* and *S. japonicum* infections have two clinical distinct stages, initial clinical symptoms appear weeks after infection and typically include fever, nausea, headache, cough and diarrhoea. The chronic form of the disease manifests several years after infection, the most noticeable symptoms are the granulomatous reactions and fibrosis in the intestines, spleen and liver.

In Portugal, endemic *S. haematobium* infections were known to occur in the Algarve region until half a century ago (Grácio 1981). Currently, local disease transmission has not been documented, however, during 1999-2000, a total of 58 imported Schistomiasis cases were diagnosed from a single laboratory (Grácio 2001). During 1992-1999 an average of 35 imported schistosomiasis cases per year were hospitalised in Portugal (IGIF 2000). The majority of these infections were by *S. haematobium* and *S. intercalatum* and acquired while individuals were in African countries (Correia 2000; Grácio 2001).

Each schistosome species is dependent on specific intermediate snail host species. Generally, *S. mansoni* uses snails of the *Biomphalaria* genus as intermediate hosts, *S. japonicum* those of the genus Oncomelania where as *S. haematobium* and *S. intercalatum* those of the *Bulinus* genus (WHO 1998, Grácio 1998). It is interesting to note that field studies conducted in Portugal showed that the freshwater snail *Planorbarius metidjensis* and not *Bulinus* water snails were responsible for the disease transmission in the past (Azevedo et al. 1948). Although *Bulinus* snails are frequently found throughout Portugal, schistosome infected ones were never captured. More recent field studies indicated that while *P. metidjensis* and various *Bulinus* species are indeed widespread in Portugal, neither snail species was infected with Schistosoma species (Grácio 1981).

Laboratory investigations revealed that *P. metidjensis* captured in the Algarve could become infected with *S. haematobium* from Guinea-Bissau. Attempts to infect the same snail species with other schistosome species failed (Azevedo et al. 1954). Additional laboratory studies conducted on *Bulinus contortus* captured in Algarve and Coimbra (Central region) showed that this snail could also become infected with *S. haematobium* from Guinea-Bissau, Angola, and

Mozambique (Xavier et al. 1972). Infections with *S. haematobium* from Guinea-Bissau were also successful in *Bulinus truncatus* snails captured in Coimbra (Azevedo & Xavier 1965). All four Schistosoma species have similar life cycles.

Schistosomiasis transmission to humans is a complex system influenced by the co-presence of the appropriate snail and schistosome species as well as humans in the same aquatic environment. In addition, transmission is also influenced by environmental factors that influence snail and schistosome survival rates and activity. Water availability and temperature being the most important. Without water, snail and parasite death is certain, and thus disease transmission ends. Studies on the relationship between disease transmission and water temperature indicate that below 15°C, parasite development inside the snail is inhibited, while above 39°C snail and parasite death occur. As snails and schistosoma larvae are mobile, they are able to react to extreme temperatures by moving to less hostile conditions within their aquatic medium. Nevertheless, water temperatures between 15-39°C are thus required for schistosomiasis transmission (reviewed in Martens 1998a).

Assuming ambient air temperatures as approximations of shallow water temperatures, it is clear from tables 8.21 and 8.22 that current ambient temperature in Portugal is conducive to schistosomiasis transmission. The same tables also indicate that future temperatures will become more favourable for transmission. However, as competent vectors in Portugal have not been reported to be infected during the past decade (Correia 2000; Grácio 2001), current (scenario 1) and future (scenario 3) potential risks of contracting schistosomiasis are very low.

Worldwide, human activities have been known to introduce fresh water snails to water bodies that do not form part of the same drainage basin (Brown et al. 1998). Focal introduction of snails infected with Schistosoma species in Portugal is thus a possibility. Moreover, focal introduction of the parasite from infected imported human cases to the currently non-infected snail population is also a potential risk. If a focal parasite infected snail population was to occur, and current climatic conditions are assumed (scenario 2), the potential risk of schistosomiasis would be low due to focal infected snail distribution. However, if a warmer climate scenario is assumed (scenario 4), the infected vector population is anticipated to widen its geographic distribution and thus increase the potential disease risk to a medium level. In addition, regions such as the Alentejo and Algarve where water shortages may be aggravated by warmer climates, authorities may opt to change irrigation systems (i.e the Alqueva dam Project), and in doing so potentially increase the host snail population distribution and survival rates in these regions (Grácio et al. 1994).

### 8.3.7 RODENT-BORNE DISEASES

Rodent-borne diseases are zoonoses that are transmitted directly to humans by contact with rodent biofluids and faeces. These diseases do not always involve an arthropod (cold-blooded) host and are therefore less directly affected by temperature. Transmission of these diseases to humans is influenced by human and rodent activities. Local rodent population density and behaviour heavily influences human exposure to infected rodents. Local food availability as well as environmental conditions such as unusually high rainfall and drought events affects rodent survival, and hence rodent population density.

Although, regional climatic changes could affect the rodent population dynamics significantly, determination of the potential effects of climate change on infectious agents transmitted by rodents to humans are more uncertain and have received less attention than have vector-borne diseases (Gubler et al. 2001).

Rodent-borne diseases known to be currently prevalent in Portugal include leptospirosis and hemorrhagic fever with renal syndrome. Potential changes in disease transmission of the former disease due to climate change in Portugal is assessed below.

#### 8.3.7.1 Leptospirosis

Leptospirosis is a zoonotic disease with world-wide prevalence caused by the bacteria of the genus *Leptospira.* It has a wide clinical spectrum, ranging from mild influenza-like symptoms to severe renal and respiratory malfunctions that may lead to death in some cases. On the other hand, some infected individuals have no symptoms at all (CDC 1999).

The disease is transmitted to humans by oral or dermal contact with water, dust (soil), and foods contaminated with urine and other biofluids from infected animal hosts. Rodents, dogs, pigs, and cattle are the animal hosts often infected with the bacteria. It is a rural, occupational, and recreational hazard world-wide (CDC 1999). Disease outbreaks often occur after heavy rainfall episodes as surface and drinking water become contaminated with animal urine and waste (Ko et al. 1999; Gubler et al. 2001).

Official records indicate that during the period of 1994-1998, 273 cases of leptospirosis were reported in Portugal. Although the disease has been an obligatory notifiable disease in Portugal since 1986, the true prevalence rate is believed to be underdiagnosed (Collares-Pereira et al. 1989; Falcão et al. 1999). Statistical records indicate a significant increase in the number of reported cases and deaths since 1997 (DGS 1999).

Disease prevalence is highest in rural populations (Collares-Pereira et al. 1989). Field studies have indicated rats and to a lesser extent cattle to be the animal hosts responsible for most infection transmissions to humans (Collares-Pereira et al. 1996; Vieira et al. 1999). Over 20% of rodents captured in rural and urban settings in continental Portugal were reported to be seropositive for Leptospira interrogans senso lato (Collares-Pereira et al. 1996; Collares-Pereira et al. 2000).

Climate change model results forecast increased flood risks for Portugal, especially in the central and northern regions (see chapter 5) where leptospirosis is currently a problem. Consequently, climate change may increase the potential risk of leptospirosis transmission in Portugal.

## 8.4 ADAPTATION MEASURES

Adaptation measures are society's responses to diminish anticipated climate change adverse impacts. Thus, within the context of the health sector, the primary objective of the adaptations interventions discussed here is to reduce population vulnerability to certain health outcomes.

Interventions can be either autonomous or planned. Autonomous (spontaneous) adaptation refers to the changes that human systems undergo in response to changing surroundings, irrespective of any policy, plan or decisions (Kovats et al. 2000b). These include biological (passive) and behavioural adaptation measures that take place at the individual level. Examples of biological adaptation include the manner by which individuals may become physiologically adapted to change in ambient temperature or when immunity levels rise in response to increased exposure to an infectious agent. Behavioural adaptation measures include actions individuals take to reduce their risk of exposure to a health hazard such as avoidance of excessive heat (McMichael & Kovats 2000b).

Planned adaptation is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to or maintain a desired state (Kovats et al. 2000b). Autonomous adaptations are in response to a changed state whereas planned adaptations are generally prospective anticipatory in nature. The latter is evidently preferable.

### 8.4.1 Approach Used to Develop Adaptation Measures

Adaptation measures to reduce human health impacts of climate change can be thought of in terms of the classical categorisation of preventive measures in public health (McMichael & Kovats 2000b):

- Primary prevention measures which are actions taken to prevent/reduce human exposure to hazards. Examples include improved housing and availability of potable water and sanitation drainage;

- Secondary prevention measures are actions taken to detect early evidences of changes in health risk or health status, and then taking specific targeted action. An example of such an adaptive measure would be the introduction of environmental controls in response to observed (monitored) increase in specific vector-borne disease incidence rate or vector abundance; and

- Tertiary prevention measures that are health-care actions taken to lessen the morbidity or mortality caused by newly encountered diseases (e.g. improved disaster response capacity, improved diagnosis and treatment of cases of heatstroke, malaria, etc.).

Secondary and tertiary prevention measures are both, in general, less effective than primary prevention measures. Furthermore, in the long term they are both usually more expensive than primary prevention measures (Kovats et al. 2000b).

Primary and secondary preventative adaptation measures for potential climate change health impacts are discussed below. Success of these measures will depend on factors such as:

- Political will
- Financial resources
- Public acceptance
- Technical knowledge
- Capacity of the health care system and public health infrastructures
- Intersectoral and cross-sectoral collaboration.

In this study, a conscious effort was made to focus on "no-regrets" adaptation measures. These are measures that will be beneficial to society even if anticipated climate change health impacts prove inaccurate.

During the course of this study insufficient monitoring and surveillance data was a constant problem. As unforeseen climate change impacts on health are possible, improvements to surveillance and monitoring systems will be highly valuable. Table 8.24 summarises suggested improvements for selected monitoring and surveillance programmes that may reduce this problem in the future. Improvements to monitoring and surveillance systems are essential climate change adaptation measures (Haines & McMichael, 1997).

### 8.4.2 ADAPTATION MEASURES FOR HEAT-RELATED DEATHS

Observed data indicate that excess deaths occur following days with high ambient temperature. Since the frequency and intensity of heatwaves are

**Table 8.24 – Suggested monitoring and surveillance improvements**

| Health impact requiring data | Suggested improvements to monitoring/surveillance |
|---|---|
| Heat-related deaths | •Improve accessibility to daily mortality data and improve monitoring of relevant morbidity data<br>•Improve monitoring of urban violence reporting<br>•Improve accessibility to monitored daily climate variables |
| Air pollution-related health outcomes | •Establish national database with daily asthma and allergic rhinitis hospital admissions and emergency room visits. This database should be easily accessibly to researchers (not just medical doctors)<br>•Improve accessibility to monitored daily mortality data<br>•Extend current air pollution monitoring programme to be more nationally representative. This is essential for long-range pollutants such as ozone. |
| Flood and drought-related health outcomes | •Improve accessibility of daily mortality data and improve monitoring of relevant morbidity data<br>•Improve accessibility to flood and drought-relief financial aid data<br>•Improve agriculture yields, pest, and disease surveillance |
| Water and food-borne diseases | •Improve drinking water monitoring and treatment systems for key pathogens<br>•Improve wastewater management to facilitate monitoring<br>•Improve food-borne disease monitoring to facilitate pathogen identification and original contamination source<br>•Improve accessibility to monitored data<br>•Improve disease surveillance to reduce the number of undetected and/or unreported cases |
| Vector and rodent-borne diseases | •Establish an integrated national surveillance programme for estimation of vector, rodent, and intermediate host populations<br>•Determination of pathogen prevalence in these population is essential<br>•Improve disease surveillance to reduce the number of undetected and/or unreported cases |

anticipated to increase significantly during the next decades, adaptation measures that may reduce the number of individuals vulnerable to heat-related deaths as well as heat-related illnesses are presented here.

Autonomous (physiological acclimatisation) adaptation is anticipated to reduce some of the impacts of future increases in the frequency or intensity of heatwaves. Acclimatisation to hotter environments may be in two forms; "instant" acclimatisation that may occur following a few days of higher temperatures, while "complete" acclimatisation to higher temperatures that will require several years to occur. Examples of both acclimatisation forms are evident at the population level. Studies have demonstrated that the impact of the first heatwave on mortality is often greater than the impact of subsequent heatwaves within a single season. Populations from areas with tropical weather are less sensitive to higher temperatures than populations from colder climates (McMichael & Kovats 2000b). However, as all individuals in the community will not achieve autonomous adaptation, planned adaptations are required.

Planned adaptation measures are crucial for vulnerable population groups such as the aged, individuals with pre-existing cardiovascular conditions, and inner city inhabitants. Several adaptation measures to reduce heat-related illnesses and deaths have been proposed (McMichael & Kovats 2000b). Adaptation measures that may prove beneficial include:

- Public education programmes to avoid heat and replace fluid loss during heatwaves;
- Establishment of nation-wide weather watch and warning systems to alert the public of anticipated dangerous hot days. For maximum efficacy, such systems should work in conjunction with public education programmes so that the general public will know what preventative measures to take during these weather conditions;
- Sensitise health personnel to detect and treat heat stress, specially personnel from urban and peri-urban health units;
- Appropriate urban planning to diminish the "heat island" effect in cities. The following includes:
  - Include design features that reduce heat load, and
  - Planting trees in urban zones.
- Sensitise architects and civil engineers so that future projects will have design features that reduce heat load and have improved ventilation features; and
- Usage of air-cooling devices such as fans and air conditioners in buildings that are already built and are susceptible to high indoor air temperatures. Implementation of this adaptation measure must be carefully considered, as this is likely to be an energy demanding practice that may increase greenhouse gas emissions. In addition, it has the potential to increase risks of adverse health outcomes, such as Legionnaires' disease.

### 8.4.3 ADAPTATION MEASURES FOR AIR POLLUTION-RELATED HEALTH IMPACTS

Data from current air quality monitoring programmes frequently report air pollution levels that may be hazardous to public health. If the climate becomes warmer and more variable, air quality is likely to be affected. Pollutant levels that may increase due to climatic changes include tropospheric ozone and aeroallergens such as pollen. Higher ambient air levels of these pollutants may exacerbate asthma and other respiratory diseases, which currently cause significant public health concerns.

Adaptation measures that may reduce population vulnerability to potential air pollution-related health outcomes include:

- Establishment of *nation-wide air* quality monitoring and warning systems to alert the public of high pollutant levels;
- Development of programmes to provide people with information on local air pollution levels, their potential health effects, and suggested means to reduce exposure;
- Reduction of local air pollution emissions;
- Establishment of a national electronic asthma and allergic rhinitis database at hospital emergency rooms;

- Reinforcing weed-control initiatives in order to minimise exposure to grass pollen;
- Educating town planners, landscapers, and the general public as to which plants produce pollen that may result in adverse health effects in sensitive populations, so as to reduce the number of such plants in landscaped environments; and
- Encouraging community programmes aimed at reducing the risks of forest and vegetation fires.

### 8.4.4 ADAPTATION MEASURES FOR FLOOD AND DROUGHT-RELATED HEALTH IMPACTS

Flood and drought are reoccurring events, resulting in significant economic and health outcomes. Climate change scenarios point to an increase in the frequency and intensity of both events. Adaptation measures that have proved useful around the world at reducing population vulnerability to these events include (Kovats et al. 2000b):

- Ensure that disaster preparedness and mitigation initiatives are in place and are updated regularly. The following measures are relavant:
  - Establish early warning systems;
  - Ensure that drainage systems and solid waste management practices are adequate and properly maintained to allow for rapid floodwater drainage;
  - Adopt and enforce land-use planning and construction design approaches to minimise erosion, flash-flooding, and restoration of wetlands;
  - Prohibit construction of houses and buildings on flood risk zones; and
  - Regulatory measures to ensure irrigation efficiency;
- Ensure that efficient disaster response and recovery programmes are in place;
- Traditional methods used for coping with floods and drought should be carefully evaluated to ensure that mistakes are not repeated;
- Critical assessment of agricultural practices to ensure that vulnerability to flood and drought risks are minimised and that they are environmentally sustainable practices;
- Encourage community programmes aimed at reducing the risks of forest and vegetation fires; and
- Improve infectious disease monitoring and surveillance systems.

### 8.4.5 ADAPTATION MEASURES FOR WATER AND FOOD-BORNE DISEASES

Current water quality and food-borne disease outbreaks pose significant public health concerns. Anticipated climatic changes have the potential to increase these concerns. Implementation of adaptation measures listed below may reduce current as well as potential climate change water and food-borne disease risks.

- Improvements in the efficacy of basic public infrastructures (nation-wide) such as:
  - Water treatment facilities;
  - Sewage and sanitation systems; and
  - Waste removal and treatment systems.
- Integrated policies to protect all water resources;
- Improvements in monitoring and surveillance programmes for key water and food-borne diseases. Rapid identification of pathogen type and original contamination source should be encouraged. Results from these programmes may be used as early warning systems;
- Establishment of alternative safe potable water distribution to the public when treated water does not meet drinking water requirements;
- Enforcement of pollution reduction and pollution control policies;
- Inform the general public of local water quality and food-borne outbreaks at regular intervals;

- Public education on safe food preparation and storage practices as well as on health hazards associated with consumption of biotoxins in seafoods;
- Introduction of extra label and handling guides for selected foods such as seafood, pre-baked foods, and fresh produce such as watercress and berries; and
- Increase enforcement efforts to ensure compliance with food safety regulations during all food production and preparation processes.

### 8.4.6 ADAPTATION MEASURES FOR VECTOR AND RODENT-BORNE DISEASES

Diseases transmitted by rodents and vectors such as mosquitoes, ticks, sandflies, and water snails are frequently reported. Projected climatic changes indicate that conditions for rodent, vector, and parasite survival may become more favourable. Potential increases in disease transmission risks are thus possible.

Primary and secondary adaptation measures effective at reducing population vulnerability have been documented (Kovats et al. 2000b). Planned adaptation measures that may be relevant for Portugal include:

- Ensuring that public health infrastructures do not deteriorate;
- Improvements to current vector and disease surveillance and monitoring system including:
    - The establishment of a national surveillance programme for vector populations or other intermediate hosts; and
    - The creation of an online database to which medical doctors can report any vector or rodent associated condition. The primary objective of this database should be to monitor changing risks as they are happening so that preventative and control measures can be promptly applied.
- Public education incentives to encourage elimination of artificial breeding sites and other vector and rodent control measures;
- Sensitise health care givers in geographically vulnerable regions;
- Improve rodent, vector and reservoir host population control measures, in an attempt to eliminate those that are infected with parasites harmful to humans;
- Anticipate effects of irrigation projects and other land-use and agricultural changes on vector breeding sites and rodent population size; and
- Promote the use of window screens, insect repellents and protective clothing in disease endemic locations.

## 8.5. RESEARCH GAPS

The lack of research on many questions related to human health and climate (and other environmental hazards) was a major setback during the current assessment. It is evident that future research is thus required in order to reduce uncertainties associated with potential climate change health impacts in Portugal. Research areas requiring urgent attention include:

- Assessment of climate change potential health impacts associated with international travel and trade,
- Assessment of potential health impacts due to sea level rise,
- Assessment of health impacts associated with food shortages due to climate variablity,
- Assessment of health impacts due to stratospheric ozone depletion,
- Assessment of potential health impacts associated with climate change adaptation meaures suggested by other SIAM groups,
- Assessment of direct health effects of extreme weather events,
- Assessment of underlying factors that contribute to cold-related morbidity and mortality,
- Distinguish more clearly between the effects on health of climate and of air pollution,

- Assessment of the role of climate on infection disease transmission. There is a need for basic laboratory and field investigations of vector (and rodent) ecology and pathogen infectivity under different climatic conditions and regions,
- Assessment of long-term human and marine animal health effects of marine algal biotoxin bioaccumulation in seafoods, and
- Assessment of remote sensed satellite data as to its efficacy to determine infectious disease risks in Portugal.

## 8.6 CONCLUSIONS

In this chapter, potential adverse health impacts of projected climatic changes in Portugal were assessed and adaptation measures to avoid/reduce these impacts were suggested. This study also offers a review of the literature on; health issues influenced by global climate change, recent global initiatives on climate change and human health assessment, and methods that are currently available to study climate change impacts on human health.

During the past three decades socio-economic improvements have resulted in significant improvements in the overall health and life expectancy years of the Portuguese. In 1998, Portugal had a population of about 9.5 million, of which 15.2% were 65 years or older and 16.8% younger than 15 years. Since life expectancy is expected to increase during the next decades, significant increases in the proportion of individuals above 65 years are expected. Legally residing immigrants make up about 2% of the total population in Portugal.

Currently, chronic diseases are the major causes of death. Infectious diseases account for only 2% of deaths. Leading causes of deaths include cancer and disorders related to the circulatory and respiratory systems. Childhood public health concerns include accidents, asthma and acute gastrointestinal and respiratory infections.

Despite significant improvements in recent years, progress towards identifying and reducing environmental health hazards has been slow in Portugal. Universal accessibility to basic public health infrastructures such as water, sanitation, and electricity has not been achieved. Moreover, poor water and air quality pose significant environmental health risks in Portugal. Portuguese population sub-groups that are currently most vulnerable to environmental health risks include the poor, the elderly, the very young, the immunocompromised, immigrant populations, and rural communities who lack basic infrastructures.

Currently, there are few published studies showing changes in the Portuguese population health status in response to the observed climatic changes. This makes identification of potential future health impacts of climate change difficult. Nevertheless, several health impacts were identified that may be adversely affected due to climate change. The present study focused on the following health categories:

- Heat-related mortality
- Air-pollution-related health effects
- Health effects associated with floods and drought
- Water and food-borne diseases
- Vector and rodent-borne diseases.

Health impacts due to stratospheric ozone depletion, sea levels rise, food shortages, and international travel were not assessed in the present study.

Key findings of each health category are summarised in table 8.25. Insufficient health and environmental data in Portugal and the significant number of knowledge gaps on the relationship between health and climate has resulted in many uncertainties being incorporated in the assessment. Consequently, no definite conclusions could be reached on the magnitude of change on potential climate change health impacts in Portugal.

**Table 8.25 – Summary of key assessment findings**

| Potential health impact | Population most vulnerable | Weather factor of interest | Direction of possible change | Example of adaptation measure suggested |
|---|---|---|---|---|
| Heat-related mortality | - The elderly<br>- People with cardiovascular conditions<br>- The poor<br>- Urban residents | - Extreme heat periods | ↑ | - Early warning system<br>- Urban planning<br>- Air conditioning |
| Air pollution-related health effects | - The young<br>- The elderly<br>- People with respiratory conditions | - Temperature<br>- Windspeed | ↑ | - Pollution control<br>- Warning system |
| Health effects associated with floods & drought | - Individuals in low-lying and erosion–prone regions<br>- The young<br>- The elderly<br>- The poor<br>- Immunocompromised individuals | - Precipitation variability<br>- Temperature | ↑ | - Early warming system<br>- Improved zoning and building codes<br>- Engineering |
| Water & food-borne diseases | - Immunocompromised individuals<br>- The young<br>- The elderly<br>- The poor<br>- Rural communities | - Ambient temperature<br>- Water temperature<br>- Precipitation | ↑ | - Improved water systems engineering<br>- Improved sanitation systems<br>- Surveillance |
| Vector & rodent-borne diseases | - Immunocompromised individuals<br>- The young<br>- The elderly<br>- Rural residents | - Temperature<br>- Precipitation variability<br>- Relative humidity | ↑ or ↓ (disease & region dependent) | - Surveillance<br>- Improve vector and rodent control programmes<br>- Improved sanitation systems<br>- Improved clinical diagnosis, treatment and public health measures |

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# Energy

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## CONTENTS

## EXECUTIVE SUMMARY

The energy sector both contributes to global climate change, on the supply side, through the combustion of fossil fuels that produce greenhouse gases (GHG), and is itself sensitive to climate on the demand side.

## Energy supply

- Fossil fuel based power plants – exisiting plants are not sensitive to changes indicated by the future climate scenarios, both with respect to higher ambient temperature levels, sea level rise and amounts of water supply for refrigeration. However, further analysis is required, especially given that a larger proportion of combined cycle natural gas and co-generation plants is planned for the future.

- Renewable energy systems – climate change impacts can be significant on their yield. The performance of solar systems may improve. Hydroelectric plants can benefit from higher winter flows in the north, while in the centre and south the potential for electricity production will be severely diminished. Large hydroelectric power plants are mainly located in the north and thus overall production may benefit from higher winter precipitation in the Douro and Cávado-Lima basins. In all cases, refurbishment of the plants will be needed. Effects of competition for water with other sectors were found to be small. Wind and wave energy potential do not seem affected. Anaerobic digestion processes will become more effective.

- Electric losses – resistance of power transport and distribution lines will increase significantly with higher temperatures.

## Energy demand

- Buildings – warmer weather leads to a reduction of energy requirements for space heating, but also a (generally larger) increase in space cooling requirements; this varies by region. The overall balance is a greater yearly demand, which increases from North to South. The impacts upon the service sector are greater than that for the residential sector. Even under socio-economic scenarios with stricter building regulations, requiring more insulation, climate change still tends to increase energy needs for comfort.

- Transportation – engine efficiency itself is not much affected, but more energy will be required for air conditioning and ventilation, especially during summertime. Some indirect effects can also be expected such as seasonal fluctuations on fuel demand; or even higher overall demand, as, for example, through more intense tourism.

- It seems likely that at least domestic hot water needs and industrial pre-process heat needs can be reduced, due to higher inlet water temperatures.

Thus, the impacts of climate change upon the energy sector are a mix of positive and negative effects. The overall balance is still unclear, as it depends very much on the future socio-economic and technological scenarios considered, and especially on mitigation policies and measures.

# 9. Energy

## 9.1 INTRODUCTION

### 9.1.1 OVERVIEW

The energy sector, defined in national accounting as the set of activities related to coal, oil and gas products, and to electricity and water supply, employed only 0.5% of the work force but ranged between 3.5--4.0% of the gross national product (GNP) for the 1990-'98 period. Although the gross added value of the sector declined about 1% with respect to the period 1986-'90, it remains one of the more important socio-economic activities. Besides, it is a crucial sector in the climate change context, being responsible for a major fraction of GHG emissions.

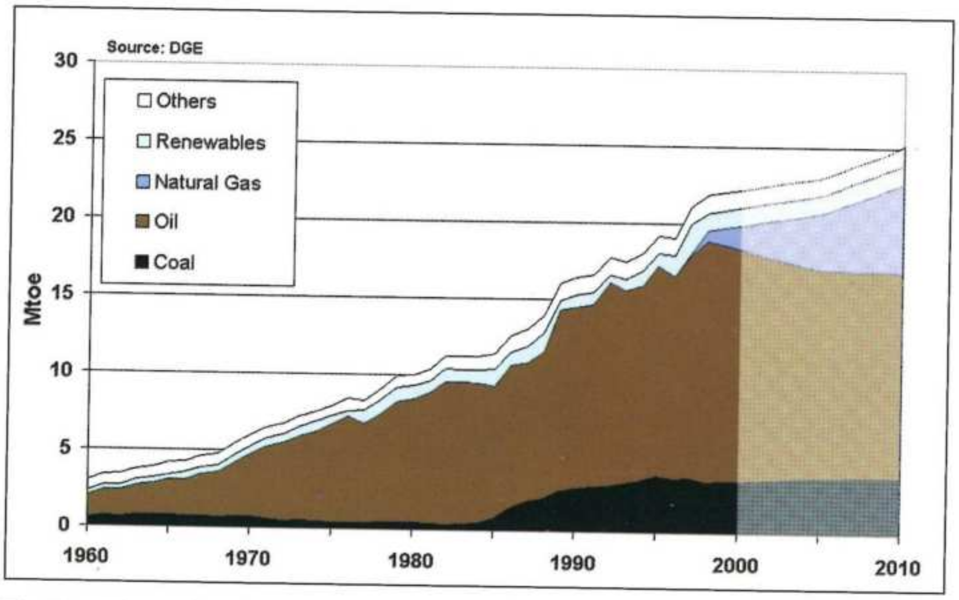

Fig. 9.1 – Time series of primary energy supply (PES), since 1960 (2005 and 2010 values are projections from DGE).

The energy supply sector shows a growing energy consumption trend (see Direcção Geral de Energia (DGE) 1998, 2001 and Figure 9.1), a low diversification of energy sources, and an increasing dependence of energy products from abroad, as known national resources in fossil fuels are very small. About 85-90% of the demand is met by imported fossil fuels, with oil having the largest share, followed by coal, and then by natural gas, which has been gaining market share. The major part of renewable energy production consists of large hydroelectric power. The fraction of energy imports in overall imports declined during 1990-'98 but then rose again: from 5.8% in 1998 to 7.0% in 1999, and to 10.7% in 2000 (this combined with appreciation of the US$ relative to the € resulted in a 109% increase in the national expenses for energy imports from 1999 to 2000).

Energy demand has been growing at an annual rate of 5-6% over the past two decades (see Figure 9.2) while GNP growth rates have only been around 3-4% per year for the same period. Demand growth is especially strong in the services and transportation sub-sectors. Although the national expenditure for energy imports has been growing rapidly, the energy price for consumers has grown at lower rates (0.8% in 1996 to 2.1% in 1998) and even effectively diminished in 1999 (-5.8%) – see Departamento de Planeamento e Prospectiva (DPP) 2001.

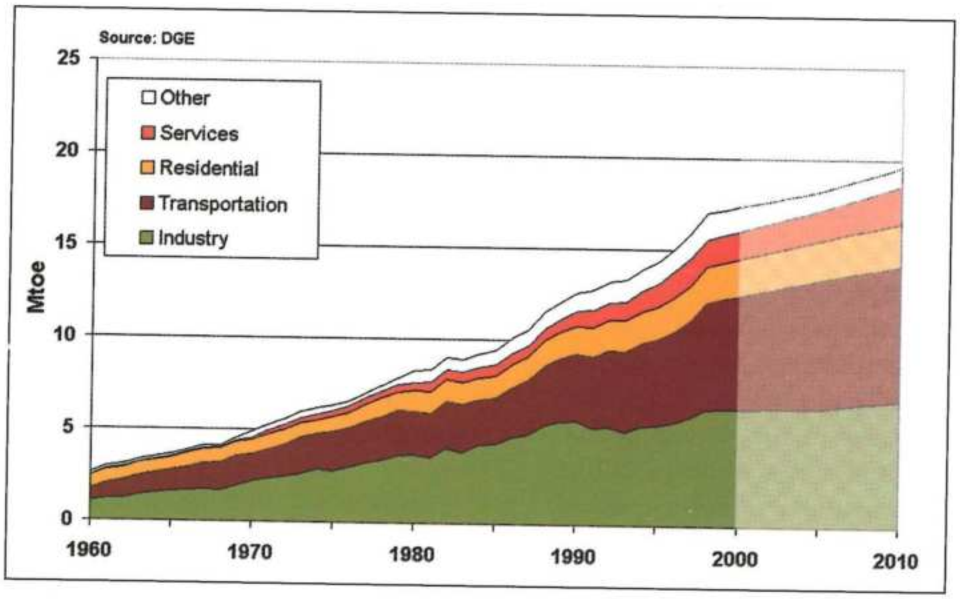

Fig. 9.2 – Time series of final energy consumption (FEC), since 1960 (2005 and 2010 values are projections from DGE).

An important indicator of the energy profile for any country economy is the primary energy supply per capita, which is represented in Figure 9.3: slow population evolution coupled with strong growth of the energy demand produces an impressive rising trend.

A comparison of this indicator with data for other countries and regional blocks is given in Figure 9.4. The supply of energy per inhabitant is above the world average, but lower than the average for OECD (developed) countries, for the EU 15 countries (see DGE 1999) or for neighbouring Spain.

Another important indicator is energy intensity, stated as PES (Primary Energy Supply) or FEC (Final Energy Consumption) per unit of GNP. The energy intensity shows also a rising trend of about 1.7% per year up to 1990, and 1.2% per year onwards (see Figure 9.5). The national energy intensity is below the world average, indeed very close to the average of OECD countries (see Figure 9.6). The DGE scenarios point to strong energy intensity reductions in all sectors (IEA 2000). However, so far only the residential sector has shown some signs of stagnation.

It must be stressed that the energy indicators are difficult to interpret, as they depend on many country specific factors such as climate, geographic characteristics, behavioural and cultural factors, level of economic development and the sectoral profile of the economy. For instance, an increase of the service sector at the expense of the industrial sector would lead to a decrease of the PES per capita, as the energy intensity in the service sector is generally lower than in industry. As another example, countries with mild climates such as Portugal should, in principle, expend much less energy per capita on space heating than, say, northern European countries, even assuming an optimal energy use efficiency of the latter. Nevertheless, it must be pointed out that while in most other EU15 countries there are clear signs of a decoupling of energy use from GDP increases, in Portugal only the building related sectors have recently started to show such signs (Aguiar 2002).

It is very probable that this panorama will be altered progressively in the next few decades, both by technological breakthroughs and by national and EU policies. The former include, for example, micro-

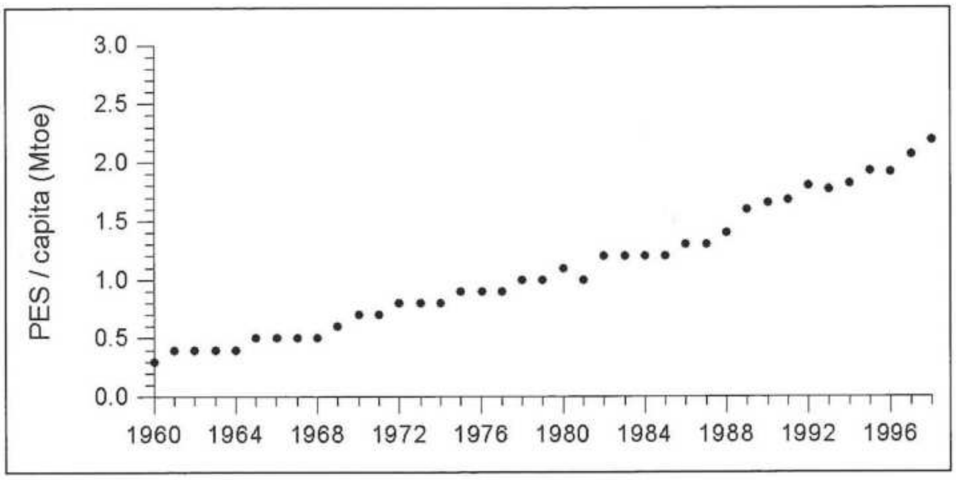

Fig. 9.3 – Primary energy supply per capita for 1960-1998. Source: DGE 2001.

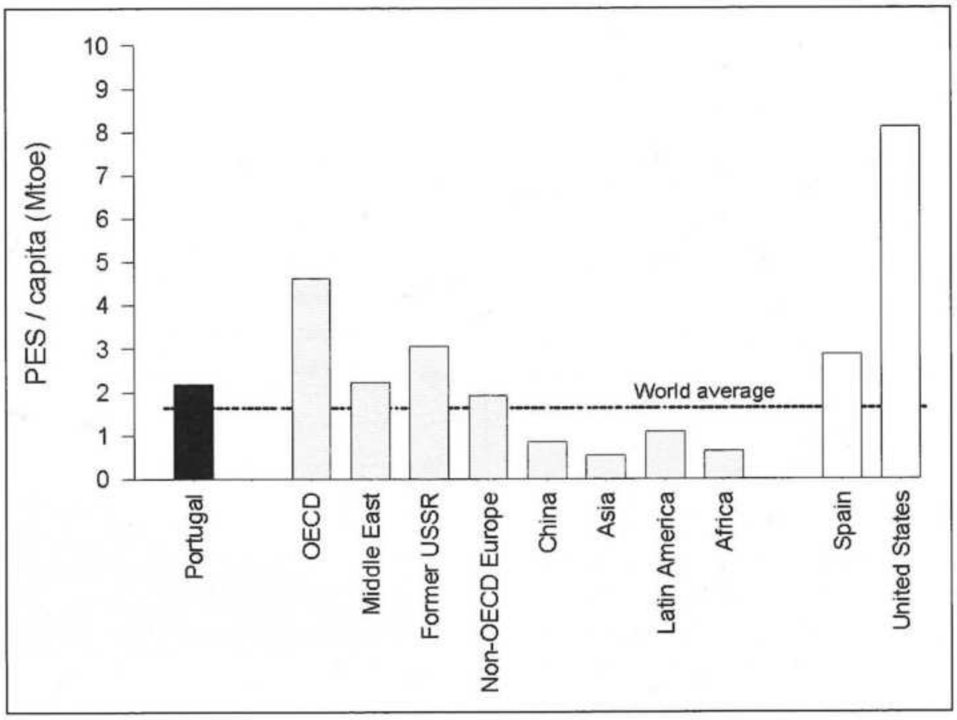

Fig. 9.4 – Primary energy supply per capita (1998), compared with other countries and regional blocs. Sources: IEA 1998a, 1998b; BP 2001.

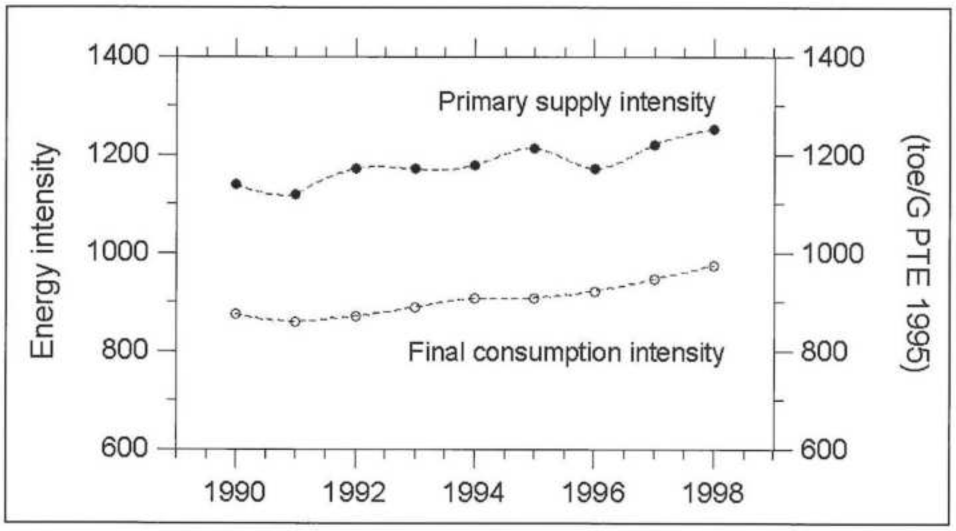

Fig. 9.5 – Overall energy intensity indicators. Source: DGE 1998.

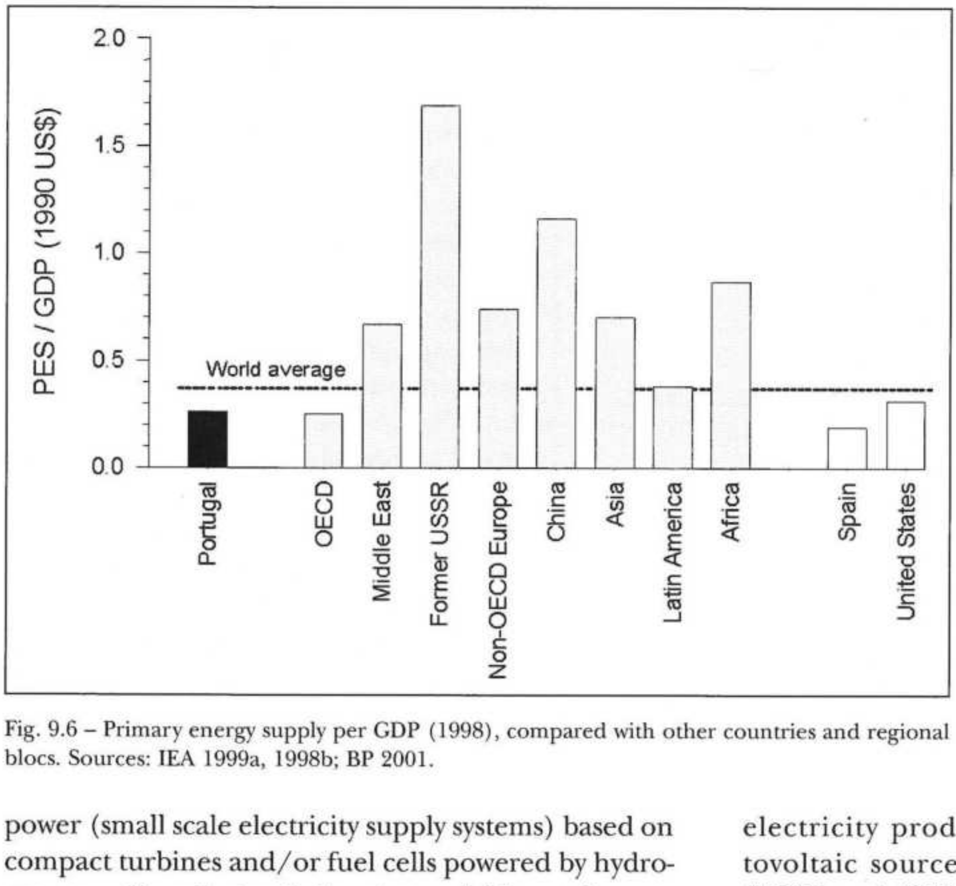

Fig. 9.6 – Primary energy supply per GDP (1998), compared with other countries and regional blocs. Sources: IEA 1999a, 1998b; BP 2001.

power (small scale electricity supply systems) based on compact turbines and/or fuel cells powered by hydrogen, as well as photovoltaic systems which are cheaper and more efficient. Major policies under implementation include the liberalisation of the EU energy market, especially the electricity (CEC 1997a) and gas markets (CEC 1998b), as very recently happened within the electricity market in the Iberian peninsula. Other important EU policies include the White Book on Renewable Energy Sources and the subsequent strategy, plans and actions aiming at a duplication of overall EU renewable energies contribution from 6-12% in 2010 (CEC 1988, 1997a, 2001a); the Green Paper on Security of Energy Supply (CEC 2000b); and the proposed EU Directives for promotion of electricity from renewable energy sources (CEC 2000c,d) – setting a 22% overall EU 2010 target for this type of electricity, signifying 39% in the case of Portugal – for promotion of combined heat and power (CEC 1998a) and for the improvement of building performance (CEC 2001b); as well as the European Climate Change Programme (CEC 2000a) launched in order to seek compliance with the Kyoto Protocol (see other relevant documents on EU plans, policies and legislation in EUR-LEX 2001).

In line with these concerns and policies, the Portuguese government recently presented a preliminary version of the Portuguese Programme for Climatic Change (PNAC 2001), which proposes for discussion and ranking numerous mitigation policies and measures related to energy issues. Several specific programmes for the energy sector supply and demand sectors were also very recently put forward, most notably the Programme for Endogenous Energies and Energy Efficiency (known as "E4") including for instance favourable buying rates for electricity produced from wind, waves and photovoltaic sources, as well as the sub-Programmes "AQS" and "3E", related to the promotion of solar thermal system use and energy efficiency in buildings, respectively (see Ministério da Economia 2001a; 2001b; 2002).

### 9.1.1.1 Energy supply

Portugal is currently about 90% dependent upon exterior energy sources (note that inter-annual fluctuations are significant due to a large component of hydroelectricity in the energy mix). In fact, endogenous resources are mainly renewable energy resources, with hydroelectric energy ranking first by far. Only small amounts of fossil energy resources have been discovered so far and they are not exploited to any significant extent. In 1998, primary energy supply (PES) was 22 Mtoe (toe = ton of oil equivalent), or 2.19 toe per capita, distributed as shown in Figure 9.7. The statistical data from the last 40 years show a growth in the national PES, amounting to 5% per year on average during the two last decades, with a sharper increase since 1986, as seen in Figure 9.1. According to scenarios developed by DGE, around 2010 the PES will be about 25 Mtoe, i.e. 2.48 toe per capita (DGE 1998; IEA 2000).

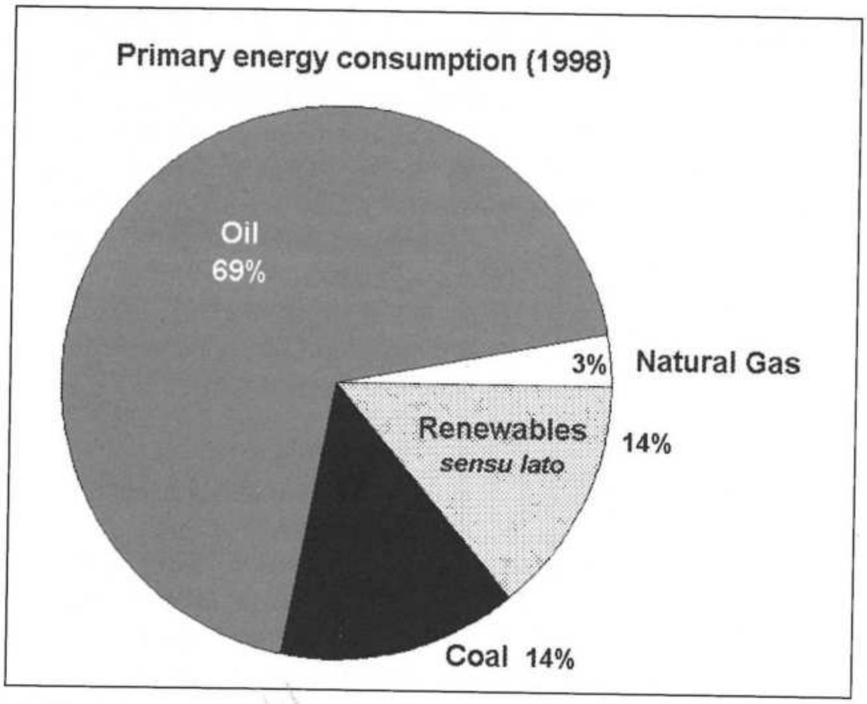

Fig. 9.7 – Primary energy supply by source, for 1998. Source: DGE 1998.

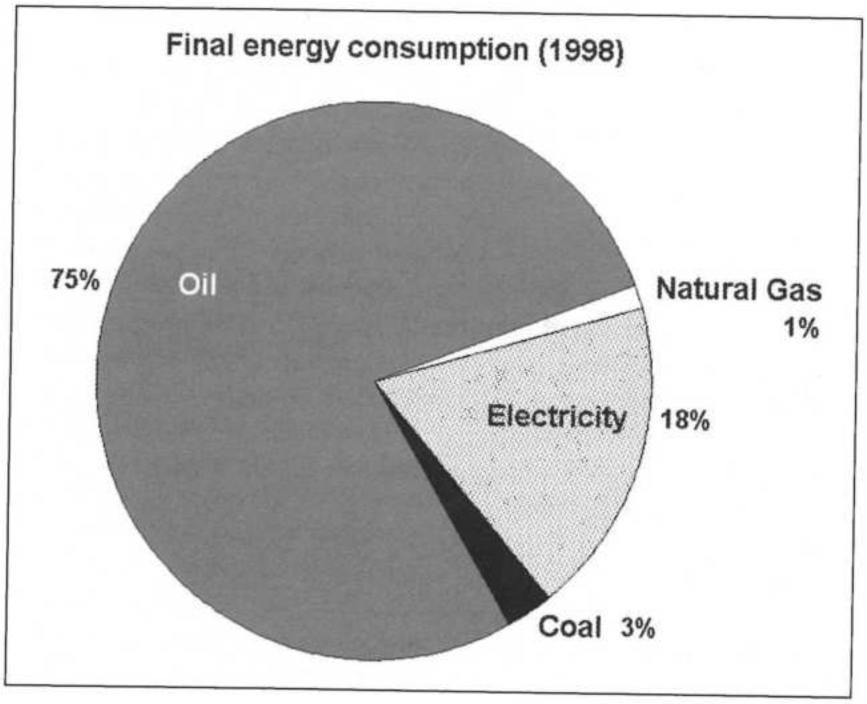

Fig. 9.8 – Final energy consumption by type, for 1998. Source: DGE 1998.

Most primary energy is currently obtained as petroleum products (71% in 2000) and DGE predicts that it will continue to be so even under very likely scenarios of much greater natural gas penetration. Natural gas was introduced in 1997 and it is foreseen that its share will grow in coming years (23% share by 2010 by DGE scenarios) due to replacement of other gases and electricity in the industrial, residential and services sector, and following changes in the structure of thermoelectric power sub-sector: various refurbished and new natural gas based facilities are planned, as well as co-generation facilities (IEA 2000), while most of the less important existing fueloil and gasoil based plants is to be decommissioned until 2010.

Coal was insignificant up to the mid-eighties, when a large thermoelectric power plant at Sines started operation, and became a significant portion of the primary energy. A similar plant was built at Pego some years later, and afterwards coal consumption has remained more or less stable, in absolute terms. The contribution of renewable energies *sensu lato,* i.e. including large hydroelectric power (larger than 10 MW systems) and wood products, was about 14% in 1998. A 6% share of this was from large hydroelectric power plants; renewable energy *sensu strictu* amounted to about 6% as well.

In the context of the energy sector, the case of electricity requires a more detailed discussion. As shown in Figure 9.8, electricity has a much larger share in the *final* energy consumption, as part of the primary energy sources are transformed into electricity. Indeed, electricity supply is crucial to everyday comfort and to numerous economic and social activities. Detailed analysis of the energy sector also shows that electricity production, transport, and distribution is by large the most important activity within the energy sector, this including the economic viewpoint of added value (DGE 1998).

The electricity mix is given in Figures 9.9 and 9.10, for the latest available data at the time of writing (year of 1999, see ERSE 2001). The installed power is distributed mainly between the several types of thermoelectric plants (coal, oil and gas based), co-generation and large hydro plants, but the contributions of other renewable energies are also significant. However, when the data is analysed in terms of electricity production, thermoelectric power emerges as more dominant, than if analysed in terms of installed power. Co-generation and hydropower are also significant. Hydropower was dominant in the electricity production, e.g. with a 75% share in 1973, but this share declined as most of the potential is now explored while the electricity demand continues to rise (around 5% per year). In recent years, hydropower share has ranged typically 30% to 40%, according to interannual variability of the climate.

The large majority of the electricity generation is produced by Electricidade de Portugal holding (EDP) both for the public system (Sistema Electroprodutor, SEP), and for the private system (Sistema Electroprodutor Não-Vinculado, SENV). However, in recent years two other firms become involved in the SEP, Tejo Energia and Turbogás, that run, respectively, coal and natural gas based thermoelectric plants; the rest of the production is from independent producers (Produtores em Regime Especial, PRE). The whole system is regulated by an independent entity, Entidade Reguladora do Sistema Eléctrico (ERSE), which also recently became the regulator of the gas market.

More significant climate change impacts are expected for hydropower than for thermoelectric plants, therefore additional information is given below. Hydropower plants can be located on dams or be run-of-river systems, and are defined as large hydro when the installed power is above 10 MW. Figures 9.11 and 9.12 depict the installed power for the SEP and SENV systems. These plants are distributed over all regions, except for the Algarve. However, the installed capacity (and the production)

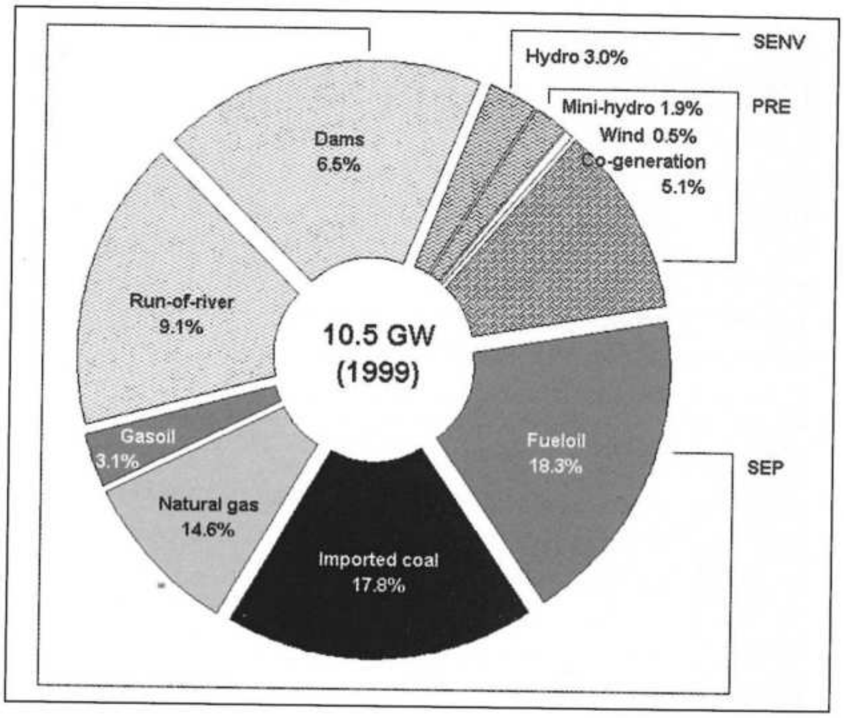

Fig. 9.9 – Electricity mix: installed power in mainland Portugal, for 1999. Source: ERSE 2001.

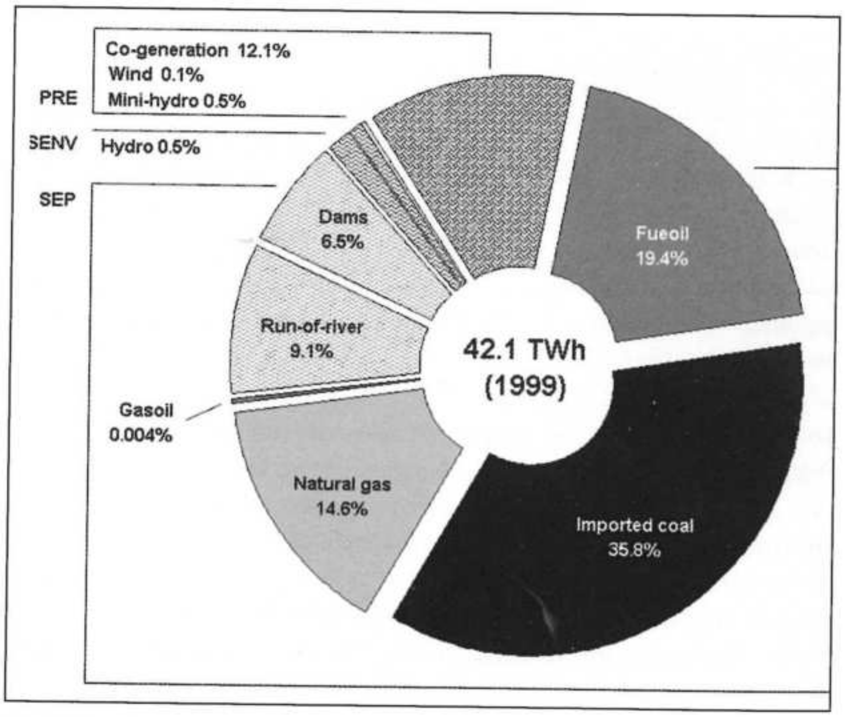

Fig. 9.10 – Electricity mix: installed power in mainland Portugal, for 1999. Source: ERSE 2001.

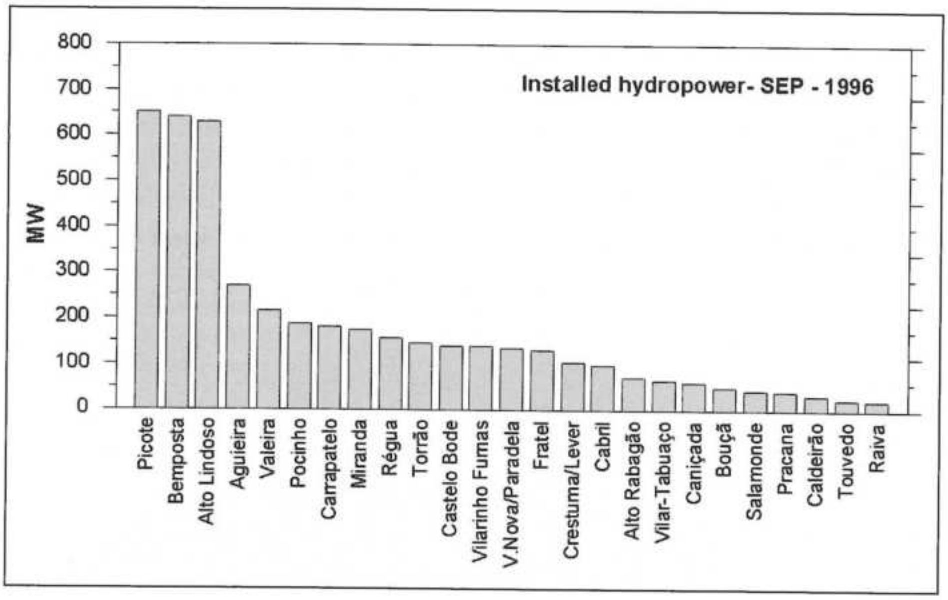

Fig. 9.11 – Installed capacity in SEP hydropower plants, 1996.

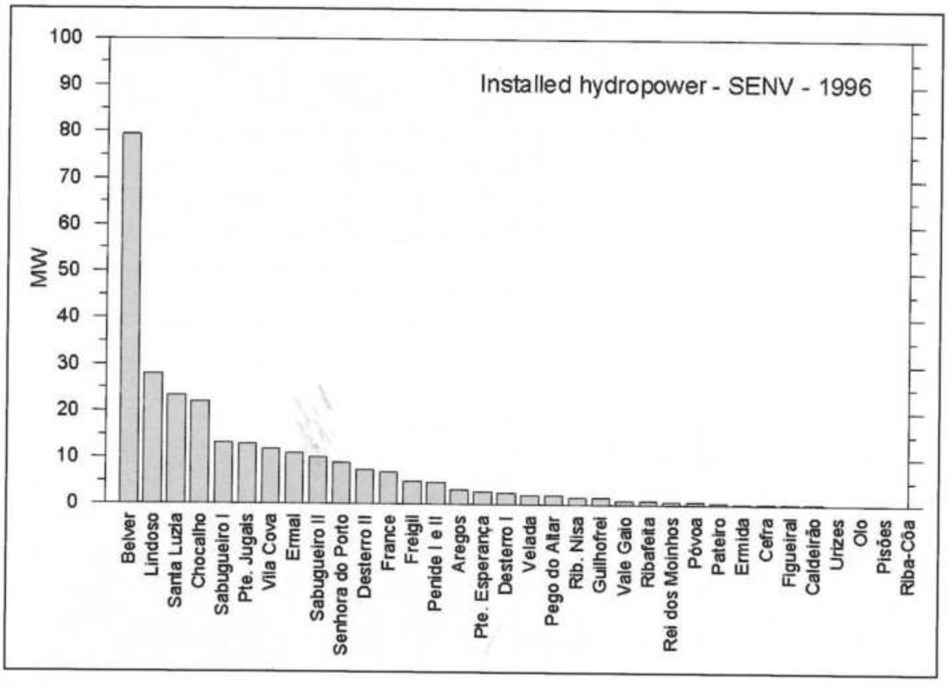

Fig. 9.12 – Installed capacity in SENV hydropower plants, 1996 (note the vertical scale much smaller than in Fig. 9.11).

is concentrated at the northern basins (see Figure 9.13), and in particular along the part of the Douro river along the Portuguese-Spanish border ("Douro internacional").

For impact studies, it is better to analyse the systems by actual power production instead of by installed capacity. This gives a different ranking (see Figure 9.14), but the major large hydro plants are still those of the Northern basin.

Many hydropower systems are installed in dams designed for other purposes, in particular residential water supply and irrigation. However, the larger systems on the northern basins that produce most of the national power production capacity, have been designed mainly for electricity generation and flood control.

Large hydropower potential is almost completely exploited; the largest planned effort consisted of the three dams Alqueva, Rocha da Galé, and Pomarão to be built on the Guadiana river, targeted more for irrigation than for energy – nevertheless this will represent 390 MW/ca. 400 GWh in a first stage, and up to 780 MW/ca. 920 GWh in a second stage. However, there have been recent changes to these perspectives, suggesting that quite lower power levels could in fact be reached (perhaps ca. 300 MW/128 GWh).

Wind turbine installation is experiencing a large growth, and there are also numerous mini-hydro spots to be explored. Pilot wave energy and biomass plants have also been installed. But even considering these recent developments of electricity from renewable sources, supported by governmental policies and measures, the simultaneous current rising trend of demand (see next section) does not seem to allow a larger penetration of such renewable primary energy sources in the next decade and even beyond. Therefore there are plans to meet the rising electricity demand through additional natural gas power plants.

#### 9.1.1.2 Energy demand

In 1998, the Final Energy Consumption was 17 Mtoe; according to the DGE scenarios it will

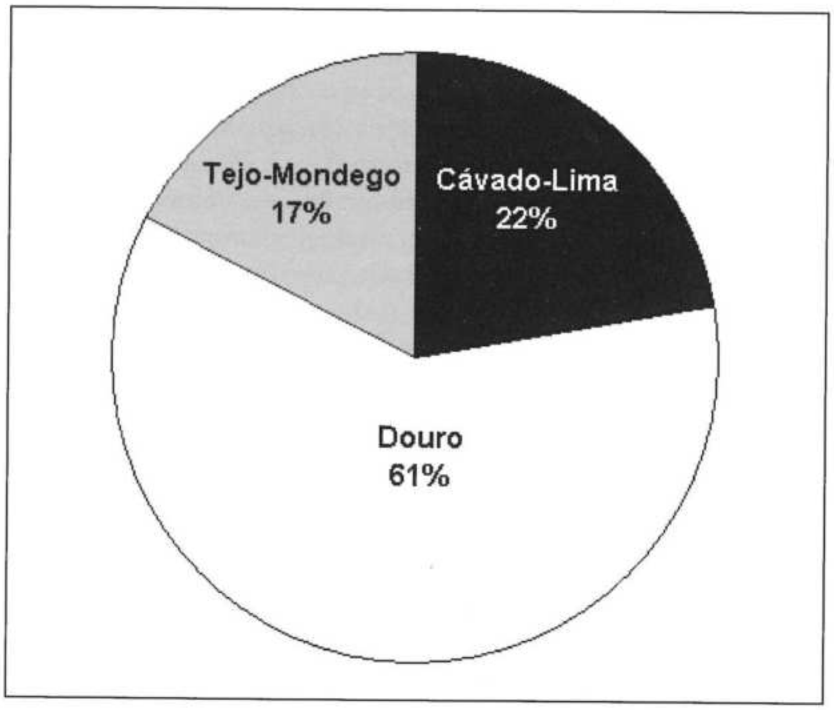

Fig. 9.13 – Hydroelectric power installed capacity in the main basins, 1996.

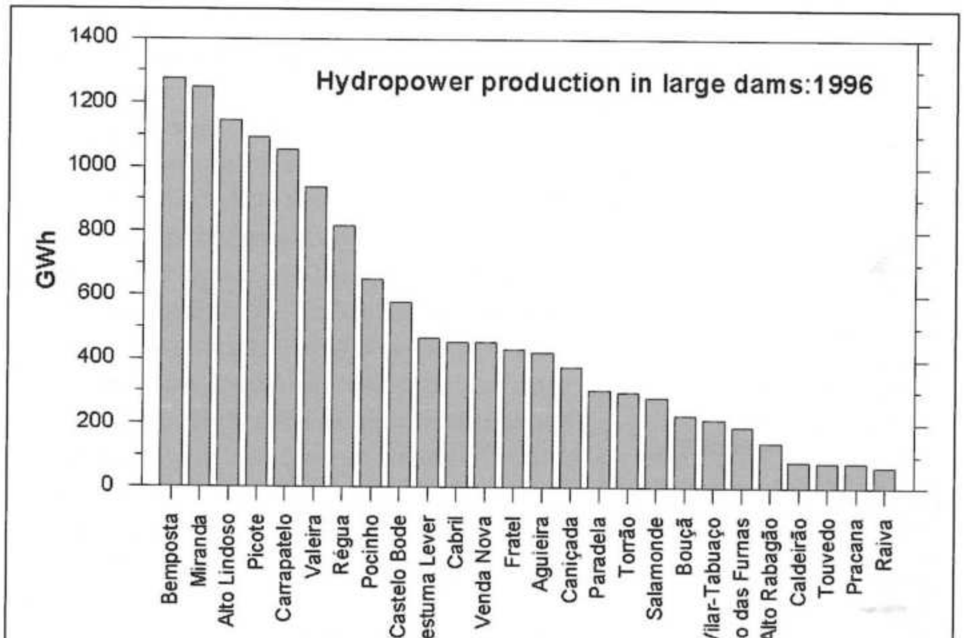

Fig. 9.14 – Production of large hydro systems (SEP), during 1996.

reach 20 Mtoe by 2010. In Figures 9.2 and 9.15, FEC estimates by activity sector are presented. Transportation and industry dominate energy consumption, holding a share of about a third each; However, the share of industry has been slowly diminishing.

Due to its large relative importance and growth trend, three sectors will be further discussed – transportation, domestic and service sector buildings.

The share of energy consumption by the transportation sector has been increasing, and for 2010 DGE predicts around 38%. Figure 9.16 shows that road transportation is by far the most important transportation mode. Air travel is still a modest share of the overall figure, in spite of the recent increases, whereas railways account for only a very small fraction of the total consumption.

As for the two building sectors, 98% of the buildings were residential by 1998; the number of regularly occupied unit dwellings (u.d.) in the domestic sector was 3.3 million. The number of dwellings continues to increase at an annual rate of 80-100 thousand, but it is important to note that 30% of residential buildings are estimated to be second residences, mostly occupied only during weekends and holidays. This may explain why the energy consumption share of the domestic sector is now expanding slowly; it is currently around 9% and DGE predicts a similar value for 2010 (for detailed characterisation of the domestic sector, see Oliveira e Camelo 2000a, 2000b; Gonçalves et al. 2001) It must be noted that the statistics related to energy consumption are quite uncertain (±1.3 Mtoe), and in particular the statistics originated at Instituto Nacional de Estatística (INE) and DGE do not match, mainly due to a different accounting of wood biomass use.

Although services accounted for only 2% of buildings by 1998, they represented a share in energy consumption similar to that of the domestic sector. Furthermore, this share continues to grow, with DGE expecting 10% by 2010. A good characterization of the buildings and respective energy consumption statistics in the service sector is difficult to obtain, one

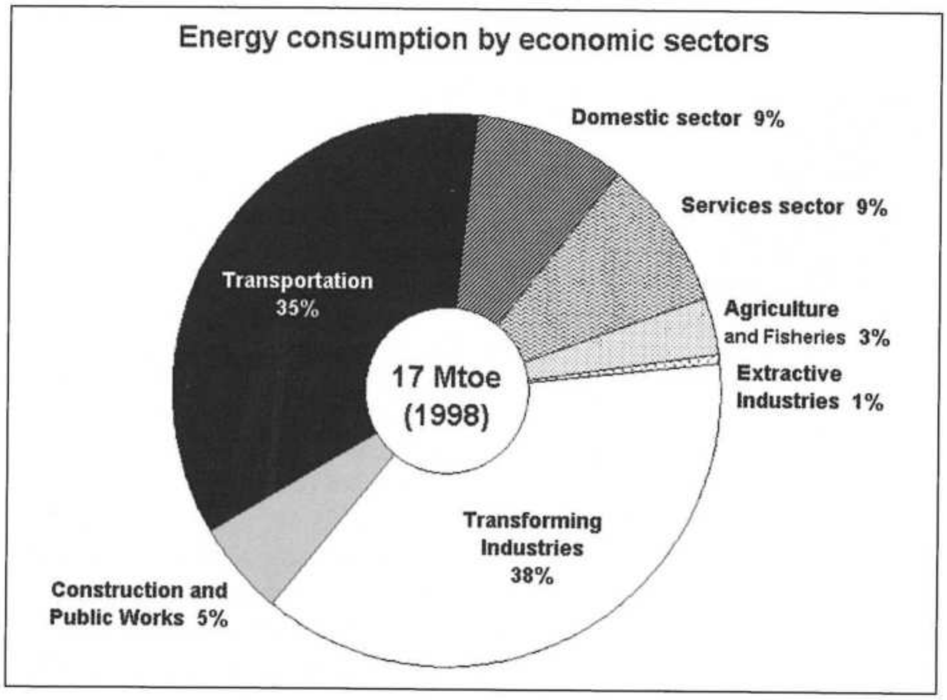

Fig. 9.15 – Energy consumption by economic sectors by 1998. Source: DGE.

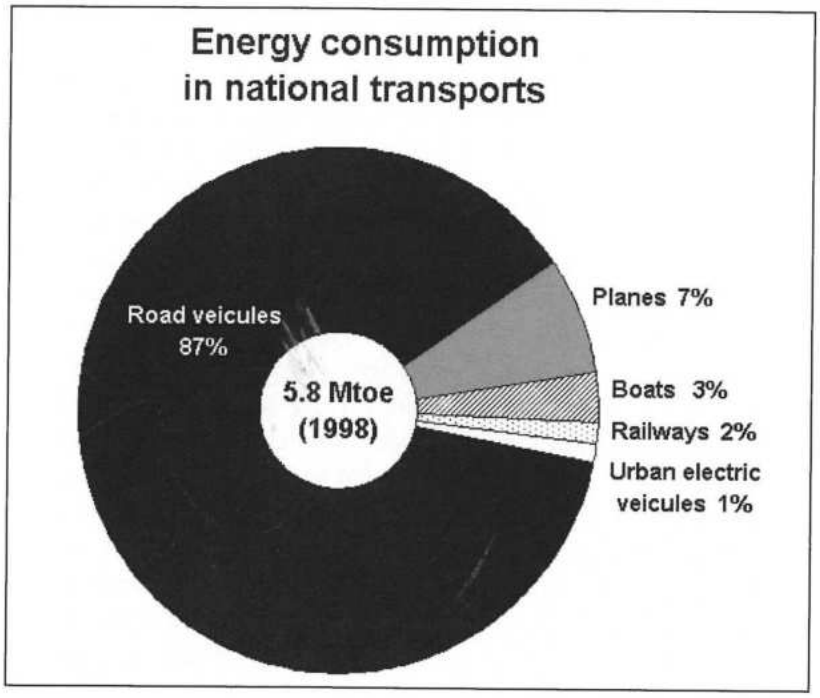

Fig. 9.16 – Energy consumption by transportation mode, by 1998. Source: DGE.

of the reasons being that it includes many different activities: offices, schools, hotels, shops, restaurants, banks, commercial centres, etc. However, they all share the feature of large internal gains (metabolic, from human occupation, and also equipments, lighting) and most are now fitted with HVAC (heating, ventilation and air conditioning) devices.

The effect of better education with respect to environmental problems may change user attitudes leading towards a more rational use of energy. Energy efficiency gains stemming from technological improvements work in the same direction. Finally, EU and domestic policies related to energy efficiency – either planned or under implementation – can also change current perspectives.

However, some of these changes will likely be effective only over the mid- to long-term. To illustrate, improved or stricter regulations generally apply only to *new* equipment, buildings, etc. But the annual renewal rate of the park of residential buildings, i.e. the new and significantly renewed buildings in proportion to the total of buildings, is only about 2-3%. Thus, the potential impacts of these regulations (typically targeted to 2010) are diluted into the whole of a sector and significant changes do not occur immediately. This makes demand side management policies, no matter how essential, less attractive in the short term than policies directed to the energy supply side, and indeed until recently they have received less public and governmental attention.

### 9.1.2 EFFECT OF WEATHER ON THE ENERGY SECTOR

#### 9.1.2.1 Energy supply

Weather impacts are only significant in terms of the yield of renewable energy systems, here including large hydroelectric power plants. In particular, hydroelectricity generation depends on surface flows and therefore on precipitation levels. During extreme events such as storms and droughts, large dams are also used to regularize the river flows; this leads to decreased ability to optimise the production of electricity at the corresponding power plants.

### 9.1.2.2 Energy demand

The energy demand of all sub-sectors depends differentially on weather patterns, in general, and on the minimum and maximum ambient temperature in particular. The effects often vary seasonally.

Effects of weather in transportation include direct effects such as more energy requirements for air conditioning and ventilation, especially during the summer, and indirect effects such as seasonal fluctuations on fuel demand, for instance related to tourism. Roadblocks due to heavy rain or snow are rare events. Indeed, there are some small zones that are frequently affected, such as roads and railways in the Santarém-Lisbon axis close to the Tagus river (floods) and roads to the Serra da Estrela mountain tops (heavy snow). These well known cases are generally well handled by population and authorities and usually only cause small and temporary impacts on traffic and economic activities. However, less dramatic weather events such as fog, and especially light snow, often cause traffic problems and accidents, as drivers (and even vehicles) are not well prepared to handle such conditions departing from a prevailing mild climate.

Effects of weather on the domestic and service sectors are dominated by the energy demand for space heating and cooling. Heating is generally required during winter and portions of spring and autumn, especially in the residential sector. Cooling, on the other hand, is required in residences during summer, and often throughout the year in certain services such as large offices and commercial buildings. Currently, however, only the service sector uses significant amounts of energy for cooling, as HVAC domestic systems are installed in only 3% of dwellings (INE 1999).

There was no information available on the dependence of other energy needs on weather, although it seems likely that at least the domestic hot water needs and industrial pre-process heat needs should be reduced during the summer. Note that refrigeration requirements in the services and industry sectors do not depend on the weather as the systems are installed within buildings with controlled temperature (thus any effects translate in additional space cooling demand). A similar situation is partially true for boilers and other water heating devices.

## 9.2 METHODOLOGY

### 9.2.1 DESCRIPTION OF ASSESSMENT APPROACH

### 9.2.1.1 State of the art

Due to the fact that the energy sector is a major source of GHG emissions, the huge majority of the climate change related work is done on characterisation and mitigation studies, rather than on impact and adaptation. Nevertheless, there is already a considerable amount of literature on impacts and adaptation in the energy sector.

Many studies rely only on expert judgment (e.g. Kerr et al. 1999, the Scottish Implications Scoping Study) and indeed some issues may require only this type of approach, in particular those impacts that are potential, but irrelevant or insignificant for the energy sector of a specific country.

Many econometric/statistical models of the energy sector of countries or regions have been made (e.g. Garcia-Cerruti 2000). In some cases these top-down models have been applied to the estimation of climate change impacts, in particular those related to temperature increases (e.g. Sailor 1998, Considine 2000).

Bottom-up numerical models of energy sector components or devices are also numerous, but they seem to be rarely applied to climate change issues. Most of the publications available to the authors focused on large hydropower plants (supply side; e.g. Sanderson 1987, Frederick 1993) and space conditioning in buildings (demand side; e.g. Singh 1988, Loveland and Brown 1990, Scott et al. 1994, Rosenthal et al. 1995, Belzer et al. 1996). In general, most studies examined use simplified models, for instance relying on parameterisations, and not detailed simulation models: e.g. space heating is made proportional to heating degree-days below some minimum comfort level (e.g. Singh 1988; Gertis and Steimle 1989), instead of being computed from thermal performance simulations of some reference building. A more widespread use of numerical models is limited by the absence of information on detailed system characteristics and meteorological data.

Hybrid models integrating the socio-economic response of the various actors in the energy sector and the technical performance of the systems (CIESIN

1995; Eyre et al. 1998; Downing et al. 1998; Hulme 2001) are still few, and as mentioned before, are generally targeted to studies on mitigation policies and measures (e.g. Hens et al. 2001; Sun 2001), and not to impacts and adaptation. Nevertheless, it is likely that this expertise will enable more sophisticated impact and adaptation studies.

Finally, the issues of socio-economic scenarios and technological change prospective studies must be mentioned. Indeed, for the time range of 50-100 years being considered for impact and adaptation studies, large changes in the energy sector can be expected – propelled by research and development, as well as by concerns on pollution, security of supply, sustainable development and the climate change impacts themselves. Therefore, more sound estimates of long range impacts and adaptations must take into account the future energy sector scenarios, not its current stage. This is an important line of work that is gaining visibility (see Rosenberg 1993, Lorenzoni et al. 2000, plus Berkhout et al. 2001 and references therein).

Several studies and reports exist sponsored by international bodies like the United Nations Environment Programme (UNEP 1998), the International Panel for Climate Change (IPCC WGII 1995) or the European Climate Change Programme (ECCP 2001). However, the very fact that they aim to analyse entire world regions, or groups of nations like the EU or the OECD, means that they find it difficult to fully exploit the potential of detailed top-down econometric or bottom-up engineering models described and used in country specific studies – therefore they rely on simplified models, generally statistical or parametric. Also, it must be considered that the impacts and possible adaptations are country specific – very dependent on geography, climate, socio-economic profile and sector characteristics – with the implication that the broad conclusions of large region studies cannot fully capture the regional variability. However, international large region studies are very valuable for providing case studies, assessment guidelines, and preliminary ranking of potential impacts, (CRU/ERL 1992, IPCC WGII 1995, Tol 1999, ACACIA 2000).

As mentioned before, impacts and adaptations are country-specific. It is noted that the type of studies that can be done depends on the available country statistical data (which is needed for producing baselines and scenarios). Both factors combine to make existing country level studies very different in approach, complexity, and issues considered. It should also be said that the most comprehensive studies conducted for the energy sector, were for northern hemisphere countries with colder climates than Portugal – good examples are the Canada (NRC 1997), Germany (Flechsig et al. 1999), USA (Rosenberg 1993, NSTC 2000), Netherlands (Tol et al. 1999, van Ierland et al. 2001) or UK (CCIRG 1996) impact assessment studies – and therefore their results are often not relevant, or useful as analogues, for the current study.

As a final note, it is interesting to point out that most of the impact and adaptation studies available survey the existing published work, regarding the energy sector of the region or country of interest; while in this case, previous work for Portugal was practically inexistent, and therefore the SIAM team had to develop its own models and analyses.

#### 9.2.1.2 Options for assessing impacts on the Energy sector

Modelling is the primary option for examining the energy sector. Energy supply devices – dynamos, turbines, renewable energy systems, etc., up to whole power plants – are well understood and designed from the start using quantitative tools. The economics of such systems are also well studied. With regard to energy demand, devices that use energy such as motors, pumps, HVAC, and boilers are also well understood and detailed quantitative models available.

However, the modelling of energy demand is more complex than energy supply. While energy supply is (currently) concentrated at some well defined sites – refineries, electricity plants, etc. – energy demand is composed of a myriad of systems. It is also difficult to represent the actions of system users, which are driven by a variety of factors, but where strictly economical considerations are not as relevant as in the case of energy supply.

Other factors complicate the use of detailed modelling. Detailed models need complex inputs. For instance, a detailed model of a natural gas powered electricity plant will require highly technical data about each specific plant – plus, these data are often confidential. Especially when country level analyses are undertaken, these data can be difficult to obtain. Also the detailed models themselves may be confidential or too expensive to buy or use.

The meteorological data required to run the models must often be very detailed, both in spatial and time scale. It may be unavailable in the climate change scenarios available.

Given the time range of climate change, technological change, regulatory strategies and socioeconomic conditions also become important for creating sound models of the energy sector, or parts of it. Scenarios for the future must be designed, and these have associated uncertainties. Thus, although detailed models can yield detailed responses with low uncertainty, the value of the large efforts invested for preparing and running them must be balanced with the fact that projections will nevertheless introduce considerable errors.

Last but not least, it is in practice impossible (and perhaps useless) to model *all* systems within the energy sector. Therefore some simplifications have always to be assumed. This leads to the consideration of two other types of models: statistical and simplified (or reduced) models.

In the case of econometric/statistical models, the energy system is viewed as a whole and not as a collection of certain devices and users. Existing models of this kind are essentially economic, e.g. input-output matrices with numerous economic sectors and sub-sectors. At least two large drawbacks of these models are that i) environmental parameters such as temperature or precipitation generally are not explicitly taken into account; ii) as they are calibrated with recent time series of economic data, it is not guaranteed that the models will still be valid under other socio-economic conditions and technological options.

The idea behind using simplified models in the current context is to obtain an adequate model of a typical or representative system of the collection of similar systems in the energy sector – e.g. a typical apartment representative of Portuguese urban residences.

Simplified models use simple physics, as well as basic configurations and user intervention. The simplification can be taken to an extreme (e.g. input-output black box type empirical models). However, totally empirical models in general do not perform well in the current context: they are adequate to represent specific systems, but they allow little variation of the input parameters and system configuration. In principle the best simplified models should be "reduced" models, resulting from a step-by-step simplification of a detailed model (Palomo *et al.* 2000). In practice most of the simplified models are partly empirical models, calibrated/validated with a set of input-output data series from existing systems. The meteorological data required are generally monthly values, with a spatial resolution compatible with present-day climate models.

Analogues in the energy sector are appealing especially when dealing with weather effects over specific classes of devices, such as power plants, cars, and dwellings as similar responses are expected from using similar technologies. In contrast, the value of analogues for user behaviour or for the response of whole sectors or sub-sectors is doubtful, because it is difficult to find countries with similar climate, size, population, cultural factors, reference economic conditions, energy sector structure, building sectors, and so on. For the specific case of Portugal, only southern European countries could be considered as country analogues; unfortunately integrated impacts and adaptation studies either do not exist or are still in incipient stages. The meteorological data required for analogues are generally long term monthly or even yearly values, which can be obtained with ease from climate models.

Expert judgement would seem to be a last resort to use, namely when there are no good models or analogues available, and/or no time or resources to develop models. However, expert judgement is very valuable for many other reasons: for instance, in the initial stages of a study, when a first ranking of potential impacts must be made; to dismiss the need for detailed studies when a potential impact is considered irrelevant or not significant; or to select the simplifications to be made when assembling simplified or reduced models. Expert judgement generally requires only basic meteorological data, e.g. tendencies for temperature and precipitation change.

#### 9.2.1.3 Description of the impact assessment strategies used

In a first stage, an attempt was made to identify the major climate change impacts on the energy sector, as almost no work had been previously done for Portugal. Therefore, to make the work effective the approach taken was to i) list the possible impacts; ii) identify tentatively the major impacts, both from expert judgement and analogues, namely following the UNEP Handbook (UNEP 1998) and advice from national specialists; iii) perform impact analysis for these selected cases; iv) whenever possible, obtain expert judgement and estimates from analogues for the remaining cases.

Thus, expert judgement was employed for all identified impacts. It was used for preliminary ranking of impacts. In practice it had to be used in many situations when meteorological and other input data required for running models was unavailable, such as the case for all types of electric power plants. It had to be also used in the demand side analyses, except in the case of HVAC demand.

For assessing impacts on electricity transmission, detailed models are known to exist in utilities or universities; however, these were not used in this first approach.

Statistical analyses were performed for national energy use and energy intensity data versus temperature data, this at yearly and seasonal time scales. Input-output economic matrix models are available, but inclusion of weather parameters is just at its beginnings, and remains an avenue for future research in the case of Portugal (Silva et al. 2000).

Simplified empirical models were used in particular for renewable energy supply systems. Preliminary analyses were performed with the RETScreen™ software (CDRL 2000), relying on empirical parameterisations and simple energy balances. These models require long-term monthly meteorological data.

Simplified reduced models were used for solar systems. Thermal domestic hot water systems were analysed with SolTerm, an energy balance model from Instituto Nacional de Engenharia e Tecnologia Industrial (INETI 1999). It only requires long-term monthly meteorological data but contains a radiation distribution parameterisation adjusted specifically with European data, including Portuguese. Photovoltaic systems were analysed with energy flow models developed in the same institution (INETI 2000). They require hourly meteorological data. The main simplifications are to be found in the description of stand-alone systems, namely in the storage electrochemistry, energy losses, and backup devices.

Detailed models were used only for the case of space heating and cooling of buildings, by analogy judged as the most important impact. The ESP-r software, the European reference program developed by the University of Strathclyde (Clarke et al. 1990; 1993), was used. It is an energy balance model with very few empirical parameterisations and simplifications that describes a building using numerical finite elements. The building model characteristics to be defined are location, geometry, construction and operation schedules (infiltration, occupation, illumination and equipment). ESP-r requires hourly data of climate conditions (temperature, relative humidity, direct and diffuse solar radiation and wind intensity and direction). The program can compute thermal loads and energy requirements for space heating and cooling on an hourly basis. The main simplifications of ESP-r as used in SIAM regard internal convection, but this is more important in terms of ventilation than for the purposes of the current study, which is targeted at thermal performance. In practice, uncertainties in input meteorological parameters and in other inputs, e.g. operation schedules, have a larger contribution to model output errors than simplifications in the ESP-r algorithms and the runtime numerical errors. This is especially true for the current case, where meteorological and socio-economic scenarios are used instead of actual data for a specific existing building and its environment. It is a good illustration of the reason why the approach of assessing impacts as anomalies in system performance rather than as absolute values was adopted in this study.

### 9.2.2 DESCRIPTION OF DATA USED

#### 9.2.2.1 Climatic Data

##### *9.2.2.1.1 Observed data*

National temperature indexes had to be developed for econometric/statistical studies on the relation of energy use to climate. The idea was to have a single parameter representing "average" national climate to compare with national energy consumption statistics.

Based on monthly temperature maximum and minimum values supplied by the Instituto de Meteorologia (IM), for Lisboa (1901-'99), Bragança (1941-'99) and Beja (1958-'99) average, maximum and minimum temperature indexes were built. Besides yearly values, "winter" (December, January and February) and "summer" (June, July and August) values were also used to build corresponding indexes.

It was concluded that the fluctuations from mean level were very similar at each station (see e.g. Figure 9.17). This supported the option of performing a simple average of the yearly or seasonal data, as different weighting of stations according to corresponding regional energy consumption would be irrelevant. Due to data gaps and quality control results, the final period considered was restricted to 1958-'99.

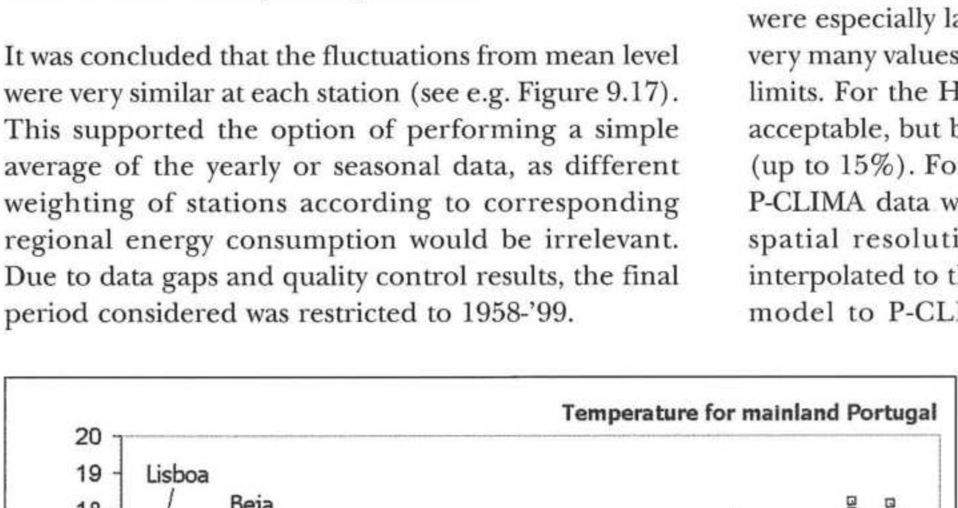

Fig. 9.17 – Time series yearly average temperature values for Portuguese stations and corresponding composed temperature index.

#### 9.2.2.1.2 *Climate-model generated data*

For the case of impacts on hydroelectric power production, the more relevant meteorological data available for impact studies were surface flow estimates issued by the water resources team. Wind speed from the HadCM3 models was used to analyse wind energy systems.

For all the other cases, the more relevant meteorological parameters were ambient temperature and solar radiation: PROMES, HadRM and HadCM3 models were all used.

However, solar radiation had to be corrected as the reference scenarios deviated too much from observed climatic data, as assessed by comparison with data from the "European Solar Radiation Atlas" (ESRA 1998) – consisting of remotely sensed data adjusted with ground station data – and from Project P-CLIMA (Aguiar 1998a) – consisting of spatial estimates from ground station insulation data converted to radiation with the help of parameterisations. The deviations were especially large for the case of PROMES, indeed very many values lay above reasonable clear-sky model limits. For the Hadley Centre models, yearly bias was acceptable, but bias at the monthly level was too high (up to 15%). For correcting the solar radiation data, P-CLIMA data was used: it had less error and better spatial resolution. Gridded numerical data was interpolated to the weather model nodes, the ratio of model to P-CLIMA data was computed, and the resulting factor multiplied by the radiation time series of both the base and enhanced greenhouse effect scenarios. These corrected radiation data was also supplied for the impact assessment work of the other sectorial teams of SIAM.

For studying solar thermal systems, an estimate of tap water temperature had to be obtained. The criteria used relates it to the ambient temperature, as follows: from November to April, tap water temperature equals mean monthly ambient temperature, for the rest of the months it is set as the average of ambient temperatures for the month and for the yearly mean.

Long-term yearly and monthly data served as input in most cases, but for photovoltaic systems and buildings, hourly data was used. However, the respective systems models are very calculation intensive, especially in the case of buildings, therefore it was impractical to use directly the hourly data time series provided by the climate models. Therefore synthetic test reference meteorological years (TRY) were assembled based on statistical and stochastic models (Camelo et al. 1998; Aguiar et al. 1999), for both the base and the enhanced greenhouse effect scenarios. A number of synthetic weather generators were available for this purpose; those based on the Projects P-CLIMA and Project CLIMED (Aguiar 1998b;c) were selected because they were based on Mediterranean data and were already tuned for the Portuguese climate; and also because they had the advantage of including the cross correlation between daily values of temperature and solar radiation, judged an important factor in the thermal performance of buildings. The TRY data generated also included diffuse solar radiation estimates (Aguiar 1995), a key factor when converting horizontal solar irradiation data provided by the weather models to tilted planes (solar collector planes, building facades, etc.).

### 9.2.2.2 Socioeconomic Data

#### *9.2.2.2.1 Observed data*

Only the assessment of impacts on energy consumption in buildings required observed socio-economic data, for defining typical dwellings, with respect to its type, area, occupancy patterns, and equipment. Data at NUTS II spatial resolution from INE (1999; 2000) and DGE (DGE 1989a; 1989b; 1996) were used. Additional population data from INE (INE 1994; 1997) was used to perform regional weighting of the results obtained for each specific type of dwelling. Office buildings were characterized with the help of a DGE survey (DGE 1994).

#### *9.2.2.2.2 Socioeconomic scenario generated data*

A complete study of the impacts would require a good picture of what the energy market could be at the end of the time range for this study, say 2070-2100. The associated uncertainty is prone to be very large, as shown by the story of unsuccessful past predictions for aspects of society and technology at such a long time range.

However, it is clear that the energy sector is changing very fast these days – as a result of rapid technological developments and strong political drive (e.g. the EU target of doubling the renewable energies share in 10 years), a drive that is partially originated in the climate change issue itself, and partly in other factors such as pollution problems and the need for security of supply. Therefore some kind of projection, no matter how uncertain, must be applied to the current socio-economic, technological and legislative panoramas. The energy scenarios developed within this study are quite different from existing projections and plans for Portugal: *viz.* DGE and DPP projections; Collares-Pereira 1998; Sá da Costa 2001. Indeed the current exercise focuses upon a period much further in time – 50-70 years instead of 10-15 years – and also, the scenarios drawn must be compatible with the non-energy parameters of the SIAM socio-economic scenarios.

The base for developing the energy scenarios were the four demographic and economic development scenarios supplied by the socio-economic team (see the respective chapter and also Berkhout et al. 2001) and complemented by expert judgment on technological and legislative trends. An effort was made to make conservatively biased projections, but nevertheless to consider the effects of adaptation and mitigation measures following current national and international policies, e.g. the Kyoto protocol.

The energy related scenarios include general projections for energy consumption (primary and final), for the share of renewable energies in the energy mix, and for the penetration of electricity in the primary energy supply. There are also specific projections for the share of each type of renewable energy source, for thermal energy demand for water heating. Building related energy scenarios were also assembled, including geographical distribution of dwelling type, areas, thermal shell characteristics (insulation mainly), HVAC and electric equipments, occupancy and operation modes.

The energy scenarios are compatible with several current trends in research, technology, and legislation, as well as the (renewable) energy resource related limitations. In particular it is important to mention:

i) stabilization of the per capita use of energy close but above the 2010 values of the DGE projections (but still below the current values of other western European countries);

ii) reliable supply of fossil fuels without large and rapid increases of the energy prices;

iii) doubling of the electricity penetration level of today (from ca. 20% up to 40%) – driven by additional equipment inside buildings, but especially by widespread use of electrical vehicles (road and railway);

iv) strong increase of the electricity production from all renewable sources in absolute values, except large hydro;

v) saturation of the favourable sites for exploitation of hydro, wind, waves and of areas for energy-related biomass production;

vi) compatibility with the EU Directives and policies pointing to a strong increase of the energy production from renewable energies (specially the 2010 doubling target); in particular for the electricity production from renewable energy sources – the current Portuguese absolute values are assumed to about triple, despite saturation of good large hydro and wind park sites.

Differences between the four scenarios are related mainly with non-energy parameters: strategies of conservation of the natural and built patrimony; available national technology; and capital available for investment (in the later case, GDP and Government investment were used as proxies). Also, as PEC and FEC parameters are specified per capita, scenario differences can also be traced to different population counts.

Scenarios for the issues that involve considerations on technology aspects specific to the energy sector are given in Tables 9.I to 9.IV.

**Table 9.1 – Long range SIAM energy scenarios: primary energy supply and final energy consumption**

| Scenario | Population M | PES/capita toe/capita | PES Mtoe | FEC/capita toe/capita | FEC Mtoe |
|---|---|---|---|---|---|
| Today (1998) | 9.98(*) | 2.19 | 21.86 | 1.71 | 17.03 |
| A1 – Global Economy | 11.5 | 2.8 | 32.2 | 2.2 | 25.8 |
| A2 – National Interest | 9.5 | 2.6 | 24.7 | 2.1 | 19.8 |
| B1 – Global Sustainability | 10.0 | 2.5 | 25.0 | 2.0 | 20.0 |
| B2 – Local Sustainability | 10.0 | 2.6 | 26.0 | 2.1 | 20.8 |

(*) estimated for consistency with the other parameters in the baseline

**Table 9.2 – Long range SIAM energy scenarios: penetration of electricity in the primary energy supply mix**

| Scenario | PES | Electricity | |
|---|---|---|---|
| | Mtoe | % | Mtoe |
| Today (1998) | 21.86 | 19.7 | 3.35 |
| A1 – Global Economy | 32.2 | 40.0 | 10.3 |
| A2 – National Interest | 24.7 | 40.0 | 7.9 |
| B1 – Global Sustainability | 25.0 | 40.0 | 8.0 |
| B2 – Local Sustainability | 26.0 | 40.0 | 8.3 |

For estimating impacts on hot water requirements, both sanitary water needs and cooking are taken into account. It will be assumed that 5% of the energy spent for cooking could be supplied as pre-heated water from solar systems. The 1996 DGE values of 0.38 Mtoe for sanitary hot water and 1.04 Mtoe for cooking energy will be considered to grow at, respectively, 5% and 2% per year, in per capita terms, and to stabilise near 2010 values. For the service sector no reliable statistical data could be found, therefore it was estimated that the needs are about the same as in the domestic sector (the energy demand is currently similar in both sectors, but it is growing in the service sector, therefore this is probably an underestimation).

Unfortunately detailed data for industrial heat and pre-heat requirements of industry is not available for Portugal. An analogue was found for Spain (Schweiger et al. 2000), wherein about 72% of the industry energy needs is in the form of heat. Industry energy requirements are held fixed at the 2010 level estimated by DGE (*viz.* 6.9 Mtoe).

As a conservative estimate, it will be assumed, that 50% of heating and pre-heating needs are achievable from solar systems with no special technical difficulties, and that to this target value solar thermal systems achieved the penetration shares listed in Table 9.IV apply. Note that additional thermal and electric energy can be achieved using e.g. biomass or anaerobic digestion, but these could not yet be studied quantitatively in this phase of SIAM and so no specific scenarios are drawn for these other sources.

## Table 9.3 – Long range SIAM energy scenarios: contribution of renewable energy sources for the primary energy supply of electricity

**Absolute values: Mtoe**

| | PV(a) | Large Hydro | Mini Hydro | Wind | Biomass | Waves | Geo-thermal | Other (b) | Total |
|---|---|---|---|---|---|---|---|---|---|
| Today (DGE 1998) | 0.0001 | 1.07 | 0.05 | 0.01 | 0.09 | 0.00 | 0.005 | 0.00 | 1.22 |
| A1 – Global Economy | 0.52 | 1.38 | 0.09 | 0.86 | 0.53 | 0.26 | 0.02 | 0.02 | 3.64 |
| A2 – National Interest | 0.43 | 1.29 | 0.08 | 0.77 | 0.53 | 0.17 | 0.02 | 0.02 | 3.29 |
| B1 – Global Sustainability | 0.60 | 1.20 | 0.09 | 0.86 | 0.53 | 0.17 | 0.02 | 0.02 | 3.47 |
| B2 – Local Sustainability | 0.43 | 1.29 | 0.07 | 0.69 | 0.53 | 0.09 | 0.02 | 0.02 | 3.11 |

**Share: % of the electricity penetration value (Table 10.2)**

| | PV(a) | Large Hydro | Mini Hydro | Wind | Biomass | Waves | Geo-thermal | Other(b) | Total |
|---|---|---|---|---|---|---|---|---|---|
| Today (DGE 1998) | 0.004 | 32.0 | 1.45 | 0.23 | 2.62 | 0.00 | 0.15 | 0.00 | 36.5 |
| A1 – Global Economy | 5.0 | 13.4 | 0.8 | 8.3 | 5.1 | 2.5 | 0.2 | 0.2 | 35 |
| A2 – National Interest | 5.4 | 16.3 | 1.0 | 9.8 | 6.7 | 2.2 | 0.2 | 0.2 | 42 |
| B1 – Global Sustainability | 7.5 | 15.1 | 1.1 | 10.8 | 6.6 | 2.2 | 0.2 | 0.2 | 44 |
| B2 – Local Sustainability | 5.2 | 15.5 | 0.8 | 8.3 | 6.3 | 1.0 | 0.2 | 0.2 | 38 |

(a) grid connected photovoltaic systems, mainly installed on buildings.
(b) anaerobic digestion, other PV, ocean currents, etc.

## Table 9.4 – Long range SIAM energy scenarios: solar thermal contribution to final energy consumption

**Residential Sector**

| | Sanitary (65°C) toe/capita | Mtoe | Cooking all types toe/capita | Mtoe | up to 100°C % | Mtoe | Potential by solar (1) % | Mtoe | Achieved with solar % | Mtoe | % of needs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Current (1996) | 0.039 | 0.106 | – | 0.38 | – | 1.04 | | | | | |
| A1 – Global Economy | 0.066 | 0.763 | 0.135 | 1.6 | 5 | 0.08 | 90 | 1.5 | 50 | 0.73 | 45 |
| A2 – National Interest | 0.066 | 0.631 | 0.135 | 1.3 | 5 | 0.06 | 90 | 1.2 | 70 | 0.85 | 63 |
| B1 – Global Sustainability | 0.066 | 0.664 | 0.135 | 1.4 | 5 | 0.07 | 90 | 1.3 | 90 | 1.15 | 81 |
| B2 – Local Sustainability | 0.066 | 0.664 | 0.135 | 1.4 | 5 | 0.07 | 90 | 1.3 | 60 | 0.77 | 54 |

**Services Sector**

**Estimates the same as in the residential sector**

**Industrial sector**

| | Energy Needs Mtoe | Heat (2) fraction % | Mtoe | Potential (3) (heat up to 100°C) % | Mtoe | Achieved with solar % | Mtoe | % of heat needs |
|---|---|---|---|---|---|---|---|---|
| A1 – Global Economy | 6.9 | 72 | 5.0 | 50 | 2.5 | 50 | 1.2 | 25 |
| A2 – National Interest | 6.9 | 72 | 5.0 | 50 | 2.5 | 70 | 1.7 | 35 |
| B1 – Global Sustainability | 6.9 | 72 | 5.0 | 50 | 2.5 | 90 | 2.2 | 45 |
| B2 – Local Sustainability | 6.9 | 72 | 5.0 | 50 | 2.5 | 60 | 1.5 | 30 |

(1) – Solar thermal potential assigned as the sum of 90% of sanitary water heat plus 5% of the cooking heat needs.
(2) – Industry overall energy needs held fixed at 6.9 Mtoe; thermal fraction 72% as estimated by (POSHIP 2001).

Scenarios are also required for evaluating electricity transmission losses. Perspectives for the future evolution of the grid include opposite effects: i) reinforcement of transmission capacity in existing high and medium voltage lines to enable for increased demand; ii) extension of the grid to remote places, with the purpose of collecting energy from additional hydroelectric plants, wind parks, *etc.*; and iii) on a medium range time scale, reduction of the power flow into and at urban areas due to local generation of electricity, for instance from micro-power systems (gas turbines or fuel cells) on large buildings (e.g. from the service sector) and building-integrated solar systems, namely photovoltaic systems; iv) there are technological evolutions, e.g. power electronics, as well as optimisation measures that can help to reduce losses and that are already considered within the current and long term policies of the utilities.

The balance of these effects over the time range of interest for SIAM is yet unclear. Also detailed analysis of the Portuguese grid could not be done in this phase of SIAM. It was supposed as a first approach that electrical distribution losses from all the building integration of power generation would be very small: photovoltaics were accounted according to Table 9.III and for micro-power a 10% share of the primary electricity supply was assigned, under all scenarios. Overall efficiency gains of 0.5% in the transport network were also assumed, in spite of the reinforcement of lines for gathering (renewable) energy from more remote areas.

Geographical distribution of residences, respective areas, and occupancy and operation patterns (family size, daily occupation), were already given in the Socio-Economics Chapter, however, some remarks and further details for the residential and service sectors will now be discussed.

A scheme of the modifications applied to the model buildings used in the studies is provided as Figure 9.18; full details are provided in Table 9.V. Floor area is increased under all scenarios, although somewhat more for the A1 "global economy" and B1 "global sustainability" scenarios. A2 "national interest" scenario is the only one where the population experiences a significant growth, and where occupancy changes from 3 to 4 persons. Under the sustainability scenarios B1 and B2 it is assumed that people spend more time at home than nowadays, the opposite being true for the A1 "global economy" scenario. Also for the sustainability scenarios it is assumed that the current comfort temperatures band is acceptable, that only a social zone with about one-third of floor area is air-conditioned, and that building envelope insulation will improve significantly (more so for the global sustainability scenario); while for the A1 and A2 scenarios the acceptable comfort band is made smaller, the entire house must be air-conditioned and only small improvements in insulation are implemented. To examine the behaviour of services buildings, a floor of a typical office building was selected; the simulation results were obtained as per square meter values, and no scenarios for evolution of building characteristics, occupation and operation patterns could yet be designed in this first SIAM approach.

Finally, the question of HVAC equipments was addressed. This is important due to the difference between computing thermal loads and computing energy requirements. Thermal load means here the amount of heat addition or removal that is needed in order to have the building's interior temperature inside a specified comfort temperature band. This may be achieved with a variety of HVAC devices (resistive heaters, various boiler and chiller types, air-conditioning with various cycles, exterior air or ground heat pumps, solar assisted desiccant cooling, etc.), resulting in a certain final combined space heating and cooling energy demand for the model building. For obtaining primary energy demand, a more meaningful figure, the mix of electricity sources must also be considered for the devices that rely on electricity. Finally for having energy requirement estimates for an entire building sector the respective energy source mix should be taken into account. It was considered very difficult to sketch a scenario for HVAC technology shares in 2070--'99. Therefore an assumedly large simplification was considered: that space conditioning would use predominantly electric reversible heat pumps, with a cooling COP of 1.4 and a heating COP of 2.1 (EREN 2002). However, an effort was made to discuss thermal load variations whenever possible, instead of energy requirements. With this purpose heating and cooling thermal loads were graphed together and even added up sometimes to provide "combined" heating and cooling impact estimates, although this is not strictly correct, as explained above. Anyway it was checked that year-round impacts pointed to the same direction irrespectively of working with combined thermal loads or with energy requirements.

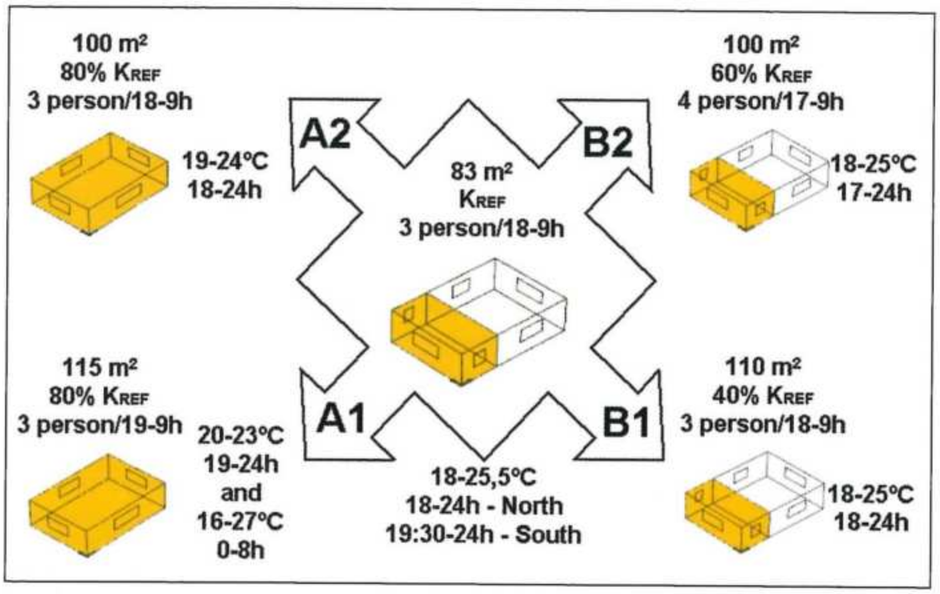

Fig. 9.18 – Long range residential building scenarios.

As will be later demonstrated, incorporating long range energy sector scenarios implies that some climate change impacts that under current conditions would be minor or irrelevant, become then quite significant. Two examples are performance of photovoltaic systems (current installed power is insignificant) and space cooling in residential buildings (currently only 3% of such dwellings have air conditioning).

## 9.3 IMPACTS OF CLIMATE CHANGE UPON ENERGY SECTOR

### 9.3.1 INTRODUCTION

### 9.3.1.1 Overview

The main large sources of energy supply large systems consist of electric power plants and have therefore received special attention.

In the case of existing thermoelectric power plants, very small efficiency changes are expected, although this may not be true for some future scenarios, e.g. if power plants with combined cycle natural gas technology become predominant. Other potential climate change effects on these large thermoelectric plants include reduced availability of water for open-cycle refrigeration, sea level rise impact on coastal structures and changed frequency of natural hazards such as floods and storms. None of these were found to be relevant in a first inspection, with the data and scenarios available.

For the case of large hydroelectric power plants, impacts can be expected stemming from precipitation and temperature changes as translated in different surface flow and evaporation conditions, and/or in different seasonal availability of water. Plants located in the North, in particular at the Douro basin, should benefit from increased winter precipitation, while those located at the Centre and South should suffer from reduced year round precipitation and increased evaporation, especially in the summer. It is not excluded however, that the overall result can be positive, as most of the large hydro capacity is located in the northern basins.

Competition for water with purposes senior to energy production, *viz.* municipal uses and irrigation – whose needs are prone to increase under elevated ambient temperatures – is likely to occur. However, this was found not significant for the current large hydropower panorama.

The resistance of transmission lines depends on temperature and it is expected that climate change in Portugal will bring an additional 1.6% increase to the power transport and distribution losses.

Renewable energy systems other than large hydroelectric plants will also be sensitive to altered weather conditions, both because the energy source may change (surface water, sun, waves or wind) and because they are often sensitive to environmental parameters – temperature in particular, e.g. photovoltaic cell efficiency and anaerobic digestion (biogas production).

Mini-hydroelectric power plants will be even more sensitive to precipitation and temperature changes than the large hydro plants. Plants located in northern basins (the majority, in fact) can benefit from increased winter precipitation but will have to be refurbished; plants in central and southern basins will see water availability diminish seriously, especially in the transition seasons. Available meteorological scenarios do not contain significant changes either in wind levels or seasonality, thus no significant impacts are expected for wind and ocean wave power systems.

**Table 9.5 – Long range SIAM energy scenarios: residential sector unit dwellings and operation patterns**

| | Baseline | Future | Observations |
|---|---|---|---|
| **Floor area** | 83 $m^2$ | A1: 115 $m^2$ | Unit dwellings built after 1990 have an average floor area of about 103 $m^2$ |
| | | A2: 100 $m^2$ | |
| | | B1: 110 $m^2$ | |
| | | B2: 100 $m^2$ | |
| **Thermal shell** | Kref (1) | A1: 80% $K_{REF}$ | Modest improvements of the thermal shell |
| | | A2: 80% $K_{REF}$ | Modest improvements of the thermal shell |
| | | B1: 40% $K_{REF}$ | Generalized environmental concerns |
| | | B2: 60% $K_{REF}$ | Conservation of built patrimony hinders additional improvements |
| **Occupation** | | | |
| No. of persons | 3 | A1: 3 | According to population counts in the general scenarios |
| | | A2: 3 | idem |
| | | B1: 3 | idem |
| | | B2: 4 | idem |
| Schedule | 15 h (18:00-9:00) | A1: 14 h (19:00-9:00) | More time spent in jobs, transports, outside meals, etc. |
| | | A2: 15 h (18:00-9:00) | |
| | | B1: 15 h (18:00-9:00) | |
| | | B2: 16 h (17:00-9:00) | Higher concern for family values, jobs closer to dwellings, etc. |
| **Equipment** | | | |
| Lighting | 180 W, 6 h | 180 W, 6 h | More lamps but more efficient |
| Specific electricity | 150 W, 24 h | 150 W, 24 h | More equipments but more efficient |
| Air renovation (2) | 1 rph | 0.5 rph | Automatic ventilation, less cracks, better doors and windows |
| **Space conditioning** | | | |
| Comfort band | 18°C-25,5°C | A1: 20°C-23°C evening<br>16°C-27°C night | Maximum comfort |
| | | A2: 19°C-24°C | Private consumption is still predominant |
| | | B1: 18°C-25°C | Generalized environmental concerns, responsible use of energy |
| | | B2: 18°C-25°C | Private consumption hindered by higher energy prices |
| Areas conditioned | 1/3 | A1: 1 | Entire house conditioned, maximum comfort |
| | | A2: 1 | Private consumption is still predominant |
| | | B1: 1/3 | Generalized environmental concerns, only social area conditioned |
| | | B2: 1/3 | Private consumption hindered by higher energy prices |
| Schedules | North: 6 h | A1: 14 h | Space conditioning during most of the evening and night |
| | South: 4.5 h | A2: 6 h | Space conditioning during the evening |
| | | B1: 6h | idem |
| | | B1: 5h | idem |

(1) $K_{REF}$: reference thermal coefficients of RCCTE
(2) rph: air renovations per hour

The performance of solar systems should increase due to greater solar radiation, while temperature effects on efficiency are secondary, and tend to reduce losses from thermal storage. Biogas production (and the anaerobic digestion process in general) will be favoured by higher ambient temperatures.

Increased year-round temperatures by about 3-4°C should impact on several aspects of the energy demand, most remarkably on heating, cooling and ventilation within buildings and vehicles, and on additional energy requirements for water pumping for municipal uses and irrigation. Lower overall demand of energy for water heating (both for domestic and industrial uses) is also expected.

The demand studies concentrated more on the thermal performance of buildings. The results obtained using typical model buildings for the domestic and service sectors indicate a generalized increase of cooling energy demand and a reduction of heating energy demand. The overall yearly thermal load increases, with the exception of a small northeast zone. Such increases are yet larger for the service sector than for the domestic sector. Regional variations can be expected: roughly speaking additional thermal loads should increase from north to south.

Other changes in energy demand, especially in electricity and transportation, stemming from factors such as internal migrations and larger tourism activity near coastal zones are also likely for Portugal, but could not yet be analysed.

### 9.3.1.2 Detailed list of impacts

#### *9.3.1.2.1 Identified*

The impacts identified from the point of view of energy supply, this including electricity transport and distribution, were as follows:

- Direct impact of higher ambient temperatures on the thermodynamic performance of thermoelectric power plants;
- Security of water supply for refrigeration, for some types of thermoelectric power plants;
- Effects of changes of the frequency of extreme weather events, in particular storms and floods, on thermoelectric power plants and other energy related structures, such as electric power transmission lines, wind energy systems, *etc.*;
- Sea level rise effects on coastal thermoelectric power plants and other energy related structures, such as refineries;
- Higher resistance losses in electricity transmission lines caused by higher ambient temperatures;
- Enhanced competition for water with other sectors such as municipal supply of water and agriculture, causing reduced water availability for electricity generation purposes;
- Changes in the availability of renewable energy resources, in particular solar irradiation (whose availability tends to increase), surface flow water, wind and ocean waves, with both direct effects (e.g. in solar systems or hydroelectric dams) and indirect effects (e.g. productivity of biomass grown for energy purposes);
- Impact of higher ambient temperatures on the performance of solar thermal and photovoltaic systems, and anaerobic digestion processes.

The impacts identified from the point of view of energy demand were as follows:

- Impact of higher ambient temperatures on the thermal performance of buildings, in particular the opposite effects on the energy requirements for space heating and cooling;
- Impact of higher ambient temperatures on the energy requirements for space heating and cooling within vehicles;
- Direct impact of higher ambient temperatures on the thermodynamic performance of engines;
- Impacts of altered frequency of extreme weather events on transportation, including airplanes and boats, as well as changed frequency of roadblocks and railway blocks;
- Effect of changes on the mean levels of meteorological parameters with impact on transportation, including reduced snow related roadblocks (due to higher temperatures) and maybe enhanced airplane fuel requirements (especially during takeoff and landing, due to slightly lower air density);
- Reduced needs for water heating for sanitary and cooking purposes and for industrial process pre-heat and heat;
- Enhanced energy needs for water pumping (municipal uses and agriculture);
- Indirect impacts of demographic and social changes reflecting in the need for adjustments of the energy supply structures at a regional level; also other effects such as enhanced energy demand from weather related activities like tourism.

#### *9.3.1.2.2 Studied*

All the impacts previously listed were considered, however, some could be dismissed from the start as irrelevant for the specific conditions of Portugal, in particular those resulting from extreme weather events. According to the wind data provided by climate models, the frequency of extreme wind events does not change appreciably. Neither does the precipitation data available at the time of study indicate more frequent extreme events that could lead to floods (please check the climate Chapter). Therefore there is at present no reason to predict additional losses from structural damage on energy related systems such as refineries, electric power plants of all kinds, or electric power transmission lines. The same can be said in respect to the impacts of extreme weather events on transportation.

The direct impact of higher ambient temperatures on the thermodynamic performance of combustion related engines such as turbines and motors typically used in Portugal is considered insignificant in the UNEP Handbook, and so this type of impacts was not studied.

A number of impacts that can eventually be found significant in future studies could not be addressed due to lack of adequate models, analogues and/or the required input data. These include enhanced energy needs for water pumping and for space heating and cooling within vehicles, sea rise effects on energy related coastal structures other than thermoelectric plants, and regional adjustments of the energy sector for changing demography, type and level of socio-economic activities resulting from climate change itself. Effects of climate change on traffic were also not studied, although in a first approach temperature elevation should decrease roadblocks by heavy snow and reduce traffic accidents due to fog and light snow.

Thus the impacts that were addressed in detail were:

i. Security of water supply for refrigeration and sea level rise effects for thermoelectric power plants and refineries.

ii. Losses in electricity transmission.

iii. Modifications in the yield of renewable energy systems, due to renewable resource changes and to environmental changes with effect on performance.

iv. Competition with other sectors for water at hydroelectric plants.

v. Energy needs for water heating.

vi. Space heating and cooling energy requirements in buildings.

### 9.3.2 SEA LEVEL RISE EFFECTS

Several large energy supply related structures, are located close enough to the sea to potentially suffer from sea rise related impacts. The cases of the EDP thermoelectric plants of Setúbal and Sines, the GALP-ENERGIA oil refinery at Matosinhos and the HOFIN petrochemical plant at Barreiro, are examples that deserve to be mentioned.

Both the Setúbal and Barreiro sites are already protected, or include, harbour structures. Thus a ca. 50 cm sea rise spread over 50-100 years should be manageable without much additional costs, as anyway these harbour structures would have to be renewed one or more times during such a long period. As for the Matosinhos refinery, it is located sufficiently above the predicted future sea level to be safe just in altitude terms. However, it is close to a beach strand, therefore a dynamic coastal model for this specific zone should be used to check that the sea rise indeed would not harm the facilities. Finally for the case of the Sines thermoelectric plant, only the channels that belong to the refrigeration water circuit may be endangered: the main facilities are in fact too far and above the sea border to inspire concern.

Numerous fuel discharge and supply facilities for boats are obviously located near the sea, being part of ports, docks, etc. Again it is noted that at some time in the future the portuary structures must be renewed anyway, for reasons other than climate change, therefore there will be ample opportunity for adapting to relatively small sea elevation effects.

### 9.3.3 THERMOELECTRIC POWER PLANTS

The impacts of sea rise were discussed in the previous section. This section focuses on the impacts of temperature and precipitation/stream flow changes.

#### 9.3.3.1 Thermodynamic efficiency

A few degrees increase at the intake air and refrigeration water have an impact in the thermodynamic efficiency of thermal engines of all kinds. Both factors reduce the temperature drop between the hot and cold sources, causing a reduction in thermodynamic efficiency. However, the effect should be very small for the currently employed technologies, namely because the hot source temperature is much above the ambient temperature (e.g. 530°C for a typical coal powered vapour turbine). Indeed the UNEP Handbook lists this effect as of secondary importance (losses estimated at 0.1%-0.2%).

However, it is likely that ambient temperature effects may be larger for other thermal systems for auto-production of electricity, namely combined cycle gas turbine (CCGT) natural gas plants, and co-generation facilities.

Only one CCGT natural gas plant is currently in place, at Tapada do Outeiro, see Table 9.6, and e.g. Martins et al. (1998) for more information. For Tapada do Outeiro in particular, an open circuit is used for cooling; the water is obtained from the Douro river, and 17 m$^3$/s of heated water are discharged (water temperature increases less then 10°C). This river is already characterised by high flow rates, and climate change for the respective basin is thought to have modest impacts on the summer surface flows, therefore water availability for this plant seems not at risk. Meanwhile, additional CCGT plants are planned (depending on the evolution of the electricity demand) and also some of the existing fuel and coal-based plants can be refurbished with this technology, therefore this is an area clearly candidate for further research.

#### 9.3.3.2 Water supply for refrigeration

Some of the thermal technologies for electricity generation require considerable amounts of water for refrigeration, in particular fuel oil and coal-based plants. This water can be unavailable during the periods and in the volumes required due to climate change.

As an example some pumps and refrigeration flows are listed in Table 9.VII; current total annual water uses for refrigeration are listed in the Water Resources chapter.

The Carregado and Pego plants (not mentioned in Table 9.7) are located by the Tejo river. The Tapada do Outeiro plant is located by the Douro river. Plants at Setúbal and Barreiro use estuary salty water, and the plant at Sines uses seawater. Flow change estimates for the rivers Tejo and Douro were not available at the time of writing, but judging from the precipitation and runoff scenarios (SIAM Water Resources team results and WRINCLE Project), changes will not be large enough to endanger the supply of the relatively modest refrigeration water volumes required.

**Table 9.6 – Main thermoelectric plants connected to the National Electricity Transport Network (situation by December 2000)**

| Plant | Location | Year of entrance into service | Installed capacity (MW) | Fuel type |
|---|---|---|---|---|
| *Electricidade de Portugal, S.A. (Public Service Electric System)* | | | | |
| Sines | Sines | 1985 | 1192 | Coal |
| Setúbal | Setúbal | 1979 | 946 | Fueloil |
| Tapada do Outeiro C.C. | Gondomar | 1998 | 990 | Natural gas |
| Carregado | Alenquer | 1968 | 710 | Fueloil/Natural gas |
| Tunes | Silves | 1973 | 197 | Gasoil |
| Alto de Mira | Amadora | 1975 | 132 | Gasoil |
| Barreiro | Barreiro | 1978 | 56 | Fueloil |
| Tapada do Outeiro | Gondomar | 1959 | 47 | Fueloil |
| *Tejo Energia S.A.* | | | | |
| Pego | Abrantes | 1992 | 584 | Coal |
| Total | | | 5454 | |

As mentioned before, many stations are being converted to use natural gas as fuel, while other combined cycle natural gas plants are planned and will substitute existing plants. The impacts from potential unavailability of refrigeration water can be relevant or not depending on the location of the refurbished and new plants.

### 9.3.4 ELECTRICITY TRANSMISSION

Power losses in electricity transmission lines are due mainly to the resistance of the materials, e.g. copper or aluminium (the

**Table 9.7 – Pump characteristics of some thermoelectric plants**

| Central | No. of pumps | Flow per pump | Operation mode | Water source |
|---|---|---|---|---|
| Tapada do Outeiro | 3 | 2.3 $m^3/s$ | Open circuit | Douro river |
| Barreiro | 2 | 1.6 $m^3/s$ | Open circuit | Tejo estuary |
| Sines | 4 | 10 $m^3/s$ | Open circuit | Seawater |
| Setúbal | 4 | 8.5 $m^3/s$ | Open circuit | Sado estuary |
| Carregado | 6 | 5.2 $m^3/s$ | Open circuit | Tejo river |
| Carregado<br>– groups V and VI | 2 | 6.2 $m^3/s$ | Open circuit | Tejo river |
|  | 2 | 10.5 $m^3/s$ | Open circuit | Tejo river |

**Table 9.8 – Length of the Portuguese electric power transport lines (km)**

| Lines | 1998 | 1999 | 2000 |
|---|---|---|---|
| 400 kV | 1234 | 1234 | 1235 |
| 220 kV | 2409 | 2357 | 2418 |
| 150 kV | 2340 | 2400 | 2361 |

Joule effect). The losses amounted to 3559 GWh in 1999, for the continental Portugal, from a net production of 40218 GWh, i.e. transmission losses were about 9%. From this total, 665 GWh were lost during transport, *i.e.* about 2% of the power flow in the grid, while the rest were lost in the distribution, thus 7%.

As cable resistance increases with temperature in the range of interest – by about 0.4% per °C – power losses will increase with warmer weather, irrespectively of the transmission phase, namely transport or distribution. Using the overall country estimate of about 4°C mean temperature elevation (as in the HadCM3 model scenario), this results in about 1.6% additional power losses that must be compensated by additional electricity generation.

More detailed estimates for the Portuguese conditions must take into account the regional differences in temperature change, in combination with models of the electricity grid – which is not distributed uniformly throughout the territory, distribution concentrating as natural in large urban centres at the Atlantic littoral strip, and transport in the same zone and also near rivers Tejo and Douro, see Figure 9.19.

As mentioned before, consideration of future scenarios can be important in determining electricity losses. In the first place, losses rise proportionally to the electricity share in the FEC mix, which is expected to about double in the SIAM energy scenarios. Currently, the transformation power in the grid has accompanied the increases in electricity demand (see Table 9.8). However, the length of the lines has stabilized, see Table 9.9. But this situation is expected to change, and the reader is asked to recall the energy sector scenarios

**Table 9.9 – Transformation power on the Portuguese medium and high voltage electricity grid (kVA)**

| Type | 1998 | 1999 | 2000 |
|---|---|---|---|
| Autotransformation (MHV/MHV) | 6 021 | 6 271 | 6 021 |
| Transformation (MHV/HV) | 10 588 | 10 592 | 10 631 |

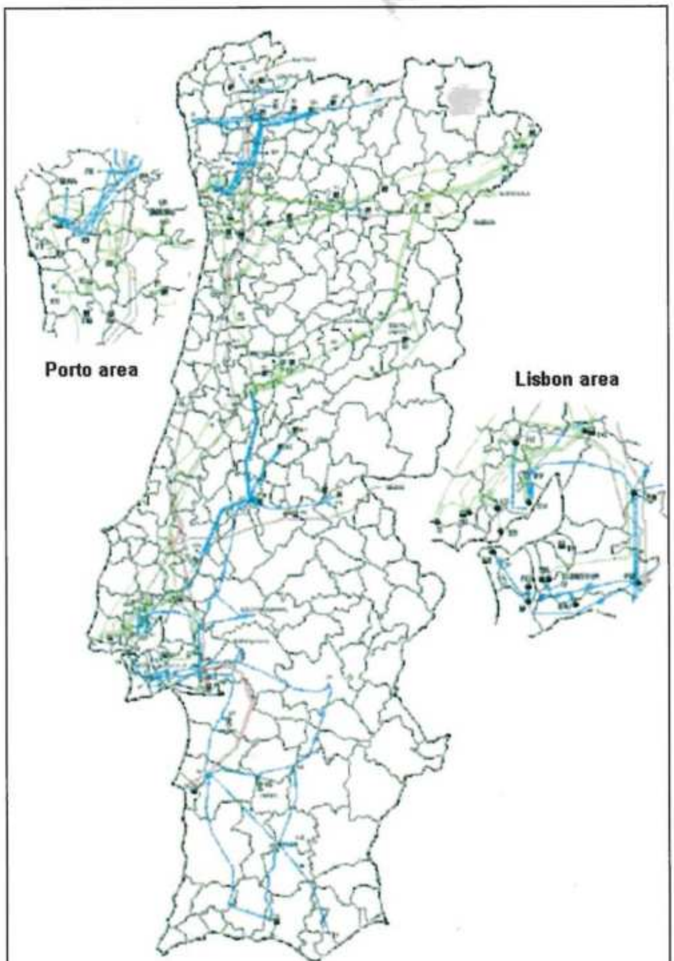

Fig. 9.19 – Portuguese electricity transport network (by the end of 2000). Source: REN.

presented before – 40% share of electricity in the PEC mix, overall 0.5% efficiency gains in the transport network, 15%-18% reduction of power flow into buildings. The results of the first attempts at estimating impacts on power transmission losses are depicted in Table 9.10. As a comparison within the electricity sub-sector, these future scenario numbers signify a doubling of the yearly production of the largest Portuguese hydroelectric power plant, or around 10% of the overall current large hydro production.

**Table 9.10 – Additional power transmission losses due to climate change on the electric transmission grid (continental Portugal only)**

| Scenario | Power flow GWh | Current losses GWh | Future additional losses GWh | Mtoe | % PES |
|---|---|---|---|---|---|
| Current situation (1999) | 40,218 | 3,559 | 640 | 0.06 | 0.3 |
| A1 – Global Economy | 150,000 | — | 2,037 | 0.18 | 0.5 |
| A2 – National Interest | 115,000 | — | 1,555 | 0.13 | 0.5 |
| B1 – Global Sustainability | 116,000 | — | 1,535 | 0.13 | 0.5 |
| B2 – Local Sustainability | 121,000 | — | 1,641 | 0.14 | 0.5 |

## 9.3.5 LARGE HYDROELECTRIC POWER PLANTS

Hydroelectric systems were predominant over thermoelectric systems up to 1986. By 1992 the installed capacity of hydroelectric power plants was about 3,070 MW. Large and medium size systems (installed capacity > 10 MW, large hydro for short) composed more than 98% of such capacity.

The impacts of climate change on the yield of large hydro result from changes in the hydraulic balance of rivers and reservoirs and from changes in the amounts of water drawn for non-energy purposes, such as municipal uses and irrigation.

The hydraulic balance of reservoirs depends essentially on the input surface flow, on the infiltration by the bottom, evaporation from the free water surface, and the output water flow. The later is subject to a desirable minimum value (the ecological flow). Changes of mean level and/or seasonality, frequency distribution, *etc.* in the precipitation over the basin upstream of the dam, may modify the surface flows. Temperature is also a factor to take into account (although secondary) as evaporation and evapotranspiration – and thus hydraulic balances – depend on it.

Note that the impact on electricity production of changes of runoff and evapotranspiration is more than proportional to these changes. Lower/higher quantities of available water means respectively less/more possibility to generate electricity, but there is also the multiplying effect of the pressure head: lower/higher water levels in the river or reservoir also indicate less/more potential energy. For instance, an estimate for the lower basin of the Colorado river (USA) indicated a 36% reduction of electricity production as a result of a reduction of just 10% in runoff (EPA 1993). Therefore the following analyses of Portuguese large hydro electricity production must be considered preliminary, and detailed models for specific systems will be required to produce quantitative estimates.

### 9.3.5.1 Water resources data available

Direct impacts of climate change on large hydro include as mentioned before the changed hydraulic balance of large rivers and reservoirs. Unfortunately, when the analyses for the current issue were done, estimated water resources' impacts included neither of them. Some valuable information was however, already available on precipitation, evapotranspiration and runoff, from the European level Project POPSICLE (Kilsby *et al.* 1998), and from the Water Resources SIAM team results.

POPSICLE used GCM HadCM2 data and included climate change analyses of one basin at the south of Portugal, although testing downscaling precipitation models was the primary objective. SIAM studies used GCM HadCM3 data and examined the Portuguese sections of some basins of varying dimension; However, it is recalled that modelling large rivers would have to take into account the Spanish part of the respective basins, and the balance of the numerous existing dams, as well as their management – not only how water is used for energy production but also e.g. significant removal of water to irrigation and even other streams, as planned both in Portugal and Spain.

Comparison of POPSICLE and SIAM results was consistent for the Portuguese region analysed in the former Project.

Very recently the results of Project WRINCLE (Kilsby *et al.* 2001) became available. WRINCLE used the HadCM3 model and supplies 0.5° × 0.5° gridded results for Europe. Again the basins are assumed free of human intervention (in particular, of large dams).

Results of SIAM and WRINCLE for runoff in some regions were compared and seem consistent, taking into account the differences between the GCM models and emission scenarios that served as input to each study. The main difference seems to be that for the northern region basins the estimates based on the HadCM3 future scenario (used by SIAM) yield larger precipitation and runoff than with HadCM2 future scenario (used by WRINCLE).

Anyway the WRINCLE data became available too late to be used as a basis of the energy sector studies, therefore the results reported hereafter are based essentially in the SIAM Water Resources team estimates, which the reader is suggested to recall before going into the next section.

### 9.3.5.2 Direct impacts of climate change

For the Cávado-Lima and Douro basins (dam-free ideal situation, as mentioned), small increases of winter and autumn flows and small reductions of summer flows are expected under the HadCM3 enhanced greenhouse effect scenario; the overall volumes would increase slightly. The same pattern is found for precipitation over these northern basins. For the central basins of Tejo, Mondego and the southern basin of Guadiana, no estimates were yet available by SIAM, but both WRINCLE runoff and the HadCM3 precipitation show a general decrease. The decrease is more pronounced in summer than in winter in terms of percentage – but it is recalled that summer monthly values are much lower than winter monthly values; in fact for numerous years both in the control and the future scenario runs, zero precipitation for summer months can be found in extended regions.

Because most of the hydropower plants are located precisely at the northern basins, this suggests that hydroelectricity production as a whole could benefit from climate change in Portugal. This idea is reinforced by the fact that hydroelectric power production is predominant during wintertime (in the central basins it is often the sole season of electricity production).

Better estimates would require modelling of the hydraulic balance of dams, at least for "typical" dams

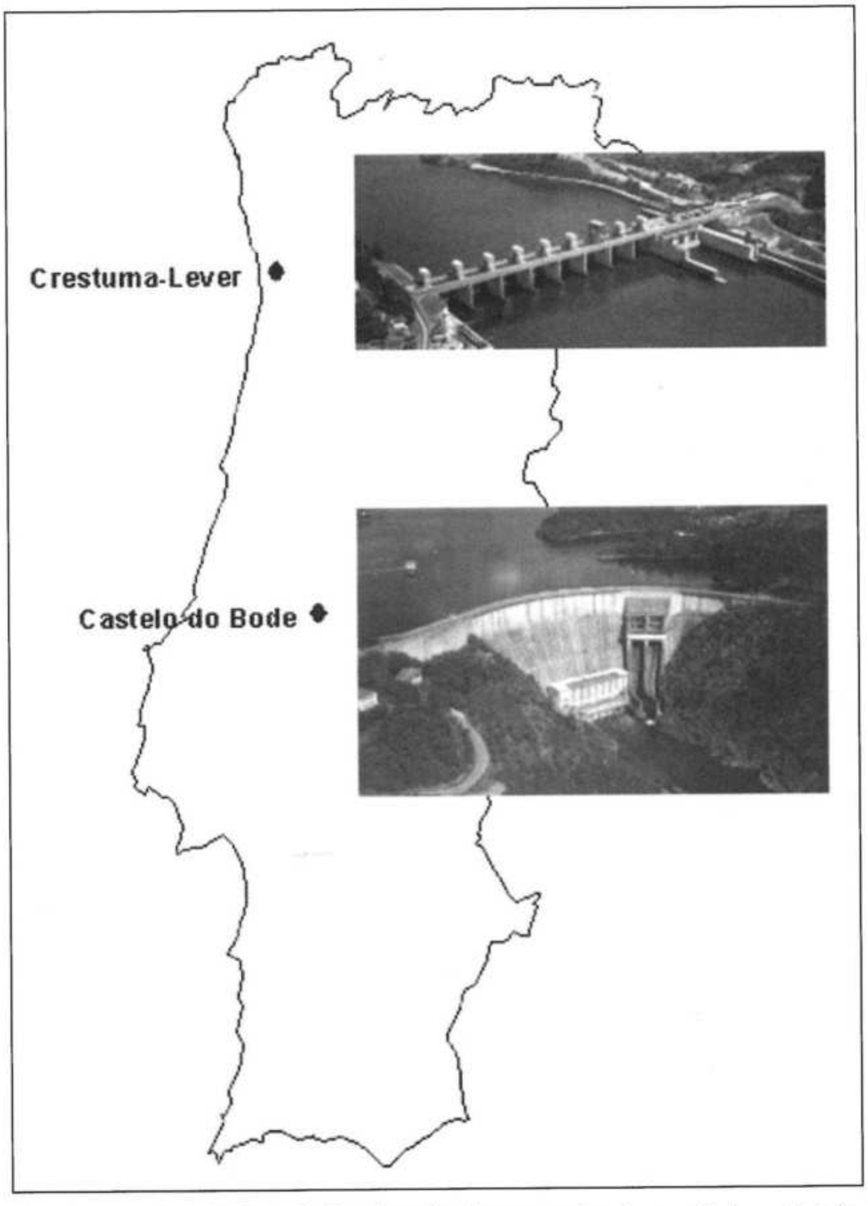

Fig. 9.20 – Present day large hydro plants in river zones simultaneously important for energy production and for other water uses.

for each of the main river basins. Evaporation would have to be explicitly included, as for instance a ca. 10% increase in the evapotranspiration at the basins of Douro and Mondego is expected, and a lot more at the Tejo and Guadiana basins (again, see the Water Resources chapter). Unfortunately the input data required for such models could not be found at the current stage of SIAM, in particular no long term records of input and output flows of large dams.

#### 9.3.5.3 Competition for water

As mentioned before, many dams were built mainly or also for non-energy purposes, thus energy production has to compete with other uses of water. Climate change will very likely increase demand for water for irrigation and for municipal uses (water supply to populations in particular). Currently these needs are considered to have precedence over energy production, and there is no reason to expect it to be different in the future.

Fortunately the largest dams, *viz.* those on the international Douro River section, do not suffer from water competition. In fact an analysis of the available descriptions of all the largest dams has shown that only two systems are significant for both energy production and other water uses: Castelo do Bode (water supply to the Lisbon area) and Crestuma-Lever (water supply to the Porto area), see Figure 9.20).

The existing statistics on water use in the Castelo do Bode and Crestuma zones are of irregular quality and present a large inter-annual variability. Anyway the situation presented in Figure 9.21 is typical. It can be observed that the electricity production is concentrated at the winter months; and when production is significant, the volumes of water used are largely superior to those used for other purposes.

Considering further that increased demand of water uses for non-energy purposes will likely occur especially during summer months, it does not seem that competition by water will have a large impact on the production of large hydropower plants identified above.

A rough calculation assuming an (extreme) scenario of duplication of water needs for non-energy purposes, leads to a maximum estimate of a 10% decrease in yearly electricity production. Finally considering that the two hydro systems correspond to less than 10% of the large hydro production, an upper bound for impacts from water competition can be placed at -1% of mean yearly production from large hydropower plants, i.e. about -17 GWh.

However, for the Alqueva dam – which recently started to be filled – it is likely that strong water competition will occur, considering that this dam is mainly directed at agriculture activities. The climate change impact on electricity generation should be large, as sensible reductions in runoff and increases of evapotranspiration are expected for the Guadiana basin. Furthermore, as mentioned before, studies for other situations, where there are water uses of greater priority than power production, indicate that expected reductions in electricity generation are more than proportional to reductions in water availability – see, for instance, Nash and Gleick 1993 study for the Colorado river.

### 9.3.6 RENEWABLE ENERGY SYSTEMS (EXCEPT LARGE HYDRO)

#### 9.3.6.1 Solar thermal systems

Solar systems for water heating were approached using the case study of domestic systems; the performance change should be similar to other types of

Fig. 9.21 – Water volumes uses at Castelo do Bode (Dam3), by 1995 (SNIRH 2001).

low-to-intermediate temperature range systems, e.g. water pre-heating for industries. However, the performance changes for high temperature concentrator systems, such as those using compound parabolic collectors, may be somewhat different.

A typical configuration for the domestic water heating system was defined (see Figure 9.22) and analysed using all climate models available. Table 9.11 lists the more relevant configuration data, and the main point to highlight is that the collector area was selected taking into consideration a target of near 100% solar fraction (i.e. percentage of energy needs supplied by the solar system) during summer months, a configuration common to systems installed in Portugal.

**Table 9.11 – Configuration data for the solar thermal domestic hot water system used in the impact studies**

| | |
|---|---|
| Collector type | flat |
| Collector azimuth | south |
| Collector tilt | knot latitude + 5° |
| Collector area | 5 $m^2$ |
| Efficiency parameter ($F' \eta_o$) | 0.7 |
| Thermal loss parameter ($F'$ U) | 7 W $m^{-2}$°$C^{-1}$ |
| Flow of the collector fluid | 60 l $h^{-1}$ $m^{-2}$ |
| Heat exchanger type | serpentine |
| Heat exchanger efficiency | 55% |
| Storage location | inside the house |
| Thermal storage capacity | 200 l |
| Thermal storage heat loss coefficient | 1 W $m^{-2}$°$C^{-1}$ |
| Consumption profile | daily, constant |
| Daily consumption (3 person) | 180 l |
| Temperature of the hot water consumed | 60°C |

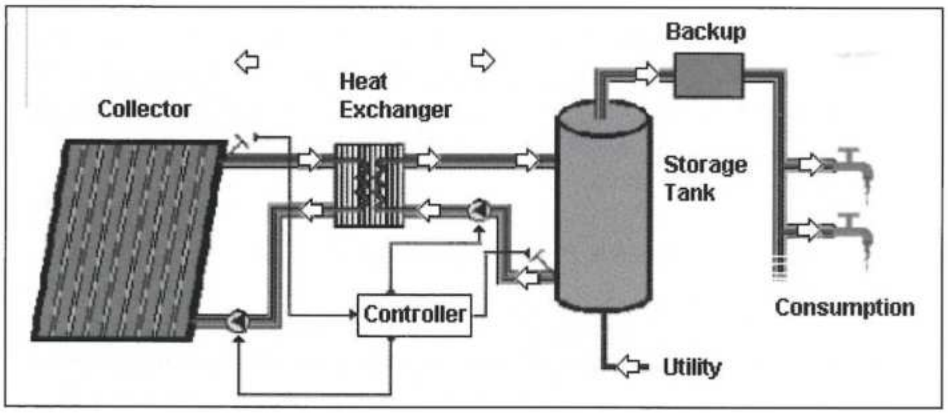

Fig. 9.22 – Typical solar thermal domestic hot water system configuration.

Preliminary impact estimates were computed using the RETScreen software (CEDRL 2000) and the PROMES meteorological data. Later some case studies were performed, with comparisons of results obtained with the RETScreen models and SolTerm, as mentioned before a software produced by INETI, which uses more sophisticated algorithms for system performance. In particular, the gathering of solar radiation is based not on simple empirical relationships with long-term monthly data but on the statistical concept of utilizability: energy collected above a threshold – related, for example, to thermal losses. Although long-term data is also the input, hourly utilizability parameterisations are available that were calibrated with the western European meteorological data, this including Portuguese data. It was found that the RETScreen tool did not give reasonable answers for the case of solar fractions near 100%, as it was the current configuration case, and so SolTerm was selected for the final studies.

For the case of the HadCM3 meteorological scenarios, all three knots in the Portuguese area were used, while for HadRM data for the knots marked in Figure 9.23 were used.

For understanding the results obtained for solar system performance, it is useful to analyse the seasonal trend of the most relevant meteorological parameters, solar irradiation and temperature. These are presented in Figure 9.24 for a typical case, the "centre region" knot of the HadCM3 model. It can be appreciated that the availability of the energy resource (solar radiation) is higher in the summer for the future climate GGa1 scenario, and also that the temperature anomaly is also higher during summer months than during the rest of the year.

The complete results are given in Table 9.XII (both HadCM3 and HadRM), while Figure 9.25 depicts typical results for the HadCM3 model. As a result of similar thermal losses in both scenarios (reference and GGa1), additional availability of solar radiation during summer, and lower energy requirements – due to increased inlet water temperature in the GGa1 scenario – the system performance is signifi-

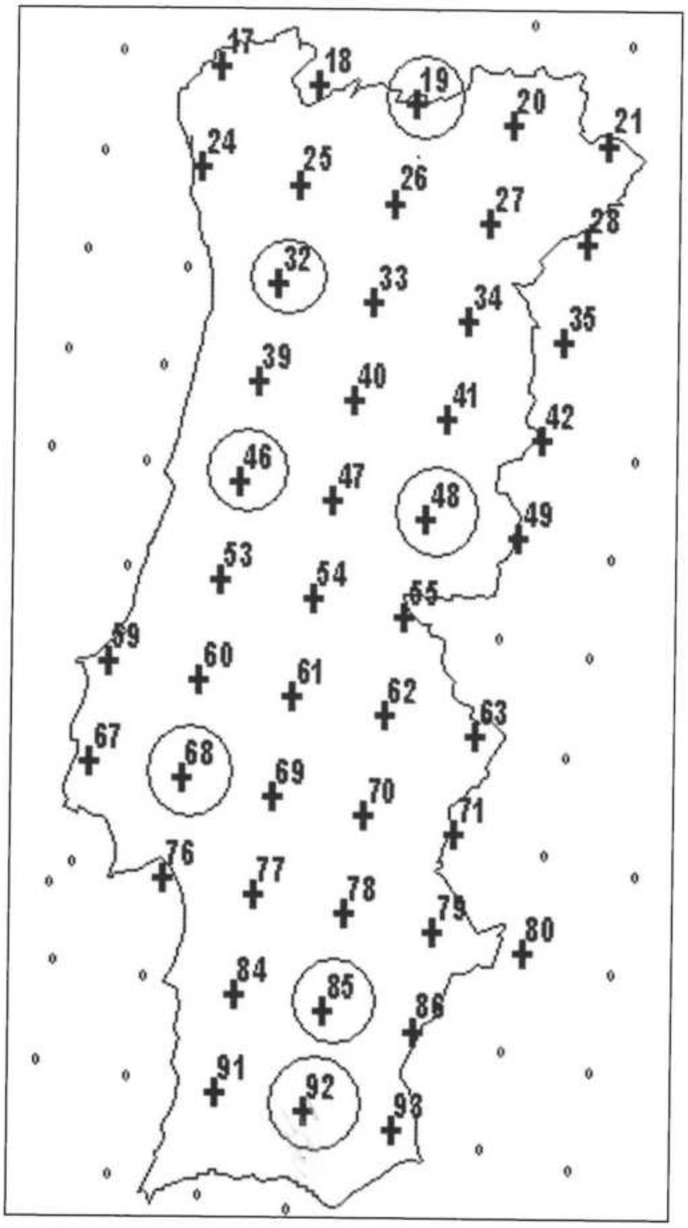

Fig. 9.23 – HadRM knots selected for analysis of solar thermal system performance (knot numbering is arbitrary).

cantly improved in the enhanced greenhouse effect case: from about +6% at the southern zone to about +10% at the northern zone.

Note that working with the same system configuration in both scenarios leads to an energy waste under the GGa1 scenario: the year-round (beneficial) effect of climate change could be improved with a better design and sizing of the solar systems. Meanwhile, it is also supposed that the same hot water volumes are required under the warmer environment situation; but that can be false, as the behaviour of the system users can change – e.g. less requirements of hot water for bathing and pre-heated water for cooking.

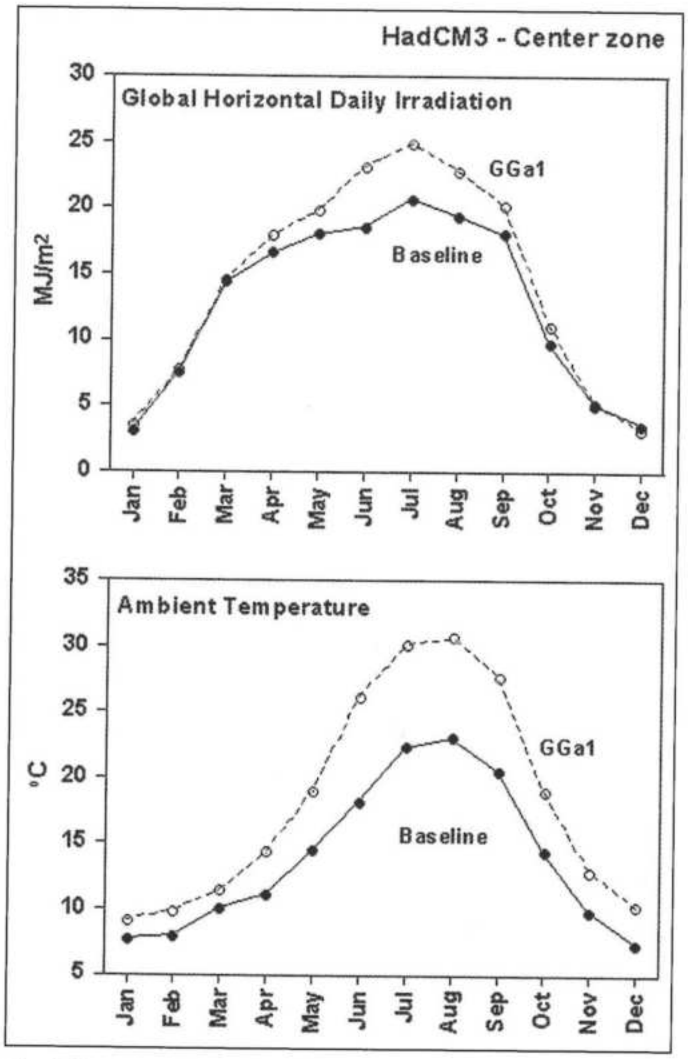

Fig. 9.24 – Seasonal profiles of horizontal global solar irradiation and ambient temperature for the central zone knot of HadCM3, for both the reference and GGa1 scenarios.

It should be stressed that the representation of solar irradiation in the climate models still suffers from some problems (e.g. overly high bias, underestimated inter-annual variability), thus the estimates obtained must be appreciated with some caution.

When socio-economic and energy scenarios are used – see Table 9.13 – these performance increases translate in an additional 0.16 to 0.21 Mtoe at the end of the SIAM analysis time horizon.

### 9.3.6.2 Photovoltaic solar systems

In this case two types of systems were analysed: i) stand-alone systems typical of current utilizations of the photovoltaic technology (e.g. telecommunication antennae, isolated dwellings), see Figure 9.26; and ii)

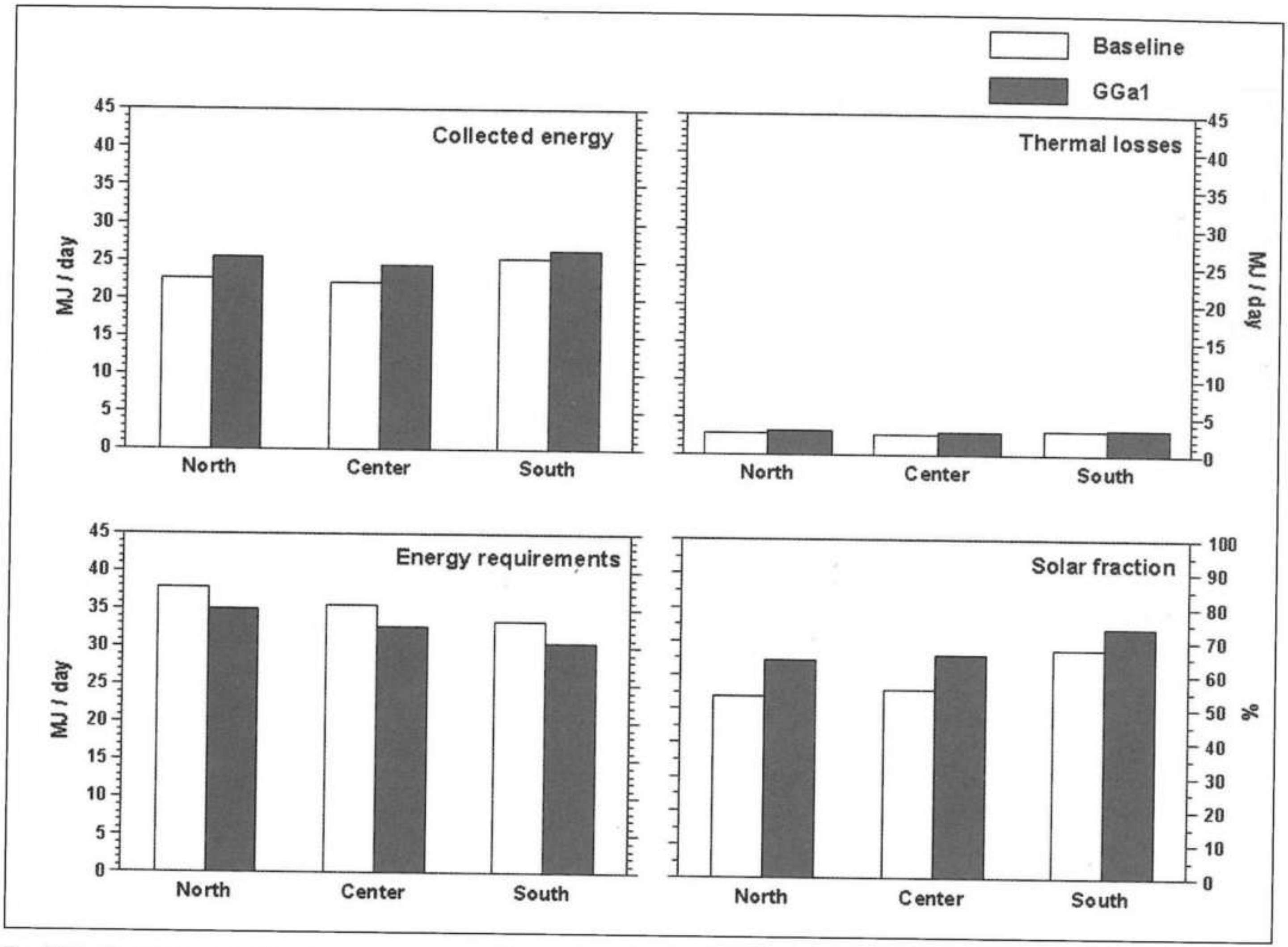

Fig. 9.25 – Energy needs and performance parameters for a typical solar thermal domestic hot water system, HadCM3 scenarios.

**Table 9.12 – Impact estimation for a typical solar thermal domestic hot water system**

| HadRM model | Collected Energy (MJ) | | Thermal losses (MJ) | | Energy requirements (MJ) | | Solar fraction (%) | |
|---|---|---|---|---|---|---|---|---|
| | **Baseline** | **GGa2** | **Baseline** | **GGa2** | **Baseline** | **GGa2** | **Baseline** | **GGa2** |
| North littoral | 25.0 | 27.7 | 3.3 | 3.6 | 36.2 | 33.7 | 63 | 73 |
| Centre littoral | 25.9 | 28.3 | 3.5 | 3.7 | 35.1 | 31.0 | 67 | 80 |
| Lisbon and Tagus Valley | 28.0 | 29.2 | 3.8 | 3.9 | 34.1 | 28.8 | 75 | 84 |
| Algarve | 28.5 | 29.9 | 3.9 | 4.1 | 34.6 | 29.3 | 75 | 85 |

| HadCM3 model | Collected Energy (MJ) | | Thermal losses (MJ) | | Energy requirements (MJ) | | Solar fraction (%) | |
|---|---|---|---|---|---|---|---|---|
| | **Baseline** | **GGa2** | **Baseline** | **GGa2** | **Baseline** | **GGa2** | **Baseline** | **GGa2** |
| North | 21.7 | 24.5 | 2.8 | 3.2 | 37.8 | 35.1 | 54 | 64 |
| Centre | 21.1 | 23.4 | 2.7 | 3.0 | 35.6 | 32.7 | 56 | 66 |
| South | 24.3 | 25.4 | 3.2 | 3.3 | 33.4 | 29.5 | 68 | 74 |

**Table 9.13 – Additional energy production in solar thermal systems from climate change effects (HadCM3 scenarios)**

| | Baseline climate Mtoe | GGa1 climate Mtoe | increase Mtoe | % PES |
|---|---|---|---|---|
| A1 – Global Economy | 2.1 | 2.3 | 0.17 | 0.5 |
| A2 – National Interest | 2.3 | 2.5 | 0.19 | 0.8 |
| B1 – Global Sustainability | 2.7 | 2.9 | 0.21 | 0.9 |
| B2 – Local Sustainability | 2.0 | 2.2 | 0.16 | 0.6 |

grid connected systems typical of the expected future uses (urban integrated generation of energy). The same climate model nodes used for the analysis of solar thermal systems were used.

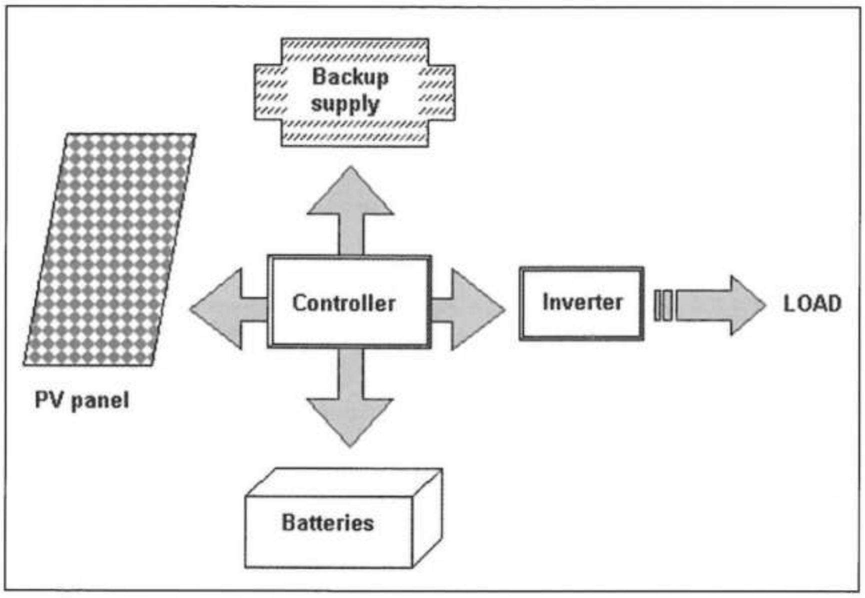

Fig. 9.26 – Typical solar photovoltaic stand alone system configuration.

Again the software RETScreen was used for preliminary analysis with PROMES data, but for final estimates the performance analysis was done using models especially developed for the purpose at INETI. They were built over the simulation environment provided by ModelMaker 3.0, and compute energy flows at an hourly time scale. The voltage-current intensity relationship for a photovoltaic panel is considered, however, for the other components of the system (batteries, controller, etc.) simple input-output models are used. Table 9.14 lists the more relevant configuration data.

**Table 9.14 – Configuration data for the solar photovoltaic systems used in the impact studies**

| | |
|---|---|
| **Photovoltaic modules (BP Solar, ref. BP275)** | |
| Nominal maximum power | 75 W |
| Voltage at maximum power | 17.0 V |
| Current at maximum power | 4.45 A |
| Short-circuit voltage | 21.4 V |
| Short-circuit current | 4.75 A |
| No. of cells | 36 |
| Voltage coefficient | –0.0021 V/°C per cell |
| Cell dimensions | 124 mm × 124 mm |
| Current coefficient | 8.9 mA/cm2/°C |
| Collector tilt | Same as latitude in the case of stand-alone systems |
| 90° South (vertical facade) in case of urban grid connected systems | |
| **Load** (case of stand-alone systems only) | |
| Constant | 166 W |
| **Storage** (case of stand-alone systems only) | |
| Voltage | 12 V |
| Capacity (discharge in 100 hours) | 2000 Ah |

The collector areas were sized with the objective of optimising electricity production during summer (see Tables 9.15 and 9.16).

While in the previous case of solar thermal systems the meteorological input data was directly available from the scenarios (long term monthly values), in the current case the hourly data had to be generated using statistical and stochastic models, as described before.

A case study was performed to evaluate the effect of not repre .senting inter-annual variability in the typical reference years (TRY) assembled. Ten TRY were generated using different random number seeds, fed into the stand alone photovoltaic system model, and the variability of the results inspected.

**Table 9.15 – Configuration data for the stand alone photovoltaic systems used in the impact studies.**

| HadRM model knot* | Zone | No. of modules | Installed power (kWp)** |
|---|---|---|---|
| 19 | Parque Peneda-Gerês | 16 | 1.200 |
| 48 | Serra da Estrela | 14 | 1.050 |
| 85 | Baixo Alentejo | 13 | 0.975 |
| **HadCM3 model knot** | **Zone** | **No. of modules** | **Installed power (kWp)**** |
| 52 | North | 20 | 1.500 |
| 44 | Centre | 18 | 1.350 |
| 36 | South | 16 | 1.200 |

(*) arbitrary SIAM numbering, refer to Fig. 9.24

(**) kWp – kW peak, i.e. nominal power under reference conditions: 1000 W/m$^2$ irradiation and 25°C ambient temperature.

**Table 9.16 – Configuration data for the grid connected photovoltaic systems used in the impact studies**

| HadRM model knot* | Zone | No. of modules | Installed power (kWp)** |
|---|---|---|---|
| 32 | Porto | 16 | 1.200 |
| 46 | Coimbra | 16 | 1.200 |
| 68 | Lisbon and Tagus Valley | 16 | 1.200 |
| 92 | Faro | 16 | 1.200 |
| **HadCM3 model knot** | **Zone** | **No. of modules** | **Installed power (kWp)**** |
| 52 | Norte | 18 | 1.350 |
| 44 | Centro | 18 | 1.350 |
| 36 | Sul | 18 | 1.350 |

(*) arbitrary SIAM numbering, refer to Fig. 9.24

(**) kWp – kW peak, i.e. nominal power under reference conditions: 1000 W/m$^2$ irradiation and 25°C ambient temperature.

It was verified that although the details of each time series set could be very different, the final yearly yield of the systems was very similar (see Fig. 9.27). This means that TRY data is indeed adequate to estimate long term system yield (although not necessarily other performance parameters more dependent on extreme events, such as the likeliness of the system being required to supply a load greater than its maximum capacity).

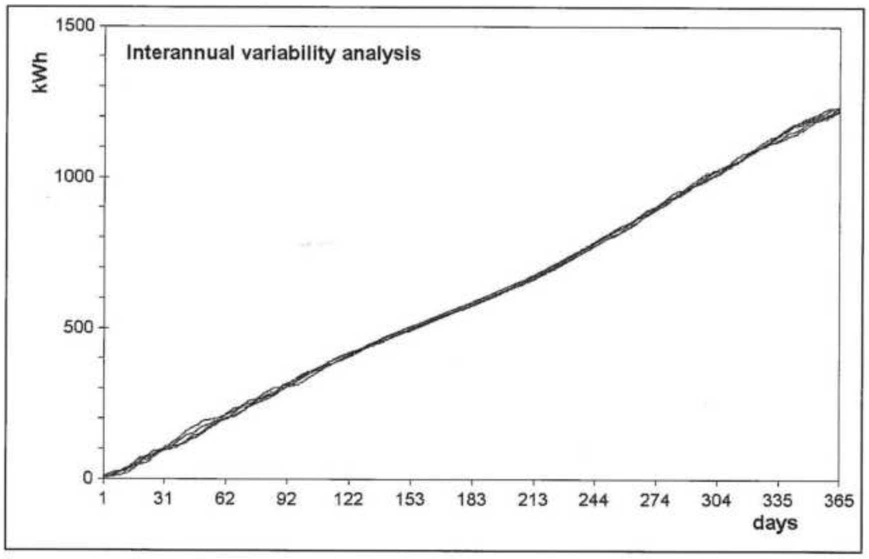

Fig. 9.27 – Performance of a typical solar photovoltaic stand alone system (accumulated daily energy) for a set of Typical Reference Years obtained from the same long term data (HadCM3, knot 44, base scenario).

A typical result of the simulations performed with the photovoltaic system models is given in Figure 9.28, in terms of accumulated daily energy generated and solar fraction. The complete results

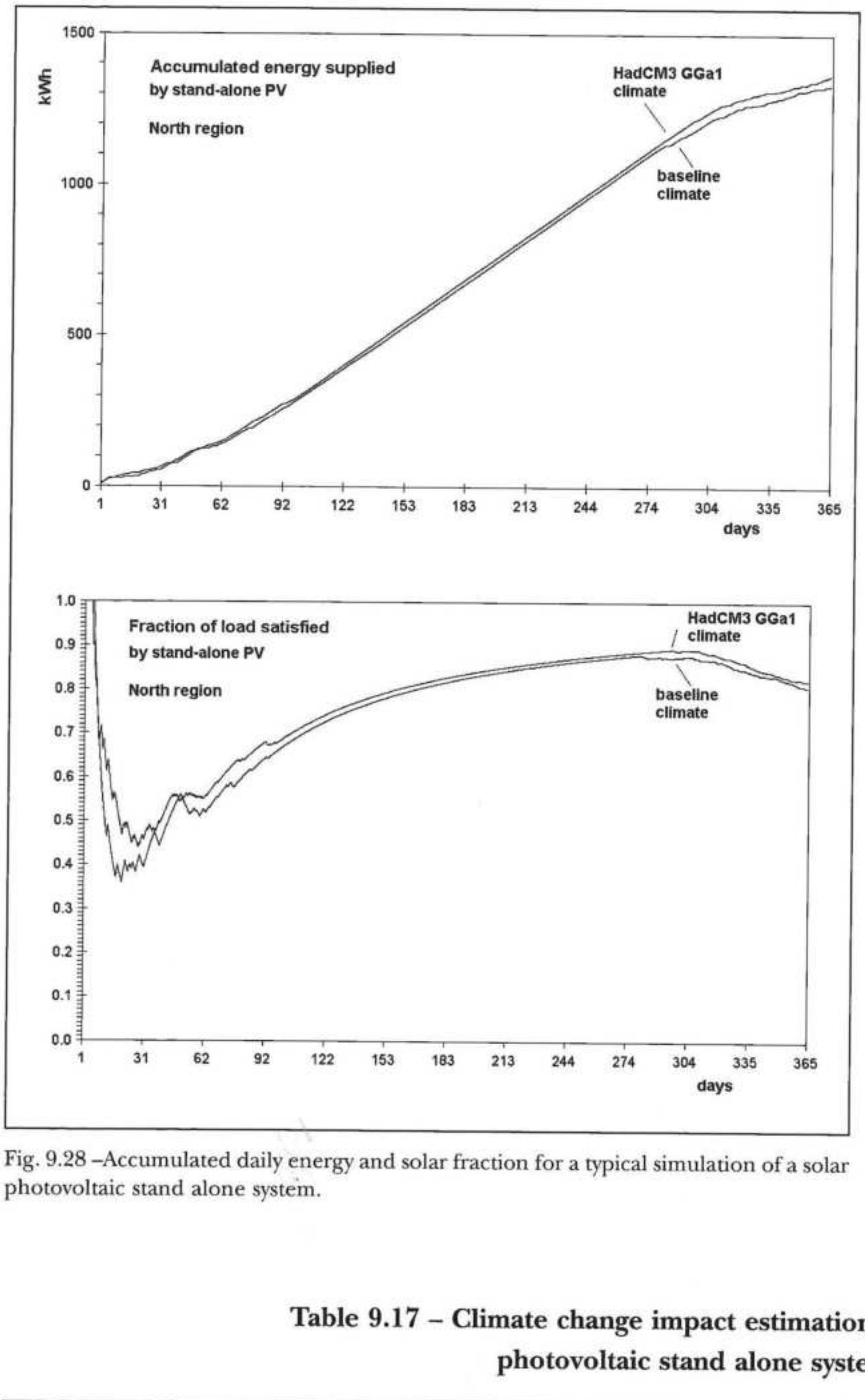

Fig. 9.28 –Accumulated daily energy and solar fraction for a typical simulation of a solar photovoltaic stand alone system.

are given in Tables 9.XVII and 9.XVIII; Figures 9.29 and 9.30 depict typical results for the HadCM3 model.

Although the system performance diminishes under high temperatures, this temperature effect is more than compensated by the increased availability of summer irradiation. Therefore, the photovoltaic systems in general could benefit from climate change in Portugal. The performance improvement is larger in the case of grid-connected systems – from +2% at the South to +9% in the North – than in the case of stand-alone systems (ca. 2%).

As was mentioned before, the representation of solar irradiation in the climate models still suffers from some problems, so the estimates obtained must be taken with some caution.

When socio-economic scenarios are incorporated (see Table 9.19), these performance increases translated to an additional 0.02-0.03 Mtoe at the end of the SIAM analysis time horizon.

### 9.3.6.3 Wind energy

Performance changes of wind energy systems due to climate change can result

**Table 9.17 – Climate change impact estimation for a typical solar photovoltaic stand alone system**

| HadRM model zone | Energy supplied (kWh) | | Solar fraction(%) | | kWh/kWp installed | |
|---|---|---|---|---|---|---|
| | Baseline | GGa2 | Baseline | GGa2 | Baseline | GGa2 |
| Parque Peneda-Gerês | 1370 | 1400 | 83.1 | 84.3 | 1140 | 1170 |
| Serra da Estrela | 1378 | 1408 | 84.5 | 85.0 | 1310 | 1340 |
| Baixo Alentejo | 1381 | 1415 | 84.0 | 85.4 | 1420 | 1450 |
| **HadCM3 model zone** | **Energy supplied (kWh)** | | **Solar fraction(%)** | | **kWh/kWp installed** | |
| | **Baseline** | **GGa1** | **Baseline** | **GGa1** | **Baseline** | **GGa1** |
| North | 1325 | 1353 | 79.6 | 80.8 | 880 | 900 |
| Centre | 1292 | 1337 | 78.1 | 80.0 | 960 | 990 |
| South | 1335 | 1364 | 80.7 | 82.3 | 1110 | 1140 |

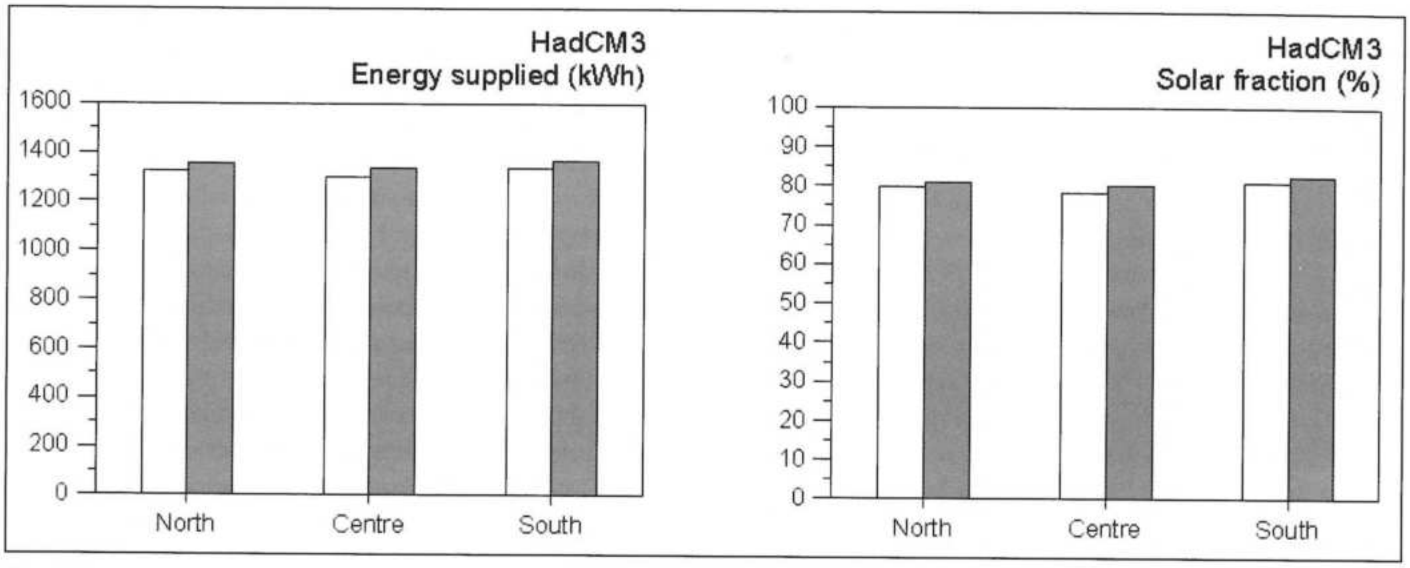

Fig. 9.29 – Performance parameters of a stand alone photovoltaic solar system for the HadCM3 model, knot 44: white bars – base scenario; grey bars – GGa1 scenario.

**Table 9.18 – Climate change impact estimation for a typical solar photovoltaic grid connected system.**

| **HadRM model** | | | | |
|---|---|---|---|---|
| | **Energy supplied (kWh)** | | **kWh / kWp installed** | |
| | **Reference** | **GGa2** | **Reference** | **GGa2** |
| Porto | 1145 | 1162 | 950 | 970 |
| Coimbra | 1162 | 1204 | 970 | 1000 |
| Lisbon and Tagus Valley | 1218 | 1226 | 1020 | 1030 |
| Faro | 1250 | 1277 | 1050 | 1070 |

| **HadCM3 model** | | | | |
|---|---|---|---|---|
| | **Energy supplied (kWh)** | | **kWh/kWp installed** | |
| | **Reference** | **GGa1** | **Reference** | **GGa1** |
| North | 1087 | 1190 | 810 | 880 |
| Centre | 1034 | 1101 | 770 | 820 |
| South | 1115 | 1142 | 830 | 850 |

**Table 9.19 – Additional energy production in solar photovoltaic systems from climate change effects (HadCM3 scenarios)**

| | **Baseline climate** | **GGa1 climate** | **increase** | |
|---|---|---|---|---|
| | **Mtoe** | **Mtoe** | **Mtoe** | **% PES** |
| A1 – Global Economy | 0.52 | 0.51 | 0.03 | 0.1 |
| A2 – National Interest | 0.43 | 0.45 | 0.02 | 0.1 |
| B1 – Global Sustainability | 0.60 | 0.63 | 0.03 | 0.1 |
| B2 – Local Sustainability | 0.43 | 0.45 | 0.02 | 0.1 |

from changes in wind intensity, turbulence intensity, and eventually in air density. Variability at all time scales (seasonal pattern, daily variability, ...) is also important por system performance and availability.

It is worthwhile to mention some basic aspects of wind energy conversion, so as to better understand why small modifications in wind patterns can translate into significant changes of energy production, even with mean wind levels remaining constant. The maximum power existing in the airflow is:

$$P = (\pi/8)\ \rho\ D^2\ v^3 \tag{9.1}$$

where $\rho$ is air density (~ 1.2 kg/m$^3$ at sea level); $D$ is rotor diameter (m); and $v$ is wind intensity (m/s).

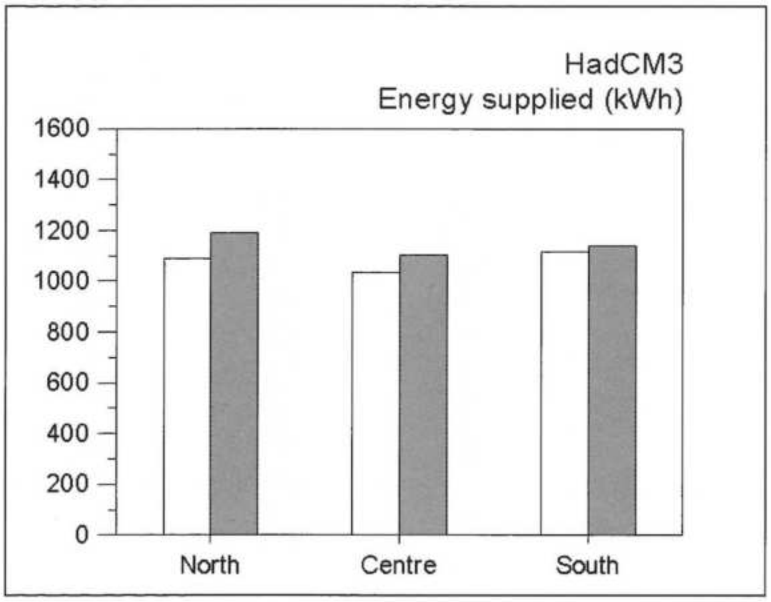

Fig. 9.30 – Performance parameters of a grid connected photovoltaic solar system for the HadCM3 model, knot 44: white bars – base scenario; grey bars – GGa1 scenario.

However, there are some limits to consider for a horizontal axis turbine: theoretical (for example, only 59.3% of the power can be extracted) and practical (power coefficients, mechanical losses, etc.). Therefore the final conversion efficiency is typically about 35%.

However, what is most significant here is the dependence of the power on the cube of the wind intensity. This means that details of the tail of the wind intensity probability distribution are very important for the yield of a system, while the shape of the distribution for low speeds is relatively unimportant. On the other hand, wind turbines only work within a specific range of wind intensities: there are cut-in and cut-off limits depending on the particular turbine. For a turbine correctly sized in relation to wind speed behaviour at a certain location, the cut-in limit is especially relevant. Both factors described contribute to make the behaviour of the more intense wind values a relevant factor for wind conversion, in addition to mean wind levels. Equation (9.1) also shows a dependence on the air density – altered slightly with climate change, as it depends on temperature, pressure and humidity.

Preliminary statistical analysis of the series supplied by the HadCM3 and HadRM models indicated only small modifications of the mean wind intensity levels and of the probability tails, under enhanced greenhouse effect, for all climate scenarios available. This situation prompted further detailed analyses of the meteorological data, as impact estimation with detailed wind turbine performance and wind park models are unnecessary in the absence of climate change induced relevant changes in wind characteristics.

The HadCM3 wind intensity data, available for a nominal 10 m height above ground, were converted to a height typical of the wind turbine (horizontal) axis, 30 m, using a logarithmic profile, and a rugosity parameter of 10 cm. A fixed altitude of 300 m and the model temperature, humidity and pressure data were used to obtain air

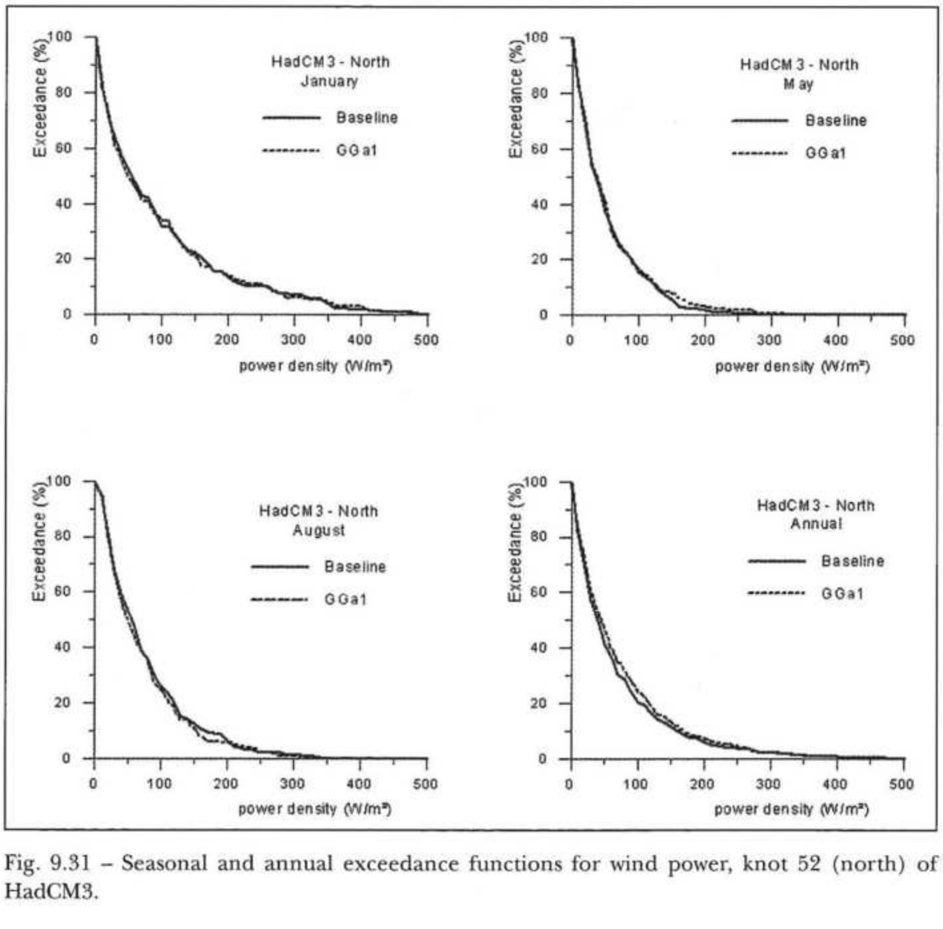

Fig. 9.31 – Seasonal and annual exceedance functions for wind power, knot 52 (north) of HadCM3.

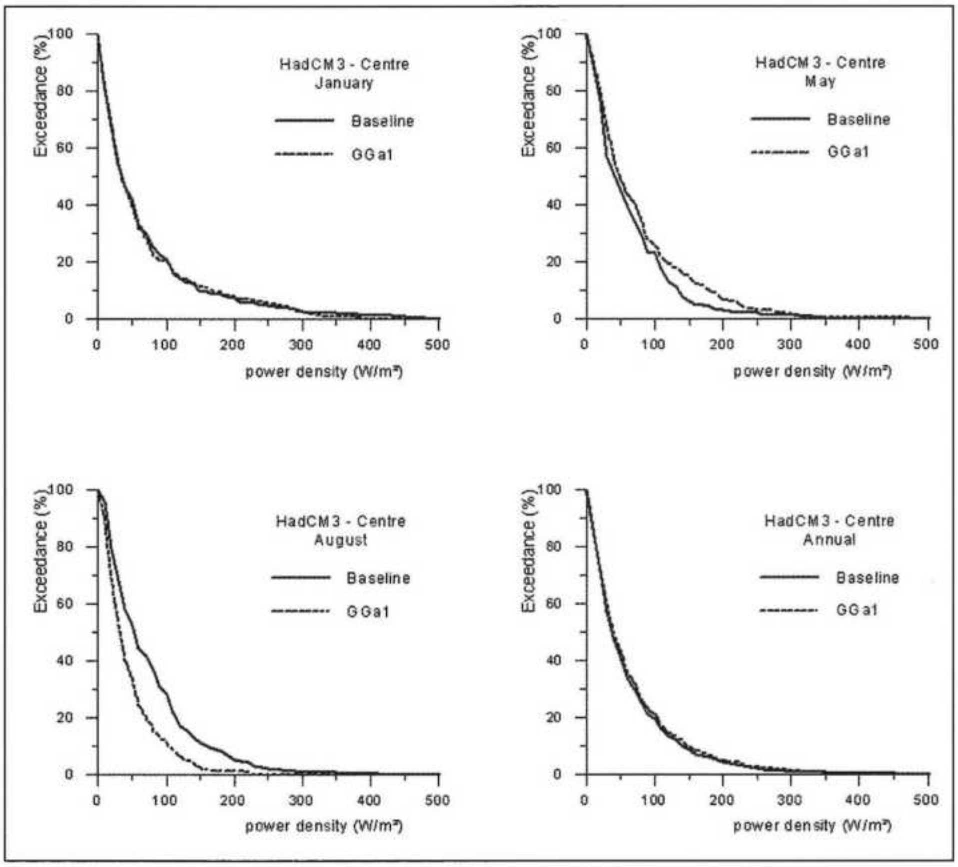

Fig. 9.32 – Seasonal and annual exceedance functions for wind power, knot 44 (centre) of HadCM3.

density. The maximum available power was computed. Probability density statistics were analysed, as well as exceedance statistics (power available above cut-in wind intensity).

Sample results are given for the HadCM3 model knots, see Figures 9.31 to 33; results for the PROMES and HadRM models were similar, regardless of the fact that they permitted a better spatial resolution, allowing for a better evaluation of coastal and mountain areas.

The wind power statistics are very similar for base and climate change scenarios. A detailed analysis has shown (see Figure 9.34) that summer values are somewhat lower for the later case, but this is compensated in the other seasons by slightly more probable strong winds. Thus, the overall yearly statistics for enhanced greenhouse effect are almost identical to that of the control period.

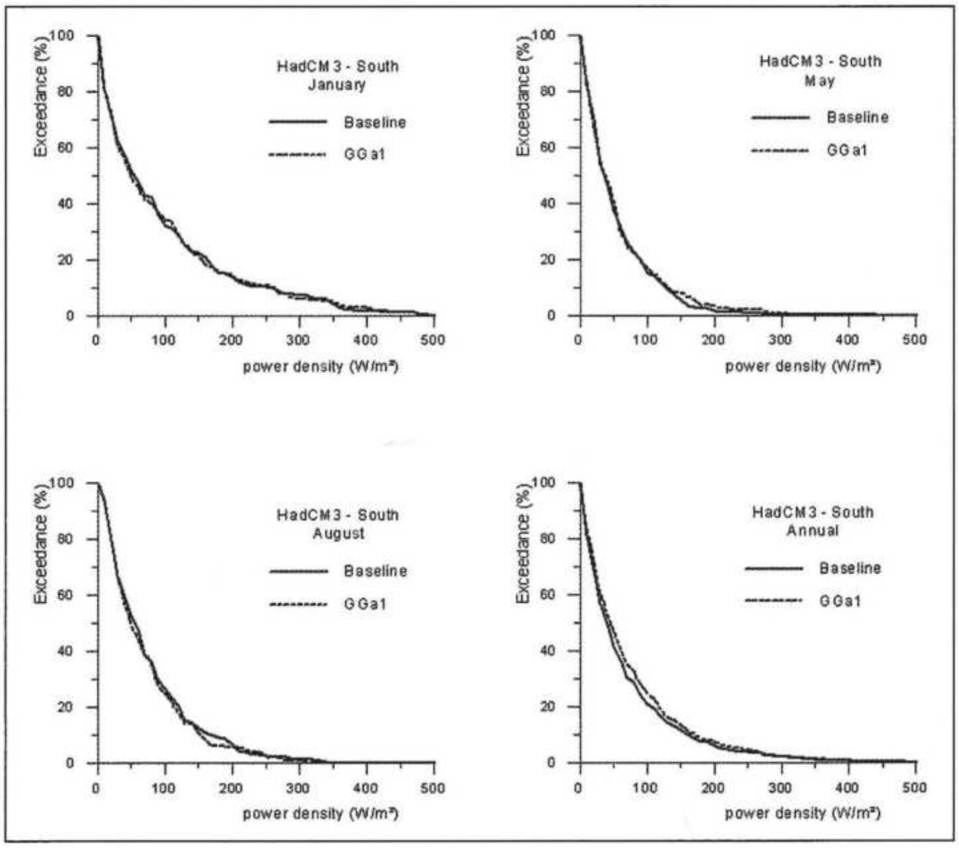

Fig. 9.33 – Seasonal and annual exceedance functions for wind power, knot 36 (south) of HadCM3.

In conclusion, the available climate change models do not indicate significant changes in electricity production from wind turbines.

### 9.3.6.4 Mini-hydroelectric systems

Frequency-duration curves based on daily values (Linsley et al. 1988) would be the most adequate tool to estimate impacts of climate change on the electricity production from mini-hydropower systems (Penche 1994). Unfortunately results on surface flow at some selected basins are rather recent at the

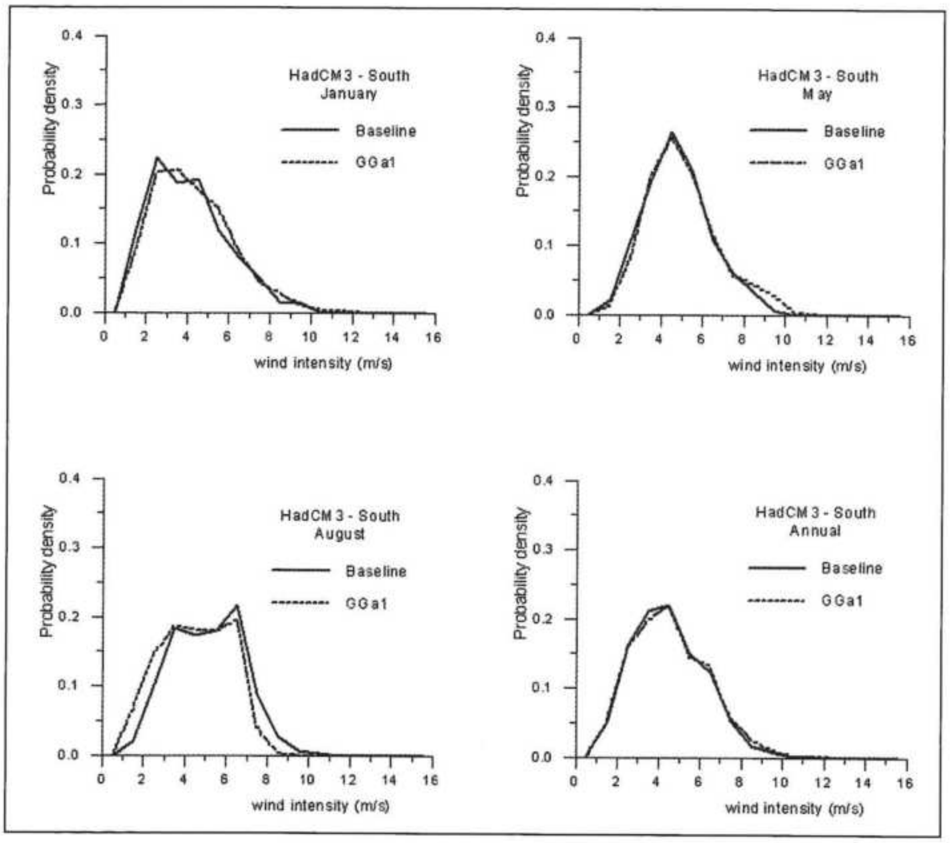

Fig. 9.34 – Seasonal and annual probability density functions for wind power, knot 36 (south) of HadCM3.

time of the writing, and consist only in monthly runoff estimates.

These runoff analyses will be briefly reviewed, for the convenience of the reader; detailed information is provided in the Water Resources chapter, and was mentioned above in section 9.2.2.1.2. Generally speaking, runoff will increase with climate change for the Northern basins, and the reverse for the Southern basins. Spring and autumn runoff decreases for all basins except for the one basin analysed that was located further north. In all cases, summer runoff decreases greatly in relative terms, however, the changes are less important in absolute values as they are already very small (or nil) in the base scenarios.

As mentioned previously, from the viewpoint of assessing mini-hydro production, the simple increase or decrease of monthly runoff is not enough; therefore the situation pictured above cannot be translated immediately in terms of electricity production. For instance, production is not proportional to river flow (Nash and Gleick 1993). Also, as in the case of wind energy systems, mini-hydro systems have a working range (Penche 1994, CEDRL 1998); and there are other limits to consider, viz. the 'reserve' or 'ecological' minimum flows determined by law and the loss of water through fishways. Finally, it must be considered that in general production is interrupted during summertime, to, clean the ducts and river bottom, and for turbine maintenance, etc.

Anyway, the existing data support the estimate of a slightly higher mini-hydro potential at the northern basins, but reductions of the potential at the central basin (also for the southern basins, but no plants have been built there so far).

The socio-economic and energy sector scenarios point to a significant increase of mini-hydro power production. New plants in the coming years are likely to be located in the Northern basins and therefore could benefit from climate change over the long-term. Meanwhile, the concept of multi-purpose water use facilities is emerging and this could modify the situation described above. For instance, the government is considering installing mini-hydro systems in almost all agricultural (small) dams and reservoirs. Most of these systems are located in the central and southern basins and therefore the expected electricity production values – estimated with the current climate – are likely to be overestimated over the long run.

### 9.3.6.5 Other systems

At the time of the writing there was no information on changes of ocean currents due to global warming. The information on changes of wave power and wave patterns is yet very sketchy and quite uncertain. Preliminary results however, indicate very modest variations in the wave height, therefore corresponding very small changes in wave power systems performances could be expected; however, no data on wave periods and wave patterns was yet available.

Again, for biogas and biomass production for energy purposes there were no available adequate cross-sectoral scenarios compatible with SIAM: expectations for amounts of urban, industrial and farming residues (e.g. pig breeding, poultry, cattle) or productivity of 'energy crops', respective area, etc.

Nevertheless it can be said that anaerobic digestion (biogas production) should benefit from higher ambient temperatures. The most common anaerobic digestion processes in Portugal (Santos 2000) use mesophilic bacteria that grow best in the temperature range 30-40°C. To obtain optimum performance, the digestor must be heated adequately. This is done using totally or in part the biogas produced in the digestor itself. The rest of the biogas goes for other uses – in particular there are at present 7 MW of installed electrical generation power. The predictions for anaerobic digestion use are towards intense grow, fundamentally driven by stricter environmental laws (the primary objective of anaerobic digestion is decontamination).

The climate change benefits are then twofold: inlet waste already at a higher temperature, and less thermal losses from the digestor to the environment.

### 9.3.7 ENERGY NEEDS FOR WATER HEATING

Hot water requirements for domestic, services and industrial sectors are an important fraction of the overall budget: for instance, about 30% in the case of the domestic sector. It is recalled that the increase of ambient temperature can have three types of effects: less heat required to reach a certain final water temperature (because of initial higher tap water temperature); reduction of thermal losses from tubes and reservoirs; changed behaviour of the water users under a hotter environment.

Only the first effect will be inspected, and only preliminary results were obtained so far. Using typically an additional 4°C for soil temperature (under increased ambient temperature) and thus tap water temperature must reflect a similar change over the long term. For the climate of Lisbon this would mean a change from 11-15°C during wintertime, and from 16-20°C during summertime. Assuming hot water to be required at 65 °C and no change in the volumes required, the impact would be about 8-9% in the heat required for sanitary domestic hot water (recall the energy scenarios in Table 9.4). This is consistent with the results obtained in section 9.3.6.1, solar thermal systems, which indicate performance increases in the range 6-10% according to region, due essentially to reduced energy requirements.

Pre-heating of water for cooking (to 100°C) was also considered, but the refined estimate of the energy savings is still very close to 8%, as the heat required for cooking with e.g. boiling water is mostly latent heat, not sensible heat.

The impact on the energy requirements for pre-heated water for industrial purposes should be lower, due to the higher target temperature ranges involved: the respective estimates obtained point to about 5-6%.

Table 9.20 provides the numerical estimates of the final savings in water heating, considering the domestic and industrial fractions, the supply by solar systems and by fossil fuels and the four socio-economic scenarios – it can be seen that the impact estimates are quite large, indeed almost 2% of the PES in the global sustainability scenario.

These estimates need to account further for the pattern of use of the hot water and for the existence of storage. For instance when there are no hot water

**Table 9.20 – Climate change impact in savings for water heating**

| | Thermal energy requirements | | | | | Savings from temperature rise | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Solar origin | | Fossil fuel origin | | All | Solar origin | | Fossil fuel origin | | All | PES fraction |
| | Mtoe | % | Mtoe | % | Mtoe | % | Mtoe | % | Mtoe | Mtoe | % |
| A1 – Global Economy | 2.7 | 33 | 5.5 | 67 | 8.2 | 6.5 | 0.18 | 5.9 | 0.33 | 0.50 | 1.6 |
| A2 – National Interest | 3.4 | 45 | 4.2 | 55 | 7.7 | 6.3 | 0.22 | 5.6 | 0.24 | 0.46 | 1.8 |
| B1 – Global Sustainability | 4.5 | 58 | 3.3 | 42 | 7.8 | 6.4 | 0.29 | 5.4 | 0.18 | 0.47 | 1.9 |
| B2 – Local Sustainability | 3.0 | 39 | 4.8 | 61 | 7.8 | 6.4 | 0.19 | 5.7 | 0.27 | 0.47 | 1.8 |

tanks in a dwelling, part of the water is close to mean wall temperature, not soil temperature; the wall temperature can be affected by the interior temperatures in the building – and indeed all the socio-economic scenarios point to an increased control of the interior building temperatures, either by passive systems or active systems (air conditioning). Therefore the numerical estimates obtained above should in fact be an upper limit.

However, in future scenarios laundry and dishwasher machines with exterior supply of hot water – obtained from e.g. gas or solar systems – can become a dominant technology (this was not considered in the energy scenarios), thus again increasing the savings estimates closer to those in Table 9.20.

### 9.3.8 SPACE HEATING AND COOLING IN BUILDINGS

#### 9.3.8.1 Econometric analysis

Climate has obvious relations with energy demand for physical human comfort, in particular with energy requirements for space heating and cooling inside buildings. This should be reflected at the daily consumption of energy in buildings, however, for annual or even seasonal values compensation of cold and warm periods can obscure the effect. Many top-down studies have found statistical evidence for this kind of linkage using country level data (Flechsig et al. 1999). In the case of Portugal however, clear evidence could not be found (with the simple models used by SIAM in this first country study).

Time series of energy consumption by the domestic and service sectors were analysed in relation to the national temperature indexes mentioned in section 9.2.1.1.2: maximum, mean and minimum annual, winter and summer values. Data was separated by final energy source: coal, oil, electricity and gas, the latter including liquefied petroleum gas as well as natural gas, to accomodate recent changes in the type of gas supply. Polynomial trends were fitted to the data, and only the series of residual values (i.e. fluctuations with respect to the trend) was correlated with the series of temperature indexes (there was no noticeable trend in these indexes for the short time range studied). An example of the whole procedure can be followed in Figure 9.35.

The results were generally inconclusive. The reasons for this are believed to include lack of statistical significance (short data series); the existence of two clear periods for energy demand behaviour (pre- and post-1974); effects of the irregular economic growth during 1974-'80. It is also remarked that winter heating of buildings using electricity; coal, oil or gas was not common in Portugal for most of the time range inspected, due partially to the mild climate and economic difficulties.

More sophisticated versions of this kind of analyses were tried, namely fitting different trends for energy demand before and after 1974, and using series of energy intensity instead of energy demand. Correlations did not improve. The series since about 1985 to the present seem to show the existence of a larger coupling of energy demand to climate, however, the significance of the statistics becomes low as only around 13 data points could be used.

Anyway for the specific case of gas consumption a -4%/°C impact was found, using the mean annual temperature index, and the data series from 1985 onwards. This can be appreciated in Figure 9.35, although the correlation is not statistically significant because the time series is not sufficiently long. This effect can be interpreted as meaning a reduction of energy needs for water and space heating during warmer years, the opposite during colder years. In absolute terms the impact per degree is small, 0.002 Mtoe/°C (*i.e.* -0.01 Mtoe for a 4-5°C temperature rise), however, gas penetration in the fossil fuel mix is expected to increase very much in the next decades, thus the -4%/°C impact relative value could mean significant savings.

#### 9.3.8.2 Bottom-up impact assessment

An alternative approach to top-down statistical analyses of the residential and service sectors are bottom-up analyses of the constitutive elements, namely the buildings. This approach was followed with much more success.

The national panorama of buildings of the domestic and service sectors is complex: both single dwellings and multi-storey buildings are common; construction materials depend on the region, as well as many other relevant parameters such as floor and window areas or occupancy. Being impossible in practice to model all the variety of existing buildings, the approach taken was to define typical single buildings for certain regions, with the average characteristics of the buildings of that region.

The typical buildings were simulated with the reference meteorological years mentioned under section 9.2.1.1.2, for base and enhanced greenhouse effect meteorological scenarios. No active systems were modelled, only passive response elements. An ideal controller (i.e. perfect sensing of room temperature and fast, uniform heating/cooling of volumes) is switched on whenever temperature would be outside of winter and summer comfort temperature ranges.

Weighted averages considering the number of dwellings of each type in each region lead to final results for the current situation in those sectors. Socio-economic scenarios were then applied to obtain projections for the time range of the study.

Although the following results focus on estimates obtained under the HadCM3 model scenarios, which were considered the most reliable, all three models were used (PROMES, HadRM and HadCM3). This enabled also some measure of the uncertainty associated with the results.

### 9.3.8.2 Model buildings

For the domestic (or residential) sector, models could be created based upon data from a recent survey undertaken by (INE 1999) and a previous study elaborated

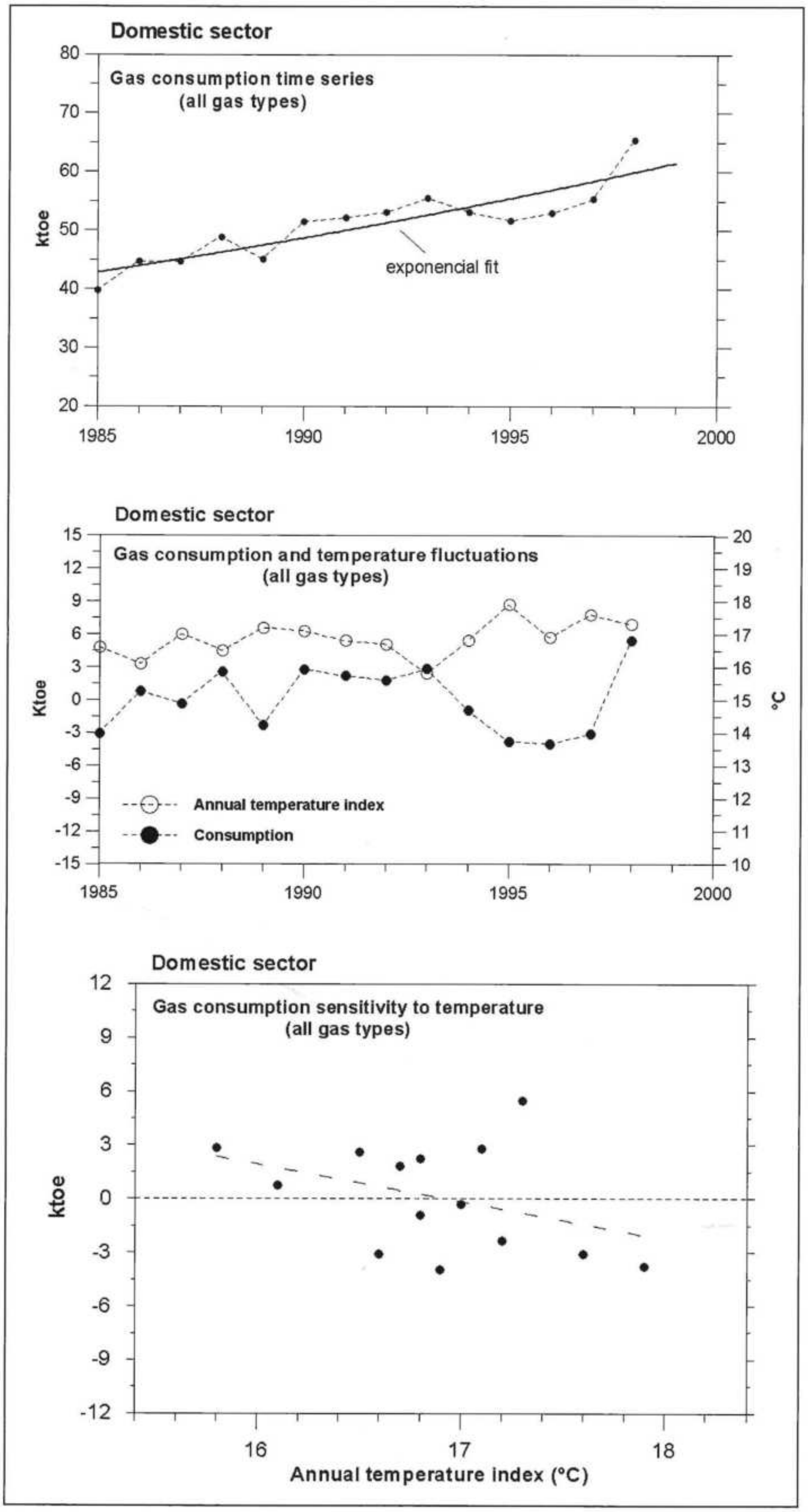

Fig. 9.35 – Relationship of gas demand residuals in the domestic sector to the average annual temperature index.

by INETI (Gonçalves et al. 2000). The service sector is even more complex than the domestic sector, as it includes hospitals, hotels, shopping centres, etc., and the surveys available are much less detailed than those for the domestic sector. Therefore a typical floor of a modern office building was chosen at this stage of SIAM to serve as model building for the service sector case.

The Portuguese Building Thermal Legislation (RCCTE 1990) divides Portugal into three winter (I1, I2, I3) and three summer climatic zones (V1, V2, V3), for a total of nine zones. These zones are represented in Figure 9.36. HadCM3 nodes were associated to each one of the winter climatic zones. The legislation requires minimum quality levels of the constructive solutions. It imposes maximum thermal loss coefficients – usually referred as U-values, $K_{REF}$ being more used in Portugal – for the opaque building envelope, depending on the winter climatic zone where the building is located.

#### *9.3.8.2.1 Domestic sector reference buildings*

Two typical building model of Portuguese residences were assembled, a single-family house and an apartment in a multi-storey urban building, based on analysis of the sector (Oliveira e Camelo 2000a; 2000b; Oliveira 2001). It is recognized that the national thermal regulation for buildings RCCTE applies only to the new buildings erected after 1990. Recently the 3E Programme already mentioned promises to improve this RCCTE version with 40% less minimum con-

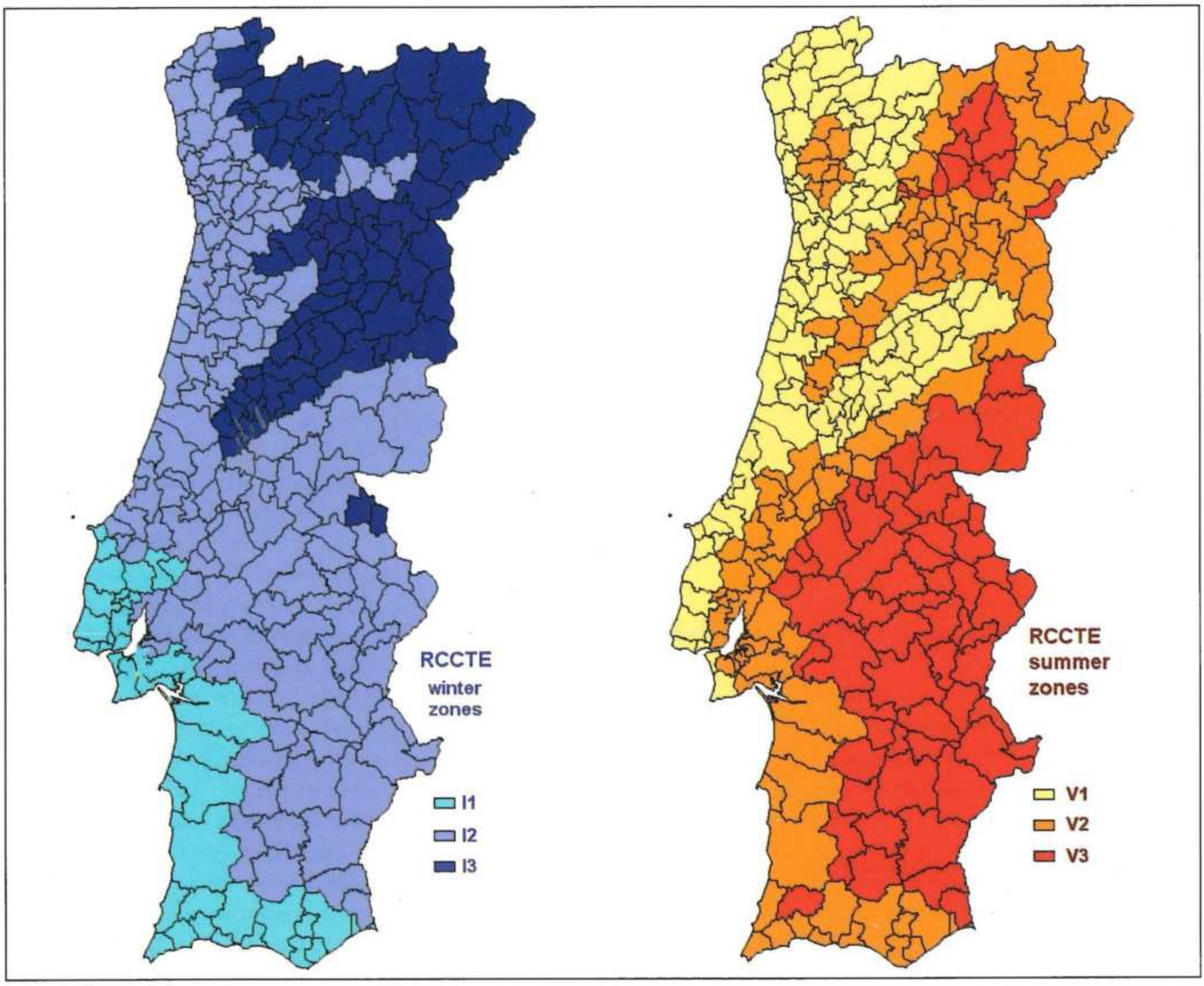

Fig. 9.36 – Climatic zones for the Portuguese thermal building regulation RCCTE.

sumption levels allowed. This new RCCTE version will be active from 2003 onwards, but was published only after completion of this first phase of the SIAM study, therefore the minimum requirements and reference values of the 1990 legislation were used. The dwelling models have single glazing; solar apertures are facing all orientations and corresponding to 15% of the floor area. Floor areas are 86.4 m² for the single-family house and 78.5 m² for the apartment model. The opaque envelope is defined by the RCCTE reference values $K_{REF}$, see Table 9.21.

**Table 9.21 – Reference thermal loss coefficients for the winter climatic zones of RCCTE**

| | Walls | | | Ceiling and floor | | |
|---|---|---|---|---|---|---|
| Climatic zone | I1 | I2 | I3 | I1 | I2 | I3 |
| $K_{REF}$ (W/m²/°C) | 1.40 | 1.20 | 0.95 | 1.10 | 0.85 | 0.75 |

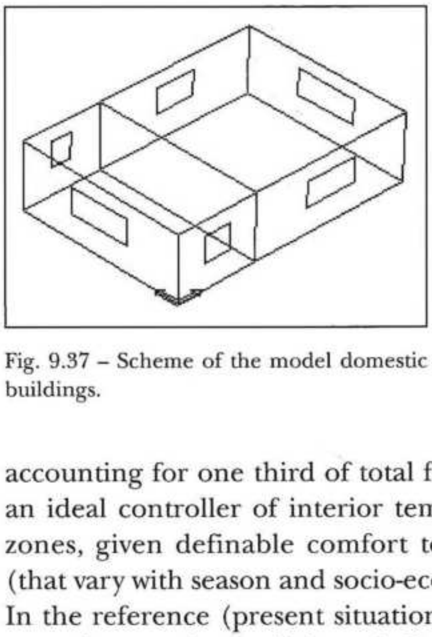

Fig. 9.37 – Scheme of the model domestic buildings.

As for the layout of the model dwellings, two zones were considered, a social zone (dining room, etc.) and a private zone (bedrooms, etc.), see Figure 9.37. The social zone is the smaller one, accounting for one third of total floor area. There is an ideal controller of interior temperature for both zones, given definable comfort temperature bands (that vary with season and socio-economic scenarios). In the reference (present situation) case, the private zone is not air-conditioned. Review the section 9.2.2.2.2 for a detailed characterization of the dwelling models under the four socio-economic scenarios.

### 9.3.8.2.2 *Service sector reference building*

A typical floor of an office building was modelled – see Figure 9.38– based on data from several previous studies (DGE 1994; Boucinha and Godinho 2000; Coelho et al. 2000; Cordoba et al. 1998; Gonçalves et al. 1999; 2000; 2001).

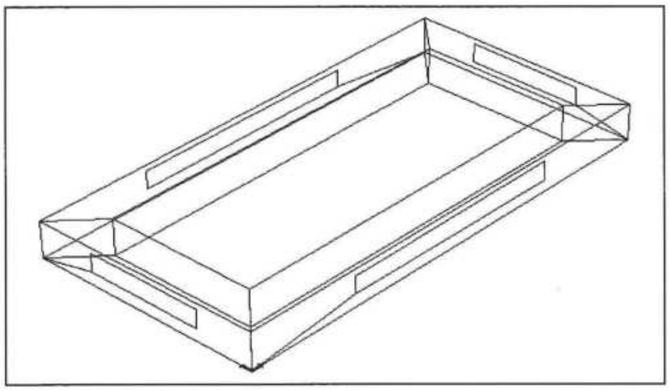

Fig. 9.38 – Scheme of a floor of the model office building (services sector).

It has four open-space type office zones, plus a central zone (bathrooms, stairs, elevators, etc.). The occupation pattern follows a typical office schedule, and is conditioned throughout the year in order that temperature stays within the comfort range of 20-25°C. Detailed characteristics are presented in Table 9.22 and Table 9.23.

**Table 9.22 – Characteristics of the model office floor**

| | |
|---|---|
| **Geometry** | |
| Floor area: | 800 m² |
| Windows: | 11% of floor area (bronze coloured glass) |
| **Thermal Shell** | |
| Thermal transmission coefficients: $K_{REF}$ specified in RCCTE | |
| Boundary conditions: pavement and ceiling in contact with similar zones | |
| **Schedules** | |
| Occupation | 8:00-18:00 (100%) and 18:00-20:00 (30%)<br>10m²/person.h |
| Illumination | 8:00-18:00 (100%) and 18:00-20:00 (30%)<br>20 W/m² |
| Equipment | 8:00-18:00 (100%) and 18:00-20:00 (30%)<br>5 W/m² |
| Ventilation | 0:00-24:00 0.75 rph (30m3/person.h) |
| **Comfort band** | |
| Heating | 7:00-20:00, temperature < 20°C |
| Cooling | 7:00-20:00, temperature > 25°C |

**Table 9.23 – RCCTE thermal shell coefficients for office buildings**

| | Walls | | | Ceilings/Pavements | | |
|---|---|---|---|---|---|---|
| Climatic zone | I1 | I2 | I3 | I1 | I2 | I3 |
| Insulation (cm) | 0.2 | 0.7 | 1.6 | 3.0 | 3.2 | 3.9 |
| $K_{REF}$ (W/m²/°C) | 1.40 | 1.21 | 0.95 | 1.10 | 0.86 | 0.75 |

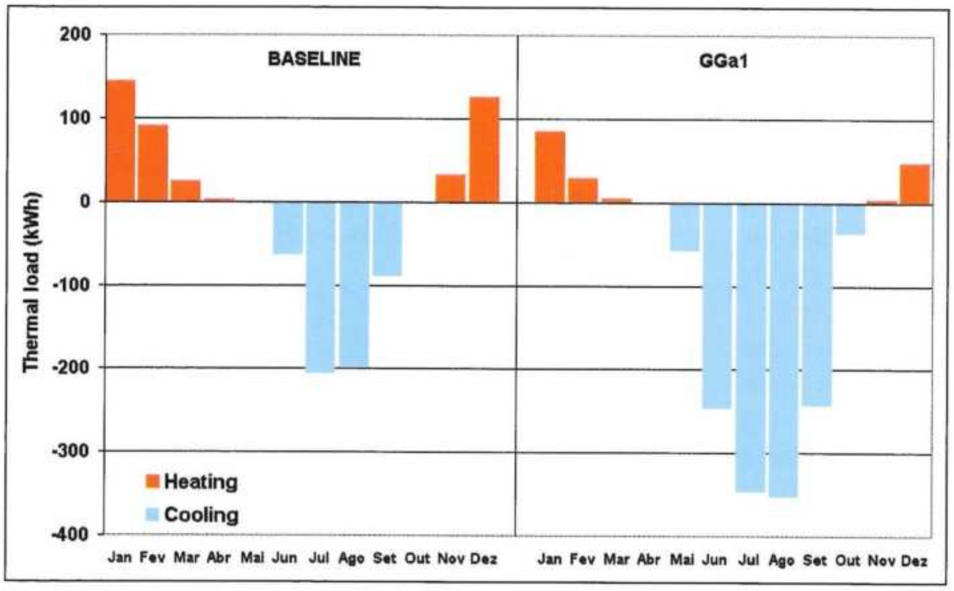

Fig. 9.39 – Climate change impacts on space conditioning of residential buildings. Seasonal behaviour for the South region, HadCM3 baseline and GGa1 scenarios.

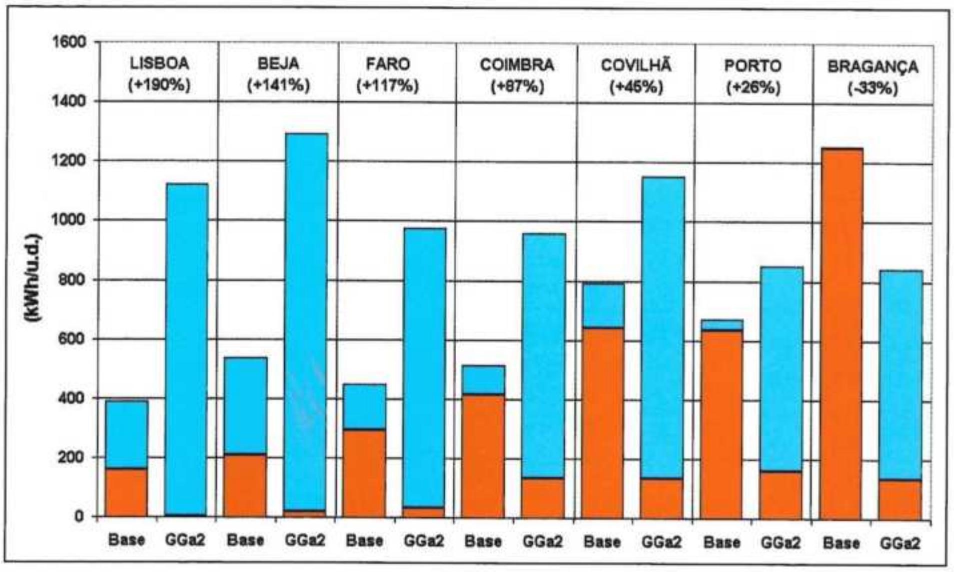

Fig. 9.40 – Climate change impacts on space conditioning of residential buildings. Thermal load values for HadRM baseline and GGa2 scenarios.

According to the results obtained under HadCM3 model scenarios for the thermal loads, the reduction of the heating load is less than the increase in the cooling load (see Figures 9.40 and 9.41). According with the SIAM energy scenarios, this should translate in increased energy requirements for space conditioning.

Regional results for the other two models, PROMES and HadRM, cannot be directly compared against each other and with HadCM3, as the model grids are different, but they follow the same trend described above, except that some year-round reductions in energy requirements could occur for the Northeast. Nevertheless, at country level and given demographic characteristics, the climate change impact of additional thermal loads and energy requirements for space conditioning in buildings is quite certain.

Working with the HadCM3 model scenarios, annual combined (*i.e.* heating and cooling) thermal loads increase 61% in the central region and 49% in southern region. The northern region is less affected by climate change, with a slight increase of 8% estimated.

These variations become yet more impressive in terms of final energy requirements, because cooling COP is less than heating COP for the HVAC system assumed: additional 29% for the southern region, 100% for the central region, and 69% for the northern region. Absolute values of additional energy requirements per dwelling caused by warmer weather conditions, reach 164 kWh for the southern region, 484 kWh in the central region and 398 kWh in the northern region. Using the HadRM scenarios enabled a higher spatial resolution and seven zones could be examined – see Figure 9.41. Absolute values of additional combined

### 9.3.8.3 Domestic sector results

#### *9.3.8.3.1 Reference situation*

The comparison between base case and enhanced greenhouse scenarios for the current case shows the pattern that could be expected intuitively: a generalized increase of monthly cooling energy demand and a reduction of monthly heating energy demand, as well as a reduction of the heating season and a consequent extension of the cooling season, see Fig. 9.39.

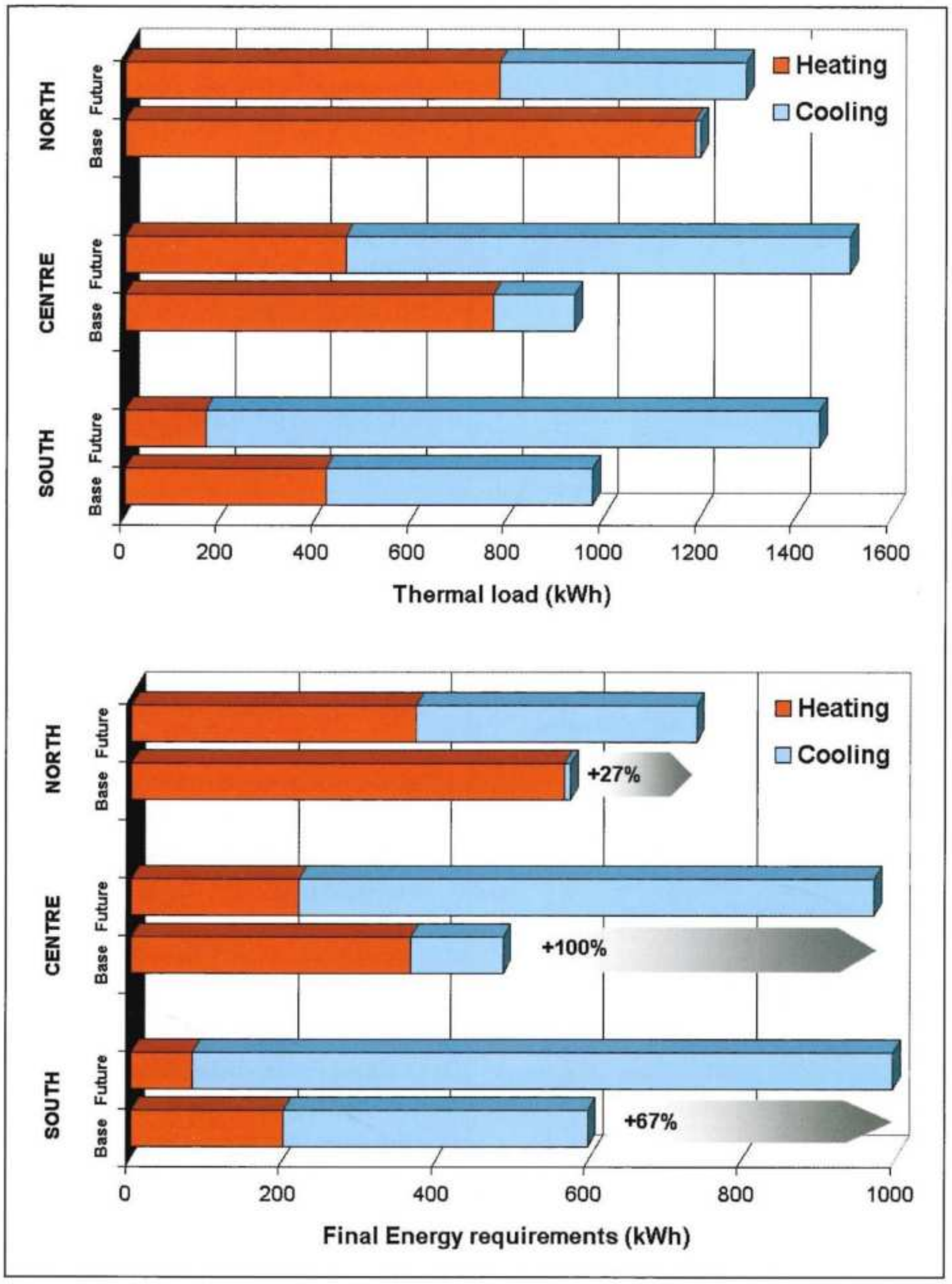

Fig. 9.41 – Climate change impacts on space conditioning of residential buildings. Yearly values for HadCM3 baseline and GGa1 scenarios. Energy needs computed with an electric reversible heat pump.

thermal loads per dwelling manifest accentuated increases in the South and Central areas (increases of 500-750 kWh and 350-450 kWh, respectively). For the north littoral area the estimate was +200 kWh. The north inland region is the only one that shows yearly combined thermal load reductions of around 400 kWh.

Even if regional variations are lower, results obtained under the PROMES scenarios present the same tendencies of the previous two models. The south and Lisbon areas present increased yearly combined thermal load values around 200 kWh to 300 kWh. As in the case of HadRM, yearly estimates in the North show a decrease, around 50 kWh in this case.

### *9.3.8.3.2 Projections for socio-economic scenarios*

Under the SIAM socio-economic scenarios, dwellings characteristics and operation modes are different than that of the reference case. It is recalled that in all cases the buildings have improved envelopes – better insulation in particular – especially for the cases of the “sustainability” scenarios B1 and B2. For the A1 (“global economy”) and A2 (“national interest”) scenarios, the entire dwelling is conditioned – both private and social zone – however, A1 has more restrictive comfort conditions. There are also changes in occupancy, equipment and larger floor areas; the details are described in section 9.2.2.2.2.

Additional energy requirements per house differ significantly according to the socio-economic scenarios. For current climate conditions, the B1 and B2 sustainability scenarios are in the same range value of the present-day reference case, with the B1 “global sustainability” scenario presenting even slightly lower values. The A1 “global economy” scenario involves a large increase of energy demand.

According to results using HadCM3, see Fig. 9.42, the impact of climate change should be an increase of final energy requirements of about 367 kWh (+70% of baseline) for the current housing sector. However, with the A1 scenario the impact would rise to 929 kWh and to 857 kWh in the A2 scenario. The impacts for the sustainability scenarios are lower but still higher than with the current dwelling characteristics, viz. for

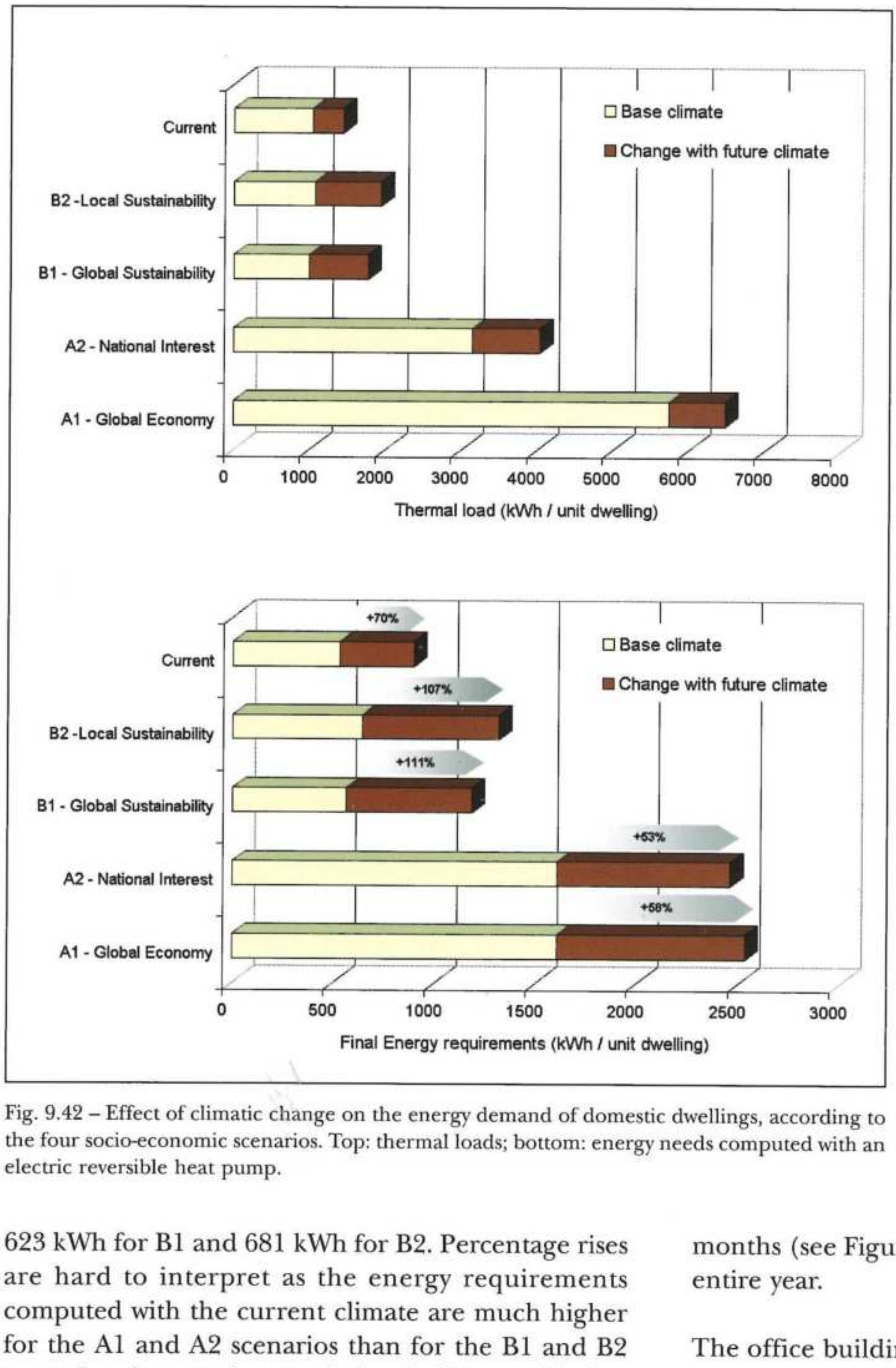

Fig. 9.42 – Effect of climatic change on the energy demand of domestic dwellings, according to the four socio-economic scenarios. Top: thermal loads; bottom: energy needs computed with an electric reversible heat pump.

623 kWh for B1 and 681 kWh for B2. Percentage rises are hard to interpret as the energy requirements computed with the current climate are much higher for the A1 and A2 scenarios than for the B1 and B2 scenarios. Anyway the conclusion is that considering socio-economic scenarios enhances the energy requirements by ca. 90-140% in respect to the (already high) impact estimates computed considering the current housing sector characteristics fixed in time.

It must be stressed here that the energy conservation strategies applied in the socio-economic scenarios focused on insulation improvement (in walls and windows), this being the current trend in building regulations. However, it was found that under climate change scenarios this strategy indeed reduces the heating energy requirements, but does less to avoid the cooling loads. Owing to the much larger weight that the cooling season will gain under enhanced greenhouse effect conditions, specific strategies directed to summer ought to be considered in future work.

### 9.3.8.4 Service sector results

As in the case of residential building models, combined thermal loads for the office building model increases under warmer weather conditions. But in the office case (and in other buildings of the service sector as well), the internal gains from occupancy, equipment and lightning are much higher, therefore the heating energy requirements are in general low, whereas the same factor makes cooling more difficult whenever it is required, especially during summer. In fact under climate change scenarios the cooling season in Portugal for these building extends from summer to embrace spring and autumn months (see Figure 9.43), and in some areas even the entire year.

The office building results presented are referenced to square meter (m$^2$) of floor area, because scenarios for the service sector could not be drawn with as much detail as in the case of the residential sector. For the HadCM3 scenarios, see Fig. 9.44, yearly combined thermal loads increase ca. 12 kWh/m$^2$ in the northern region, 19 kWh/m$^2$ in the central region, and slightly less than that, 17 kWh/m$^2$, in the southern region; nevertheless the highest absolute combined thermal loads continue to be found in the South. These variations in thermal loads translate to additional final energy requirement

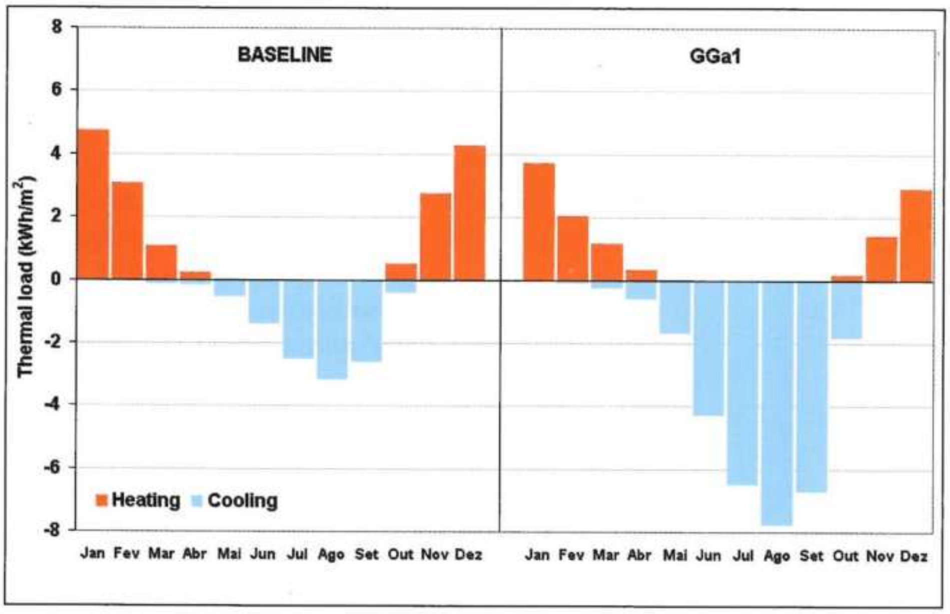

Fig. 9.43 – Climate change impacts on space conditioning of an office building. Seasonal behaviour for North littoral region, baseline HadRM3 climate.

estimates of ca. 10 kWh/m$^2$ in the northern region (+62%), 15 kWh/m$^2$ in the central region (+75%), and 13 kWh/m$^2$ in the southern region (+47%).

As for regional climate models, results have been obtained only for the HadRM scenarios. Under warmer climate conditions, combined thermal loads values increase from +9 kWh/m$^2$ in the North Inland zone to +29 kWh/m$^2$ in the South zone.

### 9.3.8.5 Uncertainty in building results

Uncertainty in the results obtained for space cooling and heating in buildings derives from numerous sources. There are simplifications and uncertainty in climate models, in their associated GHG emission scenarios, in the surveys used to assemble baseline models and conditions, and in the socio-economic scenarios.

Figure 9.45 compares office building results obtained for two climate models, HadCM3 and HadRM, to enable at least a partial assessment of the uncertainty stemming from climate modelling.

Note that the model grids are different and that the greenhouse gas emission scenarios used are also somewhat different. This information should be combined with the range of (relative) performance change estimates obtained for the various socio-economic scenarios to obtain better estimates of the range of uncertainty of the previous results.

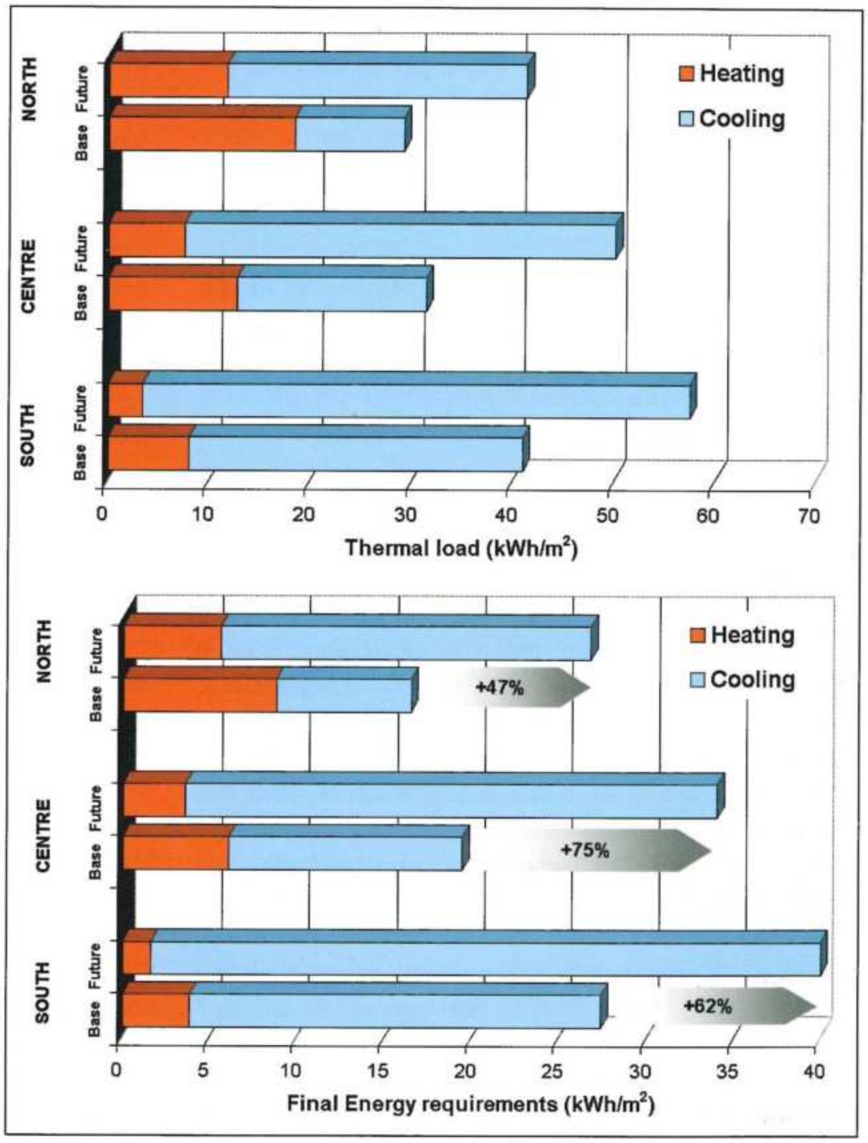

Fig. 9.44 – Climate change impacts on space conditioning of an office building. Yearly values for HadCM3 baseline and GGa1 scenarios.

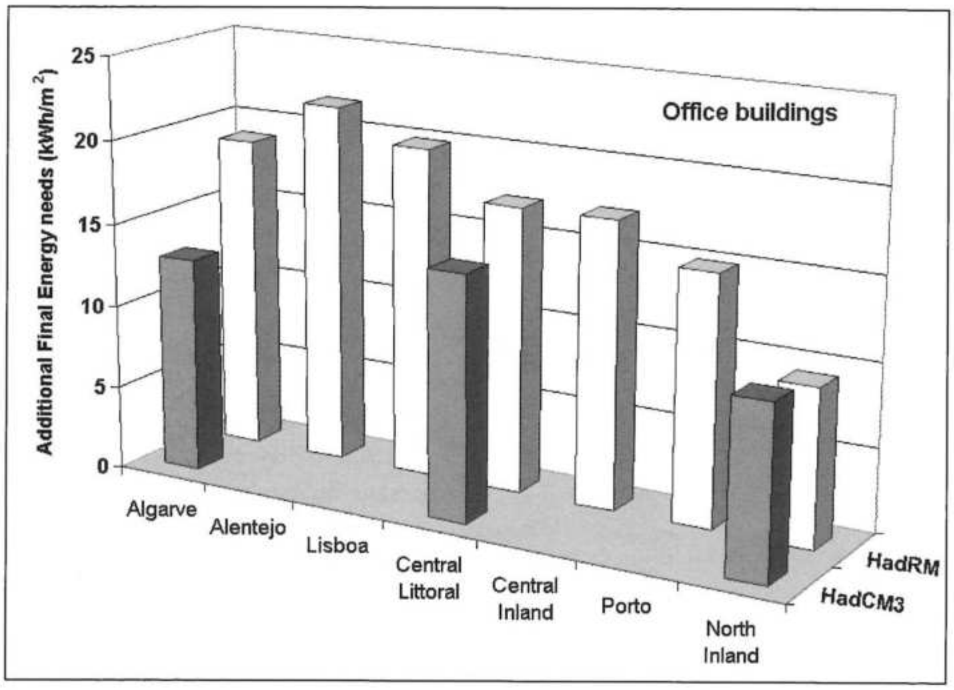

Fig. 9.45 – Assessing uncertainties in residential building estimates of climate change impacts on space conditioning (additional energy requirements computed assuming an electric reversible heat pump).

### 9.3.9 SYNERGIES BETWEEN IMPACTS

Impacts on supply and demand appear to be rather independent when examined separately. However, it is clear that climate change related impacts, as well as consequent adaptation (and mitigation) measures for either side of the supply-demand equation would impact upon the other.

For instance, larger demand would require larger energy supply, to be obtained both from larger primary energy supply (fossil fuels in particular) and final energy imports (electricity in particular). A feedback is established: the price of electricity would raise and tend to decrease consumption of electricity. Meanwhile there would be another choice open to consumers, namely to switch energy sources – but this often implies large capital investment (*viz.* substitution of existing equipment and of some infrastructure). For industries and services this is feasible and eventually performed if supported by a cost/benefit analysis. However, for residential consumers in general a similar move would be done only by the end of the lifetime of equipment – which for energy-related systems frequently reaches 20-30 years. Therefore the so-called 'elasticity' coefficients of energy source mix responses to energy prices are much larger for the industry and service sectors than for the residential sector. Anyway, the feedback supply-demand is not efficient in practice, and thus the price of electricity should be quite sensitive to climate change derived alterations in the supply and demand levels and patterns (although regulation by an independent body – currently ERSE, as mentioned before – might smooth out these problems).

The impacts upon energy supply and demand are a mixture of advantages and disadvantages, not all of which were studied with the same rigour, and therefore it is not yet clear at this stage what synergies will develop.

Cross-sectoral impacts show synergies, some of which have already been mentioned. A partial list is given below:

- enhanced competition for available water for different end uses: electricity generation, irrigation, municipal purposes; it is recalled that assessed impacts on current large hydro systems are expected to be small, but significant impacts can appear for energy systems on dams mainly dedicated to agricultural purposes
- additional energy demand for water pumping (again, for irrigation and municipal uses)
- enhanced need of refrigeration water for thermoelectric power plants near rivers decreases surface flows – for instance the water loss via the refrigeration towers in the Pego coal-based power plant by river Tejo, is about 60% (PEGOP 2001) – and increases the water temperature near the outlet of the refrigeration circuit, which may aggravate biological impacts
- changes in regional energy demand (in particular at the coastal zones) as well as additional energy demand may result from enhancement activity in other sectors, *viz.* tourism, as a result of climate change itself
- changes in energy demand for fisheries prompted by fishing strategies directed to other species, other

fishing areas, *etc.* (note however, that the current related energy consumption is a very small fraction of the overall budget)

- changes in biomass availability for energy production (from both the forests and the agriculture sectors)
- changes in availability of residues for anaerobic digestion (urban, industrial and farming wastes).

## 9.4 ADAPTATION MEASURES

### 9.4.1 APPROACH USED TO DEVELOP ADAPTATION MEASURES

The energy sector is a particular case for which adaptation measures are often difficult to distinguish from measures directed to climate change mitigation, to ensure security of energy supply or to reduce environmental impacts of the energy sector. One typical example is the effort to augment the use of solar thermal energy. This furthers all three objectives mentioned above but can also be regarded as an adaptation measure. If, as estimated, more solar radiation becomes available as a consequence of climate change, investment in solar systems will become more attractive. Another example is energy conservation in buildings. A proposed EU Directive on energy efficiency in buildings makes mandatory all investments in energy conservation with a return of investment period up to 8 years. This makes sense from an economic perspective but may be also considered as a mitigation measure, or, in the long range, as an adaptation measure directed to moderate the increase in building energy consumption from climate change, in particular the increase of space cooling energy needs.

Furthermore, the modifications of the energy sector driven by climate change mitigation, security of supply strategies, and technological advances, are expected to be far more important than those that would result from climate change adaptation measures in a strict sense.

Meanwhile it can be argued that most demand side adaptation measures in the energy sector are in fact quite trivial in a business-as-usual situation. For instance, it would be just a question of "pushing a button" for an individual consumer to adapt to larger energy needs for space cooling in a domestic dwelling; also from the supply side, larger demand could be met simply with more primary energy imports. This is indeed likely in the short-run, although in the long run more efficient (and economical) adaptation would require changing energy related devices and infrastructures and the way that the energy is used.

Finally it must be remarked that some impacts are expected to be beneficial and thus no adaptation actions at all would be required for these cases. But even in these beneficial impact situations, adaptation measures should be taken, e.g. refurbishment of power plants in the northern basins to profit from higher winter runoff.

However, when 'adaptation' is mentioned in the energy sector context, this generally does mean 'mitigation', by use of measures or technologies that reduce or avoid GHG emissions. It must be stressed that mitigation is not an issue for the current phase of the SIAM study. Therefore one should kept in mind that the adaptation measures mentioned hereafter, obtained by expert judgement, are to be considered in a very strict sense and do *not* aim to be mitigation measures (although this often happens to be also the case).

### 9.4.2 THERMOELECTRIC POWER PLANTS

Decrease of the efficiency of thermal machines under warmer environment temperatures (air and water) is unavoidable, but as said before it is estimated to be very small and can probably be compensated by better design and operation of the equipments.

Difficulties to find adequate water supply can be compensated by adequate location of the new combined cycle natural gas plants programmed for the next decades, e.g. by choosing sites near river estuaries or the sea. However, these sites should be sufficiently above current sea level so as not to suffer from climate change driven sea-level rise.

Additional warming of water bodies near the outlet of refrigeration circuits should be compensated by longer channels, cooling ponds or other systems.

### 9.4.3 ELECTRICITY TRANSMISSION

Additional power transmission losses caused by higher temperatures can be compensated by a better management of the transport and distribution grids and efficiency gains elsewhere, e.g. at the transformers. Investing in distributed power within the urban environment is another option, making the generation sites closer to the consumption sites and thus avoiding transport losses (this is also a mitigation measure). Technological breakthroughs such as high temperature superconductors could also compensate the climate change related additional power losses.

### 9.4.4 HYDROELECTRIC POWER PLANTS

Adaptation to enhanced water availability for dams in the Douro and the Cávado-Lima basins would require some adaptation of the current water management procedures, and maybe the replacement of turbines to expand installed capacity. Conversely, for the case of systems located at the central (and eventually southern) basins, for which water availability reductions are expected, existing turbines should be changed to others with lower nominal power so as to cope with lower design flows.

Plants now being considered for agricultural dams and reservoirs should allow for climate change in their planning and sizing.

Competition for water with other end uses can sometimes be partially compensated by drawing water for these other purposes downstream of the flow, instead of at the reservoirs.

### 9.4.5 RENEWABLE ENERGY SYSTEMS (EXCEPT HYDRO)

Solar system yields seem to benefit from climate change and thus the adaptation required is simply to optimise system dimensions and sizing methods taking into account the larger availability of solar irradiation during summer – e.g. in the case of solar thermal systems, slight increase of panel inclination.

Wind and ocean systems seem to be neutral in respect to climate change according to the existing meteorological scenarios.

### 9.4.6 ENERGY NEEDS FOR WATER HEATING

As a reduction of energy need requirements is expected, adaptation measures could consist on resizing of some system components to profit from the new situation. However, sensitivity tests plus practical considerations on the way the systems are dimensioned and built indicate that such adaptations do not influence significantly the performance or cost of the system (per m2 of collector).

### 9.4.7 SPACE HEATING AND COOLING IN BUILDINGS

Most measures that can be envisaged to reduce space cooling demand in buildings also fall in the class of mitigation measures, therefore no priority was given to their analysis in this phase of SIAM, as they are being analysed by specific mitigation studies and plans, such as those currently being debated in the Renewable Energies Forum organised by the Ministry of Economy, and for the 2002 version of the Portuguese Programme for Climate Change.

However, some adaptation measures can be briefly mentioned. They include the use of vegetation to shield summer irradiation, architectural solutions such as overhangs, construction solutions such as additional or differently placed wall and window insulation, and eventually technological breakthroughs such as active coatings for windows and outside walls-e.g. 'intelligent' windows, colour changing paints. Lower internal gains as a result of less consuming equipments and lighting, and other demand side management measures, including a more rational operation of the houses – e.g. schedules for use of blind shutters, internal lighting, ventilation and air conditioning, washing machines – performed by users more aware of environmental problems and/or automatically by computer based systems (e.g. Chamusca and Matias 2000), could also contribute to avoid increased summer requirements.

Finally, it is remarked that regulations should and indeed must adapt progressively to climate change: for instance, the winter and summer zones currently defined in RCCTE (recall Fig. 9.3.6) naturally will have to be modified due to climate change over the course of time.

### 9.4.8 CROSS-SECTORAL IMPLICATIONS

Again in the case of cross-sectoral adaptation measures, the options available are mostly mitigation measures. Furthermore, the energy demand fraction from the agriculture, fisheries, forests, water supply and human health sectors, that are not specifically related with transportation or buildings, are quite small, therefore these issues were analysed only superficially.

Nevertheless some cases were examined: for instance, energy needs for water pumping for municipal uses or for irrigation. In this later case it could be suggested that either less water demanding species could be planted – in itself an adaptation of the agriculture sector – or reduce the planted area, which is not acceptable having in mind that the energy requirements involved are very small at the national scale. All other cross-sectoral potential impacts examined for possible adaptation gave similar trivial results.

Sea level rise effects however, are a case in which cross-sectoral implications can be large. As mentioned before, there are at least three large energy related structures potentially endangered by sea rise in Portugal. They are near or protected by harbour facilities, so they might share the costs of adaptation to sea rise with harbour and beach authorities.

## 9.5 RESEARCH GAPS

While developing this initial assessment of the impacts of climate change on the energy sector, several areas for further research emerged. This further research will permit the assessment of additional impacts and improve the estimates given for others. A list of these research gaps follows:

- Examine the detailed effects of higher environment (air and water) temperatures in the thermodynamic performance of thermoelectric power plants, in particular for the combined cycle natural gas technology
- More detailed analyses of the Portuguese electricity transmission grid to estimate power losses, including the consideration of the planned expansion of the grid and scenarios that include larger amounts of distributed generation.
- Modelling of large hydro dams for some case studies, including water balances in reservoirs, combined energy generation and flood management strategies
- Modelling of mini-hydro and agricultural dams for some case studies, including water balances in reservoirs, energy generation strategies, and irrigation management
- Modelling 'energy cultures' – sunflower in particular – to inspect the possibility of improved productivity of biomass for biofuels under enhanced $CO_2$ and winter temperature levels (currently the productivity is much lower than in other European countries, indeed the most serious obstacle to the take-off of biofuels in Portugal)
- Obtaining better information on wind pattern and seasonality changes in Portugal under global warming – much of the wind power is available due to sea/land breezes and specific summertime circulation over the Iberian Peninsula, that are not yet adequately modelled by current climate models
- Improve the impact assessment of higher ambient temperatures on the thermal performance of buildings, in particular for the service sector (additional types of building uses, projections), using short-run and long-run scenarios
- Address the impact of higher ambient temperatures on the energy requirements for space heating and cooling within vehicles, possibly by numerical modelling
- Improve the impact assessment estimates of energy needs for water heating, in particular for cooking and for industrial process pre-heat and heat
- Address the impact of additional energy needs for water pumping, using some case studies
- Study alternative strategies to reduce additional space cooling requirements in buildings (besides the studied case of improved insulation, which was not very effective)
- Performing additional impact studies at regional level, including for the Madeira and Azores archipelagos

- Translate to monetary values the energy impacts already estimated
- Implement and/or customize economic models to the energy sector study needs, in order to have a tool to evaluate impacts and adaptation (and mitigation) options under the economic perspective
- Improve socio-economic scenarios with respect to the energy issues, in particular the long term evolution of issues such as penetration of renewable energies, the evolution of different types of power plant technologies, price of fuels, the impact of climate change mitigation measures, and enforced and/or voluntary changes in energy use by consumers
- Study adaptation measures that coincide with mitigation measures in collaboration with other teams, projects or programmes.

## 9.6 CONCLUSIONS

The Portuguese energy sector is sensitive to the predicted climate changes, from both the perspectives of supply and demand. However, some of the impacts identified and studied are beneficial while others are harmful, thus the overall balance is not as yet clear. Regional differences also exist, mostly with a north-south gradient. Adaptation options exist, in principle not too difficult to implement if good planning exists, in particular because the general mitigation measures now being considered point towards the same direction.

Sea rise does not seem to be a big problem to large energy related infrastructures and plants: although some are indeed located close to the sea, they are either well above the sea level or protected by harbour facilities which themselves have to adapt to sea rise. Anyway cooperation with harbour and beach authorities will be required.

Modifications of the patterns of extreme events – wind, waves, floods – have not been found in the climate scenarios that could bring significant additional danger to large plants and energy related devices.

Changes in precipitation (and secondarily, evapotranspiration) should have a significant impact on hydroelectric production. However, the regional details, the changes of seasonality and the specific location of the plants makes unclear the overall impact in the production – the final result may even be positive despite the predicted decrease of mean precipitation levels. It is however, clear that hydropower plants located at, or planned for, the central and southern river basins should expect a decrease in the production as compared with the current climate situation. Enough water availability for refrigeration of thermoelectric power plants does not seem a large risk.

The information so far available on future mean levels, seasonality, and patterns of wind and ocean waves, does not imply significant impacts upon wind parks and ocean energy devices.

Climate scenarios show higher summertime solar radiation levels than nowadays, with beneficial consequences to the performance of solar systems, both thermal and photovoltaic. This impact would be insignificant within the current energy sector panorama, but becomes relevant when future energy sector scenarios are taken into account (with much larger share of electricity and penetration of renewable energies in the primary energy supply).

Temperature rise is by far the meteorological factor with the most impact upon the energy sector. Current thermoelectric power plants based on coal or fuel oil are almost insensitive to the temperature rise, but it may not be so for combined cycle natural gas and co-generation plants.

Significant additional losses in the transport and distribution of electricity resulting from higher line resistance are unavoidable *per se* and must be compensated by efficiency gains, lowering power flow in the grid using distributed generation closer or in urban centres, and eventually technological breakthroughs such as room temperature superconductors. Anaerobic digestion may benefit a lot with higher environment temperatures, making it an even more attractive process for waste decontamination and leaving a larger surplus of biogas available for electricity generation than today. Energy requirements for water heating can be substantially diminished, especially for domestic sanitary purposes and during pre-heating for industrial purposes. Large impacts from temperature rise (and extra summertime radiation) are expected for space conditioning in buildings and vehicles. The thermal performance of buildings was examined in detail. The results obtained point to energy savings due to a decrease of space heating thermal loads (for some regions even disappearing); however, for most regions even larger increases of space cooling thermal loads are expected. The results depend to an extent on the HVAC technologies used and the country's energy mix, but it is likely that the result will be a very significant overall increase of energy demand for space-conditioning. Considering better insulated buildings does lessen the problem, but in the long run and considering the SIAM socio-economic and energy sector scenarios, the demand increase still shows; to fully compensate this impact other measures would be required, e.g. adapted regulations, urban planning measures, advanced materials, and domotics (i.e. applied Information and Communication Technologies for more comfort and optimised energy use, in and around buildings).

With a rapidly changing energy sector, in Portugal as well as in the world, very much depends on the evolution of the socio-economic panorama to lessen or even profit from the effects of climate change. This will require close monitoring of the energy supply and demand, careful planning, sound and constantly refined information about the impacts and adaptation options and their costs, and synergies with the mitigation policies and measures directed to the energy sector now under consideration for the Portuguese Programme for Climate Change.

## Notes

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The words "generation", "production" and "consumption" of energy have been used throughout this chapter in a colloquial way for convenience of the reader, while it is recognized that strictly speaking they correspond rather to energy transformations from one type to another (e.g. chemical or potential to electromagnetic or thermal).

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The SIAM baselines for the energy sector were drawn based essentially on data available for up to 1998, with some exceptions for more recent information. As the energy sector panorama is changing very rapidly nowadays, in particular the electricity related issues, some of the information given herein may be outdated by the time this Report is published, a situation which is unavoidable. Also many statistics became available and many publications were issued during 2001, and even in the first months of 2002, often presenting quite relevant new data that the studies performed could not take into account.

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# 10

# Forests and Biodiversity

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## CONTENTS

## EXECUTIVE SUMMARY

Forest ecosystems cover one third of the Portuguese mainland territory and provide a wide range of goods and services. The high economical importance of forests is paralleled by its importance to biological diversity, as a part of the landscape mosaic. Forests are also active carbon sinks, removing a fraction of $CO_2$ from the atmosphere and thus contributing to the mitigation of the effect of greenhouse gas emissions.

Process based ecosystem models were used to assess forest responses to climate change and simulate changes in plant cover the HadRM climate scenarios. As forest fires are important constraints to forest development and production changes in the meteorological fire risk was also assessed using the Fire Weather Index. The impact of climate change in biodiversity was based on the results of the modelling exercise for changes in vegetation and focussed upon some of the large protected areas of the country.

The major impacts of climate change on forests and biodiversity in Portugal are:

- The future climate scenarios all predict greater water deficits to plants and animals when a CO2 concentration in the atmosphere twice the present concentration is reached. This will lead to a possible decline in productivity in most of the mainland territory and a north-west shift of the physiological optimal plant distribution, in comparison to the present.

- Meteorological fire risk increases substantially in all the country, both in severity and in the length of the fire season.

- The carbon sink strength in the future may be lower than today because primary productivity and standing biomass may decrease in most of the country due to drought, changes in vegetation and increase in fire frequency. Further decreases may occur as well due to enhanced soil respiration in warmer winters.

- Biotic invasions may be favoured by climate change, as indigenous ecosystems are exposed to increased environmental stress and climate becomes suitable to sub-tropical species. Some of this species may be pathogens or forest pests or mere invaders that will affect local biodiversity.

- Some of the present biodiversity in protected areas will be under increasing environmental stress and some landscapes (e.g., some of the "montado" areas) will be dislodged under the future climate scenario.

- Populations that have limited geographical distributions, small habitat areas, or low number of individuals, are more vulnerable to rapid climate changes. Extinction may occur in populations with low reproductive and dispersal capacity. In most cases, however, the effects of land use changes induced by human society are likely to override the long-term effects of climatic change on biodiversity.

# 10. Forests and Biodiversity

## 10.1 FORESTS

### 10.1.1 INTRODUCTION

Forests are complex ecosystems, usually characterised by high biological diversity. These complex systems provide mankind with goods (such as timber and fuel wood) and services, such as soil protection and recreational areas. The appreciation of forests has changed dramatically in our culture, from an undesirable landscape (up to the Middle Ages and beyond) to a romantic source of inspiration and beauty. Not only is there today a perception of forests as a key component of the biosphere, but also the increasing urbanisation of our society has led to an ever-growing need for outdoors recreation in forests and associated ecosystems. Today, the importance of forests cannot be viewed without considering their multiple uses. Nevertheless, most forests have a certain degree of specialisation. Most of forests in Portugal have an economic function providing raw materials to industry and are, in many cases, the result of deliberate afforestation/reforestation. Other forests remain less disturbed by deliberate human action and are considered as a repository of biological diversity.

Biological diversity has an ever-increasing importance in today's political and scientific debate. Whereas there is a consensus that some biological diversity is necessary for ecosystem function, a much larger number of species is needed to insure ecological stability in a changing environment (Loreau *et al.*, 2001). The impact of climate change on biodiversity relates not only to forests but also to all other ecosystems. For practical reasons we will focus on the terrestrial ecosystems of the mainland, even though aquatic ecosystems may be equally important and prone to change under the pressures of climate change.

In the following pages we will analyse, the impacts of climate change on forests. Some aspects of the impacts on the biodiversity of terrestrial ecosystems will be analysed separately on section 10.2.

#### 10.1.1.1 Overview of Forests

#### *10.1.1.1.1 General*

Forests cover today ca. 3,200,000 ha, i.e., 36% of the total area. The main forest tree species are: maritime pine (*Pinus pinaster*) 31%, cork oak (*Quercus suber*) 22%, holm oak (*Quercus rotundifolia* syn., *Q. ilex* ssp. *rotundifolia* or *Q. ilex* ssp. *ballota*) 14% and eucalypt (*Eucalyptus globulus*) 21%, according to the National Forest Inventory (DGFa, 2001). Mainland Portugal, as well as the whole Iberian Peninsula, is the confluence of Atlantic and Mediterranean ecological influences (Ribeiro, 1986). Although the native forests were virtually wiped out in the past, enough remain to surmise about the post-pleistocene natural vegetation. Broad-leaved deciduous trees would prevail in areas of strong Atlantic influence (e.g. the Northeast) and evergreen species would dominate the areas of stronger Mediterranean influence. A large proportion of the present-day forests represent semi-natural forests, i.e. plant communities resulting from secondary ecological succession with native species after farming or wildfire.

Areas of Mediterranean influence are characterised by long hot and dry summers and cool, rainy winters, which facilitates wildfires. Therefore, fire has played a role in shaping the vegetation and the landscapes, especially after the expansion of farming (Carrión *et al.*, 2000).

Maritime pine forests occur in a coastal strip, ranging from the Sado and Tejo basins to the Minho river basin. In the north and centre regions they extend inland, climbing up to 700-900 m in altitude, covering large continuous areas (Oliveira *et al.*, 2000). A proportion of these forests is the early phase of secondary succession after abandonment of agriculture or pasture, whereas others have been deliberately planted. Eucalyptus plantations cover today ca. 700,000 ha, mostly along the western coast in areas also suitable for maritime pine. These plantations are highly productive stands (in terms of biomass) of the exotic *Eucalyptus globulus* Labill. used to provide raw materials to the economically important pulp and paper industry.

The evergreen-oak stands (cork and holm), located in the south of the country are mostly "montados", i.e., semi-natural, agro-forestry systems. These open stands (usually the percent of ground area covered by tree crowns is below 50%) have been traditionally associated with cereal crops or livestock. The percent tree cover is, on average, much lower in the case of holm oak than cork oak "montados". The area of cork oak increased in absolute terms in relation to holm-oak after the economic value of cork began to increase in the middle of the 19th century (Radich and Alves, 2000).

The area of forests has changed over time. Since prehistorical times, agriculture (including livestock) has been one of the most important activities in the country, competing with forests for land (Mateus and Queiroz, 1993; Radich and Alves, 2000). As the need of wood for uses such as fuel and ship-building, and the need of land for agriculture and pastures increased, forest area decreased, resulting in the destruction of most of the natural forests. Since the end of the 19th century, an increased afforestation/reforestation effort has given rise to a considerable expansion of the forest area, possibly by 60% or more during the last 100 years (Radich and Alves, 2000). Fast growing pioneer species (i.e., species that can survive without the protection of other trees), such as maritime pine or, later, eucalyptus, were favoured. Most of the present area of maritime pine forest emerged by the beginning of the 20th century, with the exception of some minute areas of historical pine forests along the west coast. The fast-growing *Eucalyptus globulus* increased in importance with the establishment of the cellulose pulp industries.

Most of the forestland is privately owned (85%). Only 3% are owned by the State while 12% belong to the local communities (DGFa, 2001). In the north and central part of the country, where most of the maritime pine forest is located, the individual held plots are on average less than 5 ha. This creates serious challenges to forest management and protection. A great effort has been made in recent years to promote forest owners organisations, which have increased from 67 in 1998 to 128 in 2001 (Ruela, 2001).

Forestry and industries that process forest products are important to the national economy. It has been estimated that the economic value of forests is higher than 562 million € per year, excluding the recreational value, representing 3.4 % of the National Gross Domestic Product (based upon 1993) according to CESE (1998). In terms of net imports and exports, foreign trade contributes significantly to the national economy, amounting to a net 757 million € in 1999 (DGFb, 2001), as compared to a national deficit

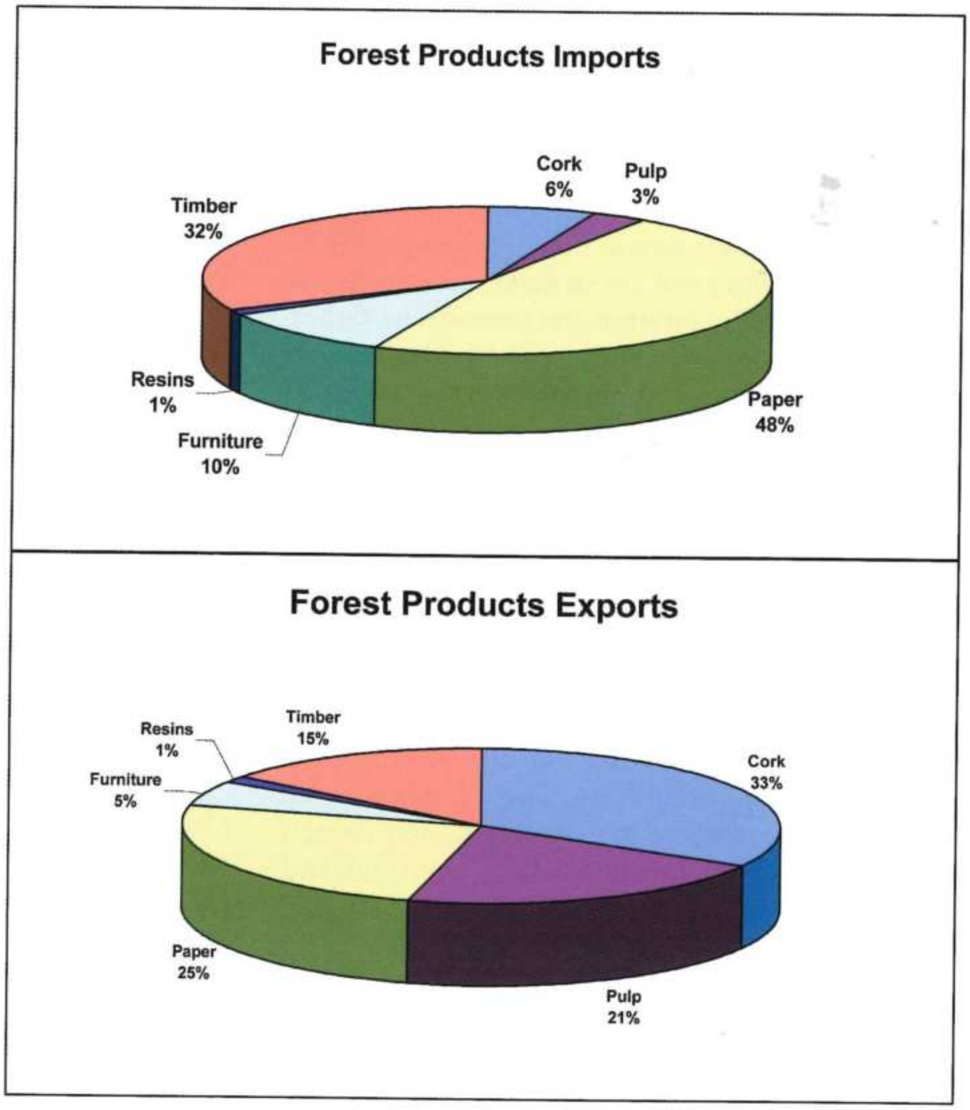

Figure 10.1 - Forest products imports and exports, revealing the importance of the cork, pulp and paper industries (DGFb, 2001).

of 14,448 million (INE, 2001). The distribution of imports and exports in products is shown in figure 10.1. The sector is estimated to employ 259,000 workers (about 6.1% of the total active population), although the official statistics only indicate ca. 100,000 (CESE, 1998). In spite of its enormous benefits to society, a large portion of forests lacks appropriate management. In the case of maritime pine, ca. 35% of the potential productivity may be lost through bad management practices (CESE, 1998).

The value of ecosystem services provided by forests is not easy to quantify. For example, in the dominant type of watersheds found in the country, forest cover on the slopes usually increases evapotranspiration and water infiltration into the soil, decreasing runoff as well as soil erosion. The high rate of silting of some rivers has been attributed to massive deforestation since the middle of the 19th century up to the 1940s in the mountains of Portugal and Spain. The roles of forest in flood regulation, as well as in soil conservation, are two of the most important services of the ecosystem and must be considered in watershed management.

#### *10.1.1.1.2 Portuguese forests and the Kyoto Protocol*

Another important service provided by forests in the context of climate change is the possibility to mitigate the consequences of greenhouse gases (GHG) emissions through carbon sequestration. Carbon dioxide is both the substrate of photosynthesis (and therefore for primary production) and a GHG. It accumulates in the atmosphere as the rate of release by burning fossil fuels and land degradation grows faster than the rate of assimilation by the terrestrial ecosystems and oceans. Forests play an important role in the global carbon cycle because they occupy large proportions of the terrestrial component of the biosphere and retain assimilated carbon in the ecosystem with an average residence time greater than in most other forms of land-use/land-cover (Schulze *et al.*, 2000; Watson *et al.*, 2000). This feature of forests led to the controversial "carbon sink" articles of the Kyoto Protocol (KP).

Article 3.3 considers that afforestation and reforestation can increase the terrestrial sink for carbon and thus reduce atmospheric $CO_2$ concentration. These afforestation and reforestation activities refer to the sink activity in the period of 2008-2012 of forests planted after 1990. Although there are problems associated with the definition of carbon sinks and with the consequences of fire and harvest in relation to forest stand age (Schulze *et al.*, 2000), this remains a major issue in the implementation of the KP. More recently, at the Sixth Conference of the Parties (COP6) in November 2000, the concept of sink management proposed in the KP was extended to consider the carbon gains and losses associated with forest management (Article 3.4). However, many doubts remain about implementation, such as how to separate the natural effects of elevated $CO_2$ "fertilisation" and N deposition from additional management activities under Art. 3.4. On the other hand, whereas Kyoto protocol favours young forest stands, some would argue that preservation of natural old-growth forests might have a larger effect on the carbon cycle because they store much larger amounts of carbon. If the carbon of these old forests would be released through land degradation or even reforestation with young forests, large amounts of $CO_2$ would be lost (Schulze *et al.*, 2000).

#### *10.1.1.1.3 Wildfires*

Wildfires have been for several decades a major threat to commercial forestry and a great socio-economic problem. The natural fire interval of 15-35 years, common in Mediterranean ecosystems, is long enough for fuel accumulation to support high in-

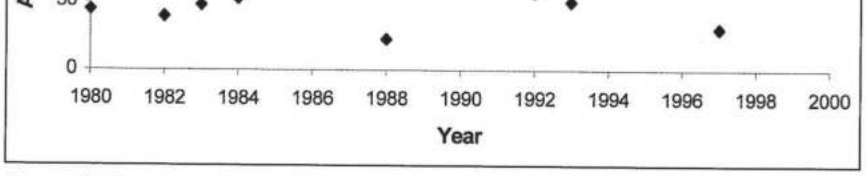

Figure 10.2 – Annual burned area in Portugal, 1980-'99 (data: Direcção-Geral das Florestas, DGF). The value for 1998 (●) is obtained from satellite-based burned area maps developed at DEF/ISA, since DGF's value of 158,369 ha represents a severe underestimation of burned area.

tensity burning, yet short enough that each generation of landowners can expect to experience a fire (Chandler *et al.,* 1983).

During the period 1980-2000, wildfires in Portugal burned an average of 94 000 ha per year. In the European Union, northwestern Iberia (i.e. Portugal and the autonomous region of Galicia, in Spain) is the region with the largest number of fires (50%), followed by the triangle Provence-Tuscany-Corsica (7%), and southern Italy (10%). The Iberian northwest also has the largest areas affected by wildfires, followed by southern Italy, and Greece (EC, 1996, 1998). Figure 10.2 shows fire incidence with time, over this period. Inter-annual variability of the burned area is large, ranging from a minimum of 22,434 ha in 1988 to a maximum of 225,171 ha in 1998 (the latter value was obtained from satellite data, and only includes areas larger than 5 ha).

In the context of climate change an important question is to know whether forest boundaries will change with climate. One of the major impacts of past climate change has been the extinction or migration of plant species. Paleoecological evidence clearly shows that plant species migrate long distances in response to climate change (Stohlgreen, 2000). Therefore, it seems likely that important changes in a number of forest limits may be expected under future climate scenarios. To answer the question of forest boundaries or the extinction/migration of key tree species regarding the Portuguese territory is complex because knowledge of the physiological tolerance limits of the different forest species is limited, and most of our forests have been planted, often pushing species toward their limits.

Under environmental stress, changes in vegetation will depend on the balance between mortality of adult trees and the establishment of new individuals. If regeneration of local species is inhibited, new species may intrude and lead to species substitution. By the same token, if competitive interactions between species are changed by weather oscillations, e.g., a series of extreme dry years, succession dominance hierarchies may also change, eventually leading to the substitution of dominant species. Due to extended longevity and late reproducing age of some tree species, the natural migration (i.e., not assisted by man) is only possible over time scales of centuries.

To analyse the impact of climate change in forests it is necessary to consider, first the ecological impacts as a basis for the evaluation of the socioeonomic impacts in the forest sector as a whole. In the following sections we will analyse the effects of future climate scenarios generated by SIAM (see chapter 2) on the productivity and survival of forests in the mainland. Special attention will be given to the role of forest fires and pests and diseases as indirect effects of climate change on forests. Adaptation and mitigation measures will be discussed within the frame of simulated responses to climate scenarios.

### 10.1.1.2 Effects of Climatic Variables on Forests

#### *10.1.1.2.1 Direct effects*

Forest composition and productivity changes mainly with climate and soil conditions as well as with the genetic potential and adaptation of plant species. Water availability and temperature represent major constraints to plant growth and survival. Climate determines the growth and survival and geographical distribution of plants, as well as the physiognomy and composition of plant communities and ecosystem function. The mere existence of forests is not possible below a lower limit of water availability, as determined by the ratio of precipitation over potential evapotranspiration (P/PET). For example at a P/PET<0.5, grossly equivalent to an annual rainfall of ca. 500 mm at our latitude, closed canopy forests are no longer the dominant ecosystems except along streams and well watered valleys.

Species differ in their capability to survive under limiting water conditions. For example, maritime pine (*Pinus pinaster*) is much less tolerant to drought than umbrella pine (*Pinus pinea*). These differences have to do with either the capacity of plants to avoid drought, extracting more water from the soil as it becomes drier, or through saving water by reducing transpiration. Species that use the water saving strategy may be less competitive than others in wetter climates but may prevail in drier climates.

The seasonality of rain is also very important. An increase in summer rainfall may boost plant productivity under Portuguese climatic conditions (Pereira and Chaves, 1995). In contrast, the increase in the length of the dry season and the recurrence of dry years, as may occur in future climate scenarios, may bring about increased tree mortality (Lloret and Siscart, 1995) and well documented reductions in forest productivity (Spiecker *et al.*, 1996). Indeed, it has been suggested that the longer dry seasons that occurred in the last two decades may have caused a decrease in maritime pine stand growth in wood volume (a surrogate for net primary productivity) in Portugal (Tomé *et al.*, 1996).

Average temperature and the annual variation in temperature also determine plant life-forms and productivity. For example, the length of the growing season in the temperate zone is largely dependent on winter temperatures, which may be cool enough to reduce metabolism to a minimum and stop growth. This would suggest that warming *per se* would increase growth, but the effect of warming on tree growth and forest productivity is difficult to measure (Spiecker *et al.*, 1996). Species differ widely in the lower temperatures that they can endure. For example, the Portuguese provenances of maritime pine are much less tolerant to cold than the French ones (Oliveira *et al.*, 2000). Likewise, species differ in the optimal and maximum temperatures for growth and carbon assimilation. It must be stressed that the reproductive phase and the survival of young plants are especially sensitive to weather conditions.

The influence of climate on forests cannot be reduced to average values of rainfall or temperature, but is also dictated by the occurrence of extreme events such as storms, extreme cold or extended droughts. For example, the concentration of rain in winter may enhance the probability of the occurrence of strong winds that may lead to massive windthrow and to the need of harvesting trees long before the appropriate harvesting age. These disturbances may be catastrophic in large areas. In late December 1999 a windstorm flattened nearly 500,000 ha of forest in France, which represented about 140 million m$^3$ of stand wood, the equivalent of 4 years of harvesting (INRA, 2001). The sudden and massive tree mortality caused by storms may impose several economic and ecological problems. In addition to the difficulties related to harvesting, the forest market may not be prepared to receive large and unexpected quantities of timber resulting from tree uprooting and breaking. In addition, uprooting and breaking of trees increase opportunities for pests and diseases, especially bark beetles and wood-borers, due to increased availability of material for insect breeding (see 10.1.3.5).

Droughts are another type of extreme event with great impact, as mentioned above. Consecutive drought years may accelerate soil degradation due, in part, to the delay or interruption of vegetation establishment, which protects soil against erosion.

There is evidence that past climate change induced dramatic alterations in vegetation with many species becoming extinct in large areas of the world. The vegetation of Portugal changed dramatically after the glacial period and began to approach its present composition and facies ca. 10,000 to 8,000 years ago (Blanco-Castro *et al.*, 1997; Mateus and Queiroz, 1993). For example, in the Quaternary, the expansion of cork oak area occurred as a result of climate warming and, in part, due to the increase in fire frequency as cork-oak replaced gradually species less resistant to fire (Carrión *et al.*, 2000).

#### *10.1.1.2.2 Carbon dioxide effect*

One of the important changes in the environment that has occurred in the last century is the increase in the carbon dioxide ($CO_2$) concentration in the atmosphere (ca. 31% since 1750). Since $CO_2$ is the substrate for photosynthesis and currently limits productivity, an increase in its concentration will lead to greater carbon assimilation and thus, stimulate growth. At the leaf level, increases in water use efficiency and changes in the foliar composition (namely decreased nitrogen concentration and increased starch and secondary compounds) are expected under these conditions (Ceulemans and Mousseau, 1994).

The effect on plant growth of elevated $CO_2$ concentration in the atmosphere, or $CO_2$ fertilising effect, may also contribute to an increase in plant production. This stimulation effect will persist until another factor (e.g., nutrient limitation, or water availability) becomes the limiting factor. In fact, an increase in productivity of up to 30% may be expected under conditions of $2xCO_2$ concentration, as was found for several relatively long-term field experiments in enriched $CO_2$ atmospheres across Europe (Medlyn *et al.*, 1999). However, there is a trend for lower responses to elevated $CO_2$ under low soil nutrient availability

(Poorter, 1998). This kind of response was found in cork-oak (*Quercus suber*) under elevated $CO_2$ where, after 4 years in an atmosphere of twice the present $CO_2$ concentration, growth was stimulated by 27%, but only when nutrients (namely nitrogen) were abundant (Maroco *et al.,* 2001). Under average conditions, an increase of 10-15%, in productivity was found due to elevated $CO_2$ while a further gain of 10-15% was related to the nitrogen deposition (Cannel, 1999).

#### *10.1.1.2.3 Indirect effects of climate variables*

The major indirect effects of climate variables are forest fires and plant/animal interactions. Another indirect consequence of climate may be the success of invasive species (see also 10.2).

##### Wildfires

Climate is related to forest fires through the control it exerts over the length and severity of fire seasons, and over the amount of forest fuel present (Chandler *et al.,* 1983). In most regions of the mainland, in addition to a climate characterised by hot and dry summers and rainy winters, vegetation is dominated by woody evergreen species that provide fuel for wildfires once ignition occurs in summer.

Some studies have addressed the relationship between meteorological conditions and the occurrence of wildfires in Portugal (Reis, 1981; Alves, 1993). Viegas and Viegas (1994) illustrated a direct relation between annual burned area and seasonality of rainfall. Precipitation from January to April is non-linearly related to burned area, peaking in the intermediate precipitation values. The proposed explanation is that with low rainfall, lower fine fuels (herbs, grasses, and fine branches of shrubs) production decreases the fuel load throughout the fire season. When winter and early spring rainfall is high, it provides an abundant soil water reserve that extends higher levels of fuel humidity through the early summer. Precipitation in June-September is inversely correlated with burned area, by means of short-term effects on the moisture content of dead forest fuels. The authors also mention that May precipitation is a good predictor of the onset of the fire season. June precipitation (the beginning of the typical fire season) reduces the burned area.

The magnitude and importance of ecological damages and economic losses caused by wildfires in Portugal has led to the development of a large and expensive infrastructure designed to support the prevention, detection and fighting against fires. Rating the daily meteorological fire danger is a key component of fire prevention and it is performed in Portugal by the Instituto de Meteorologia (IM) (Reis, 1998a) using the Canadian Fire Weather Index System (FWI) (van Wagner, 1987).

Weather is not the only factor affecting wildfires. In Portugal, the rugged terrain, common in parts of the country, the dominant evergreen and pyrophytic vegetation and the climate, with its long hot and dry summers, combine to create optimum conditions for wildfires. Demographic, as well as socio-economic trends that prevail in rural areas, reinforce the susceptibility to fire. Many rural areas have experienced a substantial population decline during the second half of the 20th century leading to the abandonment of agriculture and a reduction in the consumption of forest fuels (Silva, 1990; Rego, 1992). As happened throughout the entire Mediterranean region, areas of marginally productive agriculture have been either converted to forest plantations or abandoned to the natural processes of ecological succession, converting the land to shrublands and woodlands (Pyne, 1995; Moreno, 1999).

Figure 10.3 shows the extent and location of burned areas between 1990 and 1999 in Portugal. Fire incidence is higher in central and northern Portugal, where pine forests and shrublands are the dominant land cover types, and plant productivity is higher. A similar spatial pattern of fire occurrence had been described by Pereira *et al.* (1998) for the previous decade.

##### Pests and pathogens

Changes in climate variables may have a direct influence on insect pests and pathogens, affecting their survival and development, and an indirect influence through interactions between host species and natural enemies. Nevertheless, interactions between host plants and their natural enemies may be drastically altered by events such as extended droughts, fires or windfall. For example, plant water deficits play a major role, promoting *Phoracantha semipunctata* attacks on *Eucalyptus globulus* in Portugal

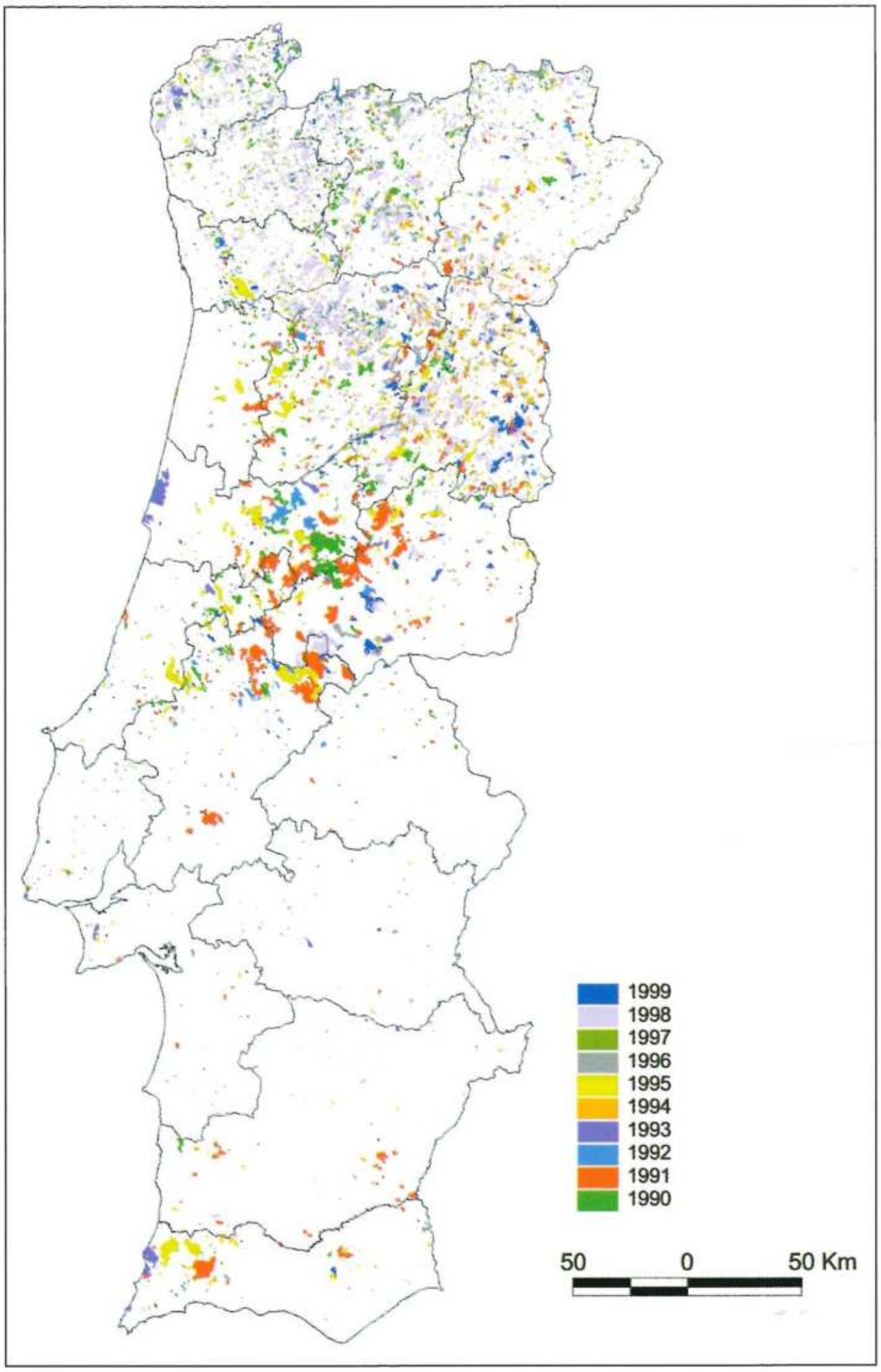

Figure 10.3 – Areas burned by wildfires in Portugal, 1990-1999, mapped with Landsat 5 Thematic Mapper imagery. The area burned is about 1.1 million ha, or 12.5% of the area of the entire country. Source: Department of Forestry, Instituto Superior de Agronomia, Technical University of Lisbon.

(Caldeira *et al.,* 2002). The consequent increased tree mortality and losses of production under drought jeopardised the economic feasibility of the crop in certain regions.

Low winter temperatures may also limit the geographic distribution of insects. The area of the pine processionary moth (*Thaumetopoea pityocampa*) has already been reported to have expanded in Europe due to recent warming (Hellrigl, 1995; Benigni and Battisti, 1999). In Portugal, mild winter temperatures are rarely a limiting factor for insect survival, reducing the risk of invasion by neighbouring species. Alien species, however, may pose a serious threat.

Determining the interaction between trees and other organisms requires the understanding of the complex interactions within foodwebs. An example of such situations is the difficulty in explaining oak decline in Europe during the last couple of decades. 15 years of research have not linked tree mortality to a single factor. Even though pathogenic fungus of the genus *Phytophtora* may be present in soils without damaging trees, it has been suggested that these pathogens might cause tree death under special environmental conditions such as dry years (Hansen and Delatour, 1999). This may also occur in Portugal in cork-oak stands (Pereira *et al.,* 1999).

Weather conditions may also have an important role in permitting or preventing biological invasions, which, in turn, may affect ecosystem processes (e.g., nutrient cycles or primary productivity) as well as biodiversity. In commercial forestry, invasions by woody alien plant species may negatively affect crops or other ecosystem services. Massive tree mortality due to climate (or wildfires) may strongly facilitate invasion by undesirable woody plants (e.g., *Acacia* spp.). This will be discussed in further detail in section 10.2.

## 10.1.2 METHODOLOGY

### 10.1.2.1 Description of assessment approach

Climate change *per se* as well as the land use policies that may emerge from the adaptation/mitigation measures related to climate change, may strongly affect the area covered by forests, as well as their nature.

#### *10.1.2.1.1 Forest composition and productivity*

With respect to forest composition and productivity, model simulation has proved itself as a powerful tool in the study of forest distribution and productivity, under past, present and future climate scenarios (Kaplan, 2001). Melillo *et al.* (2001) used a set of models to study changes in productivity and vegetation distribution in the conterminous USA under two climate change scenarios. They predicted increased plant productivity and carbon storage in areas where climate gets moderately warmer and wetter. In areas subject to periods of drought, reduced productivity and decreased carbon storage is expected. Woody vegetation would maintain or increase its territory in moderately warmer and wetter areas but might be replaced by grasslands and savannahs in the drier areas.

Cramer *et al.* (1999) compared 17 global models of terrestrial productivity, using standardised input variables. These models included three major types: models using as input satellite data (e.g., CASA), models of carbon fluxes using a prescribed vegetation structure (e.g., BIOME-BGC) and models that simulate both carbon fluxes and vegetation structure (e.g., BIOME3). Some regions showed greater differences between models, especially boreal forest in the summer and tropical evergreen forests in the dry season (Kicklighter *et al.*, 1999). Modelling of ecosystems subject to a long dry season is still subject to large uncertainties, producing in most cases the larger differences between models. Still, Cramer and Field (1999) recognise that many basic features known from direct observation are precisely modelled.

Saporta *et al.* (2000) did an extensive literature review of impacts of climate change on Canadian Forests. They identified possible increases in plant growth, due to increased temperature and increased carbon dioxide concentrations. Under the expected climate change, occurrence of drought increases in some regions, as well as forest fire intensity and frequency. Carbon sink capacity will also be affected, strongly depending on the rate of temperature increase, that controls decomposition rates. A northbound shift in the current ranges of species and communities is also expected, although limited by natural and anthropogenic obstacles.

In Europe, the ACACIA Report (Parry, 2000), presented a full review of the current knowledge of the potential impacts of climate change in Europe across sectors. In the Mediterranean region the adverse effects of climate change will be greater, than in northern Europe, with increased desertification, water shortage and forest fires. Increasing temperatures and the moderate decrease in annual precipitation in southern Europe may reduce forest productivity, even if balanced by some $CO_2$ fertilisation. In northern Europe, however, forest productivity may increase as a result of higher precipitation and temperature, increased $CO_2$ concentration and nitrogen deposition.

#### *10.1.2.1.2 Wildfires*

Recently, several studies have forecasted reductions in timber harvesting in Mediterranean regions of Europe, in association with increased drought and fire risk (Hulme and Sheard, 1999; Parry, 2000; McCarthy *et al.*, 2001). The effects of warming on the risk of fire in a Mediterranean region, was analysed by Piñol *et al.* (1998) in north-eastern Spain using ground station data. They calculated fire danger from two meteorological indices, one designed to estimate fine dead fuel moisture, and another one more closely related to fine live fuel moisture. Mean values of each index for the period June-September during 1968-'94 were correlated with the annual number of fires and burned area, with statistically significant results. Higher correlations were obtained between fire danger index values and the number of fires than with area burned. The number of days with very high fire danger index values was linearly correlated with the number of fires, and exponentially correlated with the burned area. In spite of not considering the effects of land use and land cover changes during the period under analysis, Piñol *et al.* (1998) concluded that a drying and warming climatic trend observed in recent decades is likely to have contributed to increased fire activity in NE Spain since 1968.

Global Circulation Models (GCMs) are considered to be the best available tool to evaluate the impact of future climatic change on fire danger, at coarse scales (Flannigan and Wotton, 2001). Various studies have addressed this problem in boreal (Flannigan and van Wagner, 1991; Flannigan *et al.,* 1998; Stocks *et al.,* 1998), temperate (Torn and Fried, 1992; Beer and Williams, 1995), and tropical biomes (Goldammer and Price, 1998) but, to the best of our knowledge, no GCM-based studies of future fire danger have been performed for any European country or region. We briefly review two studies conducted in temperate biomes, which are considered more relevant for comparison with Portugal.

Torn and Fried (1992) used three different GCMs and a semi-empirical fire behavior model to assess fire danger under a $2xCO_2$ atmosphere in California, in a study area with chaparral, grasslands, and redwood forests as the dominant land cover types. All changed climate simulations projected an increase in the number of days capable of promoting severe fire behavior (i.e. rates of spread > 1.6 $km.h^{-1}$), with a consequent increase in burned area. Projected changes in precipitation were not considered as an important determinant of fire danger increase, since summer precipitation is already very low under current climatic conditions. In spite of a projected rise in summer temperatures, an increase in wind speed was identified as the main cause of higher fire danger.

Beer and Williams (1995) assessed the risk of fire with the McArthur fire danger index (McArthur, 1977) with future ($2xCO_2$) climate scenarios for Australia. The models projected an increase of fire danger over much of Australia under $2xCO_2$ conditions. Annually averaged daily relative humidity was considered the most important variable in estimating fire danger on an annual basis, although the models used slightly underestimated relative humidity and overestimated fire danger.

#### *10.1.2.1.3 Pests and pathogens*

In respect to forest pathogens, climate is expected to favour its incidence, but poor knowledge of population dynamics and of the complex web of interactions between environment, hosts, pathogens and human management render impossible the precise identification of impacts (Parry, 2000; Burschel and Huss, 1997). Many individual species can be favoured by climate change, e. g., the pinewood nematode (*Bursaphelenchus xylophilus*) and its vector, *Monochamus* beetles, or the chestnut blight disease, caused by *Cryphonectria parasitica.*

### 10.1.2.2 Description of options selected for analysis

The methodology adopted in this study consisted of model simulations using the climate scenarios supplied by SIAM, expert analysis supported by quantitative data and a thorough literature review. A great deal of effort was invested in simulating changes on vegetation's distribution and productivity, as well as changes in the meteorological risk of forest fires.

#### *10.1.2.2.1 Forest productivity and carbon balance*

Primary (plant) productivity is a key ecosystem function, it is important as the source of raw materials and gained a new importance in the context of global changes with the discussion of GHG emission mitigation mechanisms. The carbon cycle can be characterised by fluxes and stocks. The carbon fluxes can be quantified, by the gross primary production (GPP; carbon assimilation by photosynthesis), net primary production (NPP; the fraction of GPP resulting in plant growth after discounting plant respiration, Ra), net ecosystem production (NEP; what is left after taking into account heterotrophic respiration, mainly from of soil organisms, Rh), and net biome production (NBP; taking nonrespiratory losses such as fire and harvest into account). When we consider ecosystem function, the main component is NPP, but when carbon sequestration is at stake it is NEP that matters, i.e., the carbon left in the system in the medium term. In the long term, carbon taken away from the biogeochemical cycle may be quantified by NBP.

Some of the commonly used process based models are biogeochemical and biogeographic in nature. Biogeochemical models (e. g. BIOME-BGC, Running and Hunt, 1993) simulate material or energy fluxes through compartments of the ecosystem (e. g., canopy, stems, litter, roots, soils), biogeographic models simulate the distribution of vegetation types throughout the globe, often including a biogeochemical core as well, e.g., DOLY (Woodward *et al.*, 1995 in Shugart, 1998), BIOME4 (Kaplan, 2001).

We used a biogeographic model, BIOME4 (Kaplan, 2001) to assess changes in biome composition and primary productivity in a $2xCO_2$ climate scenario in mainland Portugal. It is an equilibrium terrestrial biosphere model that evolved from the BIOME3 model of Haxeltine and Prentice (1996). BIOME4 is a coupled carbon and water flux model that predicts vegetation distribution, structure and biogeochemistry. The model is driven by monthly averages of temperature, precipitation, cloudiness and minimum absolute temperature. In addition, the model requires soil property information. For that purpose we used data from the Digital Soil Map of the World and Derived Soil Properties (FAO, 1995), as no other compatible source was available for the extension of mainland Portugal. The model predicts the dominant biome (major phyto-geographical area within which there may be many different kinds of ecosystems) by first selecting potential plant functional types through a bioclimatic sieve. Then, net primary production calculated for each selected functional type is used in a competition routine to assign a biome (Kaplan, 2001). One of its advantages is the detailed biome descriptions, that allow it to characterise fairly accurately the potential Portuguese vegetation distribution, unlike most models commonly used at a global scale. On in this work we focussed the analysis on vegetation distribution and net primary productivity.

During the exploratory tests to simulate NPP, we found that the model overestimated the fertiliser effect of increased atmospheric $CO_2$ concentration on vegetation. This may result from the fact that plant respiration costs may respond more strongly to increase gross productivity (induced by elevated $CO_2$) than parameterised in the model (Kaplan, personal communication). The eventual constraint on the $CO_2$ fertilisation effect of the availability of nutrients such as phosphorous (P) or nitrogen (N) may be another source of overestimation. In these circumstances, we made adjustments to produce a reasonable $CO_2$ response according to the literature (Medlyn *et al.*, 1999; Cannel, 1999).

Whereas BIOME4 estimates NPP from a most probable potential vegetation, the response of unchanged vegetation requires a different approach. The Biome-BGC model (Thorton, 1998) was used to assess changes in productivity assuming no changes in vegetation distribution. It is a biogeochemical cycle model that couples carbon, nitrogen, water and energy fluxes. It is driven by daily minimum and maximum temperature, precipitation, water vapour pressure deficit and downward short radiation flux. The model also uses information on soil properties and vegetation ecophysiological parameters that must be prescribed. The parameterisation of the model was greatly hampered by the scarce physiological information on native species. Thus, we restricted its use to simulate changes in cork-oak woodlands. We hypothesised that holm oak woodlands would be similar to cork oak in their response to climate change, as there are even fewer studies on this species in the context of the western Iberian Peninsula.

In addiction to changes in potential vegetation types, the response of the most important tree species to the future climate scenario was analysed. Generally, plant species occupy a subset of possible habitats to which they are adapted to, in terms of both growth and reproduction (Bazzaz, 1996). However, when the physiological tolerance limits of species has been reached, individuals either adjust to the new conditions, relocate to more suitable habitats or become extinct. Knowledge on the physiological stress tolerance under specific site conditions is limited, particularly in the case of major forest species – cork oak (*Quercus suber*), holm oak (*Quercus rotundifolia*) and maritime pine (*Pinus pinaster*). It can be inferred from observations of geographical distribution and some scanty experimental evidence, but current forest distribution is strongly affected by man, adding uncertainty to this analysis.

In the absence of experimental evidence on the environmental stress tolerance limits, we used geographic distribution and climatic indices (e.g., Index of Emberger, IE) to support expert judgement about future migration/extinction of keystone tree species. These species are crucial for the maintenance of communities because they typically provide the greater part of energy flow and the physical structure that supports and shelters other organisms (Barnes, *et al.*, 1980). The IE is calculated as $Q_2 = \frac{100 \times P}{(M + m) \times (M - m)}$, where P stands for precipitation, M the maximum temperature and m the minimum temperature. It was used to describe the climate tolerance limits of Mediterranean major tree species (Quézel, 1976). We analysed the Emberger diagrams for three of the most important woody species: maritime pine, holm oak and cork oak. These represent the major forest ecosystems in terms of area, economy and ecological importance. We calculated IE using the current climate (30 years observation averages) and under the control scenario, and compared it with published diagrams to assess its reliability (Quézel, 1976). Subsequently we calculated IE using the future climate scenario.

#### *10.1.2.2.2 Fire regime*

Regarding forest fires in future climate scenarios, it is still virtually impossible to assess all the variables involved. Therefore, this study is based on an assessment of meteorological fire danger under the HadRM scenario as modelled by the changes in the fire weather index (FWI) for various weather stations. The FWI is currently used in Portugal in the prevention of forest fires. Support for the use of this index was provided by Viegas *et al.* (1994), who compared the performance of various indices for fire risk assessment using weather data from southern Europe, and concluded that the Canadian FWI and a modified version of the Nesterov index, previously developed at IM (Reis, 1989) showed the better overall performance. Reis (1998b) also reviewed various meteorological fire danger indices and concluded that the FWI had the better predictive ability for the number of daily fires in Portugal (see also 10.1.1.2.3).

The FWI System integrates the effects of postulated future values of temperature, precipitation, relative humidity, and wind speed, in a quantitative index proportional to the intensity of heat release at the flame front of a vegetation fire and to the effort required to extinguish it. The FWI depends only on daily measurements of dry-bulb temperature, 10 meters open wind speed and 24 hours cumulated precipitation. Typically, such data are available from numerical weather model and surface observations. The FWI calculates fire danger based on the moisture of surface litter and duff located under forest cover structure representative of a generic pine forest. The FWI fuel moisture and fire behaviour calculations rely primarily on empirical relations between weather conditions, fuel moisture and fire behaviour data (Pyne *et al.*, 1996).

We used the climate scenarios to calculate FWI for each of the weather stations. The FWI scale is non-linearly related to the effort needed for fire control. Therefore, FWI is not considered the best choice for spatial and/or temporal averaging (van Wagner, 1987). The daily severity rating (DSR), proposed by Williams (1959), is a more linear indicator of fire control effort, and therefore is preferred for averaging through time and across sites. The relationship between DSR and FWI is:

$$\mathrm{DSR} = 0.0272\ \mathrm{FWI}^{1.77}$$

The seasonal severity rating (SSR) at a given location, which is the mean of DSR over an entire fire season, has been used in several studies of the effect of climate change on fire weather (Flannigan *et al.*, 1998), and was also used in our analysis.

#### *10.1.2.2.3 Pests and pathogens*

The approach used to analyse the impact of climate change on pests and diseases was based on expert judgement due to the complexity of processes and feedbacks involved and the lack of consistent and reliable information essential for the modelling approach. The definition of impacts was based on a complete review of the literature on the most important pests and diseases affecting national territory with the support of Emberger Index empirical relationships and future primary productivity distribution (see 10.1.4.3 and 10.1.4.4).

### 10.1.2.3 Description of data used

#### *10.1.2.3.1 Climatic data*

We used the averages of observations made during the period of 1961-1990 by the Instituto de Meteorologia to calculate the Emberger Index. The variables used were annual precipitation, average minimum temperature of the coldest month and average maximum temperature of the hottest month.

We used the daily observed values of noon temperature, precipitation (12h-12h), noon wind speed and noon relative humidity to calculate FWI corresponding to the period 1988-1997 (except Viseu, where the period was 1991-1997), for comparison with the HadRM control scenario's FWI.

For model simulating purposes, we used the HadRM daily climatic scenarios, both control and future scenarios. According to model specifications, we transformed the variables as listed below:

**Biome4 model**

| *Input HadRM variable* | *Transformation* |
|---|---|
| Daily average temperature | Monthly average |
| Daily average precipitation | Monthly average |
| Daily short-wave radiation | used to estimate monthly cloudiness |

**Biome-BGC**

| *Input HadRM variable* | *Transformation* |
|---|---|
| Daily maximum temperature | None |
| Daily minimum temperature | None |
| Daily total precipitation | None |
| Daily total short-wave radiation | None |
| Daily average temperature | used to estimate water vapour pressure deficit |
| Daily average relative humidity | used to estimate water vapour pressure deficit |

**FWI**

| *Input HadRM variable* | *Transformation* |
|---|---|
| Daily maximum temperature | Corrected for altitude and used to estimate noon temperature |
| Daily total precipitation | used to estimate noon precipitation |
| Daily average wind speed | used to estimate noon wind speed |
| Daily average relative humidity | used to estimate noon relative humidity |

### *10.1.2.3.2 Forest management options*

The response of forest stands to climate change is related to changes in growth conditions, which in turn are manipulated by silviculture. The quantity and quality of wood and other forest products is also expected to change as a result of changes in forest composition and productivity. New supply/demand conditions will most likely affect the market of forest products. Forest use may be reoriented to services other than timber or pulp production, such as tourism and recreation. To some extent, an appropriate management can counteract some of the negative impacts of climate change.

Under the threat of climate change, several options of forest management may be considered. We list below the main options available to the sector. The general objective as well as the specific forest management objectives are presented for each option. Possible impacts on industry and potential impacts on the national economy are also mentioned.

- Option I — Multifunctional silviculture

**Overall:** Enhancing quality timber production and associated resources with environmental and landscape concerns.
**Management objectives:** Wood and cork production for internal and external markets, meeting environmental and landscape concerns. As higher quality products are promoted furniture and veneer industries may reduce their external dependence on raw material. On the other hand, supply of lower quality material to industries (such as pulp or fibre board industries) may experience increased shortages.
**Risks to Forest Industry:** Increase of wood and cork imports due to reductions of supply.
**Impact in Economy:** Industry transfers to regions where supply is assured.

- Option II — Monofunctional silviculture

**Overall:** Ensuring timber and cork supply to industries.
**Management objectives:** Optimise sustainable wood and cork production; prioritise afforestation/reforestation with fast growing species (softwoods and eucalyptus) and cork oaks.
**Risks to Forest Industry:** Maintenance/increase of the installed industrial capacity; positive effects in employment and added value.
**Impact in Economy:** It may be difficult to meet non-commercial management objectives; lack of proper legislation and technical guidance.

- Option III — Natural silviculture

**Overall:** Optimising the environmental functions of forests as a component of the landscape.
**Management objectives:** Preference for natural or mixed forests. Raw material production is considered secondary; possibly leading to a reduction of afforestation. Increase of natural areas, both forests and shrublands.
**Risks to Forest Industry:** Strong decline of industries with negative effects on employment and added value.
**Impact in Economy:** Difficulties in financial support of these areas, particularly in road building, fire prevention and surveillance.

## 10.1.3 IMPACTS OF CLIMATE CHANGE UPON FORESTS

### 10.1.3.1 Overview

Ecosystem functioning and services, industrial raw material production as well as the forest capacity for carbon sequestration, depend on primary (plant) productivity. In parts of the country where water availability is not expected to be limiting, the combination of warmer winters with elevated $CO_2$ are expected to increase NPP in the future. Such gains are expected to occur in the cooler and wetter areas of the country. In most of the country, however, the present vegetation will be under greater environmental stress than today and NPP may decline. Some tree species may experience severe mortality in the drier edges of the their present range. Changes in the dominance of some species are likely to occur with changes in the boundaries of forest types.

The frequency of extreme events such as windstorms, severe droughts or long hot spells, together with increased risk of fire, will increase under the future climate scenarios. A very substantial increase in meteorological fire danger may occur due to the extended dry season.

Climate changes may also indirectly affect forest productivity and survival, modifying plant interactions with other organisms. Warmer winters may change some insect populations, increasing their growth rates. In the areas where increased aridity may be expected, the damage caused by some pests may be enhanced, as trees become more vulnerable in result of stress. Warmer temperatures, when accompanied by higher humidity, may increase outbreaks of pathogenic fungi leading either to the death of trees or increasing their vulnerability to pest attacks and drought. Warmer and wetter winters in the north and central regions of the country could increase the risk of invasive pathogens. Similarly, the risk of invasion by tropical or subtropical pests and diseases may increase under the globalisation of commerce and the "tropicalisation" of the climate.

The effects of climate change on forests may have a strong socio-economic impact. Today, maritime pine, eucalypt, and cork oak forests generate most of the revenue of the forest sector. Maritime pine and eucalypt mainly occupy the regions of greater Atlantic influence. Increased aridity or forest fires may decrease the overall productivity of these forests and put a stress on industry supply of native raw material. A similar situation may also occur in the cork-oak area, despite the fact that a great deal of planting has already occurred with this species.

Presently, all industries are fairly under-supplied, as illustrated by import/export statistics (DGFb, 2001). Within the timber sub-sector, there is a deficit of 148.6 million €, which amounts to 65% of total imports (excluding pulp and paper sub-sector). Timber imports clearly illustrate the inability of the domestic market to supply higher quality timber, as 35% of total imports correspond to tropical broadleaf logs and sawn broadleaf timber. These statistics show that industries, such as furniture or veneer, are already dependent on external markets to meet the demand, and therefore, a greater shortage in the future would not have a compelling impact.

The cork and pulp and paper industries are predominately supplied by national resources, as illustrated in figure 10.1. In the pulp industry, imports amount to 13% of the total volume of eucalypt and 16% of the pine volume in 1999. In 2000, these values were 8% for eucalypt and 19% for pine (Celpa, 2001). Future declines in productivity will have a great impact on these industries. Pulp and paper industries are vulnerable because of their dependence on national production, although it is possible to meet the demand through imports, as eucalyptus and pine are produced in many parts of the world. The cork oak industries are the most vulnerable because most of the cork is processed internally and foreign production is not enough to meet the industrial demand.

Changes in major biogeochemical cycles, namely the nutrient and hydrological cycle, are also expected. Depending on forest disturbance level, the nutrient cycle may be particularly affected due to changes in nutrient retention and decomposition rates with feedbacks on productivity and carbon storage. Changes in carbon allocation and storage in the ecosystem as a result of changes in forest composition and ecosystem function may influence both forest productivity and source/sink capacity in the context of the KP. Even if this is not a major issue in Portugal, nutrient deposition (mainly of anthropogenic origin), nitrogen in particular, might affect positively forest productivity in combination with the $CO_2$ fertilisation effect.

Forests play an important function by regulating the water regime and preventing soil erosion. An alteration in forest cover may exacerbate soil erosion processes, whether physical or ecological. This problem may be especially important if extreme precipitation events increase in the future, increasing runoff, and/or future climate conditions preclude the establishment or development of vegetation. Therefore the risk of desertification may increase in the more arid zones of the country.

In this section we will evaluate some of the impacts of climate change on the major forest types of the mainland. The socio-economic impacts, as well as the interactions between forests and other systems (e.g., the water resources) will not be dealt with in this report.

#### *10.1.3.1.1 Detailed list of impacts*

##### 10.1.3.1.1.1. Identified impacts

Climate critically influences forest structure and composition in many ways, either directly or indirectly. Here, we mention all the impacts possible, including those that could not be studied at length, but that may deserve future study.

- Forest productivity
- Distribution of forest types
- Fire regime
- The carbon sink capacity of forests
- Supply of wood products and cork
- Recreational uses
- Biodiversity
- Pathogen outbreaks
- Introduction of invasive species
- Desertification

##### 10.1.3.1.1.2 Studied impacts

Time constraints and the lack of information regarding specific issues (e.g., detailed biological data on native species, recreational use) impeded the study of all of the above impacts. We chose to focus our analysis on forest productivity, the distribution of forest types, fire regime, the carbon sink capacity of forests and pathogen outbreaks because of their importance and feasibility. Biodiversity is treated separately in section 10.2.

### 10.1.3.2 Forest productivity

Net primary production (NPP) determines ecosystem function and forest products output. On the other hand, plant mortality due to climate change will be reflected in NPP as well as changes in biogeochemical cycles and soil fertility. The main components of climate change that may affect NPP are: warming, elevated carbon dioxide concentration in the atmosphere and changes in water availability. In addition, these changes may induce modifications in vegetation composition that may change the way plants respond to the environment, and their productivity.

#### *10.1.3.2.1 Changes in the distribution of potential forest types*

The simulation with BIOME4 integrates the analysis of shifts in biome distribution – representing the geographical dominance of broad vegetation types – in response to a changing environment, providing an estimate of primary production.

In the control scenario (HadRM simulation of the current climate), temperature and precipitation represent reasonably well the current climate, although it was found a small cold bias for annual temperature in the north (see chapter 2). Precipitation was found to be excessive in some parts of the country, such as the coast north of Lisbon and the Montejunto-Estrela ridge.

Figure 10.4 shows the distribution of forest biomes under the control scenario. The simulated biome distribution under this climate scenario reproduces the actual potential vegetation distribution reasonably well. The mixed warm temperate forest biomes are assigned mainly to areas of Atlantic influence, whereas those of the sclerophyll woodlands and shrublands are assigned mainly to the Mediterranean zone. The shrubland biome is present only in the southern Alentejo, at the sites corresponding to the driest and warmest parts of Alentejo. In the Serra do Gerês, the prescribed biome is a deciduous temperate broadleaf forest typical of its mountain maritime climate with high precipitation – Atlantic vegetation (Blanco-Castro *et al.*, 1997).

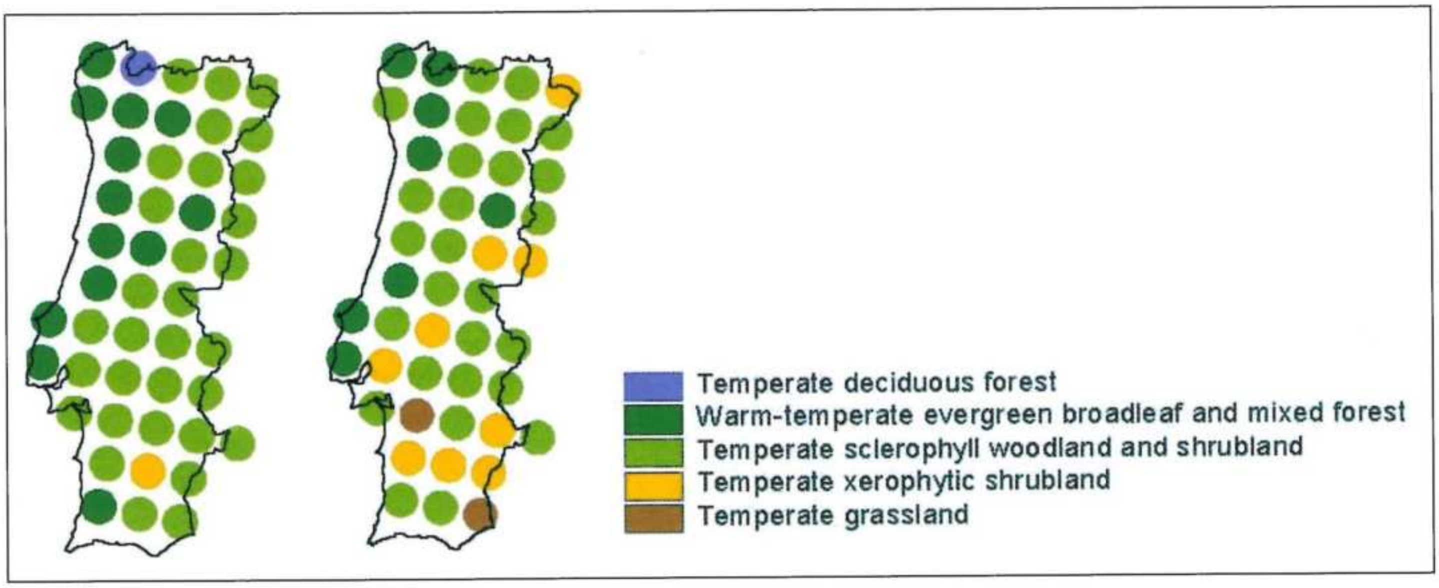

Figure 10.4 – Distribution of the main biomes present in Portugal under the control scenario (left) and future scenario (right).

### *BOX – BIOMES IN PORTUGAL (MAINLAND)*

Biomes are broad physiognomic vegetation types, where one or more plant functional types (e.g., evergreen conifers or deciduous broadleafs) dominate. See figure 10.4 for the distribution of the simulated biomes in Portugal.

*Temperate deciduous broadleaf forest*

This biome is defined by the dominance of summergreen broadleaf trees. In Portugal, it corresponds to ecosystems of deciduous oak forests. It only appears as the dominant biome in the highest sites of Gerês due to its high precipitation requirements. In the rest of the country it only exists in high altitudes (such as the bottom of high valleys with fertile soils) in regions of Atlantic influence.

*Warm temperate evergreen broadleaf and mixed forest*

These biomes are mixed and pure forests (multi-specific and mono-specific) of broadleaf and/or conifer trees. In terms of potential vegetation, these would be mixed oak forests (several species of oaks according to the region) in the more fertile sites and pine forests (both mixed and pure) in the poorer soils. The vegetation that exists today in these areas is mostly pine and eucalypt plantations, mainly resulting from agriculture abandonment.

*Temperate sclerophyll woodlands and shrublands*

Low-density forests of evergreen sclerophyllous trees (i.e., with a leaf anatomy adapted to mitigate the effects of summer drought) such as cork oak *(Quercus suber)* and holm oak *(Quercus rotundifolia)* are characteristic of this biome. Where soil fertility is too low or summer drought more intense, shrubs can become the dominant species.

*Temperate xerophytic shrublands*

This biome is dominated by non-tree species, namely xerophytic shrubs (plants that live in dry conditions). Trees would only exist in sheltered places, such as north facing slopes or along streams (i.e., riparian forest communities located on river floodplains and the stream channel, see also 10.1.4.5).

*Temperate grasslands*

Temperate grasslands are ecosystems dominated by herbaceous plants that are prescribed where the climate is too harsh for woody plants to dominate.

Under the future climate scenario, longer, more frequent and more intense drought periods are expected. Water stress will therefore be a leading constraint to primary production (see chapter 2). The combined effects of drought and high temperatures will bring about further decreases in carbon assimilation. On the positive side, the higher $CO_2$ concentration may bring about increases in photosynthesis and higher winter temperatures may induce a longer growth period and thus, a potentially greater productivity. As NPP changes, more productive vegetation types will tend to substitute the less productive.

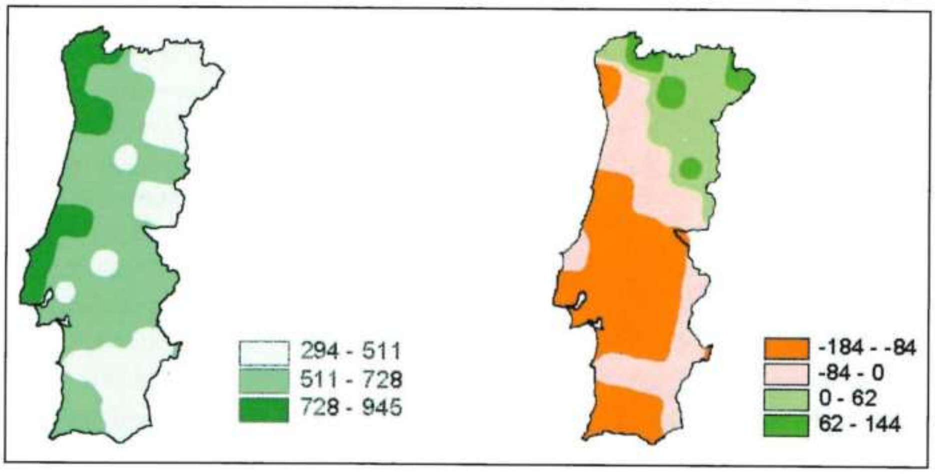

Figure 10.5 – Net Primary Productivity (gCm$^{-2}$yr$^{-1}$) for Continental Portugal, as modelled with BIOME4 under the control scenario (left) and future scenario (right).

In the future scenario, the simulation with the BIOME4 model predicted a decrease of woodlands and shrublands in the southern region, and a replacement by either shrublands or grasslands, respectively. In the north, the model predicts that sclerophyll woodlands will replace a portion of the warm mixed temperate forests. There is a tendency for migration of the southern vegetation to the north. For example, woodlands (e.g., cork and holm oak stands) are replaced by shrublands and or grasslands in the south and in the north they replace some areas of warm temperate mixed forests.

### *10.1.3.2.2 Net Primary Productivity*

The net primary production (NPP, in gC m$^{-2}$ yr$^{-1}$) predicted by the model BIOME4 is illustrated in figure 10.5. NPP follows closely the precipitation and temperature trends, decreasing from zones with high precipitation and mild temperature to zones with low precipitation and harsher temperatures. The modelled NPP for the control scenario is reasonably accurate, according to experts' opinion, and in the absence of other estimates of NPP at the national scale. There are, however, some exceptions: in the northern coastal area, the predicted NPP seems lower than reality, which may result from an exaggerated model sensitivity to low winter temperatures in the control scenario. Also, in the Tagus River Valley, an area of potentially high productivity, the modelled NPP is lower than expected, most likely due to an underestimated precipitation of the HadRM control scenario. The high productivity of the area is also related to the flow of the Tagus River, which is not explicitly modelled.

In some northern areas, a higher future NPP might be expected, as a result of the combined effects of elevated CO$_2$ and warmer winters (figure 10.5). In these regions, low winter temperatures currently limits the growing season length. If changes in precipitation are moderate, productivity may increase. Also, the control scenario has a small winter warm bias, which may enhance this trend. An increase of the duration of the growing season length of several days has already been observed in Europe, in the last three decades (Menzel and Fabian, 1999). In maritime pine, which has frequently only one shoot growth

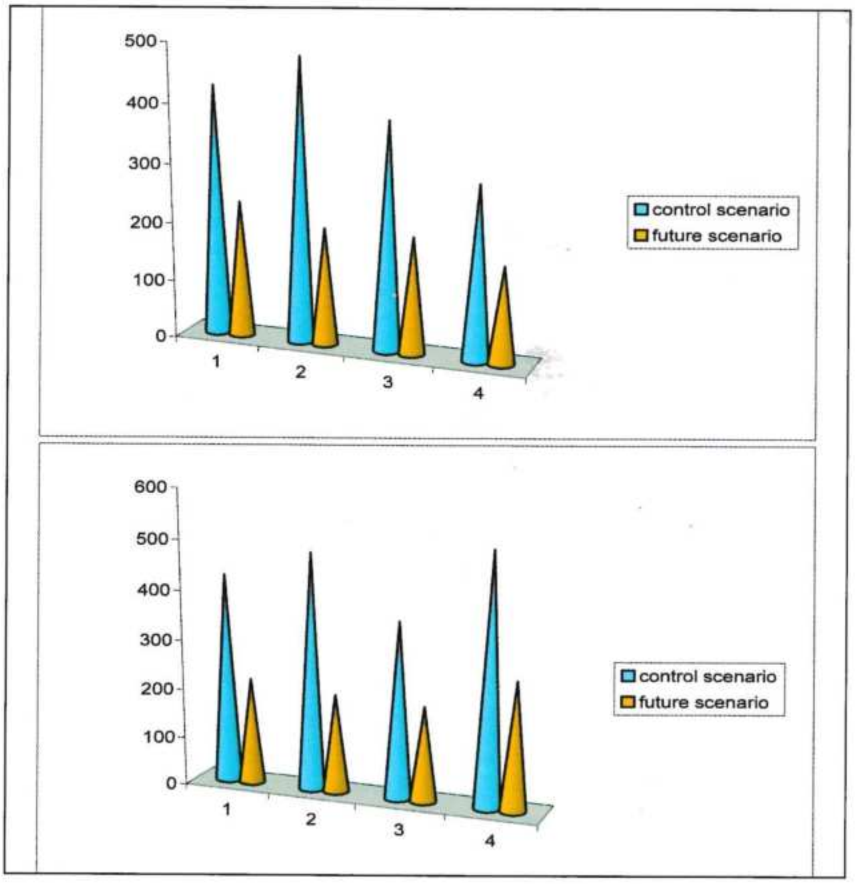

Figure 10.6 – Net Primary Production for cork oak stands along two west-east HadRM grid cells (1, west; 4, east) at the latitudes of Évora (A) and Beja (B) in southern Portugal as simulated with BIOME-BGC.

event per year, warmer winters may induce a second shoot growth event (Oliveira *et al.*, 2000). In fact, a higher frequency of multiple shoot growth events was reported in the coastal regions of Portugal during the last years, possibly related to climate warming (Paulo and Tavares, 1996).

In the southern regions, NPP will experience a moderate to low decrease (figure 10.5). Increased water stress will most likely be the strongest limiting factor, causing reduced growth and increased mortality. Where species are already at the edge of their current distribution, climate change may lead to local extinction.

This model simulation approach is far from being an absolute quantification of NPP. The simulation assumes vegetation types optimised for the prescribed environmental conditions. It is unlikely that forest tree species could be replaced naturally in the relatively short time scale of the climate change scenarios. In order to evaluate changes in productivity under the hypothesis that current vegetation structure will remain unchanged in the future, we used the BIOME-BGC model to study the effects of future climate scenarios on evergreen oaks (cork and holm oak). Two transects in the natural area of these species were analysed (figure 10.6), resulting in a strong decline in NPP, amounting to 50%. This decline, most probably related with the increased water stress, may result in a natural thinning of the denser stands due to mortality.

The impact on deciduous broadleaf forests may be high, according to the BIOME4 simulation (figure 10.4). This type of vegetation may disappear as a dominant biome, and the area where it may attain codominance – the warm temperate evergreen broadleaf and mixed forest biome – may also suffer a great reduction (about 40%). The few existing stands will probably undergo increased stress, resulting in higher vulnerability to pathogens and difficulties in regeneration. Expanding these forests can be seriously compromised, as afforestation becomes arduous and productivity is reduced. Recreational activities and tourism may be affected.

According to the BIOME4 simulation, there will be a significant decrease in warm temperate mixed forests (ca. 40% decrease). As shown in figure 10.4, some mixed forest sites – which correspond to optimum sites for pine and eucalypt plantations – may be replaced by sclerophyll woodlands. Although this change does not necessarily imply mass mortality, it will most certainly result in a greater environmental stress and a decrease in productivity, specially in those areas where the model prescribes a change to sclerophyll woodlands. It has been suggested that the increased length of dry seasons, which occurred within the last two decades, may have caused a decrease in stand growth (Tomé *et al.*, 1996).

Sclerophyllous woodlands (i.e., cork and holm oak stands) will become subject to increased stress and, consequently, decreased NPP, especially in the southern part of their distribution range. Although absolute changes in this biome by the BIOME4 simulation are low (ca. 12% reduction of this biome), they imply a significant northbound migration, which is unlikely to occur naturally in this time frame. In their present habitats, having to endure the lengthened drought periods in the future, it is highly probable that forests may experience more severe stress conditions which will promote decreases in NPP. One of the reasons may be increased tree mortality and the consequent decrease in stand density, as suggested in the next section.

Shrublands and grasslands can increase their area, at the expense of cork and holm oak areas. With increasing aridity in the southern and interior regions the tolerance limits of the key species may be exceeded, leading to the local extinction of certain forest types. Increased fire frequency may enhance this tendency.

#### 10.1.3.3 Ecological processes affecting the survival of key forest species

Some attempts have been made to describe geographical distribution of Mediterranean woody plants using the Emberger Index (IE) (Quézel, 1976). The comparison of the IE calculated for the actual climate (1961-1990 averages and HadRM's control scenario) revealed only a partial coincidence between the actual distribution of species and that proposed by Quézel (1976). This can be attributed to the marked anthropogenic influence on the distribution of tree species and is a major limitation to this type of analysis. The distribution of forest types in Portugal has been strongly influenced by human activities, which may have affected the genetic composition of local populations and therefore their fitness towards

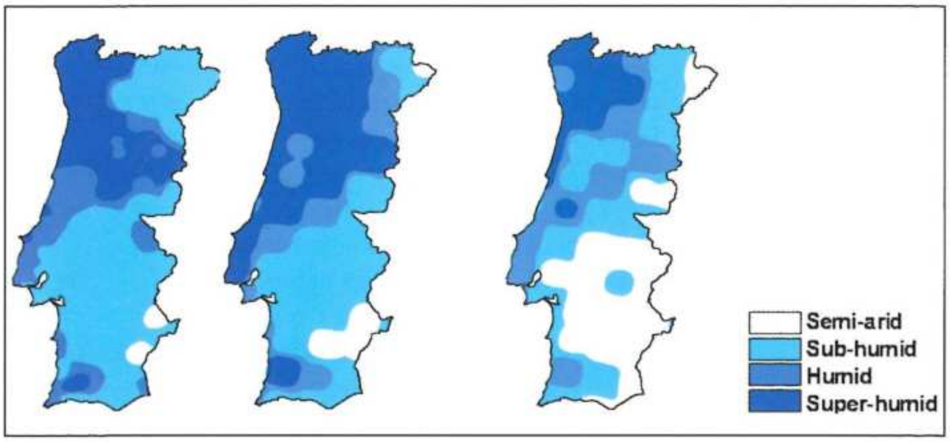

Figure 10.7 – Distribution of bioclimates (calculated with the Emberger Index) for the actual climate (30 years average) (left), control scenario climate (middle) and future scenario climate (right).

environment. This is the case for *Pinus pinaster*, where no discernible geographic pattern was found in the genetic variation of this species, using molecular genetic techniques (chloroplast microsatellites) (Ribeiro, 2001). This suggests a very strong human influence in the geographical spread of the species. A similar situation can be postulated for cork oak, although no studies have addressed this question. As a consequence, the precision of predictions of extinction/migration of major forest species is severely limited regarding the physiological tolerance limits, the ultimate criterion to evaluate ecological fitness.

Under future climate scenarios, community composition and keystone species distribution will mainly depend on stress caused by the expansion of arid and semi-arid climate throughout the country. As illustrated in figure 10.8, a dramatic increase in the number of dry months is expected to occur (see also chapter 2). Under these conditions the ecophysiological tolerance limits to water stress (e.g., the xylem vulnerability to water stress) may be attained, leading to large-scale tree mortality as occurred in *Quercus ilex* in northeastern Spain in 1994 (Lloret and Siscart, 1995). Of course, species differences are expected. For example, there was a higher mortality rate in *Quercus ilex* than in *Phillyrea latifolia* in northeastern Spain. The analysis of future scenarios IE (see figure 10.7) suggests that interior and southern regions may witness important changes in vegetation, in accordance with BIOME4 results, as some species may be approaching their limits of drought tolerance and therefore, may become especially vulnerable to the increasing length of droughts and other stresses (Pereira *et al.*, 1999). For example, a possible decline in cork oak areas may occur in the interior of Alentejo, not only as a direct result of climate change, but also due to the interaction with soil pathogens, e. g., plant water stress exacerbated by the decrease in root hydraulic conductivity promoted by *Phytophthora* fungi (Pereira *et al.*, 1999, also see 10.1.3.5). It is possible that regeneration of cork oak "montado" (either naturally or artificially) will become increasingly difficult with climate change.

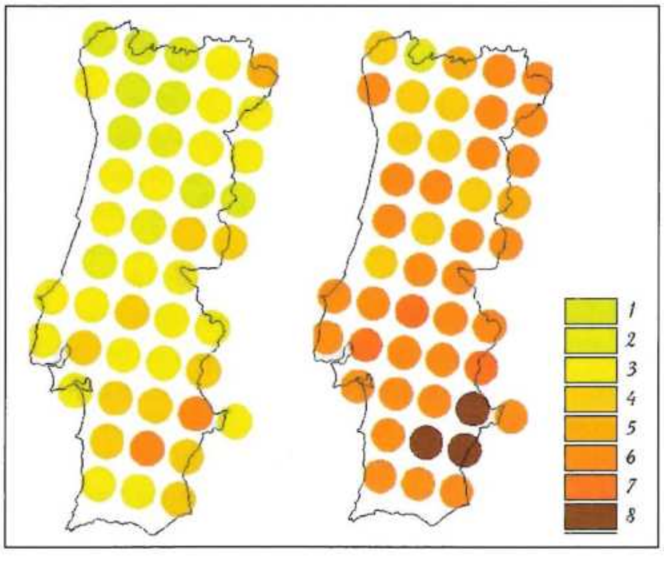

Figure 10.8 – Number of dry months under the control scenario (left) and future scenario (right).

Extinction may occur if migration, or the natural selection of better fitted populations is inhibited. This is a process that may take several decades in trees. Even rapid environmental changes, expected to lead to ecosystem disturbance and localised tree mortality, may not be sufficient to drive a species to extinction. It is more likely that a change in succession dominance will occur rather than a sudden disappearance of certain taxa. Even extreme events, such as drought, may not directly lead to species extinction unless regeneration is suppressed for many years, or catastrophic mortality occurs.

It is possible that evergreen oaks (in particular holm oak) in open stands may be able to successfully resist future water deficits in potentially semi-arid regions, if recruitment of new individuals occurs spasmodically during wetter than average years, sharing space with xerophytic scrublands (as suggested by the BIOME4 simulation in 10.1.3.2). Holm oak occurs in present semi-arid regions (e.g., Mértola region or on the left margins of the Guadiana River) where actual annual precipitation is about 400 mm/year (Correia and Oliveira, 1999).

The prediction of migration rates is complex because it depends on a species' dispersal ability, competitive interactions in the new habitat, and the effects of climate on physiological performance. In any case, given the fast rate of climate change, it is unlikely that slow growing species, that take several decades to reach the reproductive age, such as oaks (e.g., oaks in general), will be able to naturally colonise into more suitable habitats unassisted by man. Creeping tree mortality may free space and create opportunities for exotic invaders (e.g., *Acacia* spp., see 10.2). On the contrary, fast growing species with high dispersal capability (e.g., maritime pine) may increase its present range (e.g., in altitude) as the climate warms. This, of course, will not preclude its dislodgement from the more arid areas of the present range (Fensham and Holman, 1999). In the case of the cultivated exotic *Eucalyptus globulus,* the tendency of foresters, since the mid-1980s, has been to abandon the plantations in the advanced arid edges of the potential range of distribution, especially as a result of the increased attacks of *Phoracantha semipunctata* in those areas (see also section 10.1.3.5).

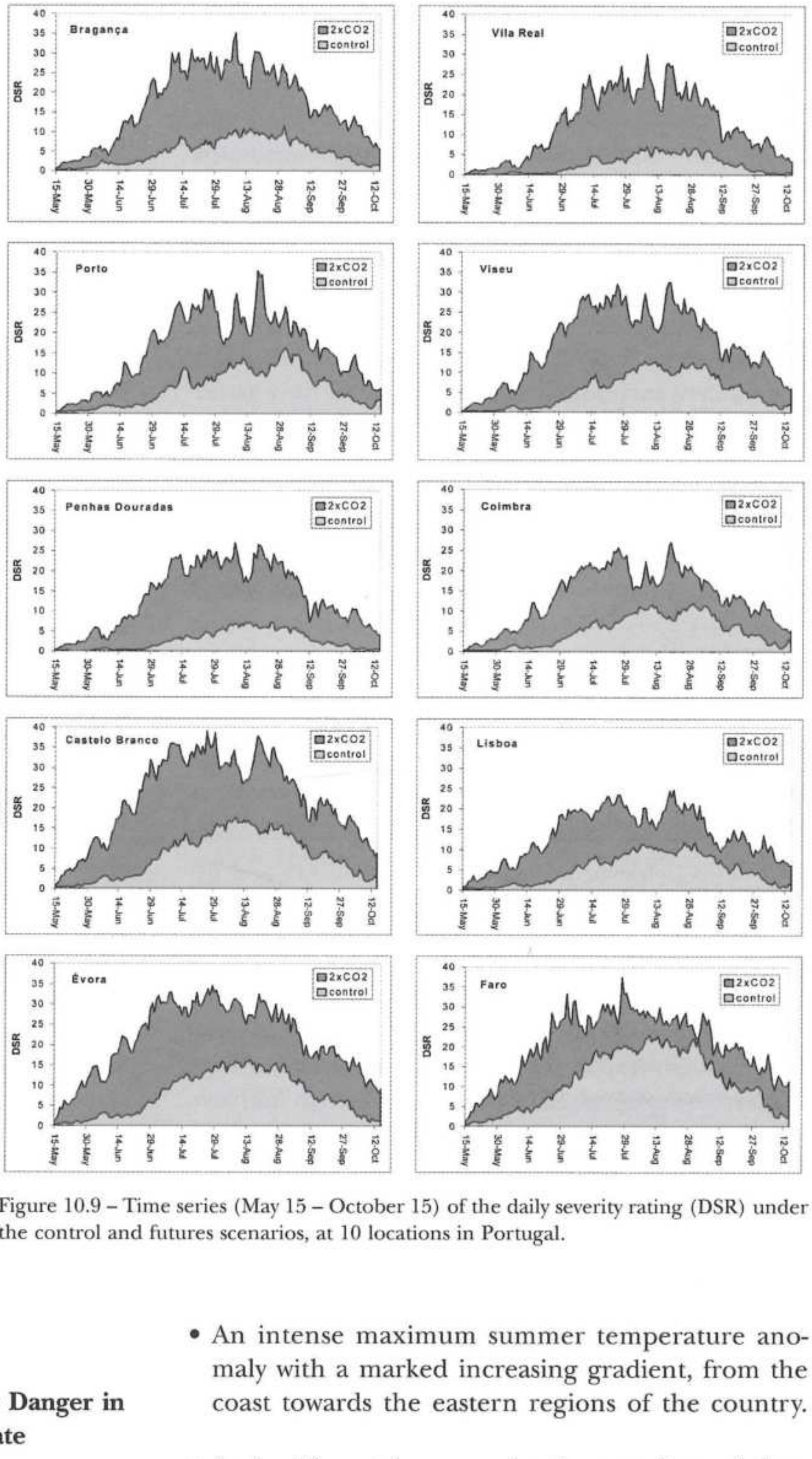

Figure 10.9 – Time series (May 15 – October 15) of the daily severity rating (DSR) under the control and futures scenarios, at 10 locations in Portugal.

### 10.1.3.4 Forest fires – Meteorological Fire Danger in Portugal Under a Changing Climate

The analysis of fire danger performed in this study only addressed the meteorological component of the problem, using the Canadian Fire Weather Index (FWI). The substantial increase in meteorological fire danger appears as an inevitable consequence of climatic change patterns presented and discussed in chapter two, especially:

- An intense maximum summer temperature anomaly with a marked increasing gradient, from the coast towards the eastern regions of the country.
- A significant increase in the number of days with a maximum temperature above 25°C, which becomes much more frequent during the spring and fall.
- A large increase in the number of days with maximum temperature above 35°C and in the duration of hot spells.

- Reduced precipitation in spring, summer, and fall, with a concomitant extension of the dry summer season from May to October.

Quantitative analyses of future fire danger was based on comparisons between the daily severity ratio (DSR – calculated from FWI) values calculated from the HadRM model outputs using the control and the future climate scenarios. The comparisons were performed for the locations shown in table 10.1. Analysis of the DSR values for the ten stations reveals a significant increase in fire severity at all sites under the future climate (figure 10.9).

| Weather station | Latitude (N) | Longitude (W) | Altitude (m) |
|---|---|---|---|
| Bragança | 41° 48' | 06° 44' | 690 |
| Vila Real | 41° 19' | 07° 44' | 481 |
| Porto | 41° 14' | 08° 41' | 70 |
| Viseu | 40° 40' | 07° 54' | 443 |
| Penhas Douradas | 40° 25' | 07° 33' | 1380 |
| Coimbra | 40° 12' | 08° 25' | 141 |
| Castelo Branco | 39° 49' | 07° 29' | 380 |
| Lisboa | 38° 46' | 09° 08' | 104 |
| Évora | 38° 31' | 07° 47' | 230 |
| Faro | 37° 01' | 07° 58' | 8 |

Table 10.1 Geographical coordinates of the 10 locations used in the meteorological fire danger analysis.

Temporal variability of DSR appears to be greater under the future scenario, as illustrated by the sharper peaks and deeper troughs of the corresponding time-series. A substantial lengthening of the fire season may also be inferred from the relatively high increase of DSR at the beginning (mid May) and end of the annual simulation period (October 15), under the future scenario.

No change was detected in the geography of the meteorological fire danger, with higher risk occurring in the interior and southern regions (e.g., at Castelo Branco, Évora, and Faro) under both scenarios. Nevertheless, a considerable increase in DSR was observed at sites that had the lower levels of meteorological fire danger under the control scenario: Penhas Douradas, Vila Real, and Bragança (figure 10.9).

Visual analysis of the graphs seems to reveal an earlier occurrence of the fire season middle date, under the future scenario. However, the statistical significance of this apparent pattern has not been evaluated.

Figure 10.10 displays the seasonal severity ratings (SSR) under the control and future scenarios. These sites are located in the eastern and southern regions (e.g., Faro, Évora, and Castelo Branco). Seasonal severity rating values larger than seven, corresponding to extreme fire behaviour potential in boreal fire weather climatologies (Stocks *et al.*, 1998), are observed only at Faro, Évora, and Castelo Branco, under the control scenario. These values are largely exceeded at all sites under the future climate scenario. The larger relative increase in SSR occurs at the sites that had the lower SSR values under the control scenario: Penhas Douradas, Vila Real, and Bragança. The SSR ratios (future/control) are very high: 1.8 at Faro, 5 at Vila Real and 5.2 at Penhas Douradas, revealing a drastic increase in meteorological fire danger and in the needed effort to control fire under a 2x$CO_2$ climate.

The magnitude of the increase in the SSR ratio is similar to that obtained in Canada (NRC, 2001) even though absolute SSR values are significantly higher in Portugal.

The lengthening of the fire season under the future climate scenario was also predicted for Canada (Wotton and Flannigan, 1993). The implications are a larger demand on fire fighting organisations, which will have to maintain elevated alertness for a considerably longer period each year.

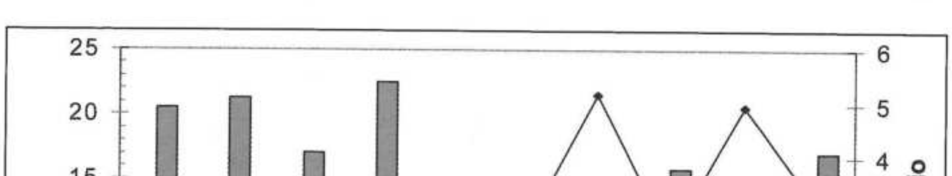

Figure 10.10 – Seasonal severity ratings (SSR) for 10 locations in Portugal, under the control and 2x$CO_2$ scenarios.

Fire regimes are expected to respond instantly to climatic changes and may override the direct effects of global warming on the patterns of species distribution and productivity (Dale *et al.*, 2001).

From figure 10.4 the pattern that emerges for future scenario is the replacement of forests by woodlands, woodlands by shrublands, and shrublands by grasslands, resulting in communities of lower biomass. Increased fire frequency will reinforce these trends, by shifting vegetation's age structure towards younger classes and thus lowering standing biomass. Where forests are replaced by shrublands, the loss in biomass (and carbon) storage may amount to as much as 90%: a mature pine or eucalypt forest has a standing biomass of ca. 150 $t.ha^{-1}$, and a mature shrubland as a standing biomass of 15 $t.ha^{-1}$. Our calculations of fire return intervals for the country, using satellite imagery from the 90's, indicate that such changes in land cover trends are already in progress.

### 10.1.3.5 Pests and pathogens

Under future climate scenarios the potential impact of pests and diseases on forests may increase. Higher temperatures and/or lower precipitation may lead to increased growth rates of some insect populations. This climate influence may facilitate outbreaks of native species, or the expansion of invasive species. In general, species that are able to produce several generations per year (multivoltine species) can benefit the most from higher winter and spring temperatures. Vector-born diseases can also increase, in response to higher vector populations. High temperature, when associated with periods of high humidity, may favour the outbreak of diseases caused by soil-borne phytopathogenic fungi, such as *Phythophthora* spp. or the root decay fungi *Armillaria* spp., resulting in tree death or increased vulnerability to bark-beetle attacks.

Climate induced changes in hosts are also a major factor, and may have opposing effects. Drought-stress can favour the incidence and severity of many pests and diseases, whereas changes in phenology patterns or physiology can reduce the incidence of pathogens.

The natural equilibrium of pathogens and their natural enemies may change, e.g., the reproduction rate of multivoltine natural enemies, specifically parasitoids, may benefit by a warmer climate, thus acting more efficiently as regulating agents.

Human intervention in ecosystems will also play a fundamental role. Changes in the efficiency of control strategies are another important and unpredictable impact of climate change. Effects would chiefly occur through influences on host resistance or management control measures (Coakley *et al.*, 1999). Climate change can also affect chemical agents, altering the dynamics of insecticide and fungicide residues on the foliage or the translocation and metabolism of systemic products. As a result, a continuous adaptation of control strategies to new conditions will be required.

Climate change has the potential to modify the type, amount, and relative importance of pathogens, as well as act upon the spectrum of diseases affecting a particular host (Coakley *et al.*, 1999). It is no surprise that a generalised simulation of pests and diseases under future climate scenarios is virtually impossible.

From the large array of possible impacts we selected some examples. Insect species such as *Coroebus undatus, Coroebus florentinus* or *Platypus cilindrus* can be favoured. These species are associated with tree stress conditions and the decline of cork oak stands. Water stress and increased forest fires may favor bark beetles, which already contribute to damages in maritime pine. They could be favoured by an intensification of summer drought. Bark beetles are also vectors of pathogenic fungi, such as *Ophiostoma* spp. on oak trees and *Sphaeropsis sapinea* on pine. The combined effect of environmental stressed trees and the increase of vector populations could favour the incidence of the diseases caused by these pathogens. *Monochamus* beetles, which are the main vectors of the pinewood nematode *(Bursaphelenchus xylophilus)*, could also be favoured by an increased drought-stress (Sousa *et al.*, 2001). In *Eucalyptus* stands, a significant correlation has been established between climate variables and the risk for an outbreak of *Phorachanta semipunctata* (Farrall *et al.*, 1999). An increased risk of pest outbreaks in regions that have now a low to moderate risk may be expected as a consequence of a increased aridity, thus, further limiting the areas where commercial plantation are feasible.

### 10.1.3.6 Synergies between impacts

Our results indicate that several forests will be under increasing environmental stress in the future, which may result in decreases in productivity and threaten the survival of some key species. An increased risk of fire, extreme weather events, and pest or disease outbreaks can amplify this consequence. For example, an increase in fire frequency and intensity, resulting from extended dry periods, may be one of the most significant driving forces of ecological change. The inability of woody plants to complete reproductive cycles will reduce their presence in the affected areas and the predominance of herbaceous annuals and fire resilient shrubs may be exacerbated. Present day maritime pine forests are especially sensitive to fire, due to their high flammability and lack of adequate management. Moreover, fire tends to be recurring, since recently burnt areas are more flammable than old growth forest. With the significant increase in future fire risk (see 10.1.3.4), unmanaged pine forests are likely to suffer a great reduction in area, as well as, productivity and carbon storage. Fire and other disturbances, such as windstorms can amplify the attack of bark beetles and insect wood borers by increasing available material for insect breeding. While the eucalypt stands are less prone to fire (see 10.1.3.4), a reduction in productivity and survival is most likely a result of longer periods of summer drought (40% longer than average) and increased pest attacks (see 10.1.3.5).

### 10.1.4 ADAPTATION MEASURES

#### 10.1.4.1 Approach Used to Develop Adaptation Measures

The present capability to manage forest ecosystems so that they can cope with environmental changes of the magnitude projected by the future climate scenario is limited due to the inability of predicting ecosystem responses. The complexity of processes associated with a lack of information, leads to a great uncertainty. It is for this reason that the methodologies to develop adaptation measures to climate change rely heavily on expert judgement. The output of model simulation approaches (see 10.1.3.1.3) together with empirical investigations and knowledge of adaptation to present and past climate variability, helped to provide insights into the processes of adaptation and the conditions needed for its successful promotion.

#### 10.1.4.2 Forest Management

Primary productivity determines not only ecosystem function but also the production of goods and services by forests. Forest productivity is also important because it is the basis for carbon storage and the function as GHG sinks. The production of goods (e.g., timber) although related to NPP, depends on the management practices and on the type of product. The economic production is valued through quantity and quality and whereas quantity is directly related to NPP, quality depends on interactions between the environment, plant genetic factors and management practices. In any case, to maintain NPP at high values in a given environment, managed forests depend on human intervention. To optimise not only the carbon sink strength but also forest productivity in general, forest policies and management guidelines must reflect awareness of climate change issues and future climate scenarios.

Considering the different types of forest management options (see 10.1.2.3.2), some alternatives may be considered:

- **Multifunctional silviculture:** Environmental restrictions exclude the extensive use of exotic species. The focus is on indigenous species or alien species that are of great economic importance (e.g., eucalypt). Possible tree improvement of indigenous species. Silvicultural management should aim at maximising the economic output in a multifunctional perspective. Higher quality products should be promoted (e.g., quality timber, larger dimensions), supporting the higher cost of environmentally sound practices. Possible increase of natural regeneration, especially on low productivity sites.

- **Monofunctional silviculture:** Focus on fast growing species and cork oak, fit to supply the industries. Possible introduction of alien species better fit to future climate conditions. Tree improvement of commercial species. Intensive management of plantation sites, allowing for shorter rotations and maximising production.

- **Natural silviculture:** Indigenous species should be used where afforestation/reforestation is needed. Possible tree improvement programmes to ensure the survival of endangered indigenous species. Forest management aims at maintaining healthy and stable forest stands. Priority on natural regeneration.

#### *10.1.4.2.1 Afforestation and reforestation*

The choice of species to be used in afforestation/reforestation must consider the site potential productivity and limitations to development, e.g. length of growing season or extent of drought period. Afforestation/reforestation with humidity demanding species should be restricted to the best sites. The use of authoctonous species will be dominant and the silviculture will aim at increasing the single tree vigour.

- Drought adjustment means that successful trees are able to use more water, rather than restricting water consumption. Decreasing stand densities to cope with water deficits may increase the probabilities of survival of forests.

- Promote or adjust tree breeding programmes in order to increase the genetic potential of some forest species to adapt to higher temperatures and increased water stress, especially for those with high economical value, e.g. maritime pine, eucalypt and cork oak. Afforestation/reforestation must use genetic material with postulated drought tolerance well in excess to the average conditions, mimicking what nature has done so often as a result of natural selection where extreme events are limiting factors.

- Stand regeneration techniques should be optimised:

  By *natural regeneration,* the different systems of successive regeneration fellings are recommended. The even, gradual or localised opening of the canopy must take in consideration the wind direction, species tolerance and site quality.

  By *artificial regeneration,* the preparation and treatment of the site should optimise the soil hydrologic balance, promoting the development of roots and overall vitality, minimising erosion.

#### *10.1.4.2.2 Silviculture and forest management*

- Tending and intermediate cuttings should aim at promoting stable stands, thus reducing the effects of windstorms. In general terms this means long rotations, the formulation of adequate thinning schedules, aiming to individual tree stability, and stand pruning to obtain large diameters and quality timber. Mixed stands of broadleafed species are considered more resistant to windthrow. In even aged high forests of intolerant conifers, the focus should be on individual tree stability.

- Use and harvesting techniques that avoid total soil mobilisation as soil erosion may be enhanced in future climate scenarios.

- The over-exploitation of forest resources should be avoided in order to maintain carbon balance and soil fertility under a harsher environment.

- Measures for the prevention and forest fires (see following section) and of land degradation need to be taken as they will exacerbate any negative effects of climate change and may enhance the risk of local extinction or decline of native key forest species, especially in the interior and south. A sustainable forest management should aim at preserving biodiversity at the stand and regional levels (see section 10.2). Land use planning rules to maintain ecological corridors and protected areas networks (e.g., Natura 2000) must be enforced.

Concerning already existing stands, adaptation to climate change is possible to some extent (see table 10.2).

### 10.1.4.3 Forest Fires

The projected increase in meteorological fire danger under the future climate scenario generates an urgent need for adaptation and mitigation measures. However, considering the magnitude of the projected future meteorological fire danger, the identification and implementation of these measures will not be easy. There are large environmental and economic values at stake, for example, the future viability of important segments of the forest industry, the lives and property of people inhabiting forested areas, and the natural and cultural resource values of several of the protected areas. Soil and water resources may be severely affected and the carbon sink potential of the country may diminish strongly under the future fire regime.

**Table 10.2 – Climate Change: Effects in forest stands and site and their silvicultural control (adapted from Burschel and Huss '1997')**

| Effect | Forest vegetation reaction | Silvicultural control |
|---|---|---|
| Temperature increase; maintenance of actual evapotranspiration rates through increase in precipitation | Acceleration of organic matter decomposition, below and above the surface | Avoid practices that accelerate organic matter decomposition: clear cutting, soil mobilisation and fertilisation |
| | Increase of net productivity when temperature is a limiting factor (mountains) | Take advantage of improved site conditions using more site demanding species |
| | Change of the competition patterns among trees and with the underlayers | Adjustment of thinning and regeneration practices |
| | Change of resistance to pests and diseases; better development conditions to pests and diseases | Impossible to foresee: difficult to fight against and with ecological effects that are unforeseeable or unclear |
| Increase of temperature during the vegetation period with no modification of the precipitation | In extreme conditions leads to tree mortality. The trees are more susceptible to pests and diseases | No adjustments are possible because we can not foresee its occurrence |
| Increase of the length and frequency of drought periods | Tree mortality<br>Desertification or substitution of forest stands by pastures or shrublands | Use drought resistant species.<br>Reduce stand density at installation<br>Reduce stand density by thinning and cleaning |

Adaptation to climatically enhanced fire danger will involve changes in the areal extent, location, species composition, and silvicultural management of these forests.

- Afforestation of areas expected to suffer more severe warming/drying should be restricted. Financial and human resources will be more effectively used intensifying the protection and management of existing forests.
- Regional forest plans will need to allocate substantial areas to networks of fuel breaks. To a large extent, these may use less productive areas along ridges and incorporate outcrops. Fuel breaks do not have to be bare and unproductive, but will require specific silvicultural practices, with a strong emphasis on fuels management programmes. Landscape-level patterns of fuel harvesting may be optimised, to further break up large scale continuity of forested areas.
- Diversification of the range of species used in commercial forestry is desirable, with an emphasis on deciduous broadleaf species, less prone to fire hazard.
- Short rotation silviculture may have economic advantages under high fire risk conditions, due to higher probability in completing rotation/revolution periods without burning.
- It is important to implement controlled burning programs for scrubland and pasture management, in order to minimise the risk of uncontrollable illegal burns, which often spread into forested areas.
- Protected areas should revise the current systematic fire suppression/avoidance policy, and should consider reintroduction of fire in protected areas, before fuels build up to loadings capable of supporting catastrophic fires. Such a change in

policy may bring potential benefits for the enhancement of biodiversity.

- It is very important to regulate housing developments in the forest-urban interface and in predominantly forested areas. This will reduce the risk of loss of life and property, and will facilitate the focus of fire fighting efforts on the protection of forest resources.

Projected increases in frequency and length of hot spells imply that forest fire activity is likely to become more concentrated in periods of extremely severe fire weather, in fires of large intensity and size, occurring simultaneously over broad areas. It is very expensive to support a fire-fighting infrastructure adequate to handle such extreme peaks of activity, and its effectiveness is likely to decrease. Therefore, fire prevention should become the main priority for fire management policies designed for a warmer, drier climate.

#### 10.1.4.4 Pests and pathogens

Possible measures to cope with potential insect and pathogen outbreaks under future climate scenarios include:

- Improvement of monitoring and prevention measures in order to make an early assessment of organisms that may become noxious under the future conditions. The appropriate agencies should also provide accurate forecasting systems and create prevention methods for the introduction of such pests and diseases across national boundaries.

- Increase scientific research aiming at the development and implementation of appropriate integrated pest management strategies.

- Use adequate forest management techniques (see section 10.1.5.2), for instance, using adequate plant species for given site conditions, because stressed plants are often more vulnerable to pathogen attacks.

- The use of mixed forest stands instead of extensive monospecific stands is advisable to minimise the risks associated with pests and diseases outbreaks. This may not always be feasible due to economic constraints, but it is at least recommendable to promote species biodiversity at the edges of monospecific stands and forest understory in order to increase habitat heterogeneity suitable for biotic natural enemies of pathogens.

- Take actions to identify pathogens in forests and monitor tree health and vitality, as it is already in process in Europe (e.g., Pan European Indicators).

- There are a number of established rules and international conventions pertaining to the transport of plants and plant products, which forbids the transport of certain forest products or requires a phytosanitary certificate for transport in order to avoid or reduce the risk of undesirable introductions. The goal is to prevent the dissemination of pests and diseases across national boundaries. In future climate conditions, there is the need to strengthen and update the list of already dangerous organisms that may be transported from risk regions.

#### 10.1.4.5 Cross sectoral implications

The importance of considering forest cover in the management of water resources has been acknowledged for a long time. The presence of forests within river basins, controls outflow and deep percolation, which in turn, affects erosional processes, flood regimes, and water supply to both urban and agricultural areas. The silting of rivers, following deforestation, is an important aspect that forest policies and practices need to take into account concerning water resources management.

Agriculture competes with forestry for land. Thus, the development of forestry is largely dependent on agricultural policies. With the expected increasing aridity, agriculture will most likely lose competitiveness, except where irrigation is possible. This may translate into a reduction of total agricultural area, releasing space for forest expansion. If left unmanaged, abandoned agricultural land will evolve through a secondary succession process into pine forests or native vegetation of the "matorral" type, which may be an important repository for biodiversity.

The possibility of forests acting as carbon sinks make the afforestation/reforestation option very attractive as a mitigation measure. However, it will not be internationally acceptable that the expansion of planted forests for carbon sequestration (carbon plantations) will be done at the expense of losses in biodiversity.

The use of biomass for energy production is considered as an industrial option and may affect forests. It is unlikely that a considerable fraction of forests may be converted to this use because of the environmental impact of short rotations and problems with costs of transportation, residues (ashes), and air pollution. The use of forest industrial residues for the co-regeneration of energy is already a valuable option contributing to the national energy budget.

The afforestation of coastal dunes is a tradition more than seven centuries old and was the reason for the creation of the Portuguese Forest Services in the nineteenth century. Besides dune fixation, coastal forests are also important as natural barriers for the salty sea winds, protecting other inland crops and urban centres. The expected sea level rise may exacerbate the importance of afforestation actions, at least in certain parts of the coast.

The forest sector may expect more pronounced changes due to human intervention than due to climate change. For example, systems, such as "montados" are considered a highly humanised landscape combining forest, agriculture, and livestock. These systems can only be maintained if they are actively managed. For this reason, impacts in forests are expected to rely more on management interventions and political options on the short and medium term, rather than on climate change *per se*. On the other hand, the adoption of measures for rural development and alternative activities in areas where increased aridity, human abandonment and ecological degradation make traditional forestry and agro-forestry systems less profitable or impossible, are recommended for social and cultural reasons.

### 10.1.5 FOREST CARBON SEQUESTRATION – A GHG MITIGATION STRATEGY

Forest carbon sequestration is directly related to NEP, a fraction of the NPP (see 10.1.3.2.1). Long-term carbon sequestration is the average amount left after non-respiratory losses, such as fire and harvest, are taken into account. Carbon in the soil, as well as in forest biomass, may be stored away from the atmosphere for a long period of time, thus counteracting $CO_2$ emissions from combustion. The KP recognised the roles of land use, land use change, and forestry (LULUCF), taking terrestrial sinks for $CO_2$ from emissions, into consideration (Watson *et al.*, 2000). Basically, the articles of the KP, with respect to this issue, emphasise that a country may account for carbon sequestration due to afforestation, reforestation, and deforestation (ARD) activities to meet its $CO_2$ emission reduction commitments (Article 3.3). They may also account for further carbon sequestration due to the presence of forests, cropland, grazing land management, and revegetation (Article 3.4). The implementation of these international agreements will require reliable methods of inventory and verification in each individual country.

There is little information about carbon sequestration in Portuguese forests. The first approximation was based on the IPCC guidelines and forest inventory (Seixas, 2000). It was estimated that forests would account for 4 Mt (Mega tons) of $CO_2$ in 1990 and their share as carbon sinks would increase as the KP commitment period of 2008-'12 approached, largely due to a predicted increase in forest area. This approach, however, needs to be improved with better estimates of stocks, as well as in terms of the carbon storage below ground and the impact of forest fires in the overall carbon storage in forests.

The underground carbon fraction (i.e., forest floor, roots, and soil organic matter) may be more than 60% of the total carbon storage. Even though we may have sufficient data for the aboveground forest biomass, the information for the belowground component is scanty and its interpretation is complicated by the great variability and the use of different definitions. For example, the soil depth needs to be stated, although this is not always the case.

Madeira *et al.* (2001) describe variations between 40% and 68% of the total carbon in the underground carbon storage in eucalypt stands within the centre of Portugal. They concluded that such variability suggests the need to consider chronosequences, soil type and conditions, as well as, management practices, in order to fully understand the effects of forests on carbon storage.

In Portugal, fast growing tree plantations planted after 1990 may count for KP sinks according to their status within the 2008-2012 period. For example, in a 6 year old eucalypt plantation, the carbon stored by the entire system, up to 60 cm of soil depth, was between 9 and 14 $kgCm^{-2}$ (Madeira *et al.,* 2001). The rise in carbon above the initial status was, however, largely due to the accumulation of woody biomass. Carbon storage in the mineral soil may be a slow process (Fisher and Binkley, 2000; Turner and Lambert, 2000). When accounting for long-term carbon storage, the short rotation for above-ground biomass harvest, the dynamics of stump and root biomass, and the half-life of the products (paper) should be taken into consideration (Watson *et al.,* 2000). The sink strength of these plantations needs to be studied.

"Montados" are quite variable due to large differences in tree density and type of agro-forestry used, among other factors. In a 1999 study in Évora, a mixed cork and holm oak stand, with 30% tree cover, had a net ecosystem exchange* that was of a weak sink (ca. 80 $gm^{-2}yr^{-1}$), but it is difficult to determine the long term system functions. Under climate change a decline in tree biomass will have a negative impact (10.1.4.3) on stocks and the belowground carbon storage will become more vulnerable due to warming. Since "montados" are mostly managed as pastures, carbon sequestration will depend upon the type of management. Well managed permanent grasslands are considered to be important carbon sinks. Although the rate of storage (mainly in the soil) is uncertain, experiments suggest maximum values of 230 $gCm^{-2}yr^{-1}$ in European grasslands (M. Jones, personal communication).

In general, carbon accumulates in forests with time. In relative terms, we may say that most Portuguese pine forests are recent and therefore prone to store carbon for quite some time, if left undisturbed. As a whole, the potential may be lowered because rotation is fairly short (compared to Nordic and Central European forestry standards) and frequent forest fires will promote the shortening of average rotation time (see 10.1.3.4), reducing the average mass of carbon stored, above and below-ground.

The long term carbon storage also varies with the nature of the system and the period of time that forest products last until decomposition (or burning) to $CO_2$ again. Therefore the use of long lasting wooden products will add to the natural value of forests to compensate for $CO_2$ emissions.

It is uncertain to know what will happen to future carbon sinks. If we make the simple assumption that carbon storage is proportional to NPP, figure 10.5 suggests that, in future climatic scenarios, carbon accumulation in new forests will follow a pattern of decline in southern and central parts of Portugal and a slight increase in the northern coastal areas. Increasing summer temperatures may not have a strong impact on below ground carbon storage because the lack of water will impede microbial activity. However summer rain storms, or more importantly, winter warming, may create the conditions for faster decomposition of soil organic matter, greater $CO_2$ efflux from the soil, and a reduction in NEP.

In summary, we need a better accounting for the role of Portuguese forests as carbon sinks in the present. Under the future climate scenarios, the ability of Portuguese forests to store carbon may decrease due to, (1) decreases (or only modest increases) in NPP, (2) lower standing biomass, possibly due to changes in vegetation and stand density, (3) decrease in standing biomass due to increased fire frequency and (4) enhanced soil respiration due to warmer winters.

### 10.1.6 RESEARCH GAPS

The proposal of forest policies for the sustainable development of forests needs to consider climate change as a driving variable. The rate of climate change in most model simulations is faster than most forest trees life cycle. That means that most forests planted today will develop into a changing environment and the regeneration of existing forests will tend to occur under a climate substantially different than that which prevailed at establishment. One of the major limitations to the formulation of such policies and to suggest adaptation measures to climate change, is the lack of information on how forest species and ecosystems will respond to the new climate conditions. Of special importance is,

- The need for better information on the response of individual tree species to climate variables in order

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* when expressed on a annual basis should be similar to NEP.

to improve model simulations of forest productivity, survival and reproduction. There is a need for improved data on the ecophysiological responses, as well as on the genetics of native and introduced tree species.

- Research to improve the understanding of soil processes under the future climate scenarios especially the short- and long-term behaviour of soil organic carbon and the interaction with other biogeochemical cycles under increasing drought.
- The development and/or adaptation of ecosystem process based simulation models adjusted to the specific Portuguese forest types, especially taking into consideration the high degree of human intervention in forests.
- Research is also needed on (i) the impacts of the hypothetical increase in forest fire frequency on the productivity and carbon balance of forests; (ii) adequate silviculture models for a changing (more arid) climate; (iii) tree breeding programmes to cope with water deficits and warming and (iv) integrated pest management strategies for existing and potentially invasive pests and diseases.
- Virtually nothing is known for forests and associated ecosystems (such as streams or scrublands) regarding emissions of GHG other than $CO_2$ ($N_2O$ or methane, $CH_4$). Some research must be devoted to these gases.
- To evaluate the capacity of terrestrial ecosystems to sequester carbon and mitigate the impact of greenhouse gas emissions, there is also a need to improve the knowledge on carbon storage and the carbon sink strength of the different types of forests and alternative forms of land use (e.g., scrublands on abandoned farm or former forest land). There is a need to quantify the rates of carbon exchange between forests and the atmosphere, the partitioning of carbon in the ecosystem and the processes underlying differences between regions and ecosystem types.
- To estimate the impact of management (i.e. forestry) on the capacity of forests to sequester carbon. This research, as well as improved inventory data on total NPP (not just stem increment) and soils, are needed to develop mechanisms for the technical verification of the changes in carbon stocks associated with the compliance of the national commitments regarding GHG emissions.
- Research is needed also on the socio-economic implications of the impacts of climate changes on forests, namely the integration of ecological simulations and uncertainties in the instruments of regional land-use planning (e.g., the consideration of the impacts changes in forest composition and productivity on industry, employment and wealth on a regional basis).
- To develop better models to assess the inter-sectorial impacts of changes in forest composition and health as a result of climate change on, (i) water resources, considering the influence of forests on water balance and (ii) the interaction with the energy sector as forests may be a source of biomass to burn and a sink to mop-up $CO_2$ from emissions.

### 10.1.7 CONCLUSIONS

A large proportion of Portuguese forests are privately owned and resulted either from deliberate afforestation/reforestation or from the abandonment of agriculture. These forests have, therefore, an economic function providing raw materials for local industries. Their importance in terms of environment protection and the preservation of biodiversity is increasingly recognised. The position of forests in relation to climate change has two main axes. On one hand, forests will suffer the impact of changes in climate but, on the other hand, they may function to sequester a proportion of the carbon resulting from fossil fuel combustion and deforestation and thus act to mitigate the impact of greenhouse gas emissions.

The future climate scenarios all predict greater water deficits to plants and animals when a $CO_2$ concentration in the atmosphere twice the present concentration is reached. This will lead to a possible decline in productivity in most of the mainland territory and a northwest shift of the physiological optimal plant distribution, in comparison to the present.

The frequency of extreme events such as windstorms, severe droughts or long hot spells may increase in the future, together with increased risk of fire, leading to further productivity losses through tree mortality and subsequent land degradation. Future environmental conditions may also favour either some of the actual pests and diseases or the intrusion of new ones originating from warmer climates, thus increasing the stress on forests.

The silviculture and land-use planning advisable in the future climatic scenario should use species and genotypes within species well adapted to drought and temperatures higher than today, avoid soil organic losses and preserve biodiversity. In a situation of increased risk of forest fire prevention, rather than fire fighting, must be the priority.

Forests may act as sinks for $CO_2$ and therefore help in climate change mitigation. There is consensus that a major effort must be concentrated in the control of GHG emissions. However, the possibility of compensating for some of those emissions through forest carbon sequestration, is an asset that must not be neglected, although limited in scope. The present capacity of Portuguese forests to store carbon may be considered potentially high. The sink strength in the future may be lower than today because primary productivity and standing biomass may decrease in most of the country due to drought, changes in vegetation and increase in fire frequency. Further decreases may occur as well due to enhanced soil respiration in warmer winters.

The proposal and implementation of forest policy measures for the adaptation of forests to climate changes needs correct and extensive scientific information on ecological processes and species. Unfortunately most critical data and simulation models are not available. This limits seriously the depth of analysis of the impacts of climate change on forests and the proposal of the corresponding adaptation measures. For this, verifiable mechanisms of accounting/verification must be put in place with solid scientific background. The research effort concerning these matters needs to be promoted.

## 10.2 BIODIVERSITY

### 10.2.1 INTRODUCTION

### 10.2.1.1 Overview of the State of Biodiversity in Portugal

Biodiversity means the complexity of life. One of the more far-reaching definitions of biodiversity is that of the Convention on Biological Diversity (UNEP, 1992): "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complex of which they are part; this includes diversity within species, between species and of ecosystems". As it is stated in this definition, biodiversity encompasses a multiplicity of ways from the genetic diversity up to ecological diversity.

The importance of biodiversity conservation is well recognised worldwide. The underlying arguments for the value of biodiversity range from its direct use (e.g., food, medicine) to indirect use as ecosystem services provided by biodiversity (e.g., nutrient cycling) to non-use values (e.g., intrinsic value). Recent theoretical and experimental work have suggested that a large pool of species is required to sustain the assembly and functioning of ecosystems in landscapes subject to increasingly intensive land use (e.g., Schulze and Mooney, 1993; Hector *et al.*, 1999; but see Huston, 1997; Aarssen, 1997).

It is not yet clear, however, whether ecosystem dependence on diversity arises from the need for recruitment of a few key species from within the regional species pool or to the need for a rich assortment of complementary species within particular ecosystems (Loreau *et al.*, 2001). In the context of climate change, it has been proposed that biodiversity can have an "insurance" or buffer effect against environmental fluctuations (e.g., Yachi and Loreau, 1999; McNaughton, 1977; Tilman, 1996) because different species respond differently to these fluctuations leading to more predictable aggregate community or ecosystem properties (Loreau *et al.*, 2001).

Although species extinction have always occurred as part of the evolution process, the present situation is alarming because the current observed rates of species extinction is about 1% per century, which is 100-1000 times the "natural" background rate (Begon *et al.*, 1996).

Mainland Portugal, as well as the whole Iberian Peninsula, is within the confluence of Atlantic and Mediterranean ecological influences (Ribeiro, 1986). The Mediterranean Basin is a hotspot for biodiversity and includes Europe's most species-rich ecosystems. The long human occupation of this region and the development of agriculture and pastoralism since prehistory led to the removal of natural vegetation in many areas. In spite of this, it still has a very high diversity, possibly as a result of the severity of drought and fire acting on a geological time scale, which created a great diversity of habitats (Cox and Moore, 2000). The historical explanation and evolutionary mechanisms of such diversification have been ascribed (at the local scale) to spatial variation in resource availability, disturbances (e.g., fire and grazing), neighbourhood effects, lottery processes and the influence of regional processes, including high topographical, climatic heterogeneity and also geomorphology, soils, hydrology and land use practices (Blondel and Aronson, 1995).

The Mediterranean region is not only diverse in terms of habitats but it was also one of the centres of development of agriculture and pastoralism. In Portugal, as in other parts of the Mediterranean, a wide range of agriculture and horticulture activities, together with grazing, clearing and burning, removed or drastically altered the natural vegetation in many areas and at least restricted or modified it in others (Cody, 1986). The large-scale changes in landscape structure have influenced diversity both positively and negatively. The opening up of landscapes by human activities in the Mediterranean Basin probably led to increased diversity since pre-historical times, although the changes in the last two centuries have mainly resulted in diversity loss (Bengtsson *et al.*, 2000).

In mainland Portugal there are a total of 3000 taxa of vascular plants (2500 spontaneous and 500 naturalised), about 86 endemisms (lusitanian) and a significant number of Iberian endemisms. About 10% of the total species are classified in need of a conservation status. There are also a considerable number of "domesticated" crops from the Mediterranean basin due to past human introductions that, associated with climatic and soil variability, created an important genotypic diversity (gene pool diversity) (ICN, 1998). As regards terrestrial vertebrates, there are a total of 419 species (91 mammals, 280 birds, 30 reptiles and 18 amphibians). About 33% of these species are presently endangered and in need of a special conservation status (ICN, 1999). Protected areas represent about 7% of the continental territory resulting in 38 protected areas: 1 National Park, 11 Natural Parks, 8 Natural Reserves, 3 Landscape Protected Areas, 10 Classified Spots and 5 Natural Monuments (ICN, 1998).

To analyse the impact of climate change on biodiversity is difficult due to the complexity of relationships between ecological communities and climate (Anderson *et al.*, 2000). To do that across habitats, geographical units or taxonomic groups is often impossible, because different types of organisms or environments (sea, wetlands, flora, fauna, etc.) require different approaches and time scales. The meaning of biological diversity also differs with spatial scale. For example, the diversity occurring in a homogeneous ecological community type (*alpha* diversity) cannot be compared with the biological diversity occurring over the wide range of community types that occur in a region (*gamma* diversity).

In view of these constraints we concentrated our study on major types of terrestrial ecosystems using the simplistic approach that assumes that the risk of species extinction under future climate conditions, may lead to diversity losses. Most of this work was done in the context of analysing the impact of climate change on forests and was reported in the first part of this chapter (section 10.1). Specific taxonomic groups or soil organisms are not addressed, emphasising examples of endangered species and specially protected areas (e.g., natural parks and reserves).

### 10.2.1.2 Effects of Climate Variables on Biodiversity

#### *10.2.1.2.1 Direct Effects*

Climate plays an overwhelming role in biodiversity changes. There is a gradient of biological diversity from the tropics towards the cooler regions of the higher latitudes. This latitudinal gradient has intrigued scientists for decades. One of the reasons for higher biodiversity in equatorial and tropical ecosystems is related to higher primary productivity rates in those regions (Cox and Moore, 2000). Warm temperature and high precipitation result in high productivity that can support more complex and diverse ecosystems than temperate forests. Another reason invoked for the latitudinal gradient is climatic stability at the tropics. Less affected by radical climate changes, such as the glacial periods in the higher latitudes, the tropics could sustain a greater diversity of species. Although this assertion is questionable (Cox and Moore, 2000), it might suggest that periods of rapid climate change could lead to mass extinctions and losses in biodiversity. Nevertheless, although gradients in primary productivity or climate stability may explain broad scale changes in diversity, the high diversity of vegetation types and communities of the Mediterranean region results largely from physiographic complexity and habitat diversity (Blondel and Aronson, 1995).

Species distribution is often correlated with climatic variables, more commonly average temperature and precipitation can explain most species geographic ranges. But occasional extreme events may be more important than average conditions. As air temperatures may fluctuate widely, the occurrence of extreme temperatures (hot or cold) may pass the lethal limits for some species or may modify ecological interactions between species, driving some to extinction (see 10.1.2.1). Drought may also lead to the extinction of some plant species as discussed above for key forest trees (see section 10.1.3.3).

Local extinctions would not be a major problem for biodiversity *per se*, if migration or speciation (i.e., the formation of new species) could occur at a comparable rate. However, rapid climate change can intensify habitat fragmentation and species extinction, having a great impact in biodiversity.

During the last 2 million years, climate has changed and there may have been as much as 16 glacial cycles, each lasting for as long as 50000 to 100000 years and brief interglacial periods of 10000 to 20000 years. Since the peak of the last glaciation (about 20000 years ago), global temperature has risen 5°C to 7°C and species richness has increased continuously, especially during the last 14 000 years (Begon *et al.*, 1996). Nevertheless, the speed at which species migrate is rather low (from 100 to 500 m per year for forest trees) and vegetation failed to accompany the speed of climate change (Begon *et al.,* 1996). To some extent, the existing patterns of species distribution still represent the recovery from the last glacial period.

In the Iberian Peninsula, relatively sheltered from glacial cold due to its mountains and low latitude, the survival of several woody formations from the pre-glaciation period was possible in refuges during the ice ages (e.g., the relict formations of Serra da Arrábida). As the climate warmed, the presence of such refuges allowed a quick colonisation by species typical of warmer climates and lead to high biological diversity in areas that had previously less diverse biomes typical from cooler climates. The recovery of vegetation after the last glaciation could then take place without large migratory movements, in contrast with the dominant process that occurred in northern Europe. However, with the increased activity of agricultural populations in the Neolithic (7000 years ago), vegetation recovery began to depend less of climate variables and increasingly more of human actions (Blanco-Castro *et al.,* 1997).

#### *10.2.1.2.2 Indirect Effects*

Indirect effects of climate on biodiversity can result from changes in biological interactions induced by changes in temperature or rainfall, which in turn may result in changes in community composition and structure.

Habitat fragmentation is caused by natural processes (e.g., fire, herbivores explosions) as well as anthropogenic activities (Forman, 1997), which can interact with climate. Fragmentation occurs when an extensive area of a given habitat is reduced to an assemblage of isolated patches or fragments with less area total than the original (Wilcove *et. al.,* 1986). The fragmentation and the loss of habitats are major sources of biodiversity loss. Still, it shouldn't be confused with habitat heterogeneity, which can allow of more biological diversity in a landscape than in homogeneous habitats, as such heterogeneity implies an increase in extent of absolute boundary of any habitat type and can lead to an increase in landscape-level or regional (*gamma*) diversity.

Fragmentation is often associated with damaging impacts on persistence of a given species or populations. This may result in the reduction of population size, change in dispersal and migration rates, and eventually species extinction. The relative connectivity of similar patches and permeability of species inhabiting the landscape plays a central role in species distribution and abundance across landscapes (Ecological Corridors) (Dunning *et al.,* 1992; Taylor *et al.,* 1993).

An important indirect consequence of climate change is related with the spread of invasive species, i.e., alien or naturalised species that have abundant offspring and outcompete native species or occupy a free niche in the ecological community. The Convention of Biological Diversity recognises biological invasions as one of the most threatening factors affecting biological diversity at the global scale (Dukes and Money, 1999) because they: 1) affect ecosystem processes (e. g., nutrient cycle, resource availability), 2) affect biodiversity, eliminating native species due to competition and/or other interactions, and 3) interfere with the economic value and other ecosystem services. In Portugal, this is exemplified by invasive species such as *Acacia longifolia* and *Acacia cyanophylla* on dunes or by *Acacia melanoxylon* and *Acacia dealbata* inland, displacing native woody species.

Once established, invasive species can alter the available resources or ecosystem structure and functions through the alteration of soil chemistry, nutrient cycles, fire and hydrologic regime (D'Antonio and Vitousek, 1992; Lodge, 1993; Binggli, 1996; Cohen and Carlton, 1998), and increasing competition, which prevents the regeneration of native species and can even lead to their exclusion (Vitousek *et al.,* 1987; Walker and Vitousek, 1991). Invasive species can also outcompete native species after natural disturbances (Tilman, 1997).

Climate may play an important role, as invasive species take advantage of ecological perturbations including droughts, wildfires or storms. For example, some plant species will be especially favoured by high fire frequency whereas others will go extinct under these conditions. On the other hand, floods may bring about the introduction of alien aquatic organisms, but the end of flooding (e.g., damming) may facilitate the invasion of riparian forests by exotic woody species, as occurred with the replacement of native poplars and willows by the eurasian *Tamarix* in the Colorado river valley (USA). Relations between invasion and disturbance are complex and they depend on the type and frequency of the disturbance, the environmental constraints and the biology of the particular species concerned (Ferreira and Moreira, 1995). Plant invasions are typically characterised by a decline in species diversity at all trophic levels within an ecosystem (Berling, 1995). It is generally considered that an increase in the disturbance of an ecosystem leads to the increased probability of invasion (Berling, 1995).

Changes in biological interactions may also result from weather induced changes in resource availability. This may happen when animal populations are negatively affected by primary productivity decreases or the extinction of some plant species that are source of food or shelter for animals, as a result of drought. Changes in resource availability may also occur when plant and animal life cycles are desynchronised. For example, when some plant species begin growing earlier in the season due to the increase in the mean temperature of winter, they may reach fruit set earlier and change the food availability for migratory birds, insects and other animals. Several case studies have shown that short-term changes in temperature may cause changes in abundance of individuals and species in communities.

In summary, biodiversity does depend directly from climate. In Portugal it is the interaction between climate, topography and land use history that determines biological diversity. Climate may have indirect effects as it influences habitat fragmentation and biological invasions.

### 10.2.2 METHODOLOGY

#### 10.2.2.1 Description of Assessment Approach

##### *10.2.2.1.1 State of the Art (of Assessing the Impact of Climate Change on Biodiversity)*

The most common way of monitoring biodiversity in terrestrial ecosystems is through the evaluation of species diversity (species number and abundance) or species richness (species number) using biodiversity indices, for example. Moreover, the diversity of plants in an ecosystem has been commonly used as a surrogate measure of total ecosystem diversity. Plant species diversity is positively correlated with structural as well with biotic interactions (e.g., insects and plant secondary compounds), which is assumed to be positively related with animal diversity. On the other hand, the home ranges of several animal species have been found to be strongly linked to vegetation. Therefore animal species that rely on vegetation may change with shifting of plant distribution (assuming no other limiting factors) (Root, 1993).

The impact of climate change on biodiversity depends on (1) the relationships among species in the community and (2) the susceptibility of the habitats to changing climatic conditions. For example, warming may alter the relative abundance or even the presence of less tolerant (or most affected) individuals or species. Nevertheless, these impacts are extremely difficult to predict due to the complexity of ecological processes and to the uncertainty about the role of biodiversity in ecosystem functioning. The resilience of many ecosystems to change, together with the possibility of acclimation of organisms to new environmental conditions, may delay the onset of changes in ecological communities as climate changes. It is recognised that "because of the complex web of interactions linking species to ecosystems to climate, isolating the direct cause-and-effect relationships between climate change and biodiversity is often impossible" (Anderson *et al.,* 2000).

The assessment options of other national reports (Anderson *et al.,* 2000; Joyce *et al.,* 2001; Parry, 2000) is based essentially on the assumptions that major shifts in vegetation types would induce a change in distribution of different community types, habitats and thus species richness. These studies use both vegetation and statistical models and climate scenarios as the base information. A thorough literature review, covering the known relations between local species and changing climate, is then used by a team of experts to identify the major impacts on biodiversity. It must be stressed that the uncertainty underlying this type of analysis is very high, and therefore the outputs consist mainly of major trends, rather than a detailed list of impacts.

##### *10.2.2.1.2 Options for Assessing Impacts on Biodiversity*

To evaluate the impacts of climate change on biodiversity we may take several approaches. Controlled experiments with the manipulation of environment conditions can be very useful to unravel basic principles but are, usually, too limited in terms of groups of organisms, or space and time scales and are beyond the scope of this project. Biogeographical models (e.g., BIOME4, see section 10.1.3.2) can reveal the general impacts of climate on biodiversity, but often they are restricted to the most important components of vegetation (e.g., trees in forests), and do not take into account other biological interactions. In addiction, the poor knowledge of the processes affecting biodiversity at different organisation levels and time and spatial scales make the assessment of impacts even more complex. Another major limitation to this approach is the inability of most models to incorporate the effects of human actions. While the assumption that natural processes are the dominant factor affecting species distribution may be true in remote areas, in most of Europe human actions are the dominant factor. Hence, simulation results for such areas must be analysed with great caution, as natural processes are often overridden by human action.

#### *10.2.2.1.3 Description of Options Selected for Analysis*

The approach used – model simulation, literature review and expert judgement – does not provide information on changes in biodiversity *per se.* Instead, we used future distributions of major vegetation types in mainland Portugal (see section 10.1.4.2), biogeographical information and expert analysis, to indirectly analyse potential biodiversity changes in the future climate scenario. These selected vegetation types, such as the evergreen oak woodlands ("montados") or maritime pine forests or temperate deciduous forests may be considered as a repository of high natural biodiversity and rare, endangered or endemic species. Loss of keystone species that characterise the existing major vegetation types may reduce ecosystem resistance and resilience, i.e., the capacity to adjust to ever-increasing rates of environmental change (see section 10.1.3.3).

Model simulations were used in the first part of this chapter to assess the possible impact on major types of vegetation in the Portuguese mainland territory. The results from the simulation with the BIOME4 model provided a general background for the assessment of impacts of climate change on biodiversity. The general approach used in this report consisted of an extensive literature review, that together with the results of model simulations (BIOME4 and Emberger Index) and expert opinions, allowed the identification of the major impacts of climate change on biodiversity. In addition we studied the risk of extinction of key forest trees comparing the postulated climatic range of a species with the Emberger Index in the future climate scenario (see section 10.1.4.4 for an explanation).

An exception was the study of protected areas, where the information regarding existing species, conservation objectives and human pressure is higher than for the rest of the country. This allowed the assessment of the vulnerability of these areas to climate change, based on the results of model simulations and expert opinion. Other factors, such as specific natural characteristics or high human pressure were also considered in this analysis. For example, "Serra de Aire e Candeeiros" and "Arrábida" are influenced by the limestone geology. The geology affects plant mineral nutrition, as well as water retention, which are essential for the existing communities. Other protected areas, such as "Sintra-Cascais", "Gerês", "Costa Vicentina", "Estuário do Tejo" and "Serra da Estrela", are highly subject to anthropogenic pressure, at least during certain periods of the year, which increases their vulnerability.

## 10.2.3 IMPACTS OF CLIMATE CHANGE UPON BIODIVERSITY

### 10.2.3.1 Introduction

#### *10.2.3.1.1 Overview*

The future climate scenario is expected to produce large shifts in vegetation distribution at unprecedented rates (the project temperature change in the 21st century can be up to 50 times larger than in the last glacial-interglacial transition). The simulated effects (see section 10.1.3.3) of increased aridity in vegetation at the ecosystem level, are similar to those attributed to past human activities that led to (1) the replacement of forests by shrublands, (2) the replacement of deciduous species by evergreen trees . Other effects of past human impact not easy detectable by existing models, are complex alterations in ecological communities. These resulted in the increase in local biodiversity in moderately perturbed habitats and a great decline in biodiversity in degraded areas (Blondel and Aronson, 1995). As in the past, many species, both plant and animal may become locally extinct due to climate change. Natural recovery processes, such as migration/dispersal or speciation, may fail to keep pace with the speed of environmental change and massive species extinction is likely to occur.

The impact of disturbances on biodiversity is strongly dependent on their intensity and frequency. Disturbances such as forest fires (see section 10.1.4.5) or extreme weather events (see chapter 2), create gaps in the landscapes, which release space and resources for new individuals to establish. On average, higher levels of species richness are maintained at intermediate levels of disturbance. As the disturbance frequency increases, species richness is expected to decrease (Begon *et al.*, 1996).

Ecotones, i.e., the boundaries between ecosystems, are more vulnerable to climate change, especially those in semiarid landscapes. The postulated changes in vegetation will lead to habitat modification and consequently, in the composition of the whole ecological community. Some animal populations, especially if they have limited geographical distributions, small habitat areas or low number of individuals, may not be able to respond to rapid changes in climate, and extinction may occur especially in populations with low reproductive and dispersal capacity. Endemic species may be especially at risk. Most of these species are already endangered and will probably become extinct if the current pressure of habitat disruption is maintained.

Increasing human population can push animal and plant populations past a critical threshold of tolerance and renewal (Cincotta *et al.*, 2000), mainly due to habitat disturbance. Cincotta *et al.* (2000) estimated that the human population growth rate between 1995--2000 was 1.3% yr$^{-1}$ for the Mediterranean Basin. Human demands for housing, arable land, freshwater, and industries can lead to widespread land degradation which threatens ecosystem functioning and increases the risk of further extinctions.

#### *10.2.3.1.2 Detailed List of Impacts*

##### 10.2.3.1.2.1 Identified Impacts

Climate change will have an impact on all living organisms, on their environment and on the interactions between them. We present here the major categories of impacts identified:

- Impacts at different spatial scales: ecological communities, along environmental gradients, at the region level.
- Impacts on different environments: soil, rivers and estuaries, sea and coastal zones, terrestrial ecosystems.
- Impacts on specific areas such as protected areas.

##### 10.2.3.1.2.2 Studied Impacts

From the wide range of possible impacts of climate change on biological diversity, we studied in detail the loss of species, biotic invasions, habitat fragmentation and impacts on terrestrial ecosystems at the regional level and on protected areas.

### 10.2.3.2 Impacts on Biodiversity

#### *10.2.3.2.1 Factors Affecting Ecological Processes*

Vegetation may undergo great changes with climate change. As shown in section 10.1.3.2, there is a risk of some biomes disappearing (e.g., the temperate deciduous broadleaf forest) whereas others may undergo a significant reduction in area, if they fail to relocate to fitter habitats. Due to relatively short time scale of these events, it is not likely that entire ecosystems are able to "migrate" and keep pace with climate change.

One of the obvious impacts of climate change may be the increase in the proportion of inhospitable areas over the present range of a given species. If the intrinsic colonisation ability of a particular species is low, or if physical barriers to dispersal are present, the fate of many species in a rapidly warming environment will depend on their ability to permanently migrate from increasingly less favourable climatic conditions to new areas that meet their physical, biological, and climatic needs. In regions characterised by a great physiographic heterogeneity this may easily induce habitat fragmentation, when combined with intense human intervention on the landscapes, as in Portugal. Landscape fragmentation, the decrease in patch areas and larger distances between habitats, can convert "core" landscapes into "marginal" landscapes, and "marginal" landscapes into "uninhabitable" landscapes. This trend may be reinforced by an increase in the frequency of disturbances (both natural and anthropogenic), leading to regional extinction and increasingly localised distributions throughout geographic ranges.

Ecosystems that are already under some degree of stress, are the most likely of being severely affected by climate change. For example, one important vegetation formation in Portugal are the riparian ecosystems. These are comprised of communities located on river floodplains that are part of a highly integrated system including the stream channel (Brinson, 1999). Riparian galleries are important forest formations with high species richness (both animal and plant) functioning as a structural element of aquatic communities. Their spatial heterogeneity and vertical stratification guarantee the maintenance of biological diversity within the corridor but the connectivity and continuity, both transversely (between aquatic and terrestrial environments) and longitudinally (among habitat fragments), make them suitable for the establishment of new communities and benefits migration processes between areas. The high species diversity of some floodplain areas is partially explained by their habitat heterogeneity and the high-frequency natural disturbance regimes. The resilience of these systems is generally high, and the recovery periods from disturbance are short. In Mediterranean-type rivers, resilience may be even higher, due to the high competitiveness and local adaptation of the natural vegetation species (Ferreira, 1992). But human intervention can change the system dynamics. Management actions, such as the building of reservoirs or the channelisation of rivers, strongly affect the disturbance regime and, consequently, species richness. For example, a study conducted in the river "Mondego" revealed that channelled sections were more vulnerable to invasions than natural sections (Aguiar *et al.*, 2001). River "artificialisation" is currently one of the major threats to biological diversity in riparian systems. In a scenario of increased water consumption, due to higher temperature, and even lower water availability, it's likely that the impact of such engineering works will become higher, increasing vulnerability of these ecosystems.

Another example of great vulnerability to climate change consists of rare and isolated populations in fragmented habitats. Endemic species from the serpentine soils of Bragança, northeastern Portugal, such as *Armeria eriophylla* or *Festuca brigantina,* have highly fragmented distributions and survive in small and isolated patches. Climate change may directly or indirectly affect their survival and they may quickly become extinct.

The number of invasive species and their dissemination will most likely increase in the future, mainly as a result of land use change and habitat fragmentation. If drought and temperature conditions change, as expected, the new conditions may negatively affect native species and favour invasive species. The most threatening invasive species are those with high drought tolerance, which improves their ability to expand their present range and to occupy native species' niches. Disturbances are expected to increase (e. g., fire, sea level rise), both in intensity and frequency, which can favour the invasion process by creating ecosystem stress and, hence, avenues for opportunistic species.

Already existing invasive species, such as *Pittosporum undulatum* or *Acacia* spp. (see also Leite *et al.*, 1999) are expected to expand their areas, as well as non-indigenous or introduced species, which may benefit from the "tropicalisation" of the climate (warmer winters). In addition, habitat fragmentation may also favour biotic invasions. Species that have highly fragmented habitats are often specialists that are more vulnerable to invasions by "generalist", i.e. species with a broad range of suitable habitats. In turn, fragmentation may be enhanced as invasive species occupy new territory, further reducing the availability of suitable habitats.

As mentioned above, one of the outcomes of model simulation is the possibility that large areas of the evergreen-oak woodlands, or "montados" may be lost in the drier part of their present range. Many plant species depend on specific ecological conditions, typically found in "montados" with sandy soils where precipitation is over 500 mm/year. A few examples include, *Tuberaria major, Euphorbia transtagana, Thymus camphoratus* (which occur near Sines), *Ononis hackelii,* and *Linaria algaviana.* Certain species listed in Annex IV of the Habitats Directive* (EUR-lex, 2000), such as

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* The Habitats Directive was adopted by the European Union in 1992, and establishes the basis for the protection and conservation of wild fauna and flora and natural habitats. The Annex II is a listing of animal and plant species of community interest whose conservation requires the designation of special areas of conservation and the Annex IV is a listing of animal and plant species of community interest in need of strict protection (EUR-lex, 2000).

*Thymus capitellatus, Thymus villosus* ssp. *villosus* and *Scilla odorata,* occur in these habitats. They form rare, sensitive populations that may be strongly affected by fragmentation and the possible reduction of "montado" area (see section 10.1.4.3.1).

Riparian species, such as *Spiranthes aestivalis,* may be especially vulnerable, due to the predicted increasing aridity in the region. Other plant species which deserve special attention, *Armeria rouyana* and *Ionopsidium acaule,* and others from the Annex II, such as *Halimium verticillatum* because they belong to the unique "montados" communities.

Coastal areas are especially vulnerable to natural and anthropogenic disturbances and the increasing construction and tourism in these areas is promoting habitat fragmentation and biological invasions. Invasions by several exotic species (*Acacia* spp. and *Carpobrotus edulis* being the most representative) have become a common occurrence on the Portuguese coast.

Rising sea level has obvious impacts in coastal ecosystems (e.g., dune systems), especially where the interland level is relatively low. For example, the region between "Serra da Boa Viagem" and "Ria de Aveiro" is a rather flat coast that extends to the littoral platform, where a previous sea level rise has submerged ancient dune systems parallel into the coastline (Dias, 1985). The terrain morphology and the intensity of western winds in this region have allowed the development of a peculiar dune system where the beach corresponds to a dune front in continuous regression. Simultaneously, large parabolic dunes moved inland about 20 to 30 km, leaving behind a dune system transversal to the coastline. Between the transversal dunes the water table level has simultaneously risen, creating flat peat land areas inhabited by *Salix arenaria.* A continuous sea level rise will probably maintain this dynamic process, influencing a coastline retreat (despite human intervention, such as seawalls and groins built in the last few decades mainly near coastal populations), as well as, a possible reactivation of the distant parabolic dunes.

Within intertidal zones, the rising sea level will impact coastal salt marshes by displacing them inland. As a result, a number of agricultural lands may experience increased salinity and create an invasion of rush-beds and *Tamarix africana* stands. These newly introduced communities may replace *Salix* and *Alnus* stands in the lower river lines.

Increased fire frequency, besides favouring biotic invasions and habitat fragmentation, can reinforce the tendency for a predominance of younger vegetation eventually preventing some species from reaching reproductive maturity (see 10.1.3.4). The north and centre will probably be the most vulnerable areas, as in the present, because of their higher NPP, and, consequently, higher biomass load. The consequences of fire may be exacerbated by the enhancement of soil erosion that may arise from the concentration of rain in the winter and the decrease in permanent plant cover. Nevertheless, most of the Portuguese vegetation is fire-adapted and the final outcome in terms of biodiversity may be broadly predictable, although the tolerance thresholds of each vegetation type are still unknown.

Climate change may affect animal populations directly, by inducing environmental stress, or indirectly, through changes in vegetation. Migration is a likely consequence of changes in climate, but where populations are unable to migrate, local extinction will probably occur.

Animal species, especially *Lynx pardina* ("lince ibérico") and *Microtus cabrerae* ("rato de cabrera"), Iberian endemisms, and *Galemys pyrenaicus,* ("toupeira de água", which only exists in Portugal, Spain and in the French Pyrenees), as well as other Iberian endemic amphibians and reptiles, are highly sensitive species and strongly depending of specific habitats. These species are already endangered and will probably become extinct unless protected.

Other currently endangered vertebrates, about 33% of total vertebrate species (excluding marine and fresh water fishes) in the mainland, share a number of vulnerability characteristics. The destruction, disturbance and fragmentation of habitats can decrease population size to critical levels, enhance population dispersion and increase environmental stress in segments of the population. For example, the lengthening of the dry season may affect water availability in certain wetlands in the interior where many migratory and endangered residential bird species live.

In general, animal species follow closely vegetation changes. As a consequence, if climatic changes induce habitat transformations by affecting vegetation types, then wildlife is also likely to be affected. For instance, it could be assumed that large mammals such as red deer (*Cervus elaphus*) or wild boar (*Sus scrofa*) would benefit in areas where shrub and woodland formations will potentially increase as a result of predicted climate changes. In the "Trás-os-Montes" region (Northeast Portugal), wild deer populations have recently increased as a result of an expansion of non-agricultural areas, in this case resulting from changes in land-use. Populations of large predators such as the Iberian wolf (*Canis lupus* ssp. *signatus*) have also increased as a response of a higher abundance of their prey – the deer. Conversely, wildlife populations would be negatively affected if climatic change will lead to negative habitat transformations. Some traditional agricultural landscapes can have high conservation value as well. The extensive cereal fields of Castro Verde, in the South of Portugal, constitute the main habitat type for a bird of high conservation value – the great bustard (*Otis tarda*). If, as a result of climatic change, the extensive cereal fields and agricultural practices preserving those fields decline, then great bustard populations would be negatively affected.

Invertebrate species, insects in particular, have a strong dependency of climate. However, it is virtually impossible to foresee the impacts of climate change, due to the complexity of interactions with the surrounding environment. The major trends discussed for pests and pathogens in section 10.1.4.6 are applicable to invertebrates and fungi in general.

### *10.2.3.2.2 Protected Areas in Mainland Portugal*

Protected areas are geographically delimited areas designated and managed to attain specific conservation objectives (UNEP, 1992). These areas are selected based on specific criteria, such as ecological uniqueness, landscape and cultural value, and scientific and social importance. When natural reserves were originally defined, climatic change was not an issue. With climate change, these areas can suffer a reduction in the habitats suitable for the species or ecosystems that they were intended to protect.

In this study, only relatively large protected areas were analysed (see figure 10.11), due to the coarse spatial resolution of the climate scenarios. Small protected areas, such as "Paúl de Arzila" or "Paúl do Boquilobo" wetlands, were not considered because of the occurrence of specific species, communities or habitats within the reserve boundaries, that depend of particular environmental characteristics. These areas are, therefore, patchy and "insensitive" to large scale modelling proposed in the present analysis. However, it is highly probable that these areas will be the first to be affected by climate change. Portuguese wetlands are in general small, highly fragmented, and poorly connected. Furthermore, water pollution and intensive agriculture activities are changing plant cover and causing biodiversity loss. In regions where the increase of drought is expected, the maintenance of these aquatic ecosystems is uncertain.

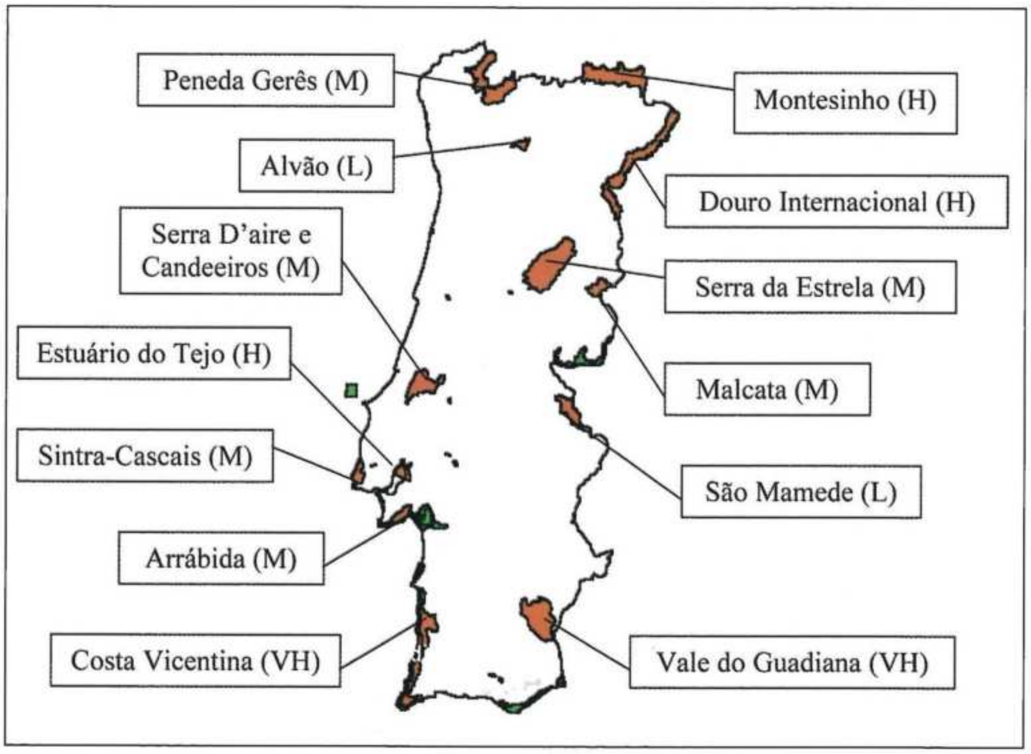

Figure 10.11 – Vulnerability of the Protected Areas to climate change (VH- Very High, H – High, M – Medium, L – Low).

The possible change of forest cover described in section 10.1.3.2 and expansion of semi-arid areas, mainly in the southern and interior regions of north central Portugal, will most certainly entail important changes in habitat and thus affect occurring species (endangered or not). Destruction, or reduction, of habitat may change species richness patterns in these areas.

Figure 10.11 presents the estimated vulnerability of the main protected areas to climate change. It must be stressed that the overall vulnerability is high, due to the extent of the predicted changes in climate. Thus, the objective of this analysis is to identify potential differences between areas, rather than to achieve an absolute classification. Dependence of water resources seems to be a key factor driving higher vulnerability, in addition to the increased aridity predicted for some parts of the country. Lower vulnerability is related to low impacts of the model simulations, and is subject to their intrinsic uncertainty.

## 10.2.4 ADAPTATION MEASURES

### 10.2.4.1 Approach Used to Develop Adaptation Measures

Biodiversity conservation is a fairly new concern worldwide, and especially in Portugal. During the last three decades, a significant amount of environmental programmes and legislation has emerged, some of which is not yet fully implemented. It is generally recognised that the full implementation of existing measures can significantly benefit the environment and biodiversity conservation. We suggest additional measures that arise from the impacts of climate change.

The focus must be on those species and ecosystems that are least likely to adjust to a changing climate. For example, if suitable habitat conditions disappear entirely, or changes are faster than the population can react to, the extinction process may occur and lead to a decrease in ecosystem species richness. However, it seems wise to define an adaptation strategy in the national context due to the uncertainties associated.

### 10.2.4.2 Biodiversity and Protected Areas

#### *10.2.4.2.1 Strategies and Policies*

Management strategies and policies should be established to assess and provide data for the interactions of climate change and biodiversity, and for the sustainable use of biological resources. The existing ecological data and knowledge of each region will provide a tool for sustainable uses of natural resources. This, together with the evaluation of the threatening effects of changing drought intensity, fire, and floods, should increase the knowledge about bioindicators of environmental quality, which are needed for sustainable land use and ecosystem restoration.

The actions proposed in the recently published National Strategy for Nature Conservation and Biodiversity, to mitigate the potential effects of climate change on biodiversity, should be implemented quickly. The proposed measures to mitigate potential effects of climate change on biodiversity should be considered in all instruments of regional land-use planning, e.g., municipal plans, "Plano Director Municipal" (PDM), or regional forest land planning, "Planos Regionais de Ordenamento Florestal" (PROF).

#### *10.2.4.2.2 Landscape and Habitat Fragmentation*

Fragmentation significantly reduces the probability of successful dispersal and establishment. Artificial and natural corridors (the importance of riparian forests is here stressed in the Portuguese case) between remaining habitat patches may become increasingly important and should be always included when evaluating and modelling climate change and biodiversity conservation.

#### *10.2.4.2.3 Monitoring Critical and Endangered Species*

It is possible with existing data to identify some of the most critically endangered plant and animal species under the future climate scenario. Some of these species were listed above, but a continuous research and monitoring effort is needed. In the case of plants, these species must have a specific monitoring plan, including qualities such as seed production, germination, and dispersal. The seasonal activity of pollination and habitat range also needs to be studied in detail.

##### *10.2.4.2.4 Upkeep and Enlargement of Protected Areas*

Nature conservation areas can be seriously affected by climate change. Increased connectivity between protected areas, either through the enlargement of existing areas, or the creation of new ones, can favour the migration of species to fitter habitats. Large protected areas, with sufficient physiographic heterogeneity to embrace a series of climatically discrete habitats, may be of even greater value. As suitable breeding habitats become increasingly localised at natural margins and through habitat fragmentation, metapopulations (i.e., an overall population in a patchy environment comprising several subpopulations interlinked by dispersal processes, each one with its own internal dynamics) fail to persist where the rate of local extinction exceeds the rate of colonisation, and in areas where the fraction of the population lost during migration between habitat patches is too high.

Increased connectivity between natural habitats and developed landscapes may assist organisms in attaining their maximum intrinsic migration rates and reducing species loss. Wise management of the matrix between existing protected areas allows for the migration of organisms and is essential to future preservation of species in protected areas. Corridors connecting different reserves could enhance the migration between them promoting, not only species richness due to rapid population movements inside and outside reserves but also gene fluxes between areas.

##### *10.2.4.2.5 Prevention and Control of Invasive Species*

The control of already installed invasive species, in certain sites, might be attainable with physical and chemical management techniques. New silviculture models need to be developed to guarantee an efficient control of potential species invasion in the new ecological conditions. In unaffected sites, the prevention of invasions needs to be based in adequate silviculture management and techniques favouring a dense canopy, the absence of openings, and frequent interespecific cleaning cuts, in order to minimise fire risk. Measures to control invasions by organisms other than plants must be enacted (see section 10.1.5.5).

### 10.2.5 RESEARCH GAPS

- There is a need to combine manipulation experiments and simulation models to assess the effects of climate change in ecological community processes and biodiversity. We need to compare models that simulate changes in species distributions with models developed to look at species turnover at specific sites (Watson *et al.*, 1997).
- Due to the strong influence of climate and land use over species distributions through alteration of dispersal routes and changes in habitat, there is a need to integrate models of land use and climate to a local extent to predict the interaction of these influences on biodiversity.
- Biological invasions are most difficult to recover from and are responsible for a great number of extinctions (Vitousek *et al.*, 1996; Meffe *et al.*, 1997; Primack, 1998). The problem is worthy of research in terms of description and processes, as well as in terms of management, as it is a very serious threat to the conservation of biodiversity.
- Improve the existing databases on biological diversity in different environments and types of organisms.
- Critically endangered species will benefit from a better knowledge of their biology and their interaction with the surrounding environment.

### 10.2.6 CONCLUSIONS

Most of the Portuguese territory has an exceptionally large number of endemic species (mainly in the Macaronesia islands, "Madeira" and "Açores" not considered in this report) in need of preservation. Changes in climate may affect biodiversity either directly, threatening species survival, or indirectly, through habitat fragmentation or biological invasions. Some populations, especially those that have limited geographical distributions, small habitat areas, or low number of individuals, may not be able to cope with rapid climate changes. Extinction may occur in populations with low reproductive and dispersal capacity. In regions where changes in vegetation are expected due to climate changes it could thus be assumed that some animal species will also be affected. In most cases, however, the effects of land use changes induced by human society are likely to interact and override the long-term effects of climatic change. The adaptation measures should be actively directed to counteract these tendencies focussing on maintaining or improving connectiviness of habitats and controlling biological invasions. Land-use planning for urban development, agriculture or forestry must take onboard conservationist principles. Protected areas are essential for the preservation of biological diversity but some may be vulnerable to changes in climate. Special measures, such as the enlargement of protected areas and the monitoring of endangered species, may need to be reinforced.

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# 11

# Fisheries

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## CONTENTS

## EXECUTIVE SUMMARY

Impacts of climate change on the distribution and abundance of marine species of commercial interest in Portugal were studied, by focussing on three species: bluefin tuna, common octopus and sardine. As their response to climate change has not yet been modelled in the bibliography (for sardine, important aspects of the stock-environment relationship have been analysed, but only some aspects for the Portuguese coast), this chapter begins with the construction of models. These are later used, in conjunction with Hadley Centre's simulated data (HadRM2), to estimate impacts on Portuguese fisheries due to climate change. Special emphasis is given to modifications in the Portuguese upwelling regime, forecasted by the HadRM2 model.

Some deficiencies were found in the HadRM2 control run, which prevented the used of simulated data (2080-2100) to estimate impacts with high degree of confidence. Instead, more qualitative hipotheses were put as to future changes in the abundance and distribution of the three species. These include meridional shifts in centres of octopus and sardine production and the reappearance of bluefin fisheries, which are nowadays undergoing a period of crisis.

It should be stressed, however, that direct anthropic forcing (overfishing, pollution, introduction of exotic species, etc.) may not allow stocks to naturally adjust themselves to the changing environment, and, as such, fisheries estimated by stock-environment relationships to become profitable may never emerge.

# 11. Fisheries

## 11.1 INTRODUCTION

### 11.1.1 OVERVIEW OF FISHERIES IN PORTUGAL IN THE 20TH CENTURY

Portugal is a country with a strong tradition in the fisheries sector and is one of the countries with the highest fish consumption per capita (60 kg *per capita*/year). Fish is part of Portugal's social and cultural heritage, as one might expect in a country with a great maritime tradition and a large littoral area. The Portuguese Exclusive Economic Zone (EEZ) comprises 1.7 million km$^2$, amounting to almost 50% of the European Union (EU) EEZ. Portuguese fishermen comprise 11.4% of total EU fishermen; nevertheless, the sector has decreased from 38,700 in 1990 to 28,458 in 1996 (Fisheries Yearly Statistics, Eurostat 1999 In INOFOR 2001). This decrease has been reported to have been caused by the precarity of employment and remunerations on this sector (Brandão Moniz et al. 2000). Other important reasons are management strategies developed within the context of the EU Fisheries Policy and the decreased esteem accorded to the activity. Further, the fishermen population, mainly composed of people with little formal education levels (but high practical knowledge, transmitted throughout generations), has been ageing (Brandão Moniz et al. 2000). Consequently, these facts created a profound crisis in the sector with increasingly evident social consequences (Brandão Moniz and Kovács 2000).

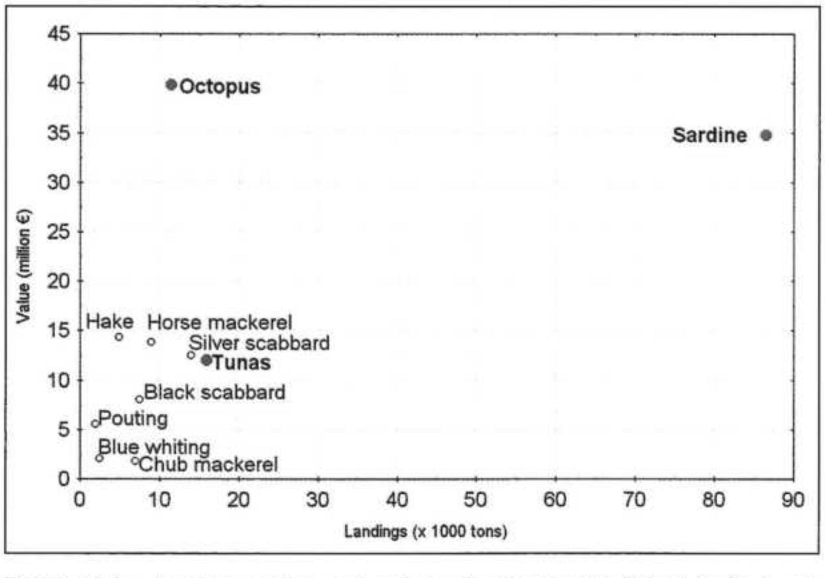

Figure 11.1 – Average catches and values of some species fished in Portugal, 1986-'96. Source: Direcção Geral das Pescas e Aquicultura (www.dg-pescas.pt)

In the last decade Portugal faced a considerable reduction in landings, especially due to the downfall in the activity of the Portuguese high seas fleet, which operated in distant waters over many centuries. Successive restrictions on access to traditional fishing grounds, namely in North and South Atlantic, together with restrictions from the Common Fisheries Policy (temporary or permanent interdiction of fishing, and the limitation of Total Allowable Catches), have had a drastic impact in the sector. According to Brandão Moniz et al. (2000), this situation caused a decrease of direct and indirect labour, an increment of imports as well as a substantial rise of sale prices. As a result, the deficit of the Portuguese commercial balance for marine products has been growing constantly.

#### 11.1.1.1 Key species: sardine, bluefin tuna and common octopus. Brief characterization.

Throughout the 20th century, three species held a capital importance in Portuguese fisheries (Figure 11.1): sardine (*Sardina pilchardus* Walbaum, 1792), bluefin tuna (*Thunnus thynnus* Linnaeus, 1758) and the common octopus (*Octopus vulgaris* Cuvier, 1797). These species have markedly distinct biological and ecological traits, which together with their socio-economic relevance makes them interesting to assess the impacts of climate change on fisheries.

##### *11.1.1.1.1 Sardina pilchardus*

In the Iberian Atlantic coast sardine comprises one of the oldest traditional fisheries and is definitely the most important halieutic resource of the Peninsula. This is owed not only to the abundance of its catches (yields nowadays are about 50% of the total fish landings in Portugal; Figure 11.1), but also to the relevant economic and social implications of its exploitation (Soares 1995), which supported canning, the most important Portuguese industry during the 19th century and early 20th century.

*S. pilchardus* is a small pelagic schooling fish, characteristic of temperate waters in the Northeast Atlantic and Mediterranean, from about 60°N to 14°N. Sardine's lifespan is relatively short–about 6 years–, being sexual maturity attained at one year of age, time at which it is recruited to the fisheries (Figueiredo 1984; Figueiredo and Santos 1988).

Characteristically, sardine spawn several times during the year, which leads to an asynchronous recruitment and sexual maturation of the offspring (Blaxter and Hunter 1982). Spawning areas are generally wide, with limits that contract and expand from one year to another, according to population abundance and oceanographic conditions (Blaxter and Hunter 1982). These areas are restricted to waters of the continental shelf down to the isobath of 150m (Regner et al. 1987:161), being eggs and larvae immediately beyond the surface and postlarvae from the surface to about 20m (Regner et al. 1987:181).

#### *11.1.1.1.2 Thunnus thynnus*

Of all the activities that developed in the Algarve (Southern Portugal), the bluefin tuna fishery is one of the oldest and was, during large periods, the most important, in terms of its impact on the socio-economy and culture of this region (Santos 1989:13; Sousa Reis 1992: 58).

*T. thynnus* is characteristic of temperate waters of the Atlantic Ocean and adjacent seas, namely the Mediterranean. Individuals can grow to over 300 cm and reach more than 650 kg. According to some authors, the oldest age considered reliable is 20 years (SCRS 1998:1). Like other tunas, bluefin tend to be found in schools that migrate for reproductive or feeding reasons, sometimes across an entire oceanic basin (Tiews 1963; Matter et al. 1967; Chase 1999). There are two major spawning areas, one in the Gulf of Mexico and another in the Mediterranean. Reproduction lasts from April to June in the West Atlantic, and from May to July in the East. Bluefin in the West is assumed to first successfully spawn at age 8 compared to ages 4 to 5 in the East (SCRS 1998:1).

#### *11.1.1.1.3 Octopus vulgaris*

Cephalopod stocks are of increasing economic importance. Recent global trends in fish catch composition appear to show shifts from fish to cephalopod stocks (Boyle 1990; Balguerias and Quintero 1998; Caddy and Rodhouse 1998), namely to benthic octopods such as *Octopus vulgaris* (Bas 1979; Sousa Reis et al. 2001: 470).

The common octopus is the only marine living resource that has shown a significant increase in Portuguese catches during the last decades (Sousa Reis et al. 2001:469). This growth has coincided with a rise of octopus market value, making it today one of the most important species in the context of Portuguese fisheries, namely in the small scale fishery.

*O. vulgaris* has a worldwide distribution, being present in tropical, subtropical and temperate waters, from the coastline to the lower part of the continental shelf (150-170m). Unlike fish, which tend to live for several years, grow slowly and spawn more than once, *O. vulgaris* shows a truly exponential growth during the early stages of its life cycle (Forsythe and Van Heukelem 1987:155) and dies after breeding. The lifespan of the females seems to vary between 12 and 24 months, while males probably live longer (Mangold 1983:358).

### **11.1.1.2 Evolution of landings and fishing effort in Portugal.**

The Portuguese fishing fleet is mainly composed of low-powered, small to medium-sized boats, being the 4th in the EU in terms of number of boats, the 6th in terms of size of the fleet in tons and almost the last in terms of power of the boats. This last fact is related to the mild conditions of Portuguese coastal waters and characteristics of target species. The fleet has been decreasing both in terms of boats and tons, and has had the highest negative variation of Europe. In the last 10 years Portuguese landings have been decreasing, from 323,266 tons in 1990 to 221,683 tons in 1997 (Fisheries Yearly Statistics, Eurostat 1999 In INOFOR 2001), as a consequence of EU policies to reduce fishing effort and also to difficulties in obtaining permits to operate in foreign waters.

#### *11.1.1.2.1 Sardina pilchardus*

Sardine is captured in the North Atlantic from ICES Divisions IV to IX. However, direct fishery to sardine is nowadays practised only by Portuguese and Spanish fleets in ICES Divisions VIIIc and IXa (Dias et al.

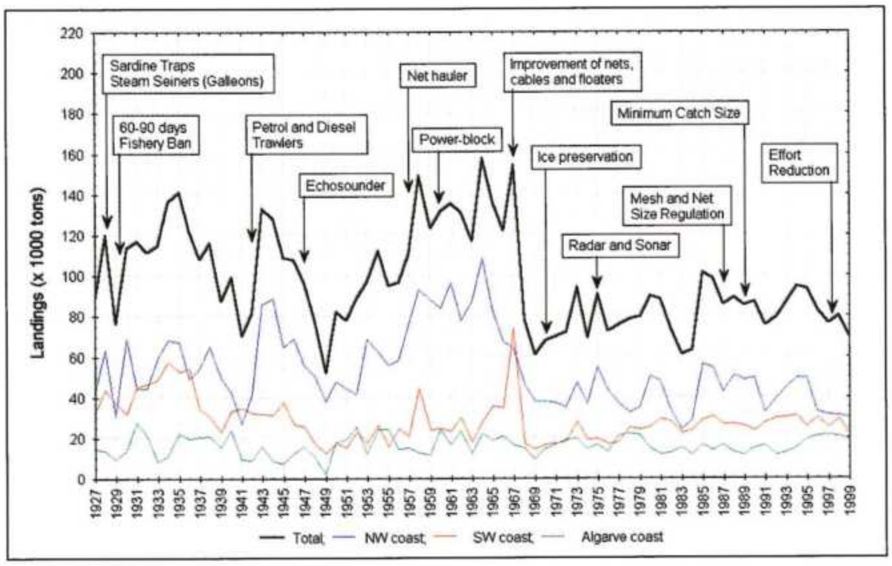

Figure 11.2 – Variation of sardine landings 1927-'99. Major technological introductions and management measures are also indicated.

1996). In Portugal, fishermen operate with purse seiners and harvest mainly young fish (of one and two years of age) that are concentrated in the upwelling areas off the coast. Significant sardine bycatch also results from trawling and beach seining. Up to date, the major part of sardine landings is destined to the canning industry, which besides the difficulties still represents an important sector in the Portuguese economy. At the same time, the market for fresh and frozen sardine has been increasing significantly.

Data on total sardine landings concerning the period between 1927 and 1999 indicate opposite trends in catches between the northwest (39.5°–42°N, 8.5°–9.5°W) and the southwest coasts (37°–39.5°N, 8.5°–9.5°W), from 1927 to 1964 (Figure 11.2). In fact, while in the northwest the trend is positive (+854 tons/yr), in the southwest it is negative (-694 tons/yr). During the same period, the trend is not significantly different from zero in the Algarve coast (~37°N, 7.4°–9°W). On the other hand, from 1964 to 1972 annual catches in the northwest coast plunged from over 100,000 tons to less than 35,000 tons, while peaking (73,316 tons in 1967) and falling in the southwest coast. From the 1970s onward, catches have undergone smaller variations in all coasts, with a slight but significant positive trend in the southwest coast (+322 tons/yr).

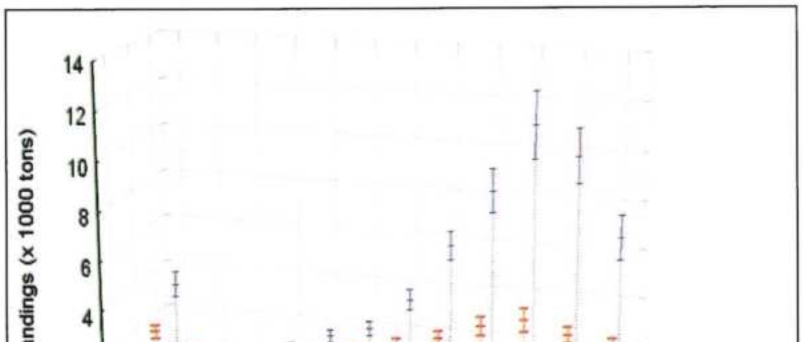

Figure 11.3 – Monthly variation of landings (data from 1927-'99; mean values +/– 2×standard error.

Within-year landings show evident seasonality (Figure 11.3). While in the west coast the highest landings occur between August and December, in the Algarve coast they increase, albeit slightly, between May and October. These changes in landings are mainly caused by bans in the first months of the year and to the rise of prices in months where the quality of fish (measured by the fat-index) and demand are higher.

### *11.1.1.2.2 Thunnus thynnus*

The set-net or trap fishery for bluefin tuna in the Algarve dates back to Phoenician and Cartaginese occupation (5th century B.C.; Santos 1989:19). Although bluefin is present in the Gulf of Cadiz throughout the year (Rodriguez-Roda 1964:35), large schools approach the shore from May to August, while migrating to and from the Mediterranean. Catches fluctuated substancially from century to century, but this fact is in part attributed to management issues (Galvão 1953). However, some authors have suggested the existence of cycles in bluefin abundance, with periods ranging from 6–7 years (Rodriguez-Roda 1978:452) to 110–115 years (Brito 1943:20). In fact, during the 20th century total catches show a notable wavering, apart from the strong decreasing trend (-1,218 fish caught/yr). Fishing effort, measured in numbers of active traps, has accompanied this tendency: while in the early 1900s more than 15 traps were operating along the Algarve coast, barely half

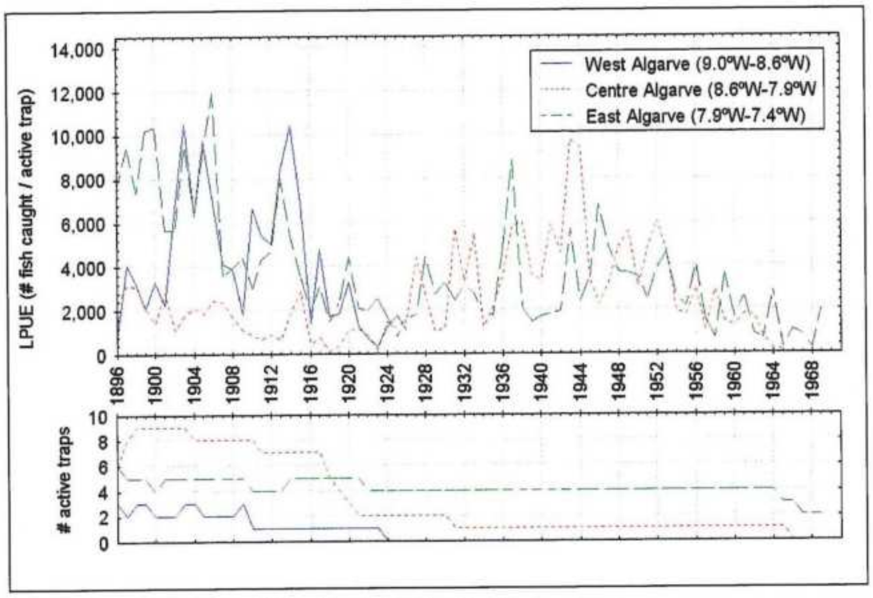

Figure 11.4 – Variation of bluefin catches in the Algarve coast.

(all from the easternmost region; Figure 11.4) remained in the 1920s and only 5 reached the year of 1931. Fishing effort then stabilized until the 1960s, when losses due to poor consecutive fisheries led to the closure of all the remaining traps up to 1972 (Costa 2000:80). In 1995, a Portuguese-Japanese enterprise set up a new kind of trap in the Algarve (Sousa Reis and Costa Monteiro 1995) as a response to the reappearance of bluefin close to shore – reported by Santos (1989:26) and Sousa Reis (1992:63) – and to the high demand for this fish all over the world.

#### *11.1.1.2.3 Octopus vulgaris*

During most of the 20th century, over 50% of Portuguese octopus catches were made in the Algarve, and mainly in the eastern region. The artisanal fleet of Santa Luzia (Tavira), headed almost entirely to this marine resource, traditionally used clay pots as fishing gears and was responsible on its own for a large proportion of national octopus landings (Sousa Reis et al. 2001:474).

After a few years of poor catches in the 1980s, setting pots were introduced as alternative gears to this fishery, leading to a new pattern of exploitation. Fishing effort – measured as the number of fishing days per season – began to decline until 1991 (trend = –50 fishing days/season), when it stabilized, whilst Landings Per Unit Effort (LPUE) maintained a highly irregular variation but a non-significant trend (Figure 11.5). Unlike effort, which is higher in summer than in the remaining seasons, LPUE shows no marked seasonality, since yearly maxima and minima are found in all seasons, with no apparent pattern.

From 1986 onward there was a strong increase of octopus fisheries in the west coast, especially north of the Tagus estuary (Figure 11.6). The rate of exploitation has recently become an important issue to stock management, and apart from the implementation of a minimum catch size (750g) several measures have been forwarded (Sousa Reis et al. 2001:475).

### 11.1.2 Effect of Weather on Fisheries

The Portuguese continental coast is located at the eastern boundary of the subtropical North Atlantic, which determines many of its atmospheric and oceanographic characteristics, namely the Portuguese

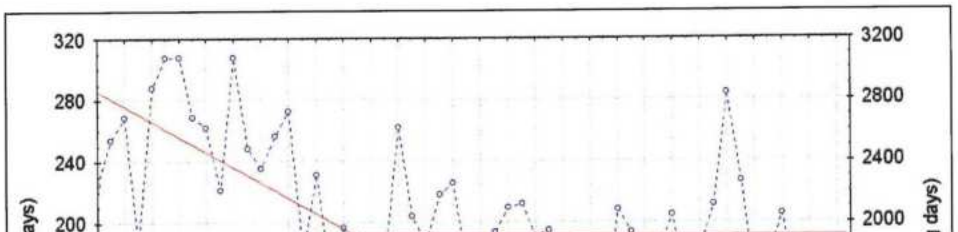

Figure 11.5 – Variation of octopus seasonal LPUE (left vertical axis) and fishing effort (right vertical axis) in the east Algarve coast (Santa Luzia, Tavira), 1986–2000. Correspondent trends are in red.

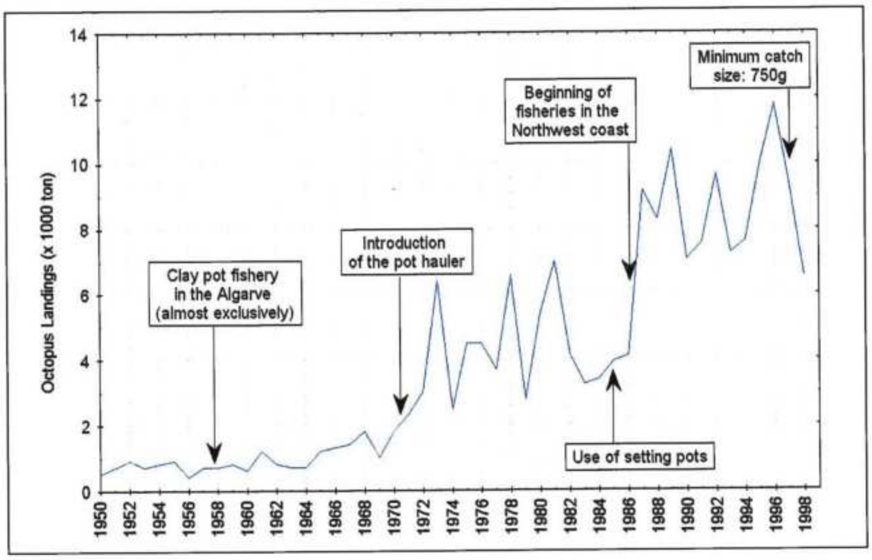

Figure 11.6 – Variation of octopus catches in the Portuguese coast, 1950–1998. Major technological introductions and management measures are indicated.

coastal upwelling system (Wooster *et al.* 1976). The dynamics of the subtropical front and the Azores high-pressure centre (Dias et al. 1996) lead to the intensification and steadiness of northerly winds along the west coast between July and September, and westerly winds off the Algarve coast between April and August. These winds, together with the Coriolis force, remove superficial waters and raise deep, cold, nutrient-rich waters to the euphotic zone. Phyto and zooplanktonic blooms soon ensue upwelling events (Santos et al. 1999), leading to the concentration of pelagic fish around thermal fronts (Olson and Podesta 1987; Santos and Fiuza 1992), for feeding and reproductive purposes. According to the hypotheses proposed by Hjort (1914, 1928) and Cushing (1972, 1974), food abundance is determinant to the survival of fish larvae, to the extent that fluctuations in the timing of planktonic blooms and larval production are responsible for the large variations observed in recruitment (that is, the amount of fish available to fisheries). Hence, the onset, strength and duration of spring and summertime upwelling episodes are likely to govern yearly productivity in the Portuguese coast.

Besides upwelling, winds also generate water turbulence which, within certain limits, increases the meeting rate of fish larvae with their prey, maximizing feeding efficiency that may be as important to recruitment as food availability (Legett and Deblois 1994). However, extreme turbulence and mixing of the surface layer can disperse food and larvae patches, thereby increasing mortality rates (Peterman and Bradford 1987). In conclusion, in a region of wind-induced coastal upwelling, the relationship between recruitment success of pelagic fish and the intensity of upwelling is likely to be dome-shaped (Cury and Roy 1989; Figure 11.7).

Seawater temperature, on the other hand, influences metabolic rates of marine organisms, modifying their food requirements, growth rate, activity and other physiological processes (reviewed by Laevastu 1993). For instance, the occurrence of inadequate temperatures in the spawning area during the reproductive season determines the migration of adults to unusual areas, where they often become inaccessible to fisheries. Changes in the vertical distribution of temperature can also force pelagic fish to migrate to deeper and colder layers (Laevastu and Hela 1970). Thus, fish may eventually choose less productive zones, diminish their feeding activity and subsequently growth, which will affect the availability of the resource to fisheries.

In the Portuguese coast, species with boreal, Mediterranean and sub-tropical affinities are present. Due to that fact, decadal changes in sea temperature are concurrent with variations in the distribution and abundance of most species of commercial interest, with significant repercussions to fisheries.

Due to its geographical position, Portugal is under the influence of the North Atlantic Oscillation (NAO).

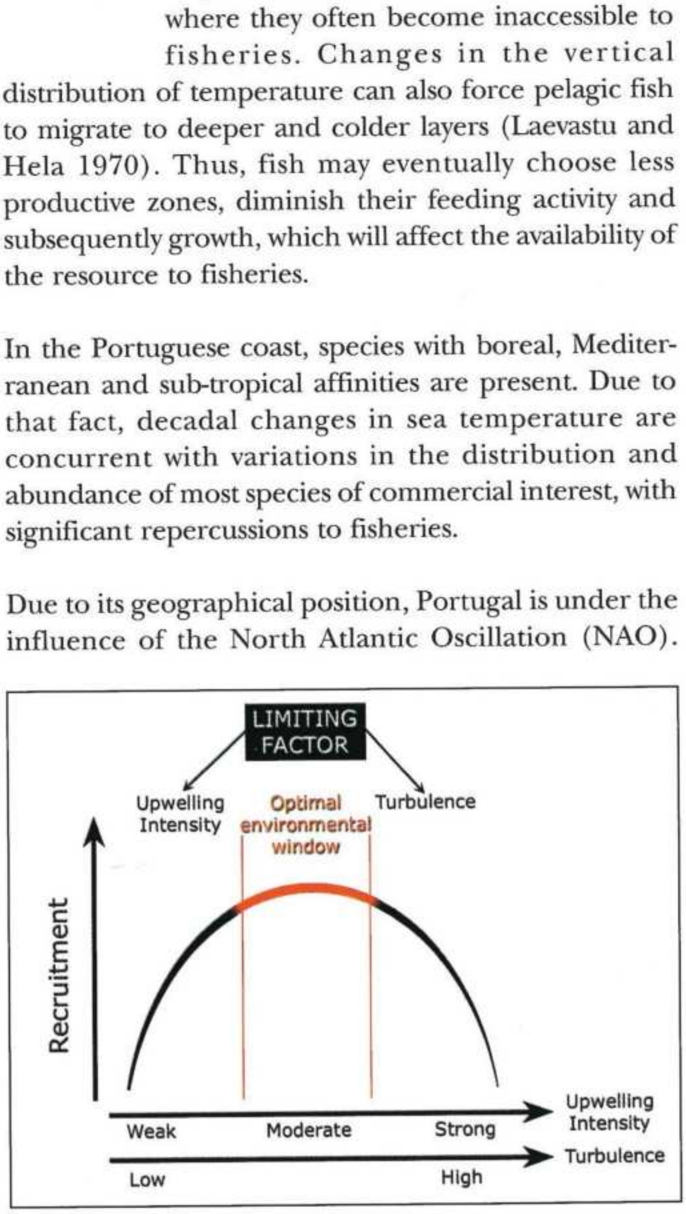

Figure 11.7 – The dome-shaped relation between wind-induced coastal upwelling and recruitment (adapted from Cury and Roy 1989).

The NAO is basically a large-scale alternation of atmospheric mass between the Icelandic low and the Azores high-pressure area, which has impacts on surface climate (Hurrell 1995, 1996), surface fluxes (Cayan 1992) and maybe even on the deep ocean (Dickson et al. 1996). NAO indices, based on the difference between mean sea-level pressure at Ponta Delgada in the Azores and Stykkisholmur in Iceland, were created to investigate the long-term variability of the NAO. When the pressure difference is large, with a deep Icelandic low and a strong Azores high, the NAO is said to be high or positive, which is associated with above-normal rain and air temperatures across northern Europe and droughts in the Iberian Peninsula (Perry 2000). When the pressure difference is less or occasionally negative as a result of persistent blocking in the Iceland–Scandinavia area, heavy rains occur throughout southern Europe while northern countries face cold, rigorous winters. In this case, the NAO is said to be negative (Van Loon and Rogers 1978).

Recently, several studies have established a connection between the NAO and river runoff, seawater temperature, turbulence, surface and subsurface currents; as well as between these environmental factors and the abundance and distribution of marine living resources in the North Atlantic and adjacent seas (e.g. Dawe et al. 2000; Hagberg and Tunberg 2000; Reid et al. 2000; Lloret et al. 2001). In some cases, the NAO is thought to be responsible for mass mortalities (Marsh et al. 1999) or invasions and retreats of several species from large oceanic areas (Alheit and Hagen 1997). It is thus clear that higher level, basin-wide phenomena such as the NAO are also relevant to the understanding of climate impacts on Portuguese fisheries, since they regulate simultaneously a variety of factors upon which they depend.

## 11.2 METHODOLOGY

### 11.2.1 DESCRIPTION OF ASSESSMENT APPROACH

### 11.2.1.1 State of the art

In view of the interest in long-term series of marine populations to study climate impacts, fishing periods of some species are beginning to be investigated. It is extremely important to start analysing fisheries in the context of climate variation to find out whether these historical fisheries may have been forced by the climatic regime.

### *11.2.1.1.1 Sardina pilchardus*

Studies based on sardine and herring fisheries in the English Channel showed that changes in the ocean/ /atmosphere system strongly affect these populations (Alheit and Hagen 1997). Here, the geographical boundary between the two species seems to move to and fro on a decadal scale. Sardine, more adapted to warm waters, becomes very abundant in years of high NAO, when the belt of the westerlies is at its northernmost position and air and sea surface temperatures are above average.

In the Adriatic Sea, a comparison between upwelling zones and the spatial distribution of sardine spawning intensity points to the fact that sardine spawn most intensively along the boundaries of upwelling zones, where seawater temperature ranges between 11°C and 22°C. If temperature falls below 10°C, sardine move to areas with more favourable temperatures even if they are less productive ones (Regner et al. 1987:189). Therefore, within its broader optimum limits, temperature is a secondary factor, being the formation of spawning centres mainly connected to trophic reasons.

In Portugal, studies indicate that sardine spawn from November to April (e.g. Ré et al. 1990), which coincides with the best conditions of larval retention close to shore and with periods of four to six days of soft wind-known as Lasker windows (Lasker 1978)-, also favourable to the survival of eggs and larvae (Dias et al. 1996). Borges and Santos (pers. comm. to Crato 2001) indicated that during winter, pulses of upwelling displace eggs and larvae offshore, diminishing their probabilities of survival and consequently reducing fishery. On the other hand, strong and steady upwelling events between July and September lead to an increase in phyto-zooplankton concentration, thereby creating ideal conditions to feed the adults as well as pre- and post-recruits (Figueiredo and Santos 1988).

### *11.2.1.1.2 Thunnus thynnus*

Cort and Rey (1983) developed a 1°×1° atlas of juvenile bluefin migration in the East Atlantic, West Mediterranean and Adriatic Sea, supported by bibliographic revisions, logbooks, oceanographic cruises, personal observations, etc.. Migratory routes were closely related to sea surface temperature distribution and were supported by numerous tagging results.

Recently, Humston et al. (2000) designed a kinesis model based on high-resolution sea surface temperature maps to simulate bluefin movements in the Gulf of Maine during summer months and obtained good agreement with empircal distibution maps. By taking in consideration that bluefin are endothermic fish (Carey and Lawson 1973), these authors forwarded the hypothesis that the distribution of schools might be correlated with the abundance of prey – which is highest along thermal fronts – and not directly to temperature (see also Brill et al. 1999).

According to fishermen experience, bluefin trap fisheries in the south Atlantic coasts of Portugal and Spain are favoured by Southerly and Southwesterly winds in May and June, while winds from the East quadrant favour catches in July and August. It is also of common knowledge that cristal-clear waters increase the chances of good catches, while turbid waters drive bluefin away from the coast (Brito 1943:18; Rodriguez-Roda 1978:452).

Bettencourt (1975) analysed tuna catches (of bluefin and others) in the Azores Islands in relation to air and sea surface temperature, frequency of foggy days, intensity of solar radiation, surface pressure and the occurrence of tropical cyclones in the North Atlantic. The results show a positive correlation between catches and sea surface temperature measured in April and May, as well as a negative association between catches and the frequency of tropical cyclones, since they cause a reduction in the number of fishing days. The position of the Azores high-pressure cell also seems to have an important role on tuna's migratory routes, since the equatorward displacement of this cell is connected with higher catches.

Binet and Leroy (1986) investigated the influence of global warming on the bluefin fishery in the Northeast Atlantic. Based upon the work of Garrod and Colebrook (1978), these authors suggested that the inflow of warm, salty Atlantic waters into the North Sea and Norwegian Sea, during the 1920s, led to an increase in the abundance of small pelagic fish, such as herring, as a response to changes in primary productivity. Bluefin also become abundant in this region during the summer months, setting in motion its regular exploitation for about 40 years. From the 1960s onwards, severe overfishing of both herring and bluefin, jointly with the decrease of the Atlantic influence, are the most likely causes for the disappearance of bluefin from these regions.

### *11.2.1.1.3 Octopus vulgaris*

Cruise data on distribution and abundance of *O. vulgaris* have been widely used to study the biology of this species, especially in the Northeast Atlantic (Hatanaka 1979; Pereiro and Laguna 1979; Guerra 1981a, 1981b; Guerra and Sanchez 1985; Balguerias and Quintero 1998; Moreno 1998). Some of these analyses also assessed the impact of fisheries, but none investigated the influence of climate change. Insights on the importance of environmental factors to the growth and reproduction of *O. vulgaris* have so far come exclusively from laboratory studies (Itami et al. 1963; Nixon 1969; Mangold et al. 1973; Laubier-Bonichon and Mangold 1975; O'Dor and Wells 1978; Imamura 1990), but the crossing of these two kinds of information is still lacking.

Temperature seems to be a key factor for the growth and survival of *O. vulgaris*. For example, high temperatures associated with a surplus of food allow a quick completion of the planktonic stage – commonly referred to as paralarval phase (Young and Harman 1988) – , thereby decreasing the high risks of predation (Mangold 1983: 359).

Light, on the other hand, seems to trigger at some point the onset of sexual maturation, although the mechanism itself has not yet been understood (Mangold and Froerch 1977). Despite, Wodinski's experiments (1977) showed that optic glands may play an important role in the reproduction and subsequent death of individuals.

There are few studies on the abilities of octopods to regulate the internal concentration of salts, but these seem to be weak (Potts and Todd 1965; Boletzky and Hanlon 1983:150). This means that low salinities might be intolerable and induce migrations to deeper waters (Hartwick et al. 1984:70), with consequences to near-shore fisheries. For instance, Kubo (1935) reported a negative correlation between rainfall and the catch of octopuses in Japan.

### 11.2.1.2 Options for assessing impacts on Fisheries

#### *11.2.1.2.1 Sardina pilchardus*

Regner et al. (1987) shed more light on the problem of sardine spawning areas by including in their analysis as many factors as possible: temperature, salinity, currents, phyto and zooplankton concentration. With collected data they developed equations to estimate the rate of egg developmental time, larval and postlarval growth, based on temperature. They also identified two distinct spawning areas and proposed a scheme for the transport of sardine plankton stages by currents. However, a shortcoming of this study is that it reports to only one cruise performed in the Adriatic Sea, during the second half of the spawning season.

Instead of collecting data on all the developmental stages of sardine and influent environmental factors provided by cruises, Alheit and Hagen (1997) assembled time series of sardine fishing periods in European waters covering several centuries. Sardine landings were then compared with historical records of sea surface and air temperature, with prevailing wind direction and velocity and with temporal fluctuations of the Belt of the Westerlies and the North Atlantic Oscillation.

The studies of Ré et al. (1990) and Dias et al. (1996) are based on the results of acoustic cruises that are carried out on a regular basis, in order to monitorize the Ibero-Atlantic stock of sardine. These cruises follow different sampling designs according to specific objectives: to relate plankton production cycles with fish resources off the Portuguese coast; to establish the seasonality of spawning in different regions of the Portuguese coast; or to determine the extent of the reproductive area of sardine during a period of maximum spawning activity. This kind of approach provides useful information about the stock behaviour according to the environmental conditions and the oceanographic traits along the coast.

#### *11.2.1.2.2 Thunnus thynnus*

In 1966, the International Council for the Conservation of Atlantic Tunas (ICCAT) was created in order to address all problems related to the sustainable exploitation of these resources. The Standing Committee on Research and Statistics (SCRS) was formed to collect, compile, analyse and disseminate fishery statistics for the whole Convention Area. Numerous approaches on the reasons for the depletion of Atlantic tunas have been experimented, being the Yellowfin Year Program (1991) one of the most interesting, in terms of impacts of weather on fisheries: during the years of 1983 and early 1984, yellowfin (*Thunnus albacares*) nearly vanished from the Gulf of Guinea and reappeared during the last months of 1984. Fontenau (1991) analysed four variables–sea surface temperature (SST), thickness of the mixing layer, depth of the 18°C isotherm and depth of the maximum temperature gradient–and found that while SST did not undergo any changes between 1980 and 1985, the depth of the thermocline increased substancially in 1983 and 1984, which migth have changed both migratory routes of schools and their degree of aggregation.

Apart from this study, however, ICCAT has mostly dealt with the problem of severe overfishing of tunas (e.g. SCRS 1998, 2000), which is lowering spawning stock biomasses to critical levels. Analyses of climate impact on fisheries has so far remained on a qualitative level, such as Binet and Leroy's investigation (1986; see also SCRS 1998:30).

In the Northern Pacific, Kimura et al. (1997) analysed the effects of El Niño events on migratory routes of albacore (*Thunnus alalunga*), by comparing the distribution of landings per unit effort (LPUE) all over this basin. T-tests were used to ascertain the significance of differences between LPUE in El Niño years and non-El Niño years, in each cell of the distribution grid. By apllying the same strategy to SST, they were able to propose an explanation for the apparent expansion of albacore's migratory routes during El Niño years. The influence of the Kuroshio was also investigated by means of t-tests, and it led to the hypothesis that in years when this current takes a large meander path, immature albacore migrate from the West Pacific towards East in order to satisfy their food requirements.

#### *11.2.1.2.3 Octopus vulgaris*

Recently, marine geographic information systems (GIS) and generalised additive models (GAM's) have been used to investigate temporal and spacial patterns of cephalopod abundance (Pierce et al. 1998:2). To date, most of the analysis has focussed on trends in the abundance of squids *Loligo* spp., but the approach is being extended to other fished cephalopods. GAM's appear to be suitable to draw inferences about the mechanisms that give rise to the distribution of these species, although not all relationships are currently interpretable (Pierce et al. 1998:8).

Autoregressive integrated moving average (ARIMA) are starting to be used in understanding and predicting fairly complex behaviours such as stock dynamics. This method allows the inclusion of linear or nonlinear, lagged or not, species interactions, environmental influences, fishing activities, etc., in the development of efficient models, and provides accurate forecasts of monthly commercial landings (Stergiou et al. 1997). Lloret et al. (2001), for instance, used transfer function models (a subclass of ARIMA) to analyse the effects of river outflows and turbulent mixing on the survival of octopus (*Eledone cirrhosa*) and fish larvae, in the Northwestern Mediterranean. However, according to the authors, none of the models was very good despite significant correlations were established for nearly all species studied, suggesting that other factors must also be taken in consideration.

Individual-based modelling for cephalopods is also taking its first steps (Grist and des Clers 1999; Jackson et al. 2000), and preliminary results clearly demonstrate that seasonal changes in environmental parameters, coupled with the unique traits of cephalopod biology, generate stock dynamics that cannot be assessed in the same way as fish.

## 11.2.2 MODELLING OF THE EFFECT OF PAST CLIMATE UPON FISHERIES

### 11.2.2.1 Sardina pilchardus

The lack of a valid measure of fishing effort made our analysis more difficult, since LPUE is regarded as a better proxy to fish abundance than plain catches. This is due to the fact that technological advances and management measures related to sardine fisheries (Figure 11.2) are bound to have had a profund impact on the rate of stock exploitation, implying that changes in catches may not reflect real variations in abundance. Thus, annual catches can only be seen as rough guides of abundance, but they may still be enough to shed some light on the effects of climate upon sardine fisheries (e.g. Alheit and Hagen 1987; Stergiou 1997; Yasuda et al. 1999).

Yearly sardine landings were obtained from Bulletins of Fisheries Statistics for the period 1927–'99 (data up to 1988 was compiled by Pestana 1989). Ports were distributed between the Northwest coast (Viana do Castelo, Póvoa do Varzim, Matosinhos, Aveiro and Figueira da Foz), the Southwest coast (Nazaré, Peniche, Ericeira/Cascais, Lisboa, Sesimbra, Setúbal and Sines) and the Algarve (Lagos, Portimão, Olhão, Tavira and Vila Real de Santo António). For each coast total catches were calculated.

Years of high (above the 75% quantile) and low (below the 25% quantile) landings in each of the three studied zones are represented in Figure 11.8. While these years tend to create distinct clusters in the west coast, they are more sparsely distributed in the Algarve coast. Another interesting feature is the lack of synchrony between zones: apart from the simultaneous fall in landings during the 1970s, observed in the west coast, the three zones seem to have a unique behaviour, which justifies their separate analysis.

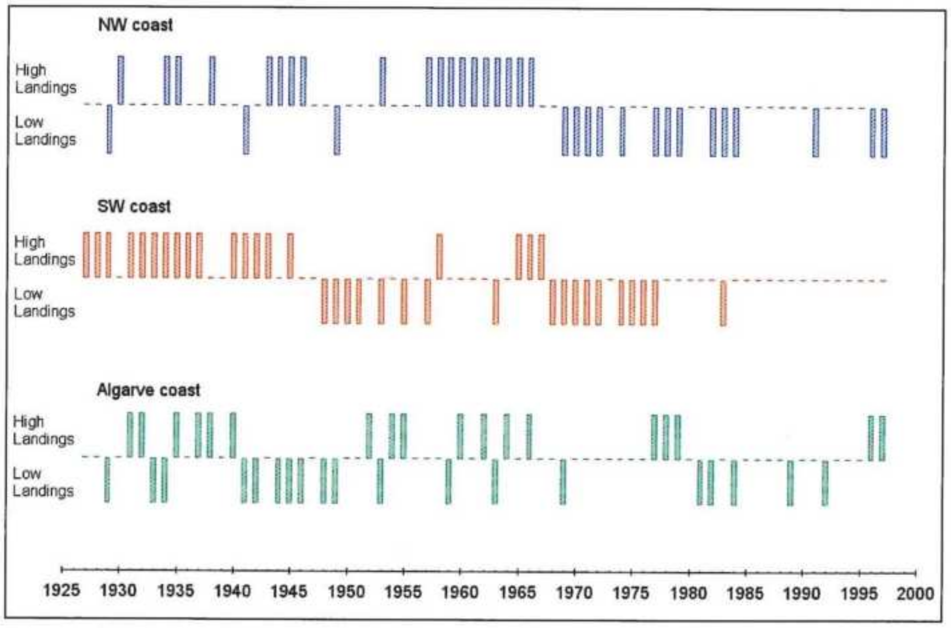

Figure 11.8 – Years of high and low landings in the Northwest, Southwest and Algarve coasts.

In order to investigate the influence of climate on sardine fisheries, we gathered and processed meteorological data into:

- An index of upwelling, derived from wind data recorded at the Meteorological Institute stations of Porto (41.23°N, 8.68°W), Lisbon (38.72°N, 9.15°W) and Faro (36.95°N, 7.90°W). These stations were considered representative of the Northwest, Southwest and Algarve coasts, respectively. However, only two daily wind measurements were available (09:00 and 18:00), which may, to some degree, bias the upwelling index. Southward and eastward wind components were separated and used to calculate the index in the following manner: since the west Portuguese coast has meridional (N-S) orientation, upwelling frequency in a given month was considered to be equal to the fraction of days where southward wind blew at speeds of more than 5m $s^{-1}$. This threshold was placed in order to confer importance to winds that not only generate moderate to strong upwelling but also significant mixing of the surface layer (MacKenzie and Leggett 1991). Upwelling frequency in the Algarve was derived analogously from the eastward wind component, due to the zonal (E-W) orientation of the coast.
- Two turbulence indices, one given by wind speed cubed (Husby and Nelson 1982) and another calculated as the seasonal frequency of Lasker events, i.e., the number of periods per season that had four consecutive days with winds of less than 5 m $s^{-1}$ (Cury and Roy 1989). Overlapping between periods was allowed so as to emphasize the importance of long, calm episodes. Unlike the upwelling index, these indices are insensitive to wind direction.

Figure 11.9 depicts the variation of summer (JAS) upwelling frequency in the Portuguese coast, from 1927 to 1999. In this period, values were almost always higher in the southwest coast, and fluctuated more substancially. In both western coasts there was an increase in upwelling frequency until the 1960s, followed by a decline until the end of the century. The Algarve coast presents a different behaviour: after a period where summer upwelling-favorable winds were rare (1950s and early 1960s), these became progressively more frequent, reaching values that are nowadays similar to the southwest coast.

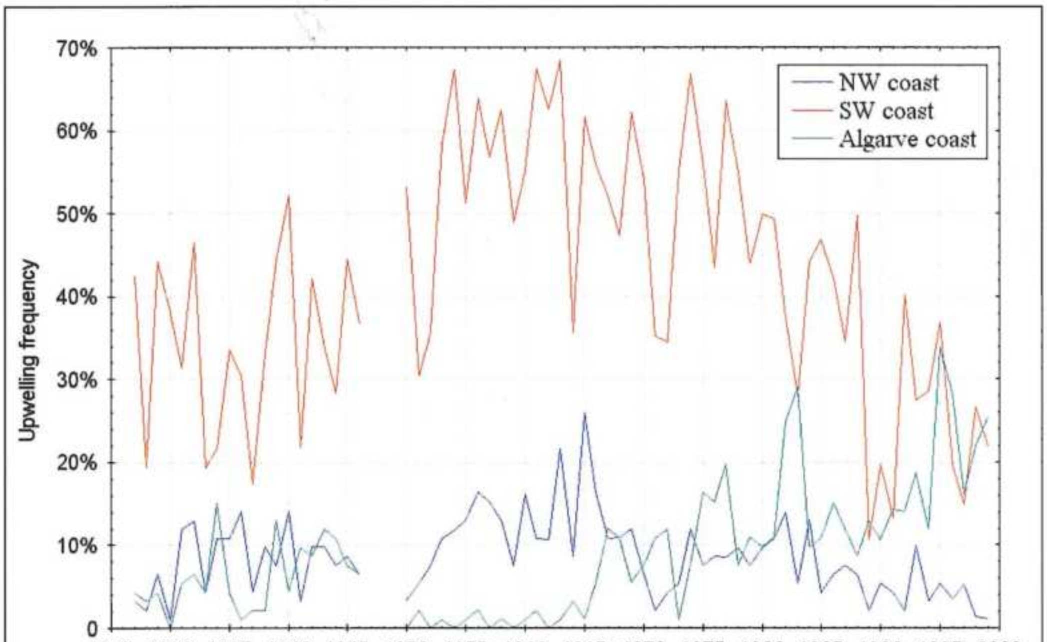

Figure 11.9 – Summer upwelling frequency in the Northwest, Southwest and Algarve coasts.

By comparing Figures 11.2 and 11.9 there seems to be an important association between summer upwelling frequency and sardine abundance in the west coast: in the nortwest highest catches coincide with periods of above-average upwelling frequency, while subnormal catches occur when upwelling is rarer. The steady increase of upwelling frequency during 1950–'55 is noteworthy, as well as the sharp decline from 1965 to 1971, since these periods agree with the most important rise and fall of sardine catches. Opposedly, in the southwest coast a negative correlation between these variables is found: the negative trend in catches from 1925 to the early 1960s is concurrent with a positive trend in summer upwelling frequency, while from the 1970s onward catches recovered at the same time summer upwelling was becoming less frequent.

So as to further investigate these findings, we plotted annual catches in the west coast against summer

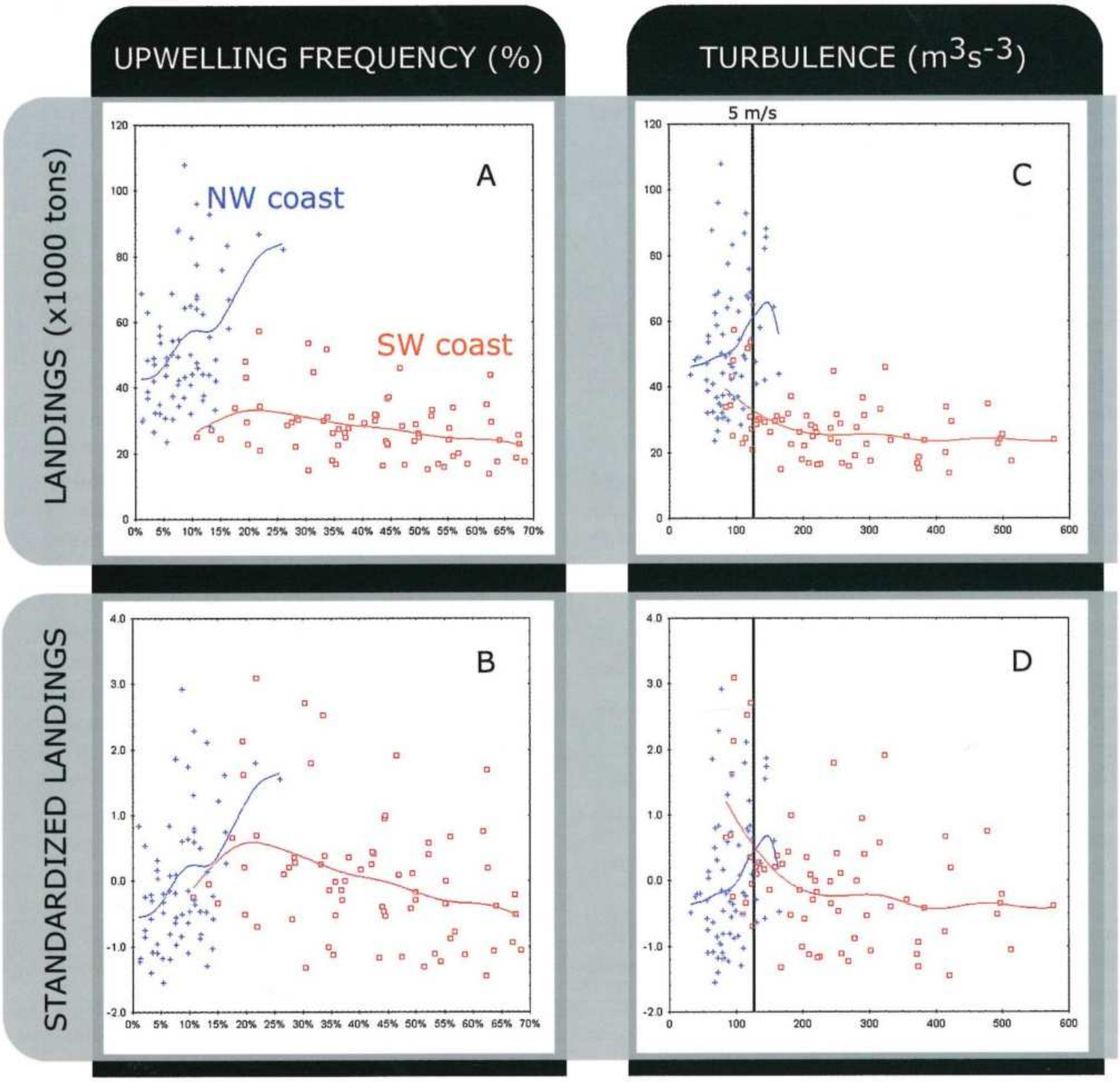

Figure 11.10 – Relation between annual sardine landings (original data or standardized values) and summer upwelling frequency and turbulence.

upwelling frequency and adjusted curves using the distance-weighted least squares procedure (Figure 11.10A). Since there is no measure of fishing effort, it is not possible to evaluate if catches in the northwest coast are on average higher than in the southwest because sardine is more abundant or because effort is higher. By standardizing annual catches in each coast (i.e., subtracting the mean value and dividing by the standard deviation), we obtained a more homogenous cloud of points, which suggests that the latter hypothesis might be true (Figure 11.10B). In any case, there seems to be an optimal window between about 10% and 35% of upwelling frequency, flanked by regions were sardine abundance is lower, which is to say that high yearly landings are favoured by 9 to 32 days of moderate to strong upwelling during summer.

Figure 11.10C (and 11.10D) reinforces the idea that calm periods are necessary between upwelling events: if average summertime wind speed is above 5 m $s^{-1}$, turbulence (>125 $m^3$ $s^{-3}$) seems to become detrimental to sardine abundance, leading to substantial decreases in catches. Hence, the mechanisms that generate the optimal environmental window proposed by Cury and Roy (1989) – verified by them for the Moroccan sardine stock – appear to be pertinent for the Portuguese stock.

In the Algarve coast, however, the dome-shaped association was not found. Here, upwelling frequency and turbulence reach significantly higher values in spring than in summer (Table 11.1), when eggs and larvae are abundant in large quantities (Ré et al. 1990).

| | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| UPW | 9.08 (0.79) | 14.60 (1.19) | 8.91 (0.93) | 5.96 (0.57) |
| TUR | 114.74 (8.73) | 105.23 (6.96) | 73.12 (4.91) | 87.86 (7.80) |
| LSK | 26.51 (2.06) | 19.63 (2.61) | 25.47 (2.58) | 33.86 (1.88) |

Table 11.1: Mean values and standard errors (in parentheses) of seasonal upwelling frequency (UPW; %), turbulence (TUR; $m^3 s^{-3}$) and number of Lasker events (LSK) in the Algarve coast, 1927-'99.

Springtime wind-related variables are also more strongly correlated with annual catches than summertime variables, to the extent that correlation coefficients are significant at $\alpha = 0.05$ in the former case but not in the latter (Table 11.2).

| | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| UPW | -0.07 | -0.24* | -0.17 | -0.22 |
| TUR | -0.20 | -0.41* | -0.26* | -0.16 |
| LSK | +0.11 | +0.28* | +0.10 | +0.15 |

Table 11.2: Spearman correlation coefficients between annual landings and seasonal upwelling frequency (UPW; %), turbulence (TUR; $m^3 s^{-3}$) and number of Lasker events (LSK), 1927-'99. Significant correlations ($P<0.05$) are marked with asterisks.

Of the three springtime variables, wind-induced turbulence appears to have the strongest impact. When plotted against annual catches, turbulence is found to have a detrimental effect even at moderate levels (Figure 11.11). This suggests that recruitment in the Algarve coast may be defined primarily by the occurrence of calm weather during spring.

### 11.2.2.2 Thunnus thynnus

Due to the fact that *T. thynnus* is a migratory species that spends very little time in Portuguese coastal waters, we investigated the evolution of landings per unit effort (LPUE) – a proxy of population density – across the northeast Atlantic and Mediterranean, in search for consistent changes. So as to facilitate their comparison, we tried to adjust periodical functions to each catch curve.

Data on trap fisheries were gathered from Portuguese Fisheries Statistics (Anonymous 1904-'74) and other publications (Sella 1928; Rodriguez-Roda 1964, 1977, 1978, 1983; Zupanovic et al. 1983; Binet and Leroy 1986). In addition, data on landings in the North Sea and Norwegian Sea (in Binet and Leroy 1986) were analysed, although they come from an array of gears (especially seine fisheries) and no measure of effort is provided.

Portuguese bluefin LPUE (number of fish caught per active trap) shows significant oscillations with periods of 8, 50 and 150 years. Henceforth, these waves will be referred to as $w_8$, $w_{50}$ and $w_{150}$, respectively. While $w_8$ captures the essence of interannual fluctuations in landings, the superposition of $w_{50}$ and $w_{150}$ closely follows the interdecadal evolution of LPUE. In fact, high landings in the beginning of the century and the near vanishment of bluefin from the Portuguese coast in the 1820s (reported by Brito 1943) and 1970s seem to derive from the constructive interference of the two waves (that is, both have either positive or negative signal), whereas the weaker fluctuations in the first half of the century are associated with destructive interference.

In other countries, $w_8$, $w_{50}$ and $w_{150}$ were also found (Figure 11.12). For example, Spanish LPUE shows all waves and precisely the same behaviour as Portuguese LPUE, apart from a small (4-year) lag in $w_{50}$. Thus the

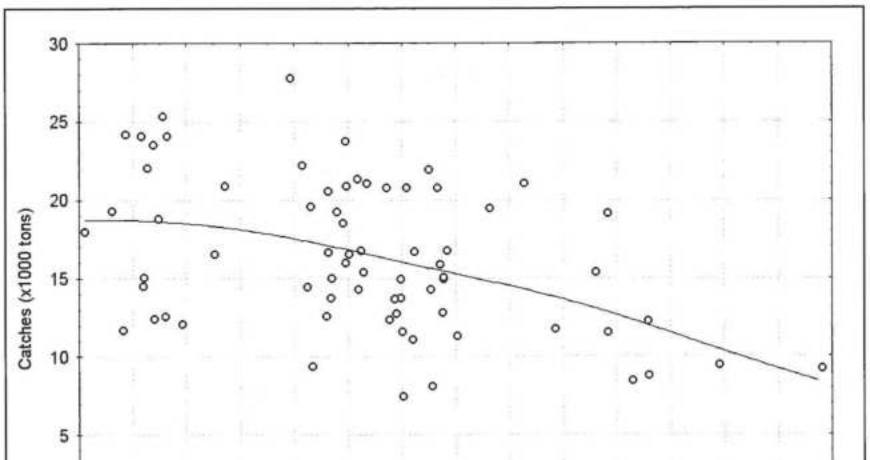

Figure 11.11 – Relation between annual landings in the Algarve coast and spring turbulence. The curve was fitted using the distance-weighted least squares procedure.

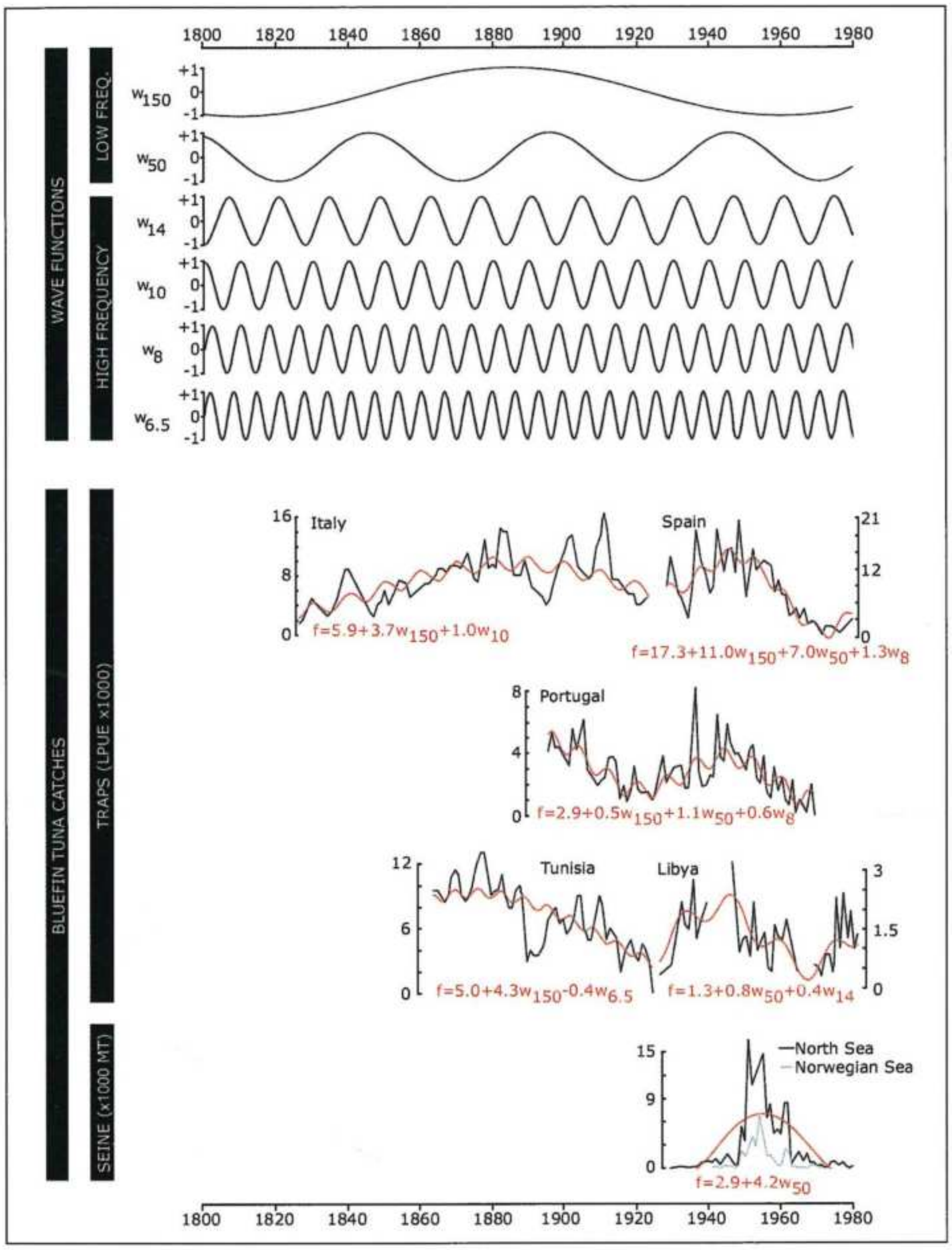

Figure 11.12 – Bluefin catches in Portugal, Spain, Italy, Tunisia, Libya and Northern Seas, in the 19th and 20th centuries. Adjusted wave functions facilitate the finding of similarities among catch curves.

resemblance between the two general curves is quite noteworthy, despite the difference in ordinates (Spanish traps catch nearly 5 times more). In contrast, Mediterranean catch curves show either $w_{50}$ or $w_{150}$ (with slight lags), as well as new high-frequency oscillations, with periods that range between 6.5 and 14 years. Nevertheless, low-frequency waves remain as the most important in describing the evolution of landings in the 19th and 20th century (as they have highest coefficients), reaching extreme values nearly at the same time in all countries. These findings suggest that interannual fluctuations in trap catches might be due to local and transient environmental changes and not to alterations in bluefin abundance, whilst interdecadal fluctuations reflect real changes in abundance, possibly as a response to basin-wide variations in environmental factors.

One clue for the nature of these factors came from the work of Kushnir (1994). By studying the variation of North Atlantic SST compiled in the Comprehensive Ocean-Atmosphere Data Set (COADS), this author verified that during the mid-1920s an accelerated warming occurred in the 20° to 40°N latitude belt, and around 1930 in the 40° to 60°N latitude belt. Positive SST change reached its maximum near 1950, and for the northern half of the North Atlantic a phase of cooling began in the mid to late 1960s, leading to a minimum in the early 1970s. Metaxas et al. (1991) described analogous interdecadal fluctuations in Mediterranean SST.

The remarkable similarity between $w_{50}$ and the variation of SST in the 20th century suggests that warm SST conditions may in some way enhance bluefin abundance. As was previously mentioned, Binet and Leroy (1986) associated the appearance of bluefin in the Northern Seas with the increase in local temperature, from the 1920s to the 1960s – a period that became known as the Russel Cycle (Cushing and Dickson 1976). Thus it seems that ocean warming might allow bluefin to extend its summertime trophic migrations further northward, into new feeding grounds. Changes in water properties in the Mediterranean (SST, salinity, depth of the thermocline, etc.) are other candidates for successful recruitment and individual growth, all leading to a concomitant increase in biomass.

Kushnir (1994) also analysed timeseries of sea level pressure (SLP), and found that during years with relatively warm SST, SLP was systematically lower than normal over the central ocean area and vice-versa. As a consequence, the author concluded that the interdecadal pressure fluctuations led the early SST fluctuation during the early century warming and lagged behind the SST fluctuation during the late century cooling. By focusing exclusively on the cold season (DJFMA) and the period 1946-'87, Kushnir (1994:151) concluded that positive SST anomalies north of about 30°N are associated with an easterly wind anomaly, implying a weakening of the westerly flow.

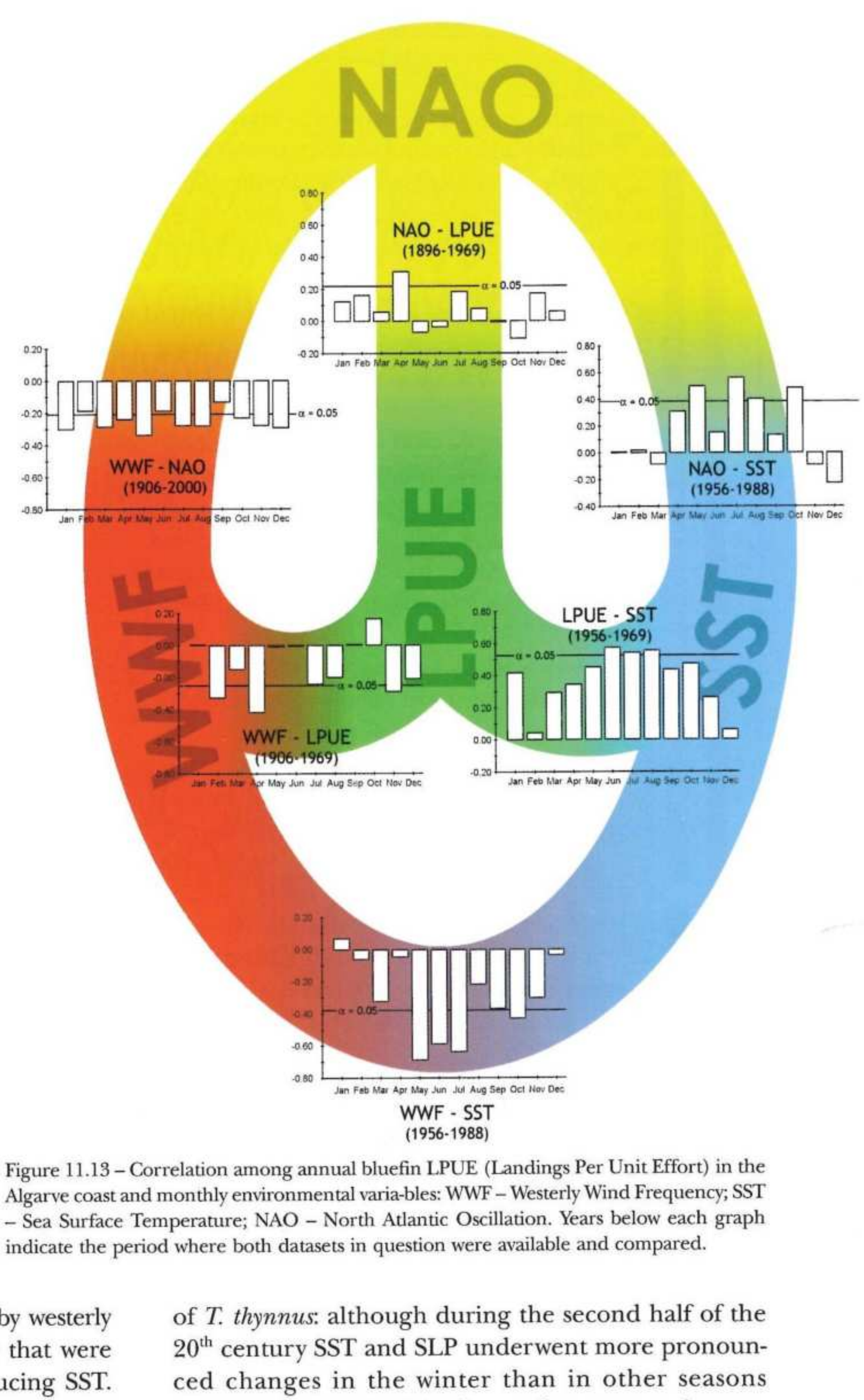

Figure 11.13 – Correlation among annual bluefin LPUE (Landings Per Unit Effort) in the Algarve coast and monthly environmental varia-bles: WWF – Westerly Wind Frequency; SST – Sea Surface Temperature; NAO – North Atlantic Oscillation. Years below each graph indicate the period where both datasets in question were available and compared.

Figure 11.13 resumes our verification of Kushnir's (1994) conclusions downscaled to the Algarve coast. Wind and SST were measured at the Meteorological Institute stations of Faro (36.95°N, 7.90°W) and Praia da Rocha (37.12°N, 8.53°W), respectively. As an indicator of SLP anomalies across the North Atlantic basin, we used the NAO index created by Jones et al. (1997), which employs pressure data from Gibraltar (36.0°N, 5.5°W) rather than the Azores and is calculated from 1826 to present (available at http://www.cru.uea.ac.uk). Our findings were that monthly Westerly Wind Frequency (WWF; computed as the fraction of days where the eastward wind component was >0 m $s^{-1}$) in the Algarve is negatively correlated with monthly NAO indices throughout the year, being this association significant at $\alpha = 0.05$ in nine months. Note that the commonly-used NAO index is calculated as the average of DJFM standardized pressure gradients. However, throughout this chapter, standardized pressure gradients will be referred as monthly NAO indices. WWF is also negatively correlated with SST but only in the summer months, which was expectable since during this season upwelling induced by westerly wind brings to the surface masses of water that were below the sharp thermocline, thereby reducing SST. Hence, it was found that the direct correlation between NAO and SST is positive and significant in May, July, August and October (1956-'88), in the Algarve coast. By analysing the relationship between annual Portuguese LPUE and monthly values of NAO and local SST and WWF, we strengthened the conclusion that spring and summertime environmental conditions are determinant to the catches and population dynamics of *T. thynnus*: although during the second half of the 20th century SST and SLP underwent more pronounced changes in the winter than in other seasons (Kushnir 1994:149), bluefin catches seem to be connected with SST from June to August alone, and with April values of NAO and WWF.

These findings led us to investigate the evolution of NAO, in search for fluctuations that might be related to bluefin abundance in a similar way as SST. However, unlike the SST series, NAO records are dominated by interannual oscillations that tend to mask the interdecadal signal. We thus applied a 15-year running mean to the timeseries, in the same manner as Kushnir (1994) did to pressure data.

Figure 11.14 depicts the variations of $NAO_{Apr}$ and $NAO_{Aug}$ in the 19th and 20th centuries. In the smoothed curve of $NAO_{Apr}$ a 50-year fluctuation is apparent from the late 19th century onwards: minima are reached around 1880, 1930 and 1980, while maxima occur near 1905 and 1955. Before 1880, $NAO_{Apr}$ displays less evident oscillations, with lower amplitude and higher frequency. Both findings agree noticeably with bluefin LPUE in the Atlantic and Mediterranean, and seem to explain why the Italian catch curve is the only one not to exhibit $w_{50}$, since its record pertains mostly to the 19th century.

On the other hand, the smoothed curve of $NAO_{Aug}$ displays a lower-frequency oscillation, with minimum and maximum in the late 1880s and 1960s, respectively. This wave seems to correspond to $w_{150}$ found in many catch curves of the northeast Atlantic and Mediterranean.

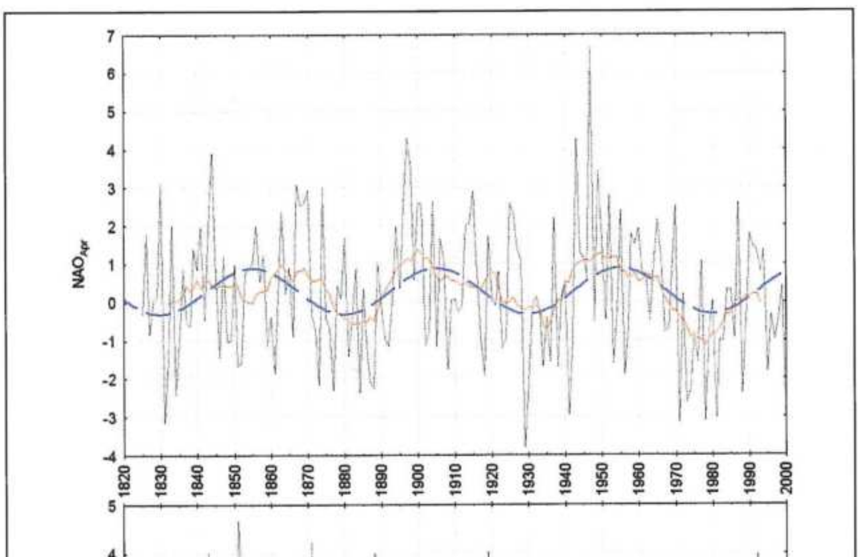

Figure 11.14 – Variation of the NAO (stippled lines) in April (above) and August (below). 15-year running means (red solid lines) were applied to raw data, and functions (blue dashed lines) with periods of 50 (above) and 150 years (below) are sumperimposed for comparison.

Although connections between $NAO_{Apr}$, $NAO_{Aug}$ and enviromnental conditions were found in the former paragraphs, as well as a positive correlation between NAO and bluefin abundance, it was not possible to ascertain if these changes affect growth rate, spawning success and/or survival of the individuals. Thus, an important part of this research is still lacking, thereby making extrapolations for future climatic scenarios still speculative.

### 11.2.2.3 Octopus vulgaris

Despite there being nowadays directed fisheries for common octopus throughout the Portuguese coast, we will only discuss the artisanal fishery located in the eastern part of the Algarve coast, since available timeseries of fishing effort are restricted to this area.

Octopus landings (in kg) per unit effort (number of fishing days) in season *S* (from Win-1986 to Aut-1999) were used as proxies of population biomass ($B_S$), since $B_s = q \times LPUEs$, where $q$ is the catchability (an unknown parameter). LPUE's autocorrelation function suggests that $B_S$ is significantly correlated only to $B_{S-1}$, and indicates that an autoregressive process might be adjusted to the timeseries. However, the association is not strong (R=+0.50, P<0.01), meaning that a large proportion of biomass variance is left unexplained. As the pre-recruitment phase (i.e., from egg-laying until individuals reach 750g) lasts roughly one year and the correlation between $LPUE_{year\,i}$ and $LPUE_{year\,i-1}$ is not significant (Spearman R=–0.45, P=0.13; Figure 11.15), it is plausible that the stock-recruitment relationship may be weak. Environmental variables may thus play a significant role in defining seasonal fluctuations of population biomass, and therefore of LPUE.

To perform this analysis, we first computed the timeseries of seasonal LPUE change rate, $C_S$, according to the equation $C_s = \log_e(LPUE_{s+1}) - \log_e(LPUE_s)$. Given the relation between $LPUE_S$ and $B_S$, then $C_S$ is also an index of biomass change rate. The advantage of this formulation is that positive values of $C_S$ indicate biomass increase while negative values indicate biomass decrease.

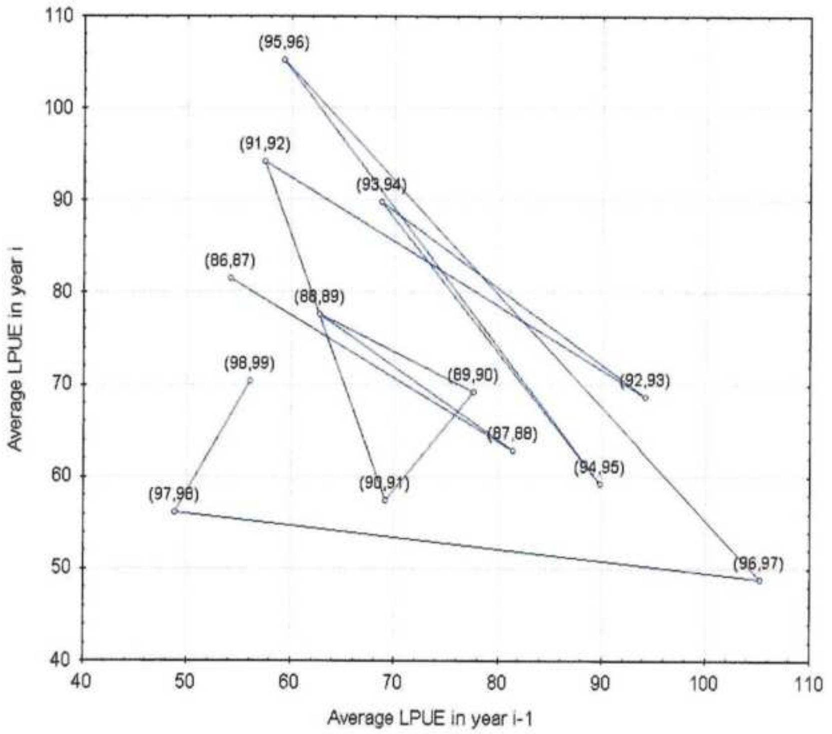

Figure 11.15 – Relationship between consecutive yearly LPUE averages, as a proxy to estimate the stock-recruitment relationship. Although data suggest a negative association (Spearman R= –0.45), which is uncommon in intensely exploited stocks, the p-value (0.13) exceeds usual significance levels.

Following, for each of the four seasons in the year, we plotted $C_S$ against seasonal values of environmental variables, in search for a set that would allow the best estimation of $C_S$, and especially the discrimination of positive and negative values. Available variables were:

- Upwelling frequency (fraction of days, within a season, where the eastward wind component blew at more than 5m $s^{-1}$) and turbulence (seasonal average of 12-hourly wind speed cubed), derived from wind data recorded at the Meteorological Institute station of Faro (36.95°N, 7.90°W).

- Seasonal average sea surface temperature blended from ship, buoy and bias-corrected satellite data (Reynolds and Smith 1994), downloaded from http://ingrid.ldgo.columbia.edu

- Seasonal Guadiana outflow at the station of Pulo do Lobo (37.80°N, 7.63°W), obtained from the National Water Institute (INAG) at http://www.inag.pt.

The four sets of variables that best estimate $C_S$ are shown in Figure 11.16. During winter, biomass decrease is frequent and seems to be associated with strong Guadiana outflows simultaneous with strong wind-induced turbulence. This is probably related to a decrease in salinity down to the sea bottom, which may increase natural mortality or force individuals to migrate into deeper waters. Since fishermen are used to moving their gears further offshore during winter months, it does not seem likely that there is a significant reduction in catchability ($q$), but rather a decrease in growth and survival rates.

Conversely, biomass frequently increases during spring, probably as a response to the rise in temperature and ecosystem productivity. Once again, wind-induced turbulence seems to be detrimental to octopus biomass growth, but the mecanism that leads to this effect is in this case unknown, as salinity gradients from sea surface to the bottom are generally small. The recruitment of small octopuses to fisheries in spring is also of great importance, implying that environmental factors which affect survival rates during early life stages may be important factors to recruit biomass variation. This is probably the case of upwelling frequency during spring of the previous year. As laboratory experiments indicate, a decrease in temperature by 4°C (from 25°C to 21°C) more than doubles the duration of the planktonic phase (from 22-30 to 60 days; Villanueva 1995), suggesting that survival rates may be worsened by cold upwelled waters, since predation risks during this stage are high. The few *O. vulgaris* paralarvae caught by traditional sampling methods (e.g. Sánchez and Moli 1985; Vecchione 1988; Sousa Reis 1989; Moreno and Sousa Reis 1995; Moreno 1998) have always been found in coastal waters, where they can settle to the bottom when this stage is complete. Hence, the occurrence of upwelling during spring may not just delay settlement but even make it impossible, since paralarvae are dragged away from the continental shelf.

Also during summer, many adults reach sexual maturity, breed and die, being replaced by the new cohort of recruits. This is reflected in the sharp decline of mean weight of captured specimens and leads to the conclusion that summer biomass depends on the survival of octopuses born one year before. As in the previous case, weak upwelling frequencies during the planktonic stage seem to be essential for successful recruitments. In contrast, strong upwelling frequencies occuring in the actual season seem to be beneficial, which may be related to the increase in ecosystem productivity generated by the input of nutrient-rich waters.

In the fall, population biomass continues to increase in years where upwelling occurred frequently during the summer and vice-versa. Again, the biomass change rate is negatively correlated with wind-generated turbulence. Figure 11.17 resumes our hypotheses on connections between environmental factors and *O. vulgaris* stock dynamics, while Figure 11.18 further investigates them by selecting the most interesting period in study: Aut – 1995 to Aut – 1996. At the beginning of 1996, LPUE had reached the highest value ever recorded (153 kg/fishing day). This was likely related to auspicious conditions prevailing from the summer of 1994 to the fall of 1995, which led to massive recruitment and indi-

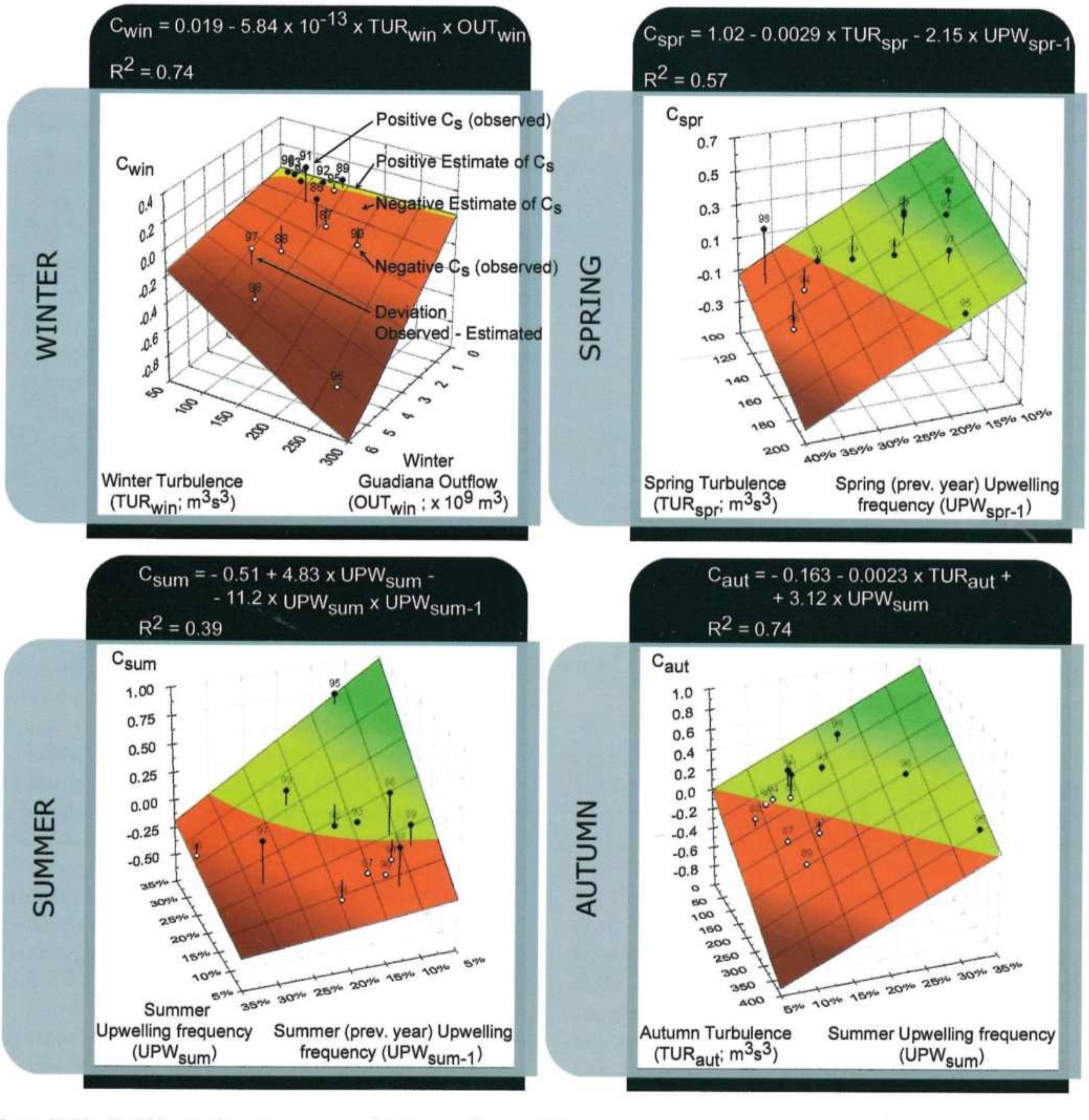

Figure 11.16 – Variables that in each season provide better estimates of $C_s$.

vidual growth in the second half of 1995. Then, very strong turbulence (264 m$^3$s$^{-3}$) and Guadiana outflow (5.174x10$^9$ m$^3$) seem to have caused biomass to plunge to values so low that LPUE did not exceed 40 kg/fishing day in the fall of 1996 – the lowest value of the record. Annual recruitment was likely compromised not only by the wintertime extreme bad weather but also by the frequent upwelling that occurred six months earlier, which paradoxically had been beneficial for bottom-dwelling recruits.

In conclusion, the presented models not only explain a significant proportion of *O. vulgaris* biomass variation in the period 1986–'99 (from 39%, in summer, to 74%, in winter and autumn) but also seem to be adequate in terms of the species' biology. The associations made with environmental factors thus allow us to have a better idea on how future climate changes will affect these populations. Nevertheless, further studies *in situ* are required to confirm the forwarded hypotheses.

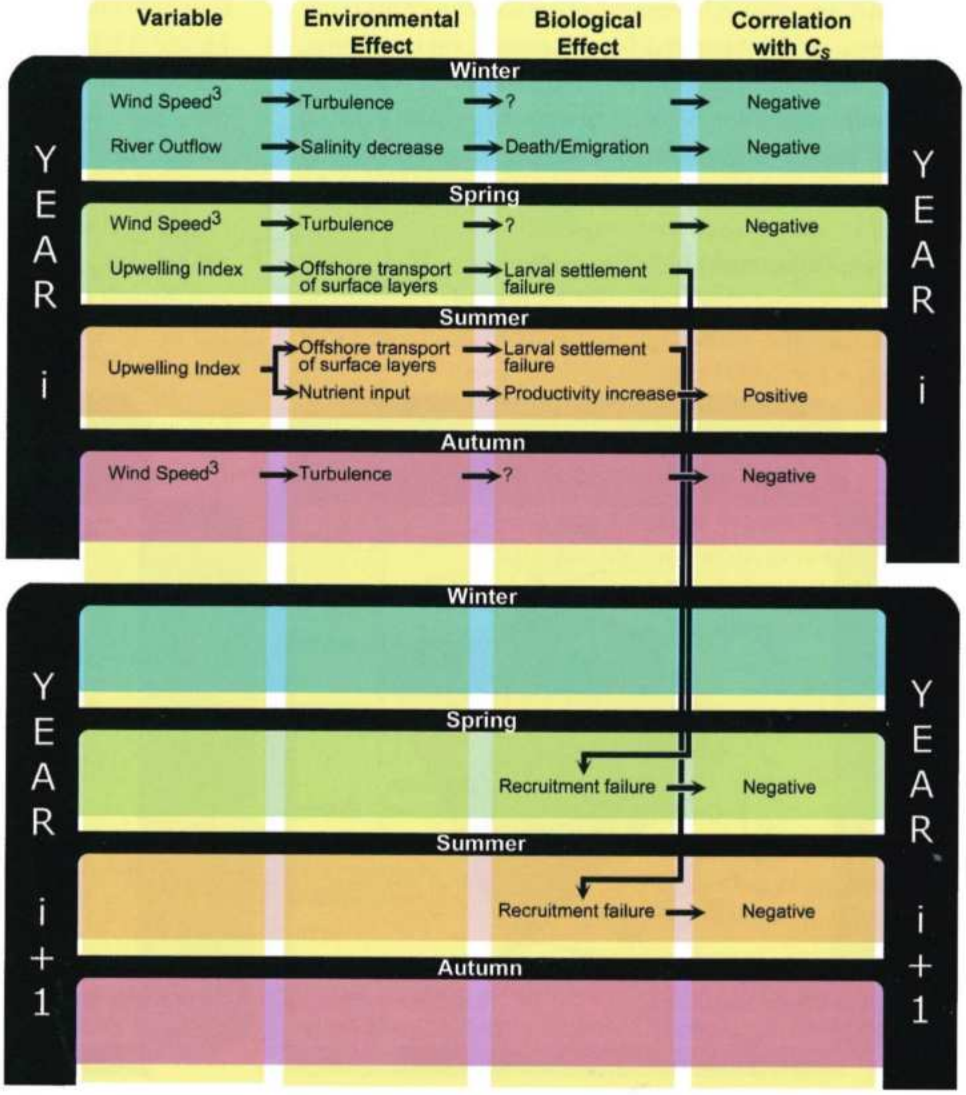

Figure 11.17 – Flowchart resuming hypotheses on environmental effects on the dynamics of *O. vulgaris* populations.

### 11.2.3 DESCRIPTION OF CLIMATE-MODEL GENERATED DATA

In order to investigate how future climate changes might influence fisheries in Portugal, we used the following set of data, generated by Hadley Centre's Regional Model 2 scenario:

- Monthly Mean Sea Level Pressure (MSLP) from the nearest HadRM gridpoints to Gibraltar and SW Iceland, respectively 36.00°N, 5.32°W and 63.96°N, 22.02°W. MSLP data were transformed into standardized anomalies by using observed data from the period 1951-'80 and differences between these two points were calculated (Gibraltar minus Iceland). This procedure was proposed by Jones et al. (1997) so as to calculate monthly NAO indices.
- Wind speed and direction, also estimated from the pressure field, were calculated in gridpoints located in the Northwest coast (41.10°N, 8.82°W), Southwest coast (38.96°N, 9.94°W) and Algarve (36.96°N, 8.18°W). From these data, we calculated upwelling frequencies and turbulence indices as were described in 11.2.2.

For the above variables, 26 years of contol runs were utilized to compare the HadRM2 model with observed data between 1961 and 1990. Simulation data extended from 2080 to 2100.

- Monthly Surface Air Temperature (SAT) over the sea, as close as possible to the Meteorological Institute stations of Peniche (39.35°N, 9.37°N) and Praia da Rocha (37.12°N, 8.53°W). The selected gridpoints were 39.79°N, 9.12°W and 36.96°N, 8.18°W. SAT was analysed as a proxy of sea surface temperature since data on the latter variable was not available from the HadRM2 model.

## 11.3 IMPACTS OF CLIMATE CHANGE UPON FISHERIES

### 11.3.1 INTRODUCTION

### 11.3.1.1 Overview

According to the Intergovernmental Panel on Climate Change (IPCC), global marine fisheries production is expected to remain about the same in response to future changes in climate, assuming that natural climate variability and the structure and strength of ocean currents remain about the same. The principal impacts will be felt at the national and local levels, as centers of production shift (IPCC 1997).

For instance, a slight change in ocean temperature, due to the way that offshore fisheries have now been nationalized, could result in systematic reallocations of stocks from one nation's Exclusive Economic Zone (EEZ) to that of an adjoining country. On a more local scale, a geographic shift in fished species within the boundaries of an EEZ may be felt economically by local or regional industries (Rothschild 1996).

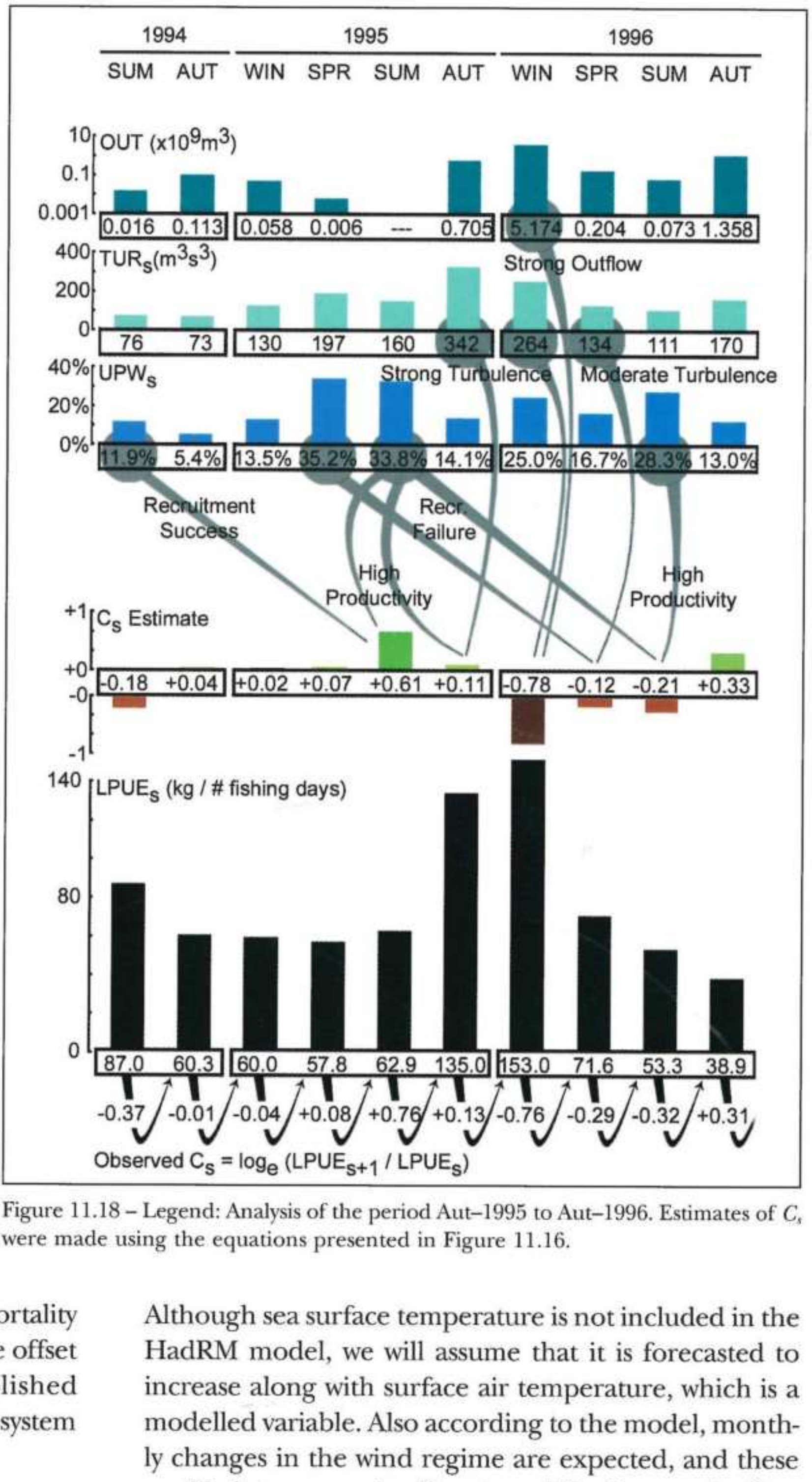

Figure 11.18 – Legend: Analysis of the period Aut–1995 to Aut–1996. Estimates of $C_s$ were made using the equations presented in Figure 11.16.

The positive effects of climate change, such as longer growing seasons, lower natural winter mortality and faster growth rates in higher latitudes, may be offset by negative factors such as changes in established reproductive patterns, migration routes and ecosystem relationships (IPCC 1997).

### 11.3.1.2 Detailed list of impacts

#### *11.3.1.2.1 Identified*

The analysis of Hadley Centre's RM2 model revealed several important changes in environmental variables throughout the Portuguese coast, forecasted until the end of the 21st century.

Although sea surface temperature is not included in the HadRM model, we will assume that it is forecasted to increase along with surface air temperature, which is a modelled variable. Also according to the model, monthly changes in the wind regime are expected, and these are likely to cause significant modifications to the Portuguese coastal upwelling system. The average intensification of wind, on the other hand, may also contribute to an increase in the depth of the mixed layer, reducing at the same time the frequency of Lasker events.

These changes are likely to affect the distribution and abundance of Portuguese fished species, including the replacement of cold-water species with others that are nowadays characteristic of lower latitudes.

Changes in sea surface temperature may also affect migratory routes of large pelagic fish, as well as the location of reproductive sites, food patches, etc. In general, the increase in temperature and turbulence are bound to enhance the contact rate between fish and their prey, but also the metabolic requirements per unit time. Therefore, mortality due to starvation may increase if not enough food is available.

The intensification of upwelling-favourable winds in the west Portuguese coast is of special interest, since strong offshore currents may drag eggs and larvae away from coastal regions into the open ocean, where they have much lower chances of surviving. Conversely, juvenile and adult fish may benefit from recurring upwelling events, since surface nutrient concentration may rise, with positive consequences to global productivity. Nevertheless, strong wind-induced turbulence may be detrimental to primary production, due to the contraction of the photic layer.

#### *11.3.1.2.2 Studied*

In agreement with the methodology followed in previous sections, we will examine impacts of climate change on the distribution and abundance of *Sardina pilchardus*, *Thunnus thynnus* and *Octopus vulgaris*. Being species of high commercial interest, it is likely that their response to future climate change will strongly affect many socioeconomic aspects of Portuguese fisheries, which is why we will focus our discussion entirely on them.

Since the selected species are very distinct in many aspects – one is a small coastal pelagic, another a large migrant, the third a bottom-dwelling cephalopod – it is also possible that the observed results for each one of them provide a good indication of climate impacts on similar species (e.g., other clupeids, tunas and large scombrids, squids and cuttlefish).

## 11.3.2 CHANGES IN THE ABUNDANCE AND DISTRIBUTION OF SARDINA PILCHARDUS

### 11.3.2.1 Relevant environmental changes

According to simulation data (2080–2100), the summer upwelling regime is likely to strengthen in the west Portuguese coast, during the 21st century (Figure 11.19). Marked increases were found in upwelling frequencies from control to simulation runs (up to +20%), between May and October. Conversely, between November and April non-significant differences were found between the two runs, meaning that the major changes forecasted for 2080–2100 will occur precisely in the upwelling season.

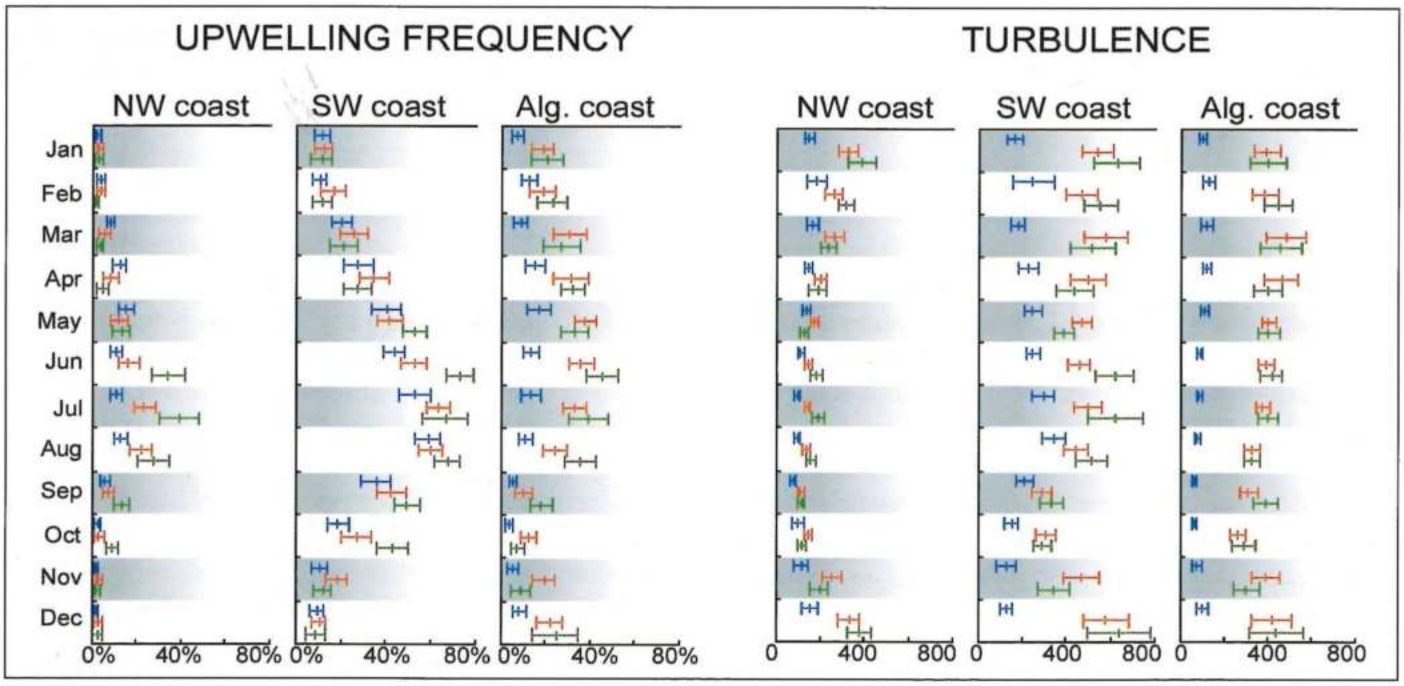

Figure 11.19 – Comparison among observed upwelling frequency and turbulence values (blue) and HadRM2 control (red) and simulation (green) runs. Wiskers represent average +/– (1.96 × standard error). Rule of thumb: considerable overlapping between blue and red whiskers can be as interpreted as successful model emulation of observed data; in these cases, if green whiskers are distant from the remaining two then significant changes are forecasted with some reliability.

Observed upwelling data in the west coast are in general agreement with the control run, but the same does not occur in the Algarve. This fact can be due to the existence of a montain range at about 37.4°N, extending zonally between 7.40°W and 8.50°W, which alters the atmospheric circulation pattern to the south of this region (Fiuza 1983:93). Therefore, the estimation of wind speed and direction from the pressure field seems inappropriate for the Algarve. As such, the significant differences between control and simulation data – found in August, September and November – must be interpreted with caution.

Turbulence data are moderately compliant with the former results. Apparently, the HadRM2 model strongly overestimates wind speed throughout the Portuguese coast, especially during winter. In order to confirm this finding, a third data source should be consulted, such as cruise measurements. Still, control and simulation runs are generally similar, suggesting that turbulence is forecasted not to change throughout the Portuguese coast. Significantly higher values of simulated turbulence were found at the beginning of summer (June and July), only in the west coast.

### 11.3.2.2 Responses

Taking into consideration the findings described in section 11.2.2., changes in the western upwelling regime are likely to have relevant impacts on sardine populations. In the Northwest coast, increases in summer upwelling frequencies ranging from +5% to +20% are likely to be beneficial for juvenile and adult feeding, since these changes move environmental conditions into the optimal window (Figure 11.20). On the other hand, non-significant variations in colder months will probably ensure that larvae remain close to the shore, where they have better chances of surviving. Thus, it seems that future environmental conditions may enhance sardine production in the Northwest coast.

An opposite scenario is forecasted for the Southwest coast, where current environmental conditions are nowadays inside the optimal window. Here, spring and summer upwelling are expected to reach average higher frequencies, simultaneous with stronger wind-generated turbulence. These changes may produce a deep mixed layer and a light-limited phytoplankton population, resulting in the reduction of primary productivity (e.g. Huntsman and Barber 1977:32). Since sardine are frequently found along thin filaments of moderately cool and "old" upwelled waters (Santos and Fiuza 1992:665), and also because intense upwelling can produce plumes which extend hundreds of kilometers offshore (Sousa and Bricaud 1992:11,347), it seems feasible that during the summer months sardine shoals will be distributed farther offshore, away from the traditional fishery grounds. Stronger summertime turbulence has a high probability of increasing mortality during the early life stages, weakening annual recruitment. On the whole, it appears that sardine biomass may decrease in this region (Figure 11.20). However, the proximity to the Northwest coast may to some extent balance this reduction, namely through the migration of juveniles and adults, during part of the year. Since springtime upwelling and turbulence conditions off the Algarve are predicted not to change, we expect sardine abundance to remain at present levels, given the stock-environment relationship discussed in section 11.2.2.1.

## 11.3.3 CHANGES IN THE ABUNDANCE AND DISTRIBUTION OF THUNNUS THYNNUS

### 11.3.3.1 Relevant environmental changes

Between 1961 and 1990, sea surface temperature has faced a significant increase in the Portuguese coast. Table 11.3 presents trends recorded in this period, at the Meteorological Institute stations of Peniche and Praia

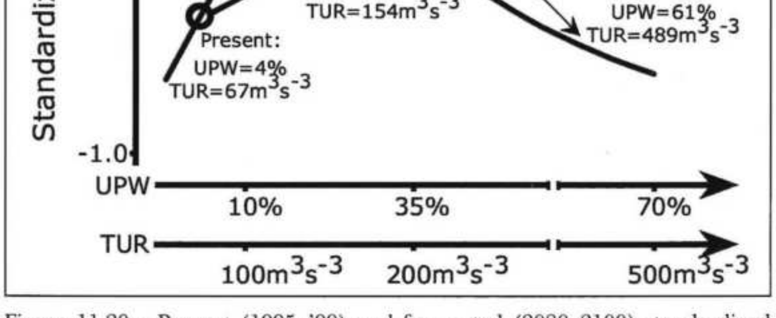

Figure 11.20 – Present (1995–'99) and forecasted (2080–2100) standardized landings in the west coast, taking into account present and forecasted values of summer upwelling frequency (UPW) and turbulence (TUR).

da Rocha, which can be considered representative of the west and south coasts, respectively. In both, highest increases are found in summer months (July-September), as well as in late fall and early winter (November-February).

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | **Year** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Peniche | +3.9* | +3.4 | -1.4 | +0.2 | +1.1 | +0.1 | +3.4* | +4.9* | +2.0 | +0.5 | +4.0* | +5.4* | +1.9* |
| P.Rocha | +3.0 | +2.9* | +0.3 | -0.7 | -4.0 | -2.6 | +0.2 | +1.4 | +1.1 | -2.7 | +3.7 | +4.5* | +1.0 |

Table 11.3: Trends (× 0.01°C $yr^{-1}$) of SST variation in the period 1961-'90, off Peniche and Praia da Rocha. Significant trends ($P<0.05$) are marked with asterisks.

According to HadRM2 simulations for 2080–2100, surface air temperature (SAT) is going to increase substancially during the 21st century. Differences between control and simulation runs are consistent throughout the year and indicate an average SAT increase rate of 0.039°C $yr^{-1}$ (Table 11.4).

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | **Year** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | +3.7 | +3.6 | +3.7 | +3.7 | +3.9 | +4.1 | +4.0 | +4.0 | +3.8 | +4.1 | +4.1 | +4.0 | **+3.9** |
| B | +3.8 | +3.6 | +3.6 | +3.7 | +3.8 | +3.9 | +4.0 | +4.1 | +3.8 | +4.2 | +4.1 | +4.1 | **+3.8** |

Table 11.4: SAT simulation minus control averages (°C), in HadRM gridpoints 39.79°N, 9.12°W (A) and 36.96°N, 8.18°W (B). All differences are significant at $\alpha = 0.05$.

These values also suggest that SST may continue to increase during the next hundred years in the Portuguese coast, at a similar (or even higher) rate to what is nowadays being observed.

While wintertime mean sea-level pressure (MSLP) gradients between Gibraltar and Iceland are correctly emulated by the HadRM2 control run, severe biasing occurs from May to October, due to an underestimation of MSLP at Gibraltar (Figure 21). Thus, summertime NAO indices – including the August index – are negatively biased in the model.

In spite of this deficiency, the HadRM2 model also presents negative correlations between NAO indices and the westerly wind frequency (WWF) recorded in the Algarve coast (Table 11.5; see also Figure 13). Nevertheless, the model overestimates the frequency and strength of westerly winds in the Algarve coast (see section 11.3.2.1.), implying that WWF values cannot be projected into the future.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ctrl. | -0.56* | -0.38* | -0.41* | -0.42* | -0.16 | -0.09 | -0.22 | -0.60* | -0.41* | -0.19 | -0.45* | -0.57* |
| Simul. | -0.54* | -0.35 | -0.56* | -0.32 | -0.49* | -0.45 | -0.18 | -0.11 | -0.12 | -0.30 | -0.54* | -0.68* |

Table 11.5: Pearson correlations between NAO and WWF at Faro, in control (N=30) and simulation data (N=20). Significant values ($P<0.05$) are marked with asterisks.

Another problem of Hadley Centre's general circulation model 2 (HadCM2, from which HadRM2 is derived) was pointed out by Osborn et al. (in press): the wintertime NAO index (DJFM average) estimated in the control run does not emulate the recent observed trend (from low values in the 1960s to high values in the early 1990s), even when anthropogenic forcing is included, which indicates either some model deficiency or that some other external forcing is partly responsible. As such, these authors question if the wintertime pressure gradient waning forecasted by Hadley Centre's model (observable in Figure 11.21) is reliable, since it implies a reversal of the anthropogenic effect early next century.

Given these difficulties, and despite some of the NAO properties are starting to be well simulated by climate models (e.g. Osborn et al. in press), we cannot

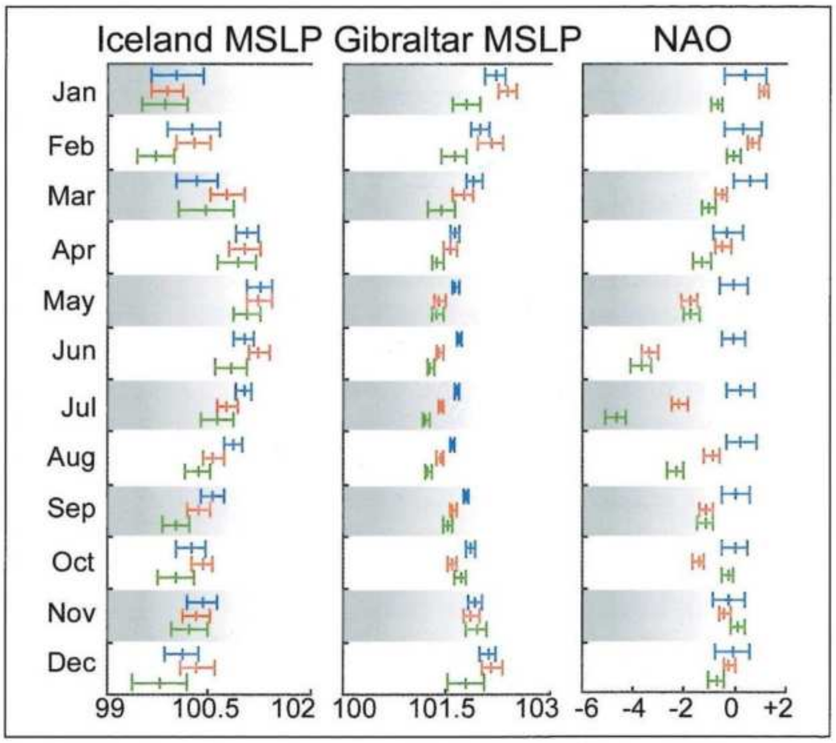

Figure 11.21 – Comparison among observed North Atlantic Oscillation (NAO), mean sea-level pressure (MSLP) values at Iceland and Gibraltar (blue) and HadRM2 control (red) and simulation (green) runs. Wiskers represent average +/– (1.96 x standard error). Rule of thumb: considerable overlapping between blue and red whiskers can be as interpreted as successful model emulation of observed data; in these cases, if green whiskers are distant from the remaining two then significant changes are forecasted with some reliability.

ascertain the signal and magnitude of forecasted pressure gradients in April and August.

### 11.3.3.2 Responses

As discussed in section 11.2.2, East Atlantic bluefin dynamics seem to be related with the North Atlantic Oscillation. This connection seems to be stronger with April and August NAO values, since bluefin abundance presents the same waves that are present in the indices. It is still unknown why bluefin seem to respond to the sea-level air pressure pattern over the North Atlantic, but the explanation may be in the strength and direction of wind-induced currents, which possibly influence energy demand during migrations. It may also be due to the intensity of wind-generated turbulence ocurring in the spawning period, which disperses food patches that can be paramount to larval survival. These hypotheses remain untested in the present study and should be addressed in ensuing analyses.

In the previous section we came to the conclusion that spring and summertime NAO estimation by the HadRM2 model seems poor. For that reason, we must abandon the investigation of future NAO variation and thereby compromise the process of forecasting bluefin abundance in the next decades. Nevertheless, if we extend and superimpose the main sinusoidal waves found in bluefin abundance, $w_{150}$ and $w_{50}$, we may argue that bluefin may display a tendency to become more abundant in the first decades of the 21st century, due to the rise of $w_{150}$, and then become scarcer again (Figure 11.22).

It must be noted, however, that these waves do not encompass neither the effect of fishing mortality nor anthropogenic forcing on climate, and therefore their use as a forecasting tool is limited. If we add a positive trend to $w_{150}$ and $w_{50}$, in order to prolong the recent strengthening of the NAO, then we may infer a stronger recovery of bluefin abundance.

On the other hand, SST projections for the Portuguese coast are likely to display a marked positive trend until the end of the 21st century. This warming is part of a global process, suggesting that worldwide alterations in the distribution and abundance of marine species are bound to occur. In the case of *T. thynnus*, it is likely that an increase in SST will considerably change the population dynamics in the Northeast Atlantic. Although the full set of biological and physico-chemical characteristics that define spawning areas and reproductive success is so far unknown, it seems reasonable to forecast an enhancement of recruitment and a recovery in bluefin abundance in the next decades, based on the events that ocurred during the 1920s-'70s.

Apart from altering production, ocean warming might also allow bluefin to extend its summertime trophic migrations further northward, into new feeding grounds. The Northern Seas may again become populated with *T. thynnus*, at the same time that small warm-water pelagics (e.g. sardine) replace characteristically autochthonus species (e.g. herring).

However, the extent of changes in the geographical distribution of bluefin as a reponse to a long-lasting increase in SST cannot yet be foreseen. It is possible, for instance, that optimal SST, salinity and nutrient concentration required for reproductive purposes will no longer be found in the traditional spawning grounds, but rather somewhere else in the Mediterranean or Atlantic.

By considering all these issues, it becomes difficult to predict if *T. thynnus* will again be abundant in Portuguese waters. It is probable that the next century

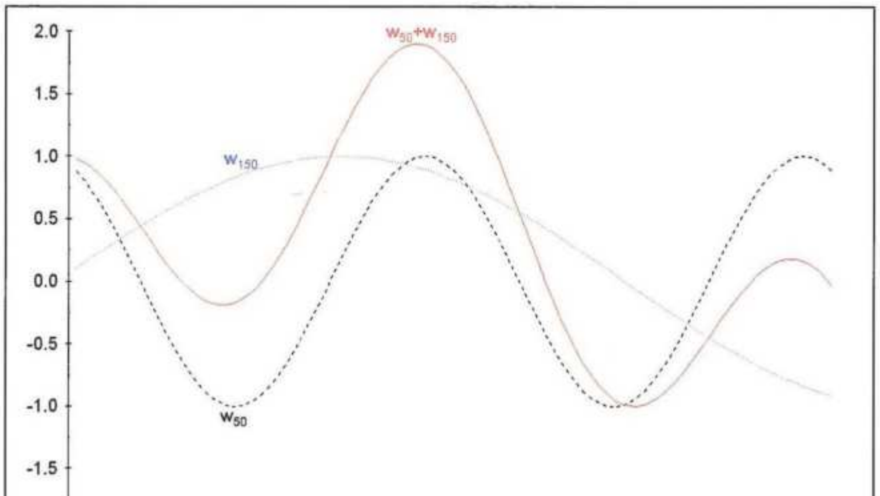

Figure 11.22 – Extension of $w_{50}$ and $w_{150}$ into the future.

will display a pattern similar to the previous, namely with periods of increased landings separated by others of shortage. Since the Algarve coast is merely a route of migration and not a destination, bluefin abundance will always be dependent on the dynamical location of reproductive and feeding areas, apart from local environmental conditions. Due to the northward displacement of trophic migrations, it is almost certain that large schools of bluefin will cross the west Portuguese coast during the summertime, but the precise location and depth of these routes is still unknown.

### 11.3.4 CHANGES IN THE ABUNDANCE AND DISTRIBUTION OF OCTOPUS VULGARIS

#### 11.3.4.1 Relevant environmental changes

Despite being an essential factor, the variation of river outflow was not accounted for in our analysis, since this variable is not only associated with rainfall and surface runoff, but also and to great extent with human activities. In the Guadiana basin, for instance, a major intervention is taking place nowadays – the construction of the Alqueva dam –, which will in future years regulate the timing and volume of Guadiana discharges. Since the HadRM2 model forecasts a decrease in rainfall for the entire Iberian Peninsula, especially in the southern regions, we will assume that river outflows are likely to become weak.

Wind-induced turbulence, already discussed in section 11.3.2.1., may probably remain the same throughout the year, since control and simulation data have almost the same monthly average values (Figure 11.19). If wind speed was not so severely overestimated by the model, some further analysis would have been made in search for extreme events, similar to the year of 1996, as they are capable of producing transient but drastic changes to environmental conditions.

There is also a low degree of confidence in the analysis of upwelling frequency data in the Algarve coast, since control and observed data diverge markedly (Figure 19; see also section 11.3.2.1.). Significant increases were found during late summer (August and September), while in November the upwelling frequency may decrease.

Finally, SST is forecasted to rise thoughout the year, as discussed in section 11.3.2.1.

#### 11.3.4.2 Responses

Laboratory experiments have clearly shown that temperature strongly influences *Octopus vulgaris*'s metabolic activity, and consequently feeding and growth rates (e.g. Mangold and Boletzky 1973; O'Dor and Wells 1987). Therefore, warmer-than-present sea surface temperature (SST) during the reproductive season will likely allow small planktonic octopuses to grow faster and thereby have better chances of avoiding predation, provided that there is enough food. Should food not be abundant, then starvation and cannibalism will achieve even greater importance than nowadays. Hence, the rise of SST may in future disturb the recruitment process in opposite ways, and these are not yet included in current models.

During winter, adverse environmental conditons may become less frequent, thereby reducing the probabilities of biomass decrease as a result of mortality. Enhanced sea bottom salinity and temperature may allow individuals to remain closer to shore and grow even during these months.

Springtime relevant environmental factors (upwelling frequency and turbulence) are forecasted not to change significantly, meaning that the biomass change rate may in future be similar to present values.

In contrast, summer upwelling is expected to become more frequent, which has impacts on summer recruitment and individual growth during the second half of the year. Since these impacts have opposite signals (negative in the former and positive in the latter), it is not immediate whether *O. vulgaris* will become more or less abundant due to this environmental change. By using the equations presented in Figure 11.16 for summer and autumn, where $TUR_{aut}$ is replaced by the presently observed average ($74.1 m^3 s^{-3}$), we obtain the following expected average values:

$$\bar{C}_{sum} = -0.51 + 4.83 \times \overline{UPW}_{sum} - 11.2 \times \overline{UPW}^{2}_{sum}$$

$$\bar{C}_{aut} = -0.33 + 3.12 \times \overline{UPW}_{sum}$$

Due to their nature, these two biomass change rates can be added, in order to calculate a six-monthly biomass change rate:

$$\overline{C}_{6\text{-}m} = -0.84 + 7.95 \times \overline{UPW}_{sum} - 11.2 \times \overline{UPW}^{\,2}_{sum}$$

Since this index reaches its maximum value (+0.57) at $\overline{UPW}_{sum} = 35.5\%$ and the present average value of summer upwelling frequency is 9.8%, we conclude that even a substantial increase in this variable would benefit octopus biomass in the Algarve coast (Figure 11.23). An optimal balance between recruitment and growth during summer would be achieved at a lower average value of summer upwelling frequency (21.6%, with a corresponding $\overline{C}_{sum}$ value of +0.01, instead of −0.21), but autumn growth would be severely reduced ($\overline{C}_{aut} = +0.34$, instead of $\overline{C}_{sum} = +0.78$).

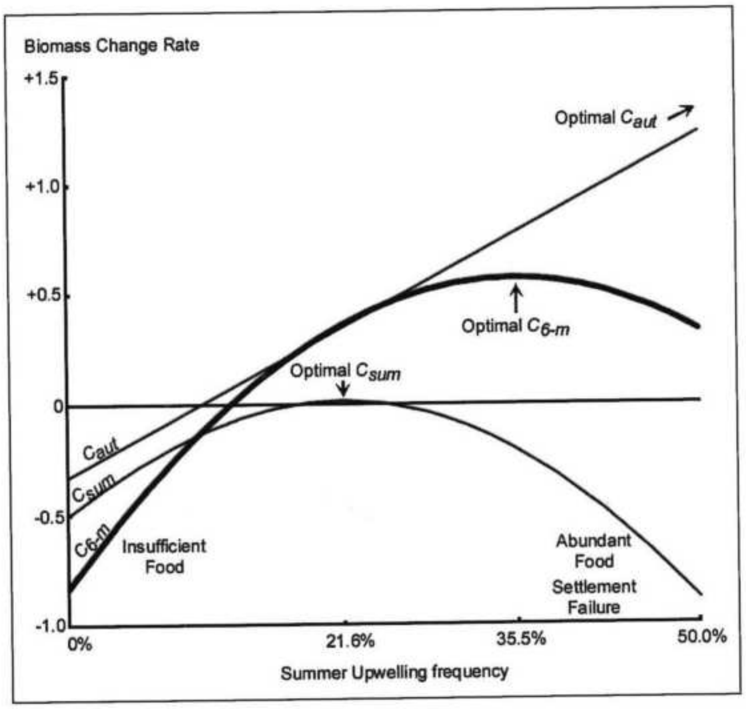

Figure 11.23 – Impacts on $C_{sum}$ and $C_{aut}$ due to a change in summer upwelling frequency.

## 11.4 ADAPTATION MEASURES

### 11.4.1 SARDINA PILCHARDUS

The adoption of distinct management decisions for the three regions in which the Portuguese coast was divided is probably the best policy to deal with opposite changes in distibution and abundance of fished populations. As shown, within the Portuguese EEZ, sardine may become more abundant in the Northwest coast than in the remaining regions. Here, the enhancement of oceanographic conditions may favour large yearly production, comparable to the late 1950s and early 1960s (Figure 11.2). Thus, efficient management policies must be enforced in order to maintain catches close to the stock's maximum sustainable yield. Overfishing and discarding should be avoided at all costs, since they may ruin a potentially lucrative fishery in the medium to long term.

If adequate measures are taken – bans in episodes of scarcity due to weak recruitments, establishment of total allowable catches (TACs) and quotas, minimum sizes, mesh-size regulations, etc. – fisheries in the Southwest coast may not experience severe losses due to the deterioration of environmental conditions. As mentioned, the proximity to the Northwest coast may also offset the decreasing trend of recruitment, thereby closening the set of management measures to be enforced. However, the strengthening of upwelling may force sardine shoals to remain distant from shore, and this may have severe impacts on local small scale fisheries. Traditional fishing grounds may become barren at the same time that large purse seiners and trawlers, equipped with better means for preserving fish and navigating away from shore for long periods, may land substantial amounts of fish. Thus, the Portuguese fishing fleet is in great need of renewing itself, especially in the Southwest coast, so that it can respond to the need to advance further offshore, in search for new fisheries and fishing grounds. The development of remote sensing techniques would also be of great interest in this field, in the sense that it would increase the efficiency of fisheries, not only by estimating the position and size of shoals but also by helping (for instance) to define spawning areas, which would be closed to fisheries.

The effects of SST rise were not taken into consideration when studying sardine, since it was assumed that temperatures up to 25°C are still within its range of tolerance. Nevertheless, further comparisons should be made with other coastal regions (down to the Senegalese coast, the southermost limit of *S. pilchardus* distribution) before stating with some degree of confidence that the abundance of sardine in the Algarve coast will not be affected by SST rise.

### 11.4.2 THUNNUS THYNNUS

Regarding *T. thynnus*, it is evident that adaptation measures must forcefully cross the national level, since the whole East Atlantic basin is composed of just one population of highly migratory individuals. In fact, it is even possible that East and West Atlantic stocks are so bound by the migration of adults that management policies must be settled among African, European and American countries. These measures would thus be a good example of the United Nations' Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks, adopted and opened for signature in 1995.

For the last decades, the International Council for the Conservation of Atlantic Tunas (ICCAT) has recommended several policies in order to allow the bluefin stock to recover. Namely, ICCAT established minimum sizes for the entire Atlantic and Mediterranean, prohibited large pelagic longliners of more than 24 m in length from fishing in the Mediterranean during the months of June and July, banned purse seine fishing from May (in the Adriatic) and July to August (in the remaining Mediterranean), etc. However, as ICCAT's Standing Committee on Research and Statistics (SCRS) itself recognizes, the effects of current regulations are being poorly enforced, and unreported landings impair any attempts to correctly assess and manage the stock.

According to projections made by the SCRS, the current catch level for East Atlantic bluefin (43,000 tons $yr^{-1}$) is not sustainable, and the formerly proposed reduction to 33,000 tons $yr^{-1}$ is still not sufficient to halt a continuing decline in spawning stock biomass. A catch of 25,000 tons $yr^{-1}$ may allow an equilibrium, but spawning stock biomass is not expected to return to historic levels. The Committee continues to be concerned about the intensity of fishing pressure on small fish, which contributes substantially to growth over-fishing and seriously reduces the long term potential yield from the resource. Additionally, recent abrupt increase of catches of large fish is of grave concern. In short, climate change will only have impacts upon bluefin tuna fisheries if they still exist in future.

As SCRS (2000) indicates, there appears to have been a general trend of increasing recruitment from the 1980s onward, which is consistent with the findings described and discussed previously. Also, 1997–'99 trap catches were the highest in recent years (SCRS 2000), suggesting that a new cycle of high bluefin abundance could iniciate in the beginning of the 21st century. Therefore, it is imperative that fishing effort is reduced, according to ICCAT's recommendations, so that bluefin are allowed to recover. Medium- an long-term revenues would largely compensate for short term losses.

In this sense, governments may have a decisive role in the future of bluefin fisheries. Fishermen could be rewarded for redirecting their gears to other non-endangered species, or even to adjust their boats for recreational fisheries (where fish are returned to the sea), during part or the whole year. By joining efforts with ICCAT, governments could implement simultaneous and prolonged bans in order to allow the bluefin stock to stabilize at higher levels, while idle fishermen would be compensated. By sponsoring the development of fishing surveillance and continuous monitoring systems (e.g., the Portuguese MONICAP system applied to trawlers), significant improvements would be made in regulating the distribution of fishing effort, as well as in ensuring the enforcement of regulations. Other technologies of remote sensing could allow fishing boats to effectively pursue schools of large adults, while juvenile fish (which generally form their own schools) would not be harvested. Thus, discards and fuel consumption would be minimized.

Further studies on the biology of *T. thynnus* are also necessary so as to predict the responses to climate change. Namely, the setting of echosounders at the straits of Gibraltar – pioneered by Lozano Cabo (1959) – could indicate not only changes in abundance but also alterations in the migration pattern of bluefin to and from the Mediterranean. Similarly, the continuous tagging of specimens in the East and West Atlantic might alert to changes in migratory patterns across the whole basin. This knowledge might then be used to reallocate fishing effort, preventing conflicts between countries and helping to maintain the maximum sustainable yield.

### 11.4.3 OCTOPUS VULGARIS

History shows that when some fisheries are no longer profitable, others may emerge to replace them. In fact, cephalopod fisheries are of that a good example, not just in the Algarve, where it to some extent substituted the bluefin tuna fishery (in terms of importance), but also throughout the world, given that they began to flourish when finfish stocks neared depletion (Caddy and Rodhouse 1998).

It seems possible that in future the harvesting of *O. vulgaris* in the Portuguese continental shelf will attain an even greater importance, while other species more adapted to colder waters become progressively less abundant, first in the South and later in the North. Octopus will probably become very abundant at higher latitudes, in the same way that ocurred in the early 1900s and 1950s, when "plagues" of *O. vulgaris* invaded the English Channel (Rees and Lumby 1954).

In our point of view, the fisheries for octopus with clay pots should be encoraged instead of setting pots or trawling, as a response to the particular increase in this species' abundance. The justification for this lies in the specificity of the artisanal fishery: bycatch is insignificant, only large specimens are caught, the loss of fishing gears is less harmful to the environment (lost clay pots are even beneficial since they act like artificial reefs, providing shelters and homes for many species) and so is the fishery itself.

As mentioned in previous sections, assessment and management policies must be designed exclusively to exploit this bountiful resource. High-intensity fisheries methods are quite recent to the cephalopod industry and as such cephalopod fisheries management is taking its first steps. Regarding the Portuguese octopus fishery, attempts must be made to update policies in near-real time, due do the responsive behaviour of stocks to environmental changes. Oceanographic and meteorological data should be collected in several stations across the country and should be analysed without much delay. Great attention should be given to extreme weather events, especially to heavy rainfall, as they might cause the collapse of recruitment and adult survival. In these cases, prompt responses must be taken in order to allow the stock to naturally recover. The easiest measure would probably be to ban fishing for no less than three to six months.

New, more complex models that include species-species interaction and community structure should also be attempted, as well as further analysis on the environmental factors that influence recruitment and biomass increase. The development of Geographic Information Systems (GIS) directed to fishing activities and high-resolution fishing charts also seems highly relevant in this case, since the knowledge of the depth and kind of substratum, seasonal distribution pattern of the stock, etc., would certainly contribute to the sustainable exploitation of this resource.

## 11.5 RESEARCH GAPS

### 11.5.1 SARDINA PILCHARDUS

The analysis of sardine landings knew great difficulties due to the absence of a long timeseries of fishing effort. Although no temporal signatures of changes in effort were found, it is certain that technological introductions and management measures must have had a profund impact on fisheries, which is probably intermingled with the effects of climate change. Therefore, attempts should be made to quantify the variation of fishing effort, or perhaps to isolate periods where it is assumed to be constant.

The existence of bans in the first months of some years (from 1929 to 1972) may also have led to some severe biasing when considering total annual landings. The implementation and duration of these bans varied from year to year as well as from port to port; in some cases, the suspension of fishing activity was mandatory between 60 and 90 days per year, but fishermen were allowed to choose when (during the year) to enforce this measure. In conclusion, historical landings should only be used as precise indicators of sardine abundance if extensive research is done in order to filter all these confounding variables.

### 11.5.2 THUNNUS THYNNUS

Further analysis on the causes for low- and high-frequency oscillations must be made. If the productivity of fisheries follows interannual, decadal, or other long-term climatic changes, then changes in the catch need to interpreted in the context of these natural cycles, as do ensuing decisions of the management and allocation of stocks. In this sense, more historical data on bluefin trap fisheries should be collected and compared with those presently available.

The geographical positioning and amount of longline and purse seine catches can also provide substancial insight on the seasonal and interannual distribution of bluefin, as well as new indices of abundance. Therefore, it might be interesting to develop a GIS with monthly catches, and to analyse the resulting maps in conjunction with environmenatl data.

### 11.5.3 OCTOPUS VULGARIS

The present state of *O. vulgaris* fisheries in the west coast was not approached in this study. The assumption that environmental factors act in the same way here as in the Algarve coast almost certainly does not hold, since the oceanographic conditions are so distinct. As shown by the research of sardine population dynamics, specific analyses must be made to each region of the Portuguese coast, followed by the gathering of results into one single diagram.

Laboratory and field experiments should also be done in order to further investigate the effects of salinity, turbulence and temperature on metabolic and feeding rates, as well as on survival. In this context, the development and application of suitable tags might be heplful. *In situ* estimations of recruitment success would also provide significant insight on the importance of environmental factors, apart from better quantifying recruitment variability.

### 11.5.4 OTHER SPECIES

It is evident that the major gap in the present study was the restriction to only three species. Numerous marine groups were not represented, such as crustaceans (e.g., lobsters), elasmobranchs (e.g., sharks and skates), demersal finfish (e.g. hake and congers), flatfish (e.g., sole), mammals (e.g., whales), etc.

Portuguese anadromous and catadromous species (i.e., species that migrate between fresh and saltwater) such as eel, lamprey, allis shad and twaite shad, etc., were also not accounted for. These species are in risk of becoming extinct, not just because of climate change but especially due to anthropogenic forcing (pollution, habitat destruction, etc.). Some careful discussion of climate impacts on these species should be attempted in further studies.

We did not discuss Portuguese freshwater species either, and these are likely to be severely affected by climate change. The rise of air temperature, for example, will cause significant increases of freshwater temperature and evaporation. Thus, metabolic rates will be enhanced at the same time that water availability will diminish, meaning that encounter rates are likely to increase substancially. The unbalancing of freshwater ecosystems is thus a likely scenario and should be addressed promptly, in order to mitigate the more adverse consequences.

According to the IPCC (1997), the rise in sea level may have an undeniable effect on the commerce in fish, since a large percentage of global fish resources spend critical parts of their lives near the shore or near the mouths of rivers. Any change in marshes or wetlands, or in the extent to which seawater intrudes into rivers, would be felt by many ocean fish. Therefore, the investigation of impacts of sea level rise on fisheries is also of great interest, and accurate analyses of adaptation processes ocurring in Portuguese coastal ecosystems should be reinforced as soon as possible.

## 11.6 CONCLUSIONS

Understanding the effects of climate change on fisheries resources, and finding cause-effect relations is extremely complex, since weather phenomena act in conjunction, and their timing of occurrence may lead to quite opposite effects. The relations among these variables are further complexed by the action of biological and ecological processes such as predation, recruitment and changes in dominant species, which are themselves influenced by environmental variables.

It seems clear, however, that significant modifications in factors such as temperature, upwelling or turbulence, may alter the values of parameters that are customarily used in fishery management models to estimate optimal production, yield and levels of stocks. This fact poses a very serious problem to developing adaptative measures, since currently employed models do not explicitly include environmental variables, and are therefore insensitive to possible impacts of changes in the environment.

Moreover, until specific changes in ocean-atmosphere circulation can be better understood, predicted and factored in, a high degree of uncertainty will prevail in the management of fisheries, contributing additional questions to present, imperfect systems of allocation. The result is greater uncertainty in long-term capital investment strategies, added tension in regulatory decision-making, and a more wasteful use of the marine resources that Nature provides.

Whether the oceans will prove sufficiently bountiful to provide an adequate supply of fish as food for future generations will depend in part on how well we do in managing the resource. Certainly needed is the development of more enlightened policies on how many fish should be harvested, where and when, as well as the more effective application of such policies, both nationally and internationally. These will demand, in turn, a deeper understanding of the causes of natural and induced variations in stocks.

At present we have little capability to forecast how environmental changes affect recruitment, and limited knowledge of how species interact with one another in the ecosystem or in the fishery. The most important needs are extensions of existing theories of natural production, and the development of enhanced data systems to support them. International research activities will contribute considerably to a broader understanding of ocean ecosystems. We can hope that what is found can be applied to a more enlightened management of what is taken from the sea.

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# Acronyms and Abbreviations

| | |
|---|---|
| ACACIA | A Concerted Action Towards A Comprehensive Climate Impacts and Adaptations Assenment for the European Union |
| AIDS | Acquired Immune Deficiency Syndrome |
| AOGCM | Atmospheric-Oceanic Global Climate Model |
| ARD | Afforestation, Reforestation and Deforestation activities |
| ARIMA | Auto-Regressive Integrated Moving Average |
| ASLR | Accelerating Sea Level Rise |
| ATP | Adenosine Triphosphate |
| AVVA | Aerial Videotape-Assisted Vulnerability Analysis |
| $C_3$ plants | Plants that fix $CO_2$ through the carboxilation of ribulose 1,5-diphosphate |
| $C_4$ plants | Plants that fix $CO_2$ through the carboxilation of phosphoenolpiruvate |
| CAM | Crassulacean Acid Metabolism |
| CCSR/NIES | Center for Climate Research Studies/ National Institute for Environmental Studies (Japan) |
| CDD | Consecutive dry days |
| CERES | Crop Estimation through Resources and Environmental Synthesis |
| CFC | Chlorofluorocarbons |
| CGCM | Canadian Global Coupled Model |
| CGCM1 | 1st generation of the Canadian Global Climate Model |
| $CH_4$ | Methane |
| CLAIRE | Climate Change and Agriculture in Europe |
| CLIVAR | Climate Variability and Predictability Programme |
| CLIVARA | Climate Change, Climatic Variability and Agriculture in Europe |
| $CO_2$ | Carbon dioxide |
| COADS | Comprehensive Ocean-Atmosphere Data Set |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation (Australia) |
| CWT | Circulation Weather Type |
| DDC | Data Distribution Centre |
| DJF | December, January, February |
| DJFMA | December, January, February, March, April |
| DL | Decreto-Lei |
| DSR | Daily Severity Ratio (fire) |
| DSSAT | Decision Support Systems for Agrotechnology Transfer |
| DTR | Diurnal Temperature Range |
| EC | European Community |
| ECHAM | European Centre/Hamburg Model |
| ECHAM4 | 4th generation of ECHAM |
| ECMWF | European Centre for Medium Range Weather Forecasts |
| EEZ | Exclusive Economic Zone |
| EU | European Union |
| FWI | Fire Weather Index |
| GAM | Generalised Additive Model |
| GCM | Global Circulation Model |
| GCOS | Global Climate Observing System |
| GDP | Gross Domestic Product |
| GFDL | Geophysical Fluid Dynamics Laboratory (USA) |
| GHG | Greenhouse gases |
| GIS | Geographic Information System |
| GPP | Gross Primary Production |
| GS | Greenhouse gases and Sulphates |
| GVA | Gross Value Added |
| HadCM | Hadley Centre Climate Model |
| HadCM2 | 2nd generation of the Hadley Centre Global Climate Model |
| HadCM3 | 3rd generation of the Hadley Centre Global Climate Model |
| HadCM3+S | 3rd generation of the Hadley Centre Global Climate Model (simulation including effect of sulphate aerosols) |
| HadRM | Hadley Centre Regional Model |
| HadRM2 | 2nd generation of the Hadley Centre Regional Climate Model |
| HFC | Hydrofluorocarbons |
| HIV | Human Immuno-Deficiency Virus |
| HSK | Hattch-Slack-Kortscak pathway, also known as dicarboxilic acid pathway, is the pathway of $CO_2$ fixation in $C_4$ plants |
| HWDI | Heat Wave Duration Index |
| HZ | Hydrographic Zero |
| IAM | Integrated Assessment Model |
| ICCAT | International Council for the Conservation of Atlantic Tunas |

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|---|---|
| ICES | International Council for the Exploration of the Seas |
| IE | Index of Emberger |
| IM | Instituto de Meteorologia |
| INAG | Instituto da Água |
| IPCC | Intergovernmental Panel on Climate Change |
| IPCC WGI | IPCC Working Group I |
| IPCC WGII | IPCC Working Group II |
| IPIMAR | Instituto de Investigação das Pescas e do Mar |
| JAS | July, August, September |
| JJA | June, July, August |
| KP | Kyoto Protocol |
| LPUE | Landings Per Unit Effort |
| LULUCF | Land Use, Land-Use Change and Forestry |
| LVT | Lisboa e Vale do Tejo (Lisbon and Tagus Valley) |
| MAM | March, April, May |
| MSF | Mediterranean Spotted Fever |
| MSL | Mean Sea Level |
| MSLP | Mean Sea Level Pressure |
| $N_2O$ | Nitrous oxide |
| NAO | North Atlantic Oscillation |
| NBP | Net Biome Production |
| NCAR | National Center for Atmospheric Research (USA) |
| NCEP | National Center for Environmental Prediction |
| NEP | Net Ecosystem Production |
| NGO | Non-governmental Organization |
| NHS | National Health System |
| NPP | Net Primary Production |
| $O_3$ | Ozone |
| OECD | Organization for Economic Co-Operation and Development |
| PDM | Plano Director Municipal (Municipal Plan) |
| PDSI | Palmer Drought Severity Index |
| PEP | Phosphoenolpyruvic Acid |
| PEPCase | Phosphoenolpyruvic Acid Carboxylase |
| PFC | Perfluorocarbons |
| PMD | Public Maritime Domain |
| PROF | Planeamento Regional de Ordenamento Florestal (Regional forest land planning) |
| PROMES | Pronostico a Mesoescala (Spanish Regional Climate Model) |
| RCM | Regional Climate Model |
| RuBPCase | Ribulose-1,5-Biphosphate Carboxylase |
| SAT | Surface Air Temperature |
| SCRS | Standing Committee on Research and Statistics |
| $SF_6$ | Sulphur hexafluoride |
| SLP | Sea Level Pressure |
| SMART | Simple Multi-attribute Rating Technique |
| SNHT | Standard Normal Homogeneity Test |
| SON | September, October, November |
| SRES | Special Report on Emission Scenarios |
| SSR | Seasonal Severity Ratings (fire) |
| SST | Sea Surface Temperature |
| TAC | Total Allowable Catches |
| TB | Tuberculosis |
| TBE | Tick-borne Encephalitis |
| TGCIA | Task Group on Scenarios for Climate Impact Assessment |
| $T_{max}$ | Maximum temperature |
| $T_{min}$ | Minimum temperature |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UTC | Universal Coordinated Time |
| VL | Visceral Leishmaniasis |
| VOC | Volatile Organic Compounds |
| WHO | World Health Organization |
| WMO | World Meteorological Organisation |
| WOFOST | World Food Studies |
| WWF | Westerly Wind Frequency |