Chapter 8

The Mediterranean Climate Change under Global Warming

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8.1. Introduction

Surprisingly, the issue of climatic change in the Mediterranean region has rather sparsely been addressed in studies performed more than 5–10 years ago. The region has recently received increasing scientific interest. In fact, the Mediterranean has some particular characteristics that demand to put it high on the research agenda. Not only is the Mediterranean connected with many other parts of the globe by long-range atmospheric teleconnections, but also changes of the inflow from the Mediterranean Sea into the North Atlantic affect the thermohaline circulation in the Atlantic (see Chapter 7). Further, the Mediterranean region has a very specific climate with very dry summers and wet winters, which may be very sensitive to potential climatic changes.

In the 1990s, several studies have used simulations from global-coupled climate models in order to assess the potential climatic change in Europe. Only a few of these studies considered the climatic change in the Mediterranean region in particular. Some of them applied statistical downscaling techniques, others analysed the output from global-coupled climate models directly. Recently, multi-model GCM analyses have looked at the consistency of climatic change signals across simulations and scenarios, and one of the regions considered in an integral way is the Mediterranean.

The coarse resolution of the global-coupled climate models implies, however, certain limitations. Regional details of the climate in the Mediterranean region cannot be simulated realistically. A prime reason is the missing of important regional characteristics such as the complex mountain ranges and the distribution of land. Further, these models have shortcomings in simulating Mediterranean cyclones and regional phenomena such as heavy rainfall events realistically.

One way to overcome these problems is by using Regional Climate Models (RCMs), driven by information provided by a global-coupled model at its lateral and lower boundaries. There was however, only one study which applied a RCM for the entire Mediterranean region, while many other simulations only included the northern and western parts of the Mediterranean. Other options are global Atmospheric General Circulation models (AGCMs) with high horizontal resolution, either with the same resolution globally or with high horizontal resolution in the Mediterranean region and lower resolution elsewhere.

In this chapter, an overview of the scientific literature on climatic change in the Mediterranean region due to the anticipated global warming is given. We distinguish between the results obtained from global-coupled climate models, results obtained via regionalization techniques (i.e. statistical and dynamical downscaling) and results obtained from global high-resolution AGCMs. We also comment on the impacts of climate change on the land surface and discuss the needs of future research on climate change in the Mediterranean region.

8.2. Global-coupled Climate Models

Different model simulations of anthropogenic climate change can lead to different estimates of climatic changes for a number of reasons. GCMs have, for instance, different parameterizations of subscale processes. This may lead to differences in the simulated climatic feedback mechanisms, eventually affecting the climatic change signals produced. Another aspect is the existence of decadal climate variations that one may imagine as being superposed to a greenhouse gas signal. They may play an important role when rather short simulation episodes are considered. Further, different scenarios for various greenhouse gases and aerosols can be used. These effects are very complex and may lead to some of the differences between the studies referred to in the following.

As for the mean temperatures at 2-m height, the common future change is an increase both in winter and summer. Typical ranges are 2–4 K with CO_2 doubling for both summer and winter (Déqué et al., 1998). This trend was confirmed by the ACACIA experiments constructed from 5 different global-coupled models

(Parry, 2000). They found an increase of the winter temperatures from the 1961–1990 mean to the 2080s which is in the range of 4–5 K (6–7 K) in winter (summer) using the A2 marker scenario (Houghton et al., 2001).

Some simulations of the greenhouse gas-induced climate change show a northward shift of the North Atlantic winter storm track going along with a shift and intensification of the North Atlantic Oscillation (Ulbrich and Christoph, 1999). This leads to increasing precipitation in northern Europe but reductions over many parts of the Mediterranean. A close link between winter rainfall and baroclinic activity over the North Atlantic has been demonstrated by Ulbrich et al. (1999) for Portugal and by Knippertz et al. (2003) for north western Morocco. Thus, both the northward shift of baroclinic waves and reduced moisture transports from the Atlantic are consistent with the reduced precipitation in the scenario simulations. The ECHAM4 model simulation following the IS92a scenario, for instance, shows a strong decrease of precipitation over the whole Mediterranean basin, in particular over the western Iberian peninsula, southern Turkey, the Near East, and Egypt, with the changes exceeding 30% (Fig. 131). These results are consistent with Sanchez et al. (2004), considering a simulation with a different climate model. In contrast, Déqué et al. (1998) found 30% increases in winter precipitation over the Mediterranean with a doubling of CO_2 concentrations using the ARPEGE model. Also the ACACIA scenarios (Parry, 2000) are more in line with the latter study, suggesting an increase (decrease) of winter rainfall in the northwestern (southeastern) Mediterranean basin towards the 2080s. For summer, all models produce a reduction of rainfall, typically on the order of 10–30%. The ACACIA simulations, on the other hand, give a reduction of about 50% in summer rainfall (Parry, 2000). Multi-model GCM analyses have looked at signals in different regions of the world, including the Mediterranean (Kittel et al., 1998; Giorgi and Francisco, 2000; Giorgi et al., 2001a,b). These studies suggest that summer drying over the Mediterranean is a consistent signal across different GCMs and for different scenarios. Concerning the winter results, it is elucidating to consider the origin of the different signals, for example looking into the statistics of the simulated cyclones.

Due to their small scale, the analysis of Mediterranean cyclones in scenario simulations is a difficult task. Results based on the ECHAM4 simulation (Pinto et al., 2005a,b) show a rather realistic representation of cyclonic activity over the basin (Fig. 132A), although the details of the very small-scale cyclones could not be resolved due to the coarse model resolution (T42). The changes in cyclonic activity in a $2 \times CO_2$ situation are characterized by a strong reduction of the number of cyclones over the basin (Fig. 132B) and by a general northward shift of the cyclone tracks. These are consistent with the changes in precipitation mentioned in the preceding paragraph and can largely be attributed to alterations

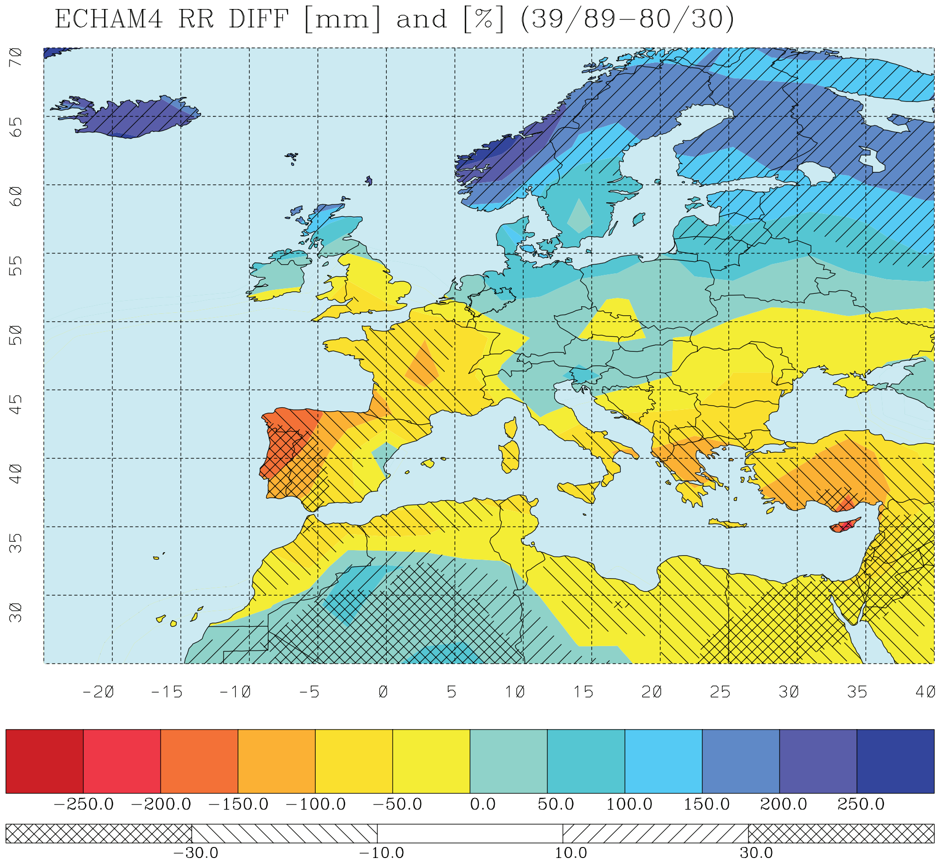

Figure 131: Difference of annual precipitation related to greenhouse gas forcing (scenario IS92a, difference of simulated rainfall between 50 year averages for years 2039–2089 and 1880–1930) as produced by the ECHAM4/OPYC3 coupled atmosphere–ocean GCM. Units (colour bar) are mm. The relative differences (in %) are given by hatching.

in the sea-level pressure and the upper tropospheric baroclinicity (Figs. 132C, D), showing less favourable conditions for the development of cyclones at lower latitudes, including the Mediterranean region.

In another study, the differences in cyclonic activity have been estimated for two 30-year long-time slice experiments, carried out with the ECHAM4 model at a high resolution of T106 (Lionello et al., 2002). For the present day climate, this model version shows a slightly higher number of cyclones as compared to the low-resolution model (Fig. 133, left panel). The climate change signal is a decrease in cyclone number. The doubled CO_2 simulation is

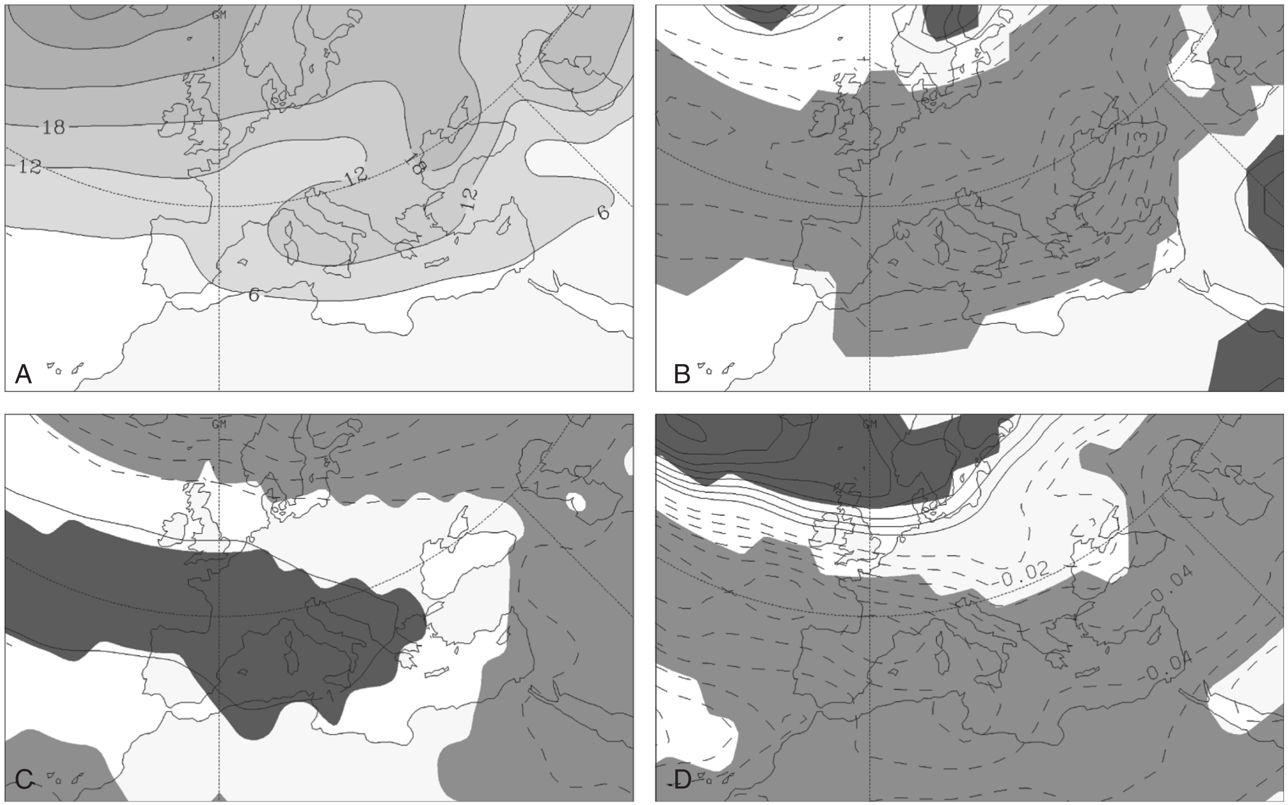

Figure 132: (A) Winter (Oct–Mar) cyclone track density (cyclone days/winter) for the present day climate in the ECHAM4/OPYC3 atmosphere–ocean GCM; (B) As (A) but differences between a climate with increased greenhouse gas forcing (mid-21st century, forcing according to the IS92a scenario) and present climate; (C) as Fig. (B) but for mean SLP (hPa) and (D) as Fig. (B) but for upper tropospheric baroclinicity (day^{-1}). For all panels, area with statistically significant differences (99% level according to a *t* test) are shaded.

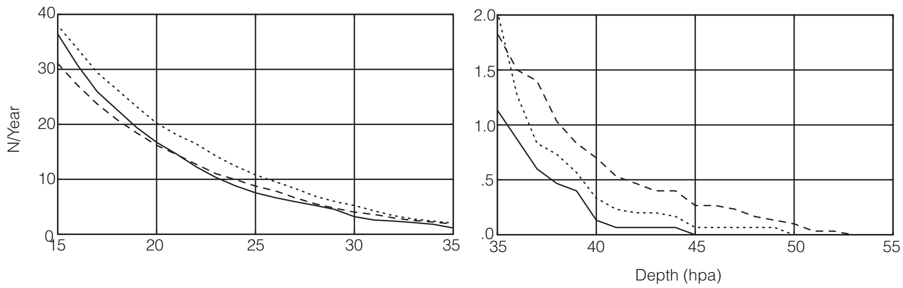

Figure 133: Left panel: Cumulated distribution, that is the average number of cyclones per year (y axis) whose depth exceeds a given threshold (x axis, in hPa) for the present scenario (dotted line), doubles CO_2 (dashed line) and ERA-15 (solid line) scenarios; Right panel: The tail of the cumulated distributions, shown in the left panel, that is cyclones with depth exceeding 35 hPa (from Lionello et al., 2002).

characterized by more deep lows, but the difference between the two time-slices is hardly significant (Fig. 133, right panel). The changes are not associated with a variation of the regions of formation of the cyclones. A recent study on the climatic change over Europe based on several coupled climate models has shown a consistent reduction of cyclonic activity for the Mediterranean region under future climate conditions (Leckebusch et al., 2005). The same tendency is further confirmed by Somot (2005) considering a GCM with variable resolution and employing a different identification and tracking scheme for the cyclones (see Section 8.3.3).

One of the effects imposed by cyclones is the occurrence of strong winds and their effects. Using the 30-year time-slice experiments mentioned above, Lionello et al. (2003) investigated future changes in storm surges in the Adriatic Sea, using a dynamical downscaling approach, but did not find any statistically significant change in the extreme surge level. On the other hand, a reduction of the extreme wave height in a doubled CO_2 scenario was found in the southern Adriatic Sea. In a recent extension of this work, Lionello et al. (2006) used wind fields computed by regional climate simulations to compute the wave field. Figure 134 shows the mean annual cycle for the present climate (CTR) and those corresponding to the A2 and B2 emission scenarios, respectively. The most pronounced signal is the reduction of wave height in November, December and May.

In this section, we have restricted ourselves to a discussion on some simulated effects at the ocean surface. Work on the sensitivity of the Mediterranean thermohaline circulation to anthropogenic global warming is described in Section 7.5 of this book.

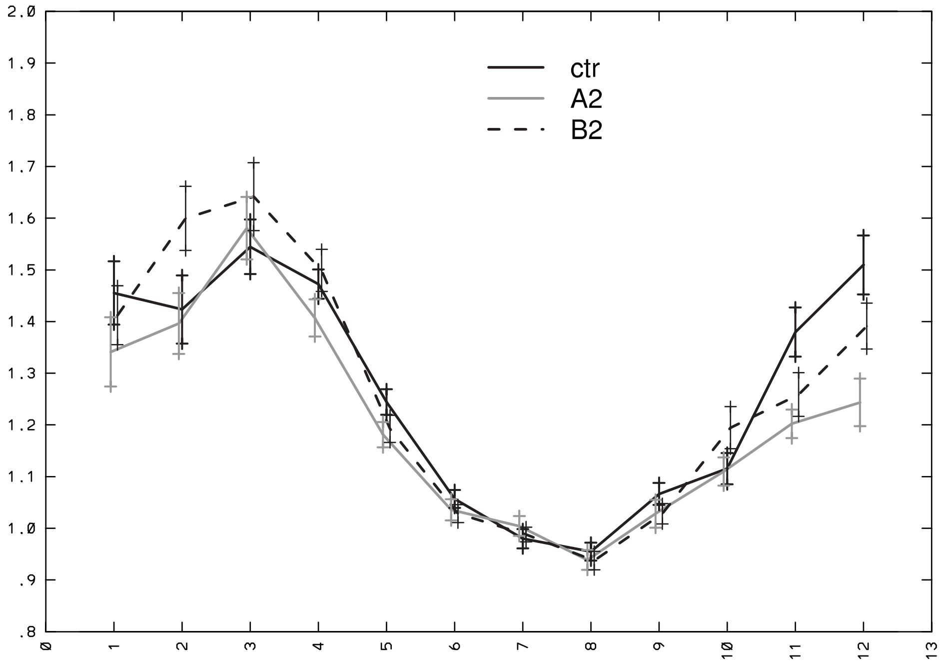

Figure 134: Mean annual cycle of monthly surge wave height (values in m, y axis) in the A2 (grey curve), B2 (dashed curve) and present climate (CTR, black curve) simulations. Calendar month on the x axis. The vertical bars show the standard deviation of the mean monthly values (from Lionello et al., 2006).

8.3. Regional Climate Scenarios

8.3.1. Statistical Downscaling

The coupled climate models currently used for simulating climate change have a coarse spatial resolution of several 100 km. They are generally able to reproduce large-scale circulation characteristics, but not the regional climate parameters. A common approach used for obtaining local values is statistical downscaling. While this approach has frequently been applied in studies dealing with present day climate, its use for estimations of future climate in the Mediterranean region has been rather limited.

Trigo and Palutikof (2001) and González-Rouco et al. (2000) have applied several statistical downscaling methods in order to obtain precipitation scenarios over Iberian peninsula. They used the HadCM2 greenhouse gas plus sulphate scenario simulations as a basis. As for precipitation over the Iberian peninsula, they found an increase of precipitation in winter and small decreases for spring and autumn.

Sumner et al. (2003) also considered precipitation in Spain, but based their study on the ECHAM4/OPYC3 output. Comparing the time periods 1971–90 and 2080–99, they used the closest analogue amongst 19 identified atmospheric circulation patterns under present-day conditions for downscaling. This approach, however, assumes that the relationships between circulation type and daily precipitation distribution remain the same also for the future climate. The statistical model produced decreases in the frequency of circulations with a westerly or northerly component. Their conclusion is that the changes in circulation lead to opposing signals in different regions. They inferred a reduction in annual precipitation for Andalusia and the upland parts of Catalonia (6–14%), while an increase of up to 14% was found along the northern part of the Spanish Mediterranean coast.

8.3.2. RCM Simulations

In the PRUDENCE project, several RCMs have been run with lateral boundary conditions from different global General Circulation Model. Comparing two 30-year time-slices (1961–1990 for present day, 2071–2100 from the A2 scenario), Räisänen et al. (2004) found widespread increases of the mean temperatures in the Mediterranean region, amounting 6 K and more in summer over the land areas and less pronounced increases in winter (3–4 K). Differences between the results from two different driving models (ECHAM4 and HadAM3H) investigated by Räisänen et al. (2004) are much smaller than the mean signal. Sanchez et al. (2004) considered maximum daily temperatures in a regional model driven by HadAM3H, finding changes very similar to those obtained by Räisänen et al. (2004) for mean temperatures. It is interesting to note that the number of heat waves (temperature anomalies exceeding 5 K occurring over more than 6 consecutive days) are not increasing in all regions. Sanchez et al. (2004) interpreted this result in terms of a reduced duration of heat waves at some locations, while the number of extremely hot days increases. Further, it was noted that minimum temperatures also increase, with stronger changes in summer (about 5 K) than in winter (3 K).

Sanchez et al. (2004) and Räisänen et al. (2004) also computed average precipitation changes, finding different signs of the signal (depending on the season and the particular part of the Mediterranean region). The simulations produce rainfall increases of up to about 20% in the western and northern parts of the Mediterranean in winter when driven by HadAM3H but reductions in the southern parts (about 10%). Using ECHAM4, the region with increased precipitation is shifted northwards by a few degrees and the reductions in the south are somewhat stronger (up to 30%). The rainfall reductions in winter are mainly due to the more frequent anticyclonic circulation in this region, which is imposed by the driving GCM (Giorgi et al., 2004). A strong decrease in precipitation is found for summer in all regions (widely more than −50%), again with different foci dependent on the driving models. For ECHAM4, the maximum reduction is over France but for the HadCM3 model, over the central Mediterranean Sea (Giorgi et al., 2004; Räisänen et al., 2004). Over land, the reduced rainfall leads to increasing temperature maxima due to drying of the soil. Simulations carried out by Arribas et al. (2003) suggest that land degradation (which is not included in the simulations mentioned before) may even enforce the simulated increase in temperatures and decrease in rainfall.

Giorgi et al. (2004) also investigated the future changes in the characteristics of daily rainfall events over the Mediterranean region. They identified a general decrease in the number of rainy days. This effect is accompained by an increase in the intensity of daily rainfall in spring and autumn, while there is a decrease in the intensity of daily rainfall events mainly in summer and winter. These changes in the characteristics of daily rainfall can be accompanied by changes in the intensity of heavy precipitation events. Frei et al. (1998) found, for instance, a 25% increase in the frequency of heavy precipitation events exceeding 30 mm/day in southern Europe for the month of October due to the anticipated greenhouse warming.

Giannakoupolous and Palutikof (2003) presented first results of a study dealing with the changing extremes in the Mediterranean region. On the basis of simulations until the year 2100 performed with the global low-resolution HadCM3 and the respective regional model HadRM3 they found increases in the number of tropical nights (from about 20 in a period with greenhouse gas forcing of the 1960s to about 100 in the year 2100) and, correspondingly, in the number of heatwaves over land. The increases were larger for the western Mediterranean area than for the central and eastern Mediterranean region.

8.3.3. AGCM Simulations with Variable Resolution

The LMDZ-Mediterranean model is a variable-grid global AGCM, with a resolution of about 160 km over the Mediterranean region. The control simulation uses the present-day climate, represented by conditions at the end of the twentieth century (LMDZ/CTRL). Three simulations are performed for future scenario at the end of the twenty-first century. They differ by their boundary conditions coming from three global-coupled climate models from IPSL, CNRM and GFDL, respectively, all using the A2 emission scenario (Houghton et al., 2001). The three regional-zoomed simulations will be referred to as LMDZ/IPSL, LMDZ/CNRM and LMDZ/GFDL.

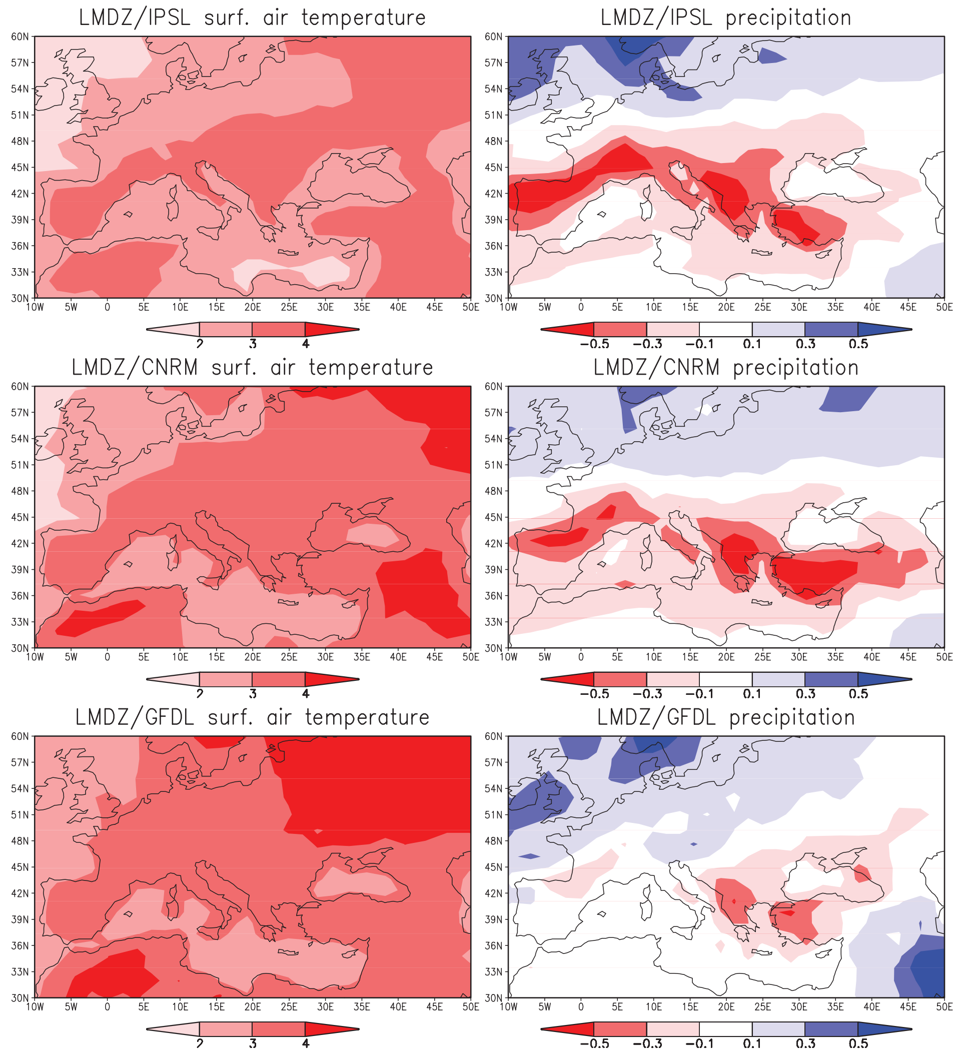

Figure 135: Annual mean changes of the surface air temperature (K; left column) and precipitation (mm/day; right column) for the end of the twenty-first century, simulated by the LMDZ AGCM with stretched grids over the Mediterranean Sea. From top to bottom are three climate scenarios for the IPCC-A2 emission scenario as given by three different global coupled climate models, i.e. IPSL, CNRM and GFDL, respectively.

The left panel of Fig. 135 displays the annual-mean changes in the surface air temperature for the three simulations. The spatial pattern is similar for the three runs, with a warming from 2 to 3 K over the sea, and 3–4 K for the surrounding lands. LMDZ/IPSL gives the smallest warming and LMDZ/GFDL the largest.

The right panel of Fig. 135 gives the changes in precipitation. There is a general increase of precipitation for the North of Europe and a decrease for the South, including the Mediterranean basin. This general tendency is in agreement with other results reviewed here. Several centres of negative anomalies are located in northern Spain and southern France, over the land mass between the Adriatic Sea and the Aegean Sea, and in Turkey. The magnitude is rather small in LMDZ/GFDL (about -0.1 mm/day) and quite large in LMDZ/IPSL and LMDZ/CNRM (about -0.6 mm/day).

Regional water cycle is an important element of the Mediterranean climate. As pointed out in Chapter 7 of this book, the Mediterranean Sea is a concentration basin with evaporation much larger than rainfall (Mariotti et al., 2002). Furthermore, the Mediterranean water cycle is also characterized by a strong seasonal cycle. Figure 136 displays the seasonal variations of the atmospheric part of the Mediterranean water cycle. i.e. precipitation (P), evaporation (E) and water deficit ($E - P$), in the control simulation LMDZ/CTRL (upper panel) against, observation-based values (lower panel; Mariotti et al., 2002). Annual-mean values are also given in the legend. The seasonal cycle of the simulated precipitation is quite realistic with a minimum in July–August and a maximum in November–December, although the absolute rainfall seems to be underestimated by the model. Evaporation, on the other hand, is overestimated by the model, and the seasonal cycle presents a one-month temporal shift: the minimum is reached in May for observation, but in June for the simulation. As a consequence, the water deficit budget is overestimated by the model and the one-month seasonal shift is also visible.

Table 9 gives the future changes of the annual-mean values for changes in E, P and E minus P for the three simulations. All the three simulations show a decrease of precipitation rate, while evaporation increases for LMDZ/IPSL and LMDZ/CNRM and slightly decreases for LMDZ/GFDL. The net water deficit thus increases in the three scenarios, about 10% for LMDZ/IPSL, 14% for LMDZ/CNRM, but only 1.3% for LMDZ/GFDL. The last line of Table 9 shows the changes in the gain of the total heat flux at the sea surface for the three scenarios compared to the control simulation. Instead of losing heat into the atmosphere as in the control simulation (-2.1 W/m^2), the Mediterranean gains energy from the atmosphere for future scenarios. The net gain of heat flux varies from 3.6 to 11.9 W/m^2 for different runs.

Gibelin and Déqué (2003) used the ARPEGE-CLIMATE global AGCM with variable resolution in order to study the anthropogenic climate change over the Mediterranean. Their model has a resolution of about 0.5° over the Mediterranean region and about 4.5° at the lowest resolution point close to New Zealand. The high-resolution atmospheric GCM is able to simulate many of the regional details that low-resolution coupled climate models cannot resolve

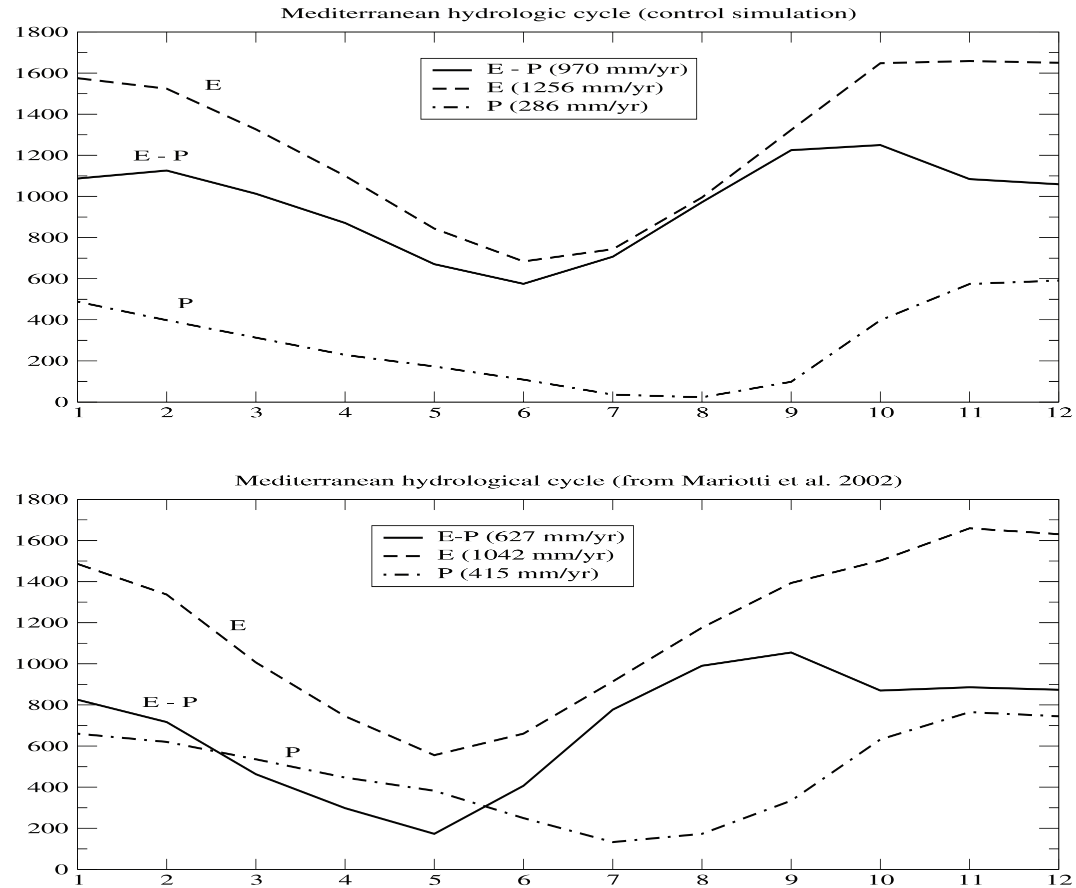

Figure 136: Monthly mean changes of precipitation (P), evaporation (E) and the difference E−P over the Mediterranean Sea for the present-day climate simulated by LMDZ/CTRL (upper panel) and observations (lower panel).

Table 9: Annual-mean changes of evaporation, precipitation, water deficit and gain of heat for the whole Mediterranean Sea and for the three scenarios respectively.

	LMDZ/IPSL	LMDZ/CNRM	LMDZ/GFDL
Evaporation (E) (mm/year)	39	57	−7
Precipitation (P) (mm/year)	−57	−74	−20
E−P (mm/year)	96	131	13
Gain of heat flux (W/m^2)	3.6	5.8	11.9

and, hence, able to add regional details to the prediction of the potential future climate change. Comparing the scenario period (2070–2099) and the present-day period (1960–1989), the simulation predicts a warming and drying of the Mediterranean region in the future. The decrease in mean precipitation is associated with a significant decrease in soil wetness and could have a considerable impact on the water resources around the Mediterranean basin. Somot (2005) has investigated the relation of the precipitation changes in this model with respect to its association with cyclones. In agreement with the studies mentioned in Section 8.2, a statistically significant 16% decrease in the number of intense cyclones was found (minimum intensity of 1.5×10^{-4} s^{-1}) which is more emphasized in winter. Regionally, the Gulf of Genoa and the Aegean/Turkey area are most affected. For the Gulf of Genoa area, the simulated precipitation associated with the cyclones was studied by the mean of composites for the time of the maximum 850 hPa vorticity, which must exceed a minimum strength of 1.5×10^{-4} s^{-1}. In summer, the amount of precipitation associated with a typical cyclone decreases up to −30% going from 18.5 to 13.0 mm/day (average in a 50-km radius circle around the cyclone centre). This result is similar for cyclones born in the Aegean Sea/Turkey Mountains area. This large decrease could explain at least in part the drying observed in the IPCC A2 scenario (Gibelin and Déqué, 2003) for the Mediterranean region in summer.

Contrary to the summer situation, the cyclones associated precipitation increases in autumn (+17%, 21 mm/day in the scenario) and spring (+23%, 13 mm/day in the scenario) for the same Northern Mediterranean areas. In the present-day climate, autumn and spring are already the seasons during which intense rainy events occur around the Mediterranean basin, often associated with cyclones. Consequently, this kind of events might increase at the end of the twenty-first century following our simulation. Finally, no change is observed for winter precipitation composites with a typical value of 11.0 mm/day in the scenario as in the present-day climate.

8.4. Impacts on Land Surface and Vegetation

The climate system does not consist only of the atmosphere and ocean. For the Mediterranean area, the biosphere and the soils are parts of the system that have only recently been taken into account. In addition to their role as part of the system, they are important with respect to impacts of climatic change. Only a few studies are available which elucidate potential future tendencies.

Taking tree ring growth under CO_2 doubling as a parameter to quantify climate change impacts on the biosphere, Keller et al. (2000) considered regional effects on the French parts of the Mediterranean. They used meteorological data from the Arpège-CLIMATE model, simulating a temperature increase of 3 K and a small increase of precipitation. Results for 5 tree species were obtained using an approach which involved an artificial neural network and an empirical tree ring model. A sensitivity to climate change was only found for few populations located at the boundaries of their ecological area, including enhanced growth of high altitude populations as well as growth reduction due to water stress in summer.

As soil wetness is a parameter used in atmospheric models, it has been considered more frequently, but with the underlying assumption that there is no change in the (parameterized) vegetation. A common result (Wetherald and Manabe, 2002; Manabe et al., 2004) is reductions in soil moisture on the Mediterranean coast of Europe, similar to any other semiarid regions of the world. The relative change is particularly large during the dry season.

The role of the land surface and of vegetation under climate change can be expected to be more complex than what is found out by simulating it under the precondition of constant vegetation types, soils or even the complete absence of feedbacks. Even direct anthropogenic effects on vegetation must be taken into account. A study going into parts of these problems was performed by Dümenil-Gates and Liess (2001). They estimated the impacts of deforestation in the Mediterranean region as they are arising from the particular parameterizations used in a GCM. They found a reduction of precipitation in summer, resulting from lower plant evapotranspiration and lower evaporation from soils, assuming that they are eroded. The occurrence and the impacts of erosion under climate change have been explored for a small forested catchment in Catalonia. Given a 4-K temperature increase, Avila et al. (1996) have investigated the effects of a simultaneous 10% increase or decrease in precipitation. They found enhanced weathering rates in the case when only rainfall was increased, and that the resulting effects on runoff water chemistry were much larger than those arising from changing atmospheric input of Sahelo-Saharan dust. The small number and diversity of research results make it clear that more comprehensive work must be performed into the complex reaction of the climate system to the imposed rise of greenhouse gas and other anthropogenic forcing.

8.5. Future Research

It appears that the number of studies on the future climate in the Mediterranean region is still rather sparse. Future research needs to comprise studies evaluating the stability of results produced by the different global and regional climate models. It is still an open question whether the differences between simulated changes are due to specific characteristics of the models, in particular due to the parameterizations in the models, or whether they are due to internal decadal variability in the climate system. The coupling of atmospheric models with models of the Mediterranean Sea (Chapter 7) is also an important aspect for the progress in the assessment of climatic change in this region. Aspects that clearly need more attention are the occurrence of different kinds of extreme weather events or the complex feedbacks with the biosphere and soils. The combinations of climatic features that produce the particular vulnerability of the Mediterranean environment (e.g. irregular or scarce water availability combined with an occurence of floods or heat waves) should be considered in depth. Future research should include both efforts for a better understanding of the mechanisms of climate changes and statistical approaches. Multi-model ensemble simulations with both global and regional models help to assess the uncertainties of climatic change and to provide probabilistic estimates of long-term changes.

In order to minimise the risks of climate change, it is also important to perform more research into the adaptation of its effects. This requires more joint work of many different scientific disciplines. In this context, it is a goal of future research to establish earth models that integrate all aspects of the climate system simultaneously. As this will require several decades of research work it is presently important to continue work employing more specialized approaches. Their subsequent integration into joint interdisciplinary research projects on particular aspects of the (regional) earth system under climate change could be a promising perspective, in particular for the Mediterranean basin.

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