20th Century Portuguese Climate and Climate Scenarios

Pedro M A Miranda  
Faculdade de Ciências da Universidade de Lisboa  
Centro de Geofísica da Universidade de Lisboa

Fátima Espírito Santo Coelho  
Instituto de Meteorologia

António Rodrigues Tomé  
Universidade da Beira Interior  
Centro de Geofísica da Universidade de Lisboa

Maria Antónia Valente  
Centro de Geofísica da Universidade de Lisboa

Anabela Carvalho  
Instituto de Meteorologia

Carlos Pires  
Faculdade de Ciências da Universidade de Lisboa  
Centro de Geofísica da Universidade de Lisboa

Henrique Oliveira Pires  
Instituto de Meteorologia

Vanda Cabrinha Pires  
Instituto de Meteorologia

Carlos Ramalho  
Centro de Geofísica da Universidade de Lisboa

Reference:  
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:


- 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 especially 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.
2.1 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 change 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.

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, average 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 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.

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. 2.3a). The average minimum temperature in winter varies between 2°C in the mountainous interior zone and 12°C in the Algarve (Fig. 2.3b).

The number of days of the year with a 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.

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

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

![Fig. 2.6 – Mean annual accumulated precipitation. Data from 1961-1990 observations.](image)

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).

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 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.
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 $\geq 10$ mm. Data from 1961-1990 observations.

Fig. 2.9 – Average cloud cover at 9:00 UTC in oktas. Data from 1961-1990 observations.
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. (1999b) 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., 1997). 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., 2000; 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. Morberg 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.

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.

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 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, 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 temperature. 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 increased 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. 2.14 – 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).
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. 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.

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

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 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, see also Table 2.1) the main feature that comes out is the systematic reduction of spring accumulated precipitation, accompanied by a small reduction in winter and 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 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. Table 2.1 shows average seasonal precipitation in the two climate normals, indicating a decrease in precipitation in spring, partially compensated by smaller increases in the other seasons. 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

<table>
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<th>Spring</th>
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<td>373.0</td>
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<td>6.8</td>
<td>-9.6</td>
</tr>
<tr>
<td>∆%</td>
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<td>4.9</td>
<td>-18.5</td>
<td>12.6</td>
<td>-1.0</td>
</tr>
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</table>

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 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 oscillating regularly, with a smaller amplitude oscillation, around the mean values. Because the two normals correspond to different trends in global regional 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 350mm, 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 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 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, 2001). 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, 2001). Fig 2.27 shows the time series on 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 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.

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).
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 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).

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. 2.28 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. 2.28 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 DaCamara (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 DaCamara (2000), although the dataset used here is an extended and improved version of the one that was available at that time.

The circulation weather types (CWTs), as defined by Trigo and DaCamara, 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 near 27% of all cases and, if they were well distributed among them, it would represent less than 2% for each one and we could, as done by Trigo and DaCamara, 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 DaCamara, 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.
Table 2.2 – CWTs frequency (%) in the NCEP/NCAR reanalysis data

| Time | A  | C  | NE | E  | SE | S  | SW | W  | NW | N  | NE | E  | hA | E  | hA E | HASE | HA | S  | HASW | hA W | HANW | hA N | hA E | HANE | hA E | HASE | HA S | HASW | hA W | HANW | hA N |
|------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 00h  | 17.4 | 3.8 | 12.5 | 9.5 | 4.1 | 2.5 | 9.5 | 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 | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| 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 | 0.5 | 0.4 | 0.3 | 0.3 | 0.2 | 0.2 | 0.1 |

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 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).

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

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.
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.

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.
Table 2.3 – Some climate indices

TEMPERATURE INDICES

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Su</td>
<td>Summer days (Nr. of days with maximum temperature above 25°C)</td>
</tr>
<tr>
<td>Tr</td>
<td>Tropical nights (Nr. of nights with minimum temperature above 20°C)</td>
</tr>
<tr>
<td>HWDI</td>
<td>Heat Wave Duration Index (Maximum period &gt;5 consecutive days with Tmax&gt; 5°C above the 1961-90 daily Tmax normal)</td>
</tr>
</tbody>
</table>

PRECIPITATION INDICES

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R10</td>
<td>Nr. of days with precipitation amount ≥ 10mm</td>
</tr>
<tr>
<td>CDD</td>
<td>Maximum number of consecutive dry days (Maximum nr. of consecutive days in a period with precipitation amount &lt;1mm)</td>
</tr>
<tr>
<td>R5D</td>
<td>Greatest 5-day precipitation total (Maximum 5-day precipitation sums)</td>
</tr>
</tbody>
</table>

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 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 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 – Time series of Palmer Drought Severity Index (PDSI) at 4 stations in mainland Portugal.
Table 2.4 – PDSI classification

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00 or above</td>
<td>Period of heavy rain</td>
</tr>
<tr>
<td>3.00 – 3.99</td>
<td>Period of severe rain</td>
</tr>
<tr>
<td>2.00 – 2.99</td>
<td>Period of moderate rain</td>
</tr>
<tr>
<td>0.50 – 1.99</td>
<td>Period of light rain</td>
</tr>
<tr>
<td>0.49 – -0.49</td>
<td>Normal period</td>
</tr>
<tr>
<td>-0.50 – -1.99</td>
<td>Period of light drought</td>
</tr>
<tr>
<td>-2.00 – 2.99</td>
<td>Period of moderate drought</td>
</tr>
<tr>
<td>-3.00 – -3.99</td>
<td>Period of severe drought</td>
</tr>
<tr>
<td>-4.00 or less</td>
<td>Period of extreme drought</td>
</tr>
</tbody>
</table>

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%).

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 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 feedbacks 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 CGM 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 CO₂ (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 CO₂ concentration in the atmosphere was about 350 ppmv. From 1990 onwards the models consider an idealised emissions scenario with a 1% /year increase in the CO₂ compound concentration (includes other greenhouse gases, such as methane
CH$_4$, nitrous oxide N$_2$O, halocarbons and ozone O$_3$). This is close in terms of radiative forcing to the IPCC IS92a (“business as usual” scenario) (Leggett, 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 IPCCIII WGI (2001) report (Acacia Report, 2000).

Table 2.5 –

<table>
<thead>
<tr>
<th>Model</th>
<th>Entity</th>
<th>References</th>
<th>Emissions scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSIRO Mk2</td>
<td>Commonwealth Scientific Industrial Research Organisation (Australia)</td>
<td>Hirst et al. (1996), Gordon and O’Farrell (1997), Hirst et al. (2000)</td>
<td>0.9%/year</td>
</tr>
<tr>
<td>ECHAM4/OPYC3</td>
<td>European Centre/ Hamburg/ Deutches Klimarechenzentrum (Germany)</td>
<td>Roeckner et al. (1996), Zhang et al. (1998)</td>
<td>1%/year compound</td>
</tr>
<tr>
<td>HadCM2 Simulations: GGa1-GGa4, GSa20</td>
<td>Hadley Centre for Climate Precipitation and Research (UK)</td>
<td>Johns et al. (1997), Mitchell and Johns (1997)</td>
<td>1%/year compound</td>
</tr>
<tr>
<td>HadCM3 Simulations: GG, GS</td>
<td>Hadley Centre for Climate Precipitation and Research (UK)</td>
<td>Gordon et al. (2000)</td>
<td>1%/year compound</td>
</tr>
<tr>
<td>CGCM1</td>
<td>Canadian Center for Climate Modelling and Analysis (Canada)</td>
<td>Reader and Boer (1998), Boer et al. (2000)</td>
<td>1%/year</td>
</tr>
<tr>
<td>GFDL – R15a</td>
<td>Geophysical Fluid Dynamics Laboratory (USA)</td>
<td>Manabe and Stouffer (1996), Haywood et al. (1997)</td>
<td>1%/year compound</td>
</tr>
<tr>
<td>NCAR DOE-PCM</td>
<td>National Center for Atmospheric Research (USA)</td>
<td>Washington et al. (2000), Meehl et al. (2000)</td>
<td>1%/year linear</td>
</tr>
<tr>
<td>CCSR/NIES</td>
<td>Center for Climate Research Studies/ National Institute for Environmental Studies (Japan)</td>
<td>Emori (1999)</td>
<td>1%/year compound</td>
</tr>
</tbody>
</table>

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).
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 CO₂ scenarios described before. 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 CO₂ concentration constant in time and, in most cases, at levels comparable to the baseline period 1961-1990. The HadCM control runs are performed with CO₂ 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.

![Graph showing mean temperature anomalies in the Iberian Peninsula](image)

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

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 CO₂) increase only.

The Acacia report (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 CO₂ 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 CO₂ 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 CO₂ 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.
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 on 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.

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

These annual precipitation results broadly agree with those of the Acacia report (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 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 CO2 concentration increases, as shown in Fig. 2.42, presenting monthly anomalies from the reference 1961-1990 period of the increasing CO2 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 (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 CO2 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 50 km 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 CO₂ 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 CO₂ 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. van 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.

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

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 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 CO₂ 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...
CO₂ 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 pronounced 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.
much smaller, of the order of 4°C, and shows a small north-south gradient, with no coastal signature, whereas 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) 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 significant 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. 2.51b, 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 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.

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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”).
The next plots represent the maximum number of consecutive days with minimum temperature below 0°C ("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. 2.55 – Maximum number of consecutive days with minimum temperatures below 0°C ("longest cold spell") for (a) HadRM control run (30 year period); (b) HadRM GG02 simulation (2080-2100 period).](image)

All these temperature results are in line with the Acacia (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).
The accumulated precipitation in the wetter days (above 10 mm/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 CO₂ 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 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.

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. 2.59 – 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).

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.

![Figure 2.60](image)

Fig. 2.60 – Annual and seasonal total precipitation in the HadRM G Ga2 simulation in percentage (%) (100 × G Ga2/control). (a) annual; (b) winter (DJF); (c) spring (MAM); (d) summer (JJA); (e) autumn (SON).

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.

![Graphs showing monthly thermo-pluviometric anomalies](image)

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.

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...
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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 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

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).

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 (Osborne 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 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 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).

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 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.

![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.](image-url)
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 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.

Table 2.6 – Frequency distribution (%) of the CWTs for the HADCM3 control period (1961-1990) and the HadCM3 GG scenario (2070-2099)

<table>
<thead>
<tr>
<th>CWT</th>
<th>Control Year DJF</th>
<th>Control Year MAM</th>
<th>Control Year JJA</th>
<th>Control Year SON</th>
<th>Scenario Year DJF</th>
<th>Scenario Year MAM</th>
<th>Scenario Year JJA</th>
<th>Scenario Year SON</th>
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<td>A</td>
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<td>17.8</td>
<td>21.0</td>
<td>7.8</td>
<td>16.6</td>
<td>14.3</td>
<td>20.5</td>
<td>18.5</td>
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<td>3.1</td>
<td>3.4</td>
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<td>1.8</td>
<td>1.7</td>
<td>2.6</td>
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<td>9.9</td>
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<td>10.0</td>
<td>22.2</td>
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<td>12.2</td>
</tr>
<tr>
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<td>9.2</td>
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<td>12.8</td>
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<td>12.7</td>
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<td>0.7</td>
<td>5.8</td>
<td>3.7</td>
<td>4.6</td>
<td>5.5</td>
</tr>
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<td>1.3</td>
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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).

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 CO2 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 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, to be discussed later.
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 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 above. 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).
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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 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.

2.5 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 respect 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.
References


simulation of present-day climate. Max-Planck Institute for Meteorology, Report Nr. 218, Hamburg, Germany.


