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Climate change impacts in the Mediterranean resulting from a 2°C global temperature rise

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Climate change impacts in the Mediterranean resulting from a 2°C global temperature rise

Summary

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The goal of the present study is to provide the first piece of the puzzle in understanding the impacts of a 2°C global temperature rise on the Mediterranean region, using high temporal resolution climate model output that has been made newly available. The analysis has been based on the temperature, precipitation and wind daily outputs of the HadCM3 model using the IPCC SRES A2 and B2 emission scenarios. The study is focussed on the thirty-year period (2031-2060) centred on the time that global temperature is expected to reach 2°C above pre-industrial levels, as defined by an earlier companion study. Changes in both the mean (temperature, precipitation) and the extremes (heatwaves, drought) under the different scenarios were assessed. The impacts of these climatic changes on energy demand, forest fire, tourism and agriculture were subsequently investigated either using existing numerical models or an expert-based approach. Based on recent studies, the impacts on biodiversity, water resources and sea level rise in the region were also discussed.

Our results show that a global temperature rise of 2°C is likely to lead to a corresponding warming of 1-3 °C in the Mediterranean region. The warming is likely to be higher inland than along the coast. The largest increase in temperature is expected to take place in the summer, when extremely hot days and heatwaves are expected to increase substantially, especially in inland and southern Mediterranean locations.

Under the A2 scenario, a drop in precipitation seems to be the dominant feature of the future precipitation regime. Under the B2 scenario, rainfall increases in the northern Mediterranean, particularly in winter. However, under both scenarios precipitation decreases substantially in the summer in both the north and the south. In the south, the reduction in precipitation extends year round. Longer droughts are shown to be common, and are accompanied by shifts in timing. In terms of extremes, the number of dry days is shown to increase while the number of wet and very wet days remains unchanged. This

can imply that when it rains it will rain more intensely and strongly, especially at certain locations in the northern Mediterranean.

Based on the above climatic variables, we calculated the Canadian Fire Weather Index to provide an indication of the forest fire risk under the future climate scenarios. Under both A2 and B2 scenarios, fire risk is shown to increase nearly everywhere in the Mediterranean region, especially in inland locations. The southern Mediterranean is at risk of forest fire all year round. In the Iberian Peninsula, northern Italy and over the Balkans, the period of extreme fire risk lengthens substantially. The only region that shows little change in fire risk is in the southeastern Mediterranean.

Based on the same climatic data, we investigated the changes in agricultural crop yields using a well-established numerical model. Our results show a general reduction in crop yields (e.g. C3 and C4 summer crops, legumes, cereals, tuber crops). The southern Mediterranean is likely to experience an overall reduction of crop yields due to the change in climate. In some locations in the northern Mediterranean, the effects of climate change and its associated increase in carbon dioxide may have little or small positive impacts on yields, provided that additional water demands can be met. The adoption of specific crop management options (e.g. changes in sowing dates or cultivars) may help in reducing the negative responses of agricultural crops to climate change. However, such options could require up to 40% more water for irrigation, which may or may not be available in the future.

We calculated heating degree days (HDD) and cooling degree days (CDD) in order to examine the change in heating and cooling requirements. Under both climate scenarios, HDD decreases substantially in the northern Mediterranean and CDD increases everywhere in the Mediterranean, especially in the south. This change can potentially shift the peak in energy demand to the summer season with implications for the need for additional energy capacity and increased stress on water resources.

Changes to tourism in the Mediterranean were examined through discussions with experts and stakeholders. We expect that warmer northern European summers would encourage northern Europeans to take domestic holidays and thus, not travel to the Mediterranean. In addition, more frequent and intense heat waves and drought are likely to discourage holidays in the Mediterranean in the summer. We expect that the Mediterranean holiday season may shift to spring and autumn.

Based on results from existing studies, a global warming of 2°C and its associated reduction in precipitation are expected to reduce surface runoff and water yields in the Mediterranean region. In some countries, this could result in water demand exceeding available water supply. In terms of biodiversity, climate change is likely to lead to shifts in the distributions and abundances of species, potentially increasing the risks of extinction. In addition, forest fires are expected to encourage the spread of invasive species which in turn, have been shown to fuel more frequent and more intense forest fires.

Acknowledgments

The authors would like to thank Clare Goodess, Bob Bunce, Rafael Navarro, Antonio Navarra, Riccardo Valentini, Michael Case and Lara Hansen for their comments on earlier drafts of this report. Special thanks goes to Clare Goodess for her help during the initial phase of the project, and to Mark New, Daniel Scott and Jacqueline Hamilton for their helpful discussions.

Contents:

Climate change impacts in the Mediterranean resulting from a 2^{o}C global temperature rise

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1. The Mediterranean region and climate: Basic issues

The Mediterranean Region has many morphologic, geographical, historical and societal characteristics, which make its climate scientifically interesting. In general, the Mediterranean climate is characterised by mild wet winters and by warm to hot, dry summers and may occur on the West Side of continents between about 30° and 40° latitude.

The Mediterranean Sea, a marginal and semi-enclosed sea, is located on the western side of a large continental area and is surrounded by Europe to the north, Africa to the south, and Asia to the east. Its area, excluding the Black Sea, is about 2.5 million km 2; its extent is about 3700 km in longitude, 1600 km in latitude and surrounded by 21 African, Asian and European countries. The average depth is 1500 m. with a maximum depth of 5150 m in the Ionian Sea. The Mediterranean Sea is an almost completely closed basin, being connected to the Atlantic Ocean through the narrow Gibraltar strait (14.5 km wide, less than 300m deep at the sill). These morphologic characteristics are rather unique. In fact, most of the other marginal basins have much smaller extent and depth or they are connected through much wider openings to the open ocean. Moreover, high mountain ridges surround the Mediterranean Sea on almost every side. Furthermore, strong albedo differences exist in south-north directions (Bolle, 2003). These characteristics have important consequences on air masses and atmospheric circulation at the regional scale (e.g. Xoplaki 2002). The Mediterranean sea is an important heat reservoir and source of moisture for surrounding land areas. It represents an important source of energy and moisture for cyclone development and its complex land topography plays a crucial role in steering air flow, so that energetic meso-scale features are present in the atmospheric circulation.

Because of its latitude, the Mediterranean Sea is located in a transitional zone where both mid-latitude and tropical variability is important and competes against each other. The Mediterranean climate is exposed to the South Asian Monsoon in summer and the Siberian high- pressure system in winter. The southern part of the region is mostly under the influence of the descending branch of the Hadley cell, while the northern part is more linked to the mid-latitude variability.

A further important characteristic of the Mediterranean Sea is the emergence of the first highly populated and technologically advanced societies since, at least, 2000BC.

Because of the demographic pressure and exploitation of land for agriculture, the region presents since ancient times important patterns of land-use change and important anthropogenic effects on the environment, which are themselves interesting research topics.

Nowadays, about 400 million people live in the countries around the Mediterranean Sea. This densely populated area has large economic, cultural and demographic contrasts. There are approximately 10-fold differences in GDP between the largest economies of the European Union countries and small Middle East nations, and a 3 to 6-fold difference in the GDP per-capita between Western European countries and the other nations. Demographic trends are also quite different. European countries (also including non EU nations) are close to a null growth and expected to stabilise or even decrease their population, while North African and Asian countries are growing and are expected to double their population by mid 21st century. In contrast to European Countries, urbanisation for most African Nations is an ongoing process that is changing the socio-economic structures of these regions. All these different trends are likely to produce contrasts and conflicts in a condition of limited available resources. Moreover, different level of services, of readiness to emergencies, technological and economical resources, are likely to result in very different adaptation capabilities to environmental and climate changes. Poorer societies with recently increased urbanisation are likely to be critically vulnerable to weather extremes and incapable of adapting to changing climate patterns. Hence the need is paramount for the best possible prediction of future climate scenarios and descriptions of possible impacts and adaptation strategies.

2. Present trends of the Mediterranean climate

2.1 Introduction

Instrumental data reveal significant trends of Mediterranean temperature and precipitation at different time and space scales. For instance, during the last 50 years of the 20th century large parts of the Mediterranean experienced winter and summer warming. For the same period, precipitation over the Mediterranean decreased. However, the statistical significance is low due to the large interannual variability. These trends, however, differ across regions and periods under consideration showing variability at a range of scales in response to changes in the direct radiative forcing and variations in internal modes of the climate system. It is one of the main challenges for future research to understand the physical processes and causes responsible for these trends. They seem to be hemispheric to global (such as external forcings and changes in the large-scale atmospheric circulation), anthropogenic as well as local/regional (such as changes in earth surface and land use, orography).

2.2 Observed Temperature Trends over the Mediterranean

Giorgi (2002) analysed the surface air temperature variability and trends over the larger Mediterranean land-area for the 20th century based on gridded data of New et al. (2000). He found a significant warming trend of 0.75°C per century, mostly from contributions in the early and late decades of the century. Slightly higher values were observed for winter and summer. Based on the same data, Jacobeit et al. (2003) found a distinct summer warming for the 1969-1998 period. The structure of climate series can differ considerably across regions showing variability at a range of scales in response to changes in the direct radiative forcing and variations in internal modes of the climate system (New et al. 2001; Hansen et al. 2001; Giorgi 2002). Figure 1 (right) presents the linear trends of summer surface air temperatures (°C/50yr) for the period 1950-1999. It also shows the stations, which experienced a significant trend.

A clear east-west differentiation in Mediterranean summer air temperature trends is visible. Cooling, though mostly not significant, was experienced over the Balkans, and parts of the eastern basin. In the other areas, there is a significant warming trend of up to 3°C/50yr. However, the warming in these regions did not occur in a steady or monotonic fashion. Over most of western Mediterranean for instance, it has been mainly registered in two phases: from the mid-1920s to 1950 and from the mid-1970s onwards (e.g. Brunet et al. 2001a, 2002, Galan et al. 2001). A glance at summer air temperature trends for the 1900-1949 period reveals that warming, though less extreme than that in 1950-1999, was experienced in the western basin. A cooling trend over 1900-1949 was only prevalent over Libya and Egypt. The trend of winter temperature over 1900-1949 indicates a general cooling in the central basin but a warming in the east and west. For the 1950-1999 period, except for the eastern part, there was warming experienced. Xoplaki et al. (2003) found a significant cooling trend of Mediterranean winter Sea Surface Temperatures (SSTs) east of 20°E over the period 1950-1999, while the western basin experienced warming.

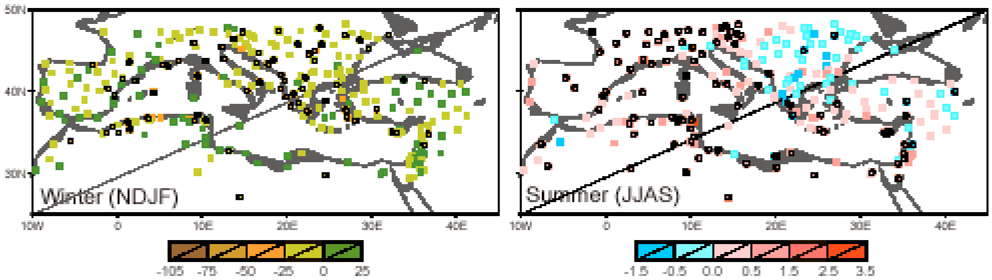


Figure 1. (left) Linear trends of winter (NDJF) station precipitation (mm/50yr) and (right) summer (JJAS) surface air temperatures (°C/50yr) for the 1950-1999 period. Stations with a significant trend (90% confidence level, based on the Mann-Kendall test) are encircled (*adapted* from Xoplaki 2002).

2.3 Observed Precipitation Trends over the Mediterranean

Recent studies revealed that the 20th century was characterized by significant precipitation trends at different time and space scales (e.g. New et al. 2001, Folland et al. 2001). Giorgi (2002) found negative winter precipitation trends over the larger Mediterranean land-area for the 20th century.

Using the same data, Jacobeit et al. (2003) showed for the last three decades some rainfall increases in autumn (western Iberia and southern Turkey), but dominating decreases in winter and spring.

A glance at the Mediterranean regional precipitation trends reveals a more detailed picture of the general findings. Sub regional variability is high, particularly in areas with contrasted topography near coastland where also significant trend in variability and monthly totals have been observed (e.g. Turkes 1996, 1998). The evaluation of regional data series (Figure 1, left) indicate, that trends in many regions are not statistically significant in view of the large interannual variability (Xoplaki, 2002). However, significant decreases are prevalent in western, central and the eastern Mediterranean.

For the Mediterranean Sea, precipitation variability has been investigated using gauge-satellite merged products and atmospheric re-analyses (Mariotti and Struglia, 2002). NCEP re-analyses show that during the last 50 years of the 20th century Mediterranean averaged winter precipitation has decreased by about 20%, with the decrease mostly occurring during the period late 1970s to early 1990s.

2.4 Observed *Daily* Rainfall and Temperature Trends over the Mediterranean

Only few areas have been studied on a *daily* basis in the Mediterranean because high quality data are rather scarce (e.g. De Luis et al. 2000). Difficulties exist in determining trends of very rare events (e.g. Frei and Schär, 2001). One exception is the dense daily rainfall data-base for the east of the Iberian Peninsula (Romero et al. 1998, 1999) which show successive drying in western Catalonia and central and western Andalusia for the period 1964-1993. Brunetti et al. (2001ab) have found a negative trend for the number of wet days and annual rainfall in Italy, while the heaviest events class interval show a positive trends. Alpert et al. (2002), Brunetti et al. (2001ab), Goodess and Jones (2002) also report on a tendency to more intense concentration of rainfall to have occurred along some Mediterranean coastal areas, essentially Italy and Spain. Similar results were found in two long observations in the north-eastern inland of Spain (Ramos, 2001).

Over the western Mediterranean little change or even an increase of the day/night temperature differences has been highlighted for the last 130 years (Brunet et al. 2001bc) and for the 20^{th} century (Brunet et al. 1999, Abaurrea et al. 2001, Horcas et al. 2001). Maximum temperature increased at larger rates than minimum temperature. This diurnal differential rate of warming, opposite to the observed on larger spatial scales, has been mainly intensified during the second half of the 20th century.

3. Study overview

In this study, we conduct a “first-order” investigation on the impacts of a 2^{o}C global temperature rise in the Mediterranean basin. The analysis is based on the temperature, precipitation and wind daily outputs of the HadCM3 model using two emission scenarios. The study period is a thirty-year period (2031-2060) centred on the time of the 2^{o}C global temperature rise. Changes in both the mean (temperature, precipitation) and the extremes (heatwaves, drought) under different future climate scenarios are assessed. Subsequently, the impacts of these climatic changes on energy demand, forest fire, tourism and agriculture are investigated. Impacts are examined using impact models where such models exist in the literature (such as agriculture, forest fire, energy) or using an expert-based approach when such models have not yet been developed (such as for tourism). The likely magnitudes of uncertainties and the sensitivity of HadCM3 relative to other climate models are discussed. Based on recent work in the published literature, we also examine the consequences of such a change in climate on water availability, biodiversity and sea level rise in the region. The goal of the present study is to provide the first piece of the puzzle in understanding the impacts of a 2°C global temperature rise on the Mediterranean region, using high temporal resolution climate model output that has been made newly available. Although only a single climate model has been used in this study, we believe that our results are representative of average or conservative values within the range of similar estimates from currently available climate models. This arises from the use of a model of average sensitivity to investigate a period during which there is reasonable agreement among models (Section 4.3). Before larger scale and more comprehensive multi-model, multi-year studies are undertaken, such a first-order study can provide invaluable information in the planning of future research or policy directions.

Within the context of ongoing studies, the present study is an extension of the 3-year European project MICE (Modeling the Impacts of Climate Extremes), which has involved 8 institutes since 2002 in analyzing the occurrence of extremes in climate models and quantifying the impacts of climate extremes on selected European environments, using the same climate model output from HadCM3 (Giannakopoulos and Palutikof, 2005; Palutikof, 2004). MICE has now been superseded by the Integrated EU project ENSEMBLES (involving 72 European research Institutes) , which compliments MICE by providing probabilistic estimates of climatic risk and by characterising the level of confidence in future climate scenarios through ensemble integrations of climate models (Hewitt and Griggs, 2004).

4. Data and methods

4.1 Time of 2°C global temperature rise

Monthly data from six coupled ocean-atmosphere GCMs, each driven by several forcing scenarios, were downloaded from the IPCC Data Distribution Centre with the aim to determine the time of the 2°C global temperature rise. These models (seen in Figure 2) exhibit a range of sensitivity to greenhouse gas forcing. Following New (2005), for each model, control-run surface temperature data were used to calculate a "pre-industrial" mean temperature climatology, and these were spatially averaged to calculate a global mean pre-industrial surface temperature. For each climate change simulation, the global temperature fields were spatially averaged to calculate time-series of global mean annual temperature, which were then differenced from the "pre-industrial" global mean temperature. The resulting global mean temperature-anomaly series were then smoothed with a 21-year moving average, and the date at which the 21-year mean global temperature anomaly exceeded 2°C above pre-industrial levels was taken as the time of 2°C global temperature change.

The time at which the simulated global mean temperature exceeds the control run global mean by 2°C ranges from between 2026 and 2060. The inter-model spread for a single scenario (e.g. B2) is nearly as large as the total spread; however, there is a tendency for the scenarios with greater accumulated radiative forcing (e.g. A2) to exhibit a greater rate of warming, and an earlier year of 2°C global rise.

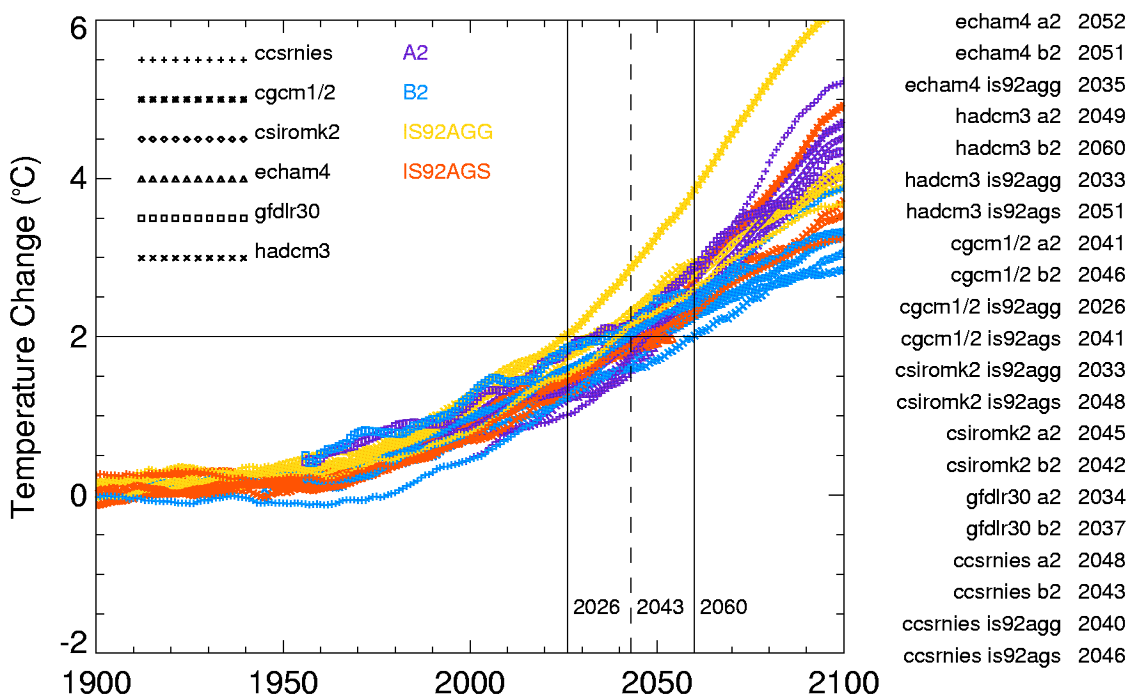
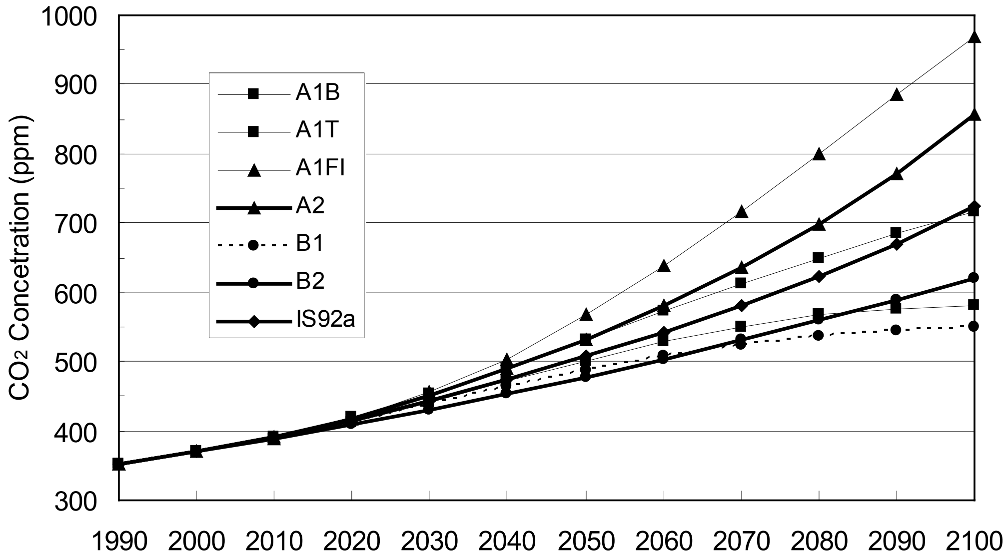


Figure 2. Global mean annual temperature anomalies relative to control climatology, smoothed with a 21-year moving average. Vertical lines indicate the range in time at which the 21-year global mean temperature anomaly exceeds +2°C. Figures on the right show the time at which the 21-year mean global temperature anomaly exceeds +2°C for each GCM-scenario combination (adapted from New, 2005).



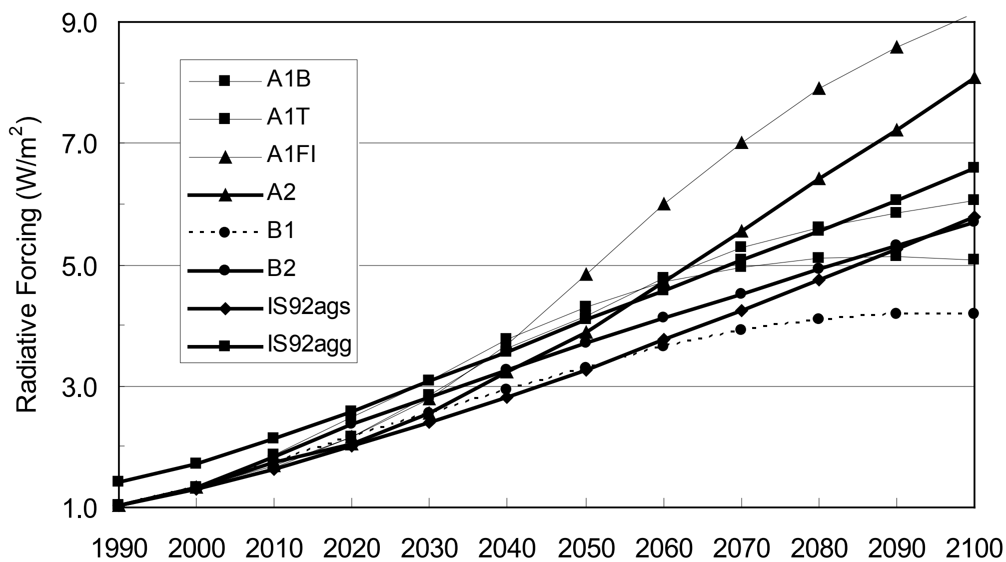


Figure 3. Estimated concentrations of CO_2 and globally averaged increase in radiative forcing from all greenhouse gases and aerosols (relative to preindustrial levels) arising from various IPCC emissions scenarios. Scenarios used in this study are in bold. Data from Appendix II of IPCC (2001b). Adapted from New (2005).

We focused on the results from 2 IPCC forcing scenarios, namely A2 and B2. As described in Nakicenovic et al. (2000), the A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2 and intermediate levels of economic development. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels. The B2 scenario family is based on the long-term UN Medium 1998 population projection of 10.4 billion by 2100. The A2 scenario family is based on a high population growth scenario of 15 billion by 2100 that assumes a significant decline in fertility for most regions and stabilization at above replacement levels. It falls below the long-term 1998 UN High projection of 18 billion.

The radiative forcing under the two scenarios are less divergent for the expected period of 2°C global temperature rise (2026-2060, Fig. 2) than for the latter part of the century (Fig. 3).

4.2 The HadCM3 ocean-atmosphere coupled GCM

We have used *daily* output data from a coupled atmosphere-ocean general circulation model (GCM) HadCM3, consisting of an atmospheric GCM coupled to an ocean GCM. HadCM3 is a coupled atmosphere-ocean GCM, developed at the Hadley Centre and described by Gordon et al (2000) and Pope et al (2000). Unlike earlier atmosphere-ocean GCMs at the Hadley Centre and elsewhere, HadCM3 does not need flux adjustment (additional "artificial" heat and freshwater fluxes at the ocean surface) to produce a good simulation. The higher ocean resolution of HadCM3 is a major factor in this. HadCM3 has been run for over a thousand years, showing little drift in its surface climate. The control run is basically the GCM being run for 240 years at 1961-1990 atmospheric concentrations. Any variation in the control run is, hopefully, due solely to natural variability. The last 30 years of the control run, 1961-1990, are used here as reference for comparison with future predictions. The control run is unforced and thus common to any scenario that may apply after 1990.

The atmospheric component of HadCM3 has 19 levels with a horizontal resolution of 2.5° of latitude by 3.75° of longitude, which produces a global grid of 96 x 73 grid cells. This is equivalent to a surface resolution of about 417 km x 278 km at the Equator, reducing to 295 km x 278 km at 45° of latitude (comparable to a spectral resolution of T42). Thus the model geography is much simpler than the real-world geography. As an example, only five grid boxes cover the UK and one land grid box represents continental

Greece (Fig. 4). This has to be kept in mind when analysing results. The oceanic component of HadCM3 has 20 levels with a horizontal resolution of 1.25 x 1.25°. At this resolution it is possible to represent important details in oceanic current structures. Mediterranean water is partially mixed with Atlantic water across the Strait of Gibraltar as a simple representation of water mass exchange since the channel is not resolved in the model.

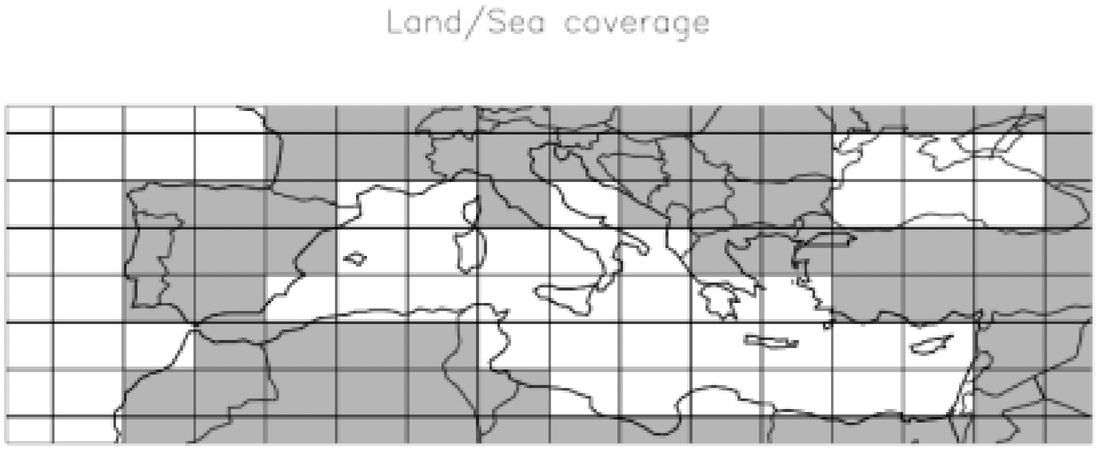


Figure 4. Land-sea mask of HadCM3 over the Mediterranean. The squares represent the size of the HadCM3 grid cell. Grey colour denotes land and white denotes sea as represented in the model.

The transient climate response (TCR) is often used to compare differences in model response to the same standardised forcing. The TCR of HadCM3 is 2°C, which occupies an average position within the range of TCRs (1.4°C – 3.1°C) of the 19 GCMs assessed in the IPCC Third Assessment Report (IPCC, 2001a). More specifically for this study, HadCM3 exhibits an average response to the A2 scenario and the most conservative response to the B2 scenario, when compared with the five other models used to derive the time of 2°C global temperature rise (Figure 2). Therefore, we believe that our results represent average or conservative estimates of the impacts of a 2°C global temperature rise.

The choice of HadCM3 over the other GCMs was made mainly because of the availability of daily data in HadCM3 (which is fundamental for the study of extremes in a region such as the Mediterranean) over the desired time period of the 2°C global temperature rise. Output from regional models would provide higher spatial resolution but are not available for this period. A study that uses one model, with one ensemble, only gives one picture of the climate response to a given forcing scenario. In theory, using more models and more ensembles should give more statistically reliable results. In practice, this can be misleading because the models may all use the same forcing model, which can influence the projected climate response more than the emissions scenario. Moreover, there may be insufficient models/ensembles to give a representative mean projected climate response so that the climate response can be biased towards the least representative (probably the worst) model. Under these cases, it is arguably better to use a single model that generally gives a good overall representation of current climate and extremes and where you understand its weaknesses, which is what was done in the present study. In addition, model comparison studies have shown that results from different models for the study period agree with one another fairly well, while most of the divergence takes place in the latter part of the century (2070-2100) (IPCC, 2001a).

4.3 Methodology

In order to determine the changes in the Mediterranean climate and their impacts as a result of a 2°C global temperature rise, our study focused on the period of 2031-2060 (Fig. 2).

The meteorological data from HadCM3 model have been processed to produce yearly characteristics such as the maximum length of the drought, the number of summer days, or percentile values. These parameters have been averaged over the 1961-1990 (reference or control period) and the 2031-2060 periods. The results for the two periods are then compared.

Both scenarios (A2 and B2) give similar results, except in few cases specifically noted hereafter. The two scenarios bring more differences in the 2070-2100 period, which is not the period of interest here.

Precipitation, and maximum (daytime), minimum (night- time), and mean temperatures have been examined. Wind (max and mean) do not show any significant changes and will not be discussed here.

4.4 Uncertainties

Most of our findings in this study will be subject to uncertainties corresponding to more than one of the classes below:

1. Incomplete or imperfect observation. This is a joint property of the system being studied (e.g., Earth's climate, crop responses to climate) and our ability to measure it.
2. Incomplete conceptual frameworks, e.g., models that do not include all relevant processes, etc.
3. Inaccurate prescriptions of known processes, e.g., poor parameterizations etc.
4. Chaos. This is a property of the system (e.g., Earth's climate, crop responses to climate) being studied.
5. Lack of predictability. Some aspects of societal prediction are much less amenable to prediction than others. For example, in considering new technologies, uncertainties associated with rates of market penetration of new technologies are smaller than those associated with rates of onset of the new technologies themselves.

In seeking to characterize uncertainty, the concept of the 'uncertainty cascade', shown below, has been developed (IPCC, 2001b). This starts with different socio-economic assumptions that affect projections of GHG emissions, and flows through differing potential emission scenarios and ranges of GHG concentrations, radiative forcing, and climate system responses and feedbacks. These in turn affect the estimation of the range of potential impacts, and the consideration of adaptation and mitigation responses and policies.

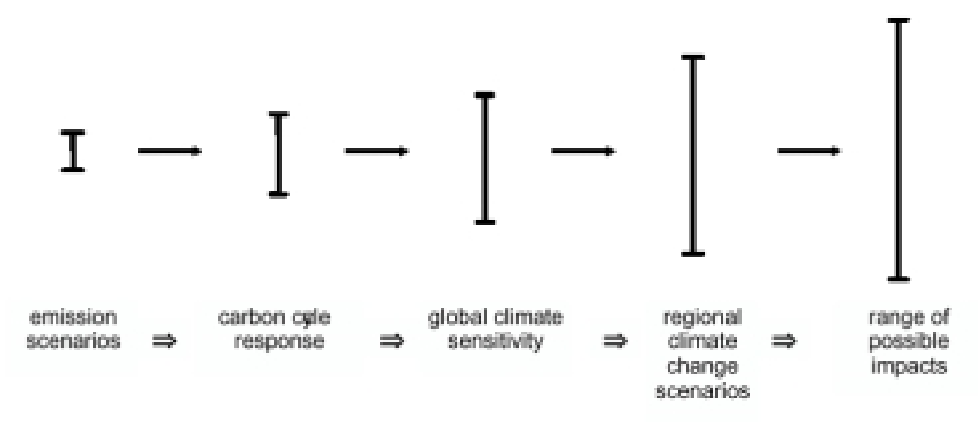


Figure 5. The concept of "uncertainty cascade" in climate change impact analyses. Adapted from IPCC (2001b).

From the schematic, in this study, we are working in the region where the range of uncertainty is potentially large, because of the combined effects of the sources of uncertainty higher up the cascade. It, therefore follows that, even if we had used more than one models to perform the simulations and assess the impacts, our results would still be subject to uncertainty. For example, in discussing uncertainties associated with predictions of crop yields under climate change, the sources of uncertainty will come both from the crop-climate impacts models and from the climate models which provide the climate scenarios. For this, it is important to treat the results in this report with caution. They do provide an estimate of the future climate and impacts in the Mediterranean, but under no circumstances should we use them in a formal quantitative way. A qualitative discussion, as has been done in this report, is only possible.

5. Climate change analysis

5.1 Mean temperatures

We focus here on the annual and seasonal mean temperature changes averaged over the two 30year periods: the control (1961-1990) and the study periods (2031-2060). This will provide a summary of how much the temperature will be increased above present values, as a result of an increase of 2°C in global mean temperature over pre-industrial levels. Spatial variations along the Mediterranean region are discussed.

5.1.1.Annual changes

Fig. 6 presents the differences between the daily mean temperature averaged over 2031-2060 and 1961-1990 for scenario A2. It is clear that the average rise in temperature (daily mean averaged over 30 full years) is between 1-2 °C along the coast and France, and between 2-3 °C inland. The thermal inertia of the Mediterranean Sea is obvious. Under scenario B2 (fig.7), the rise in temperature is somewhat larger than in A2 (especially in France), but in general, the patterns of changes are broadly similar.

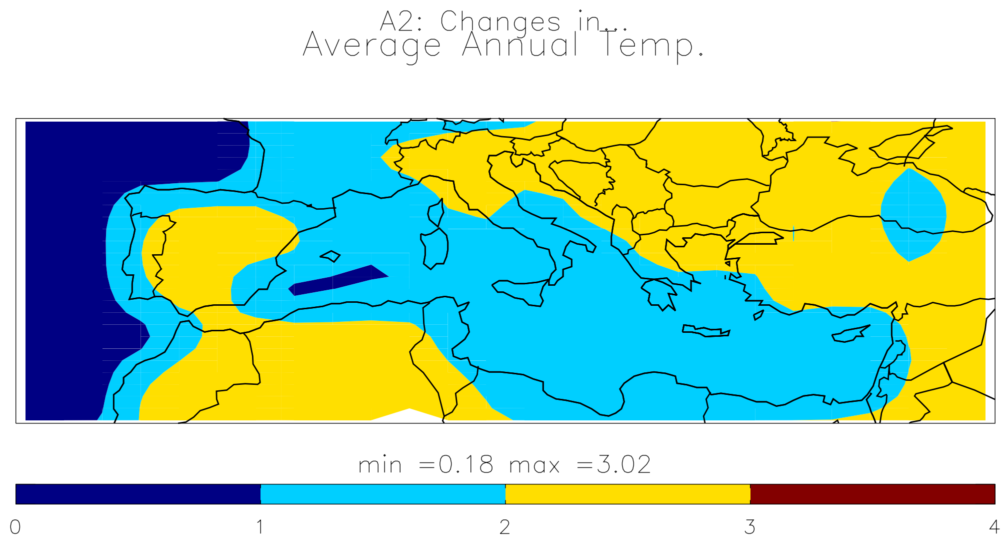


Figure 6. Difference between the daily mean temperature averaged over 2030-2060 and over 1961-1990, for scenario A2.

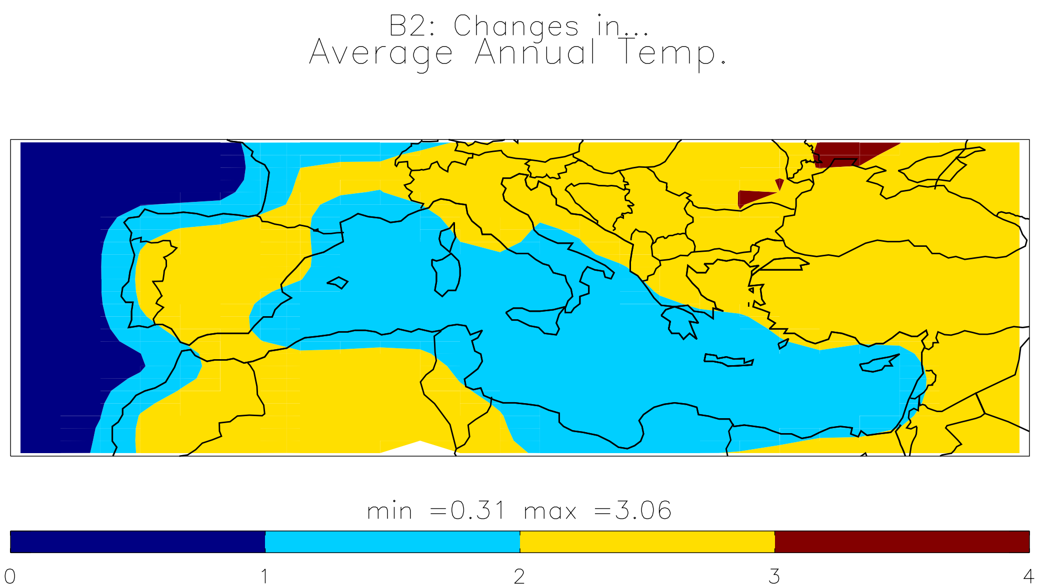


Figure 7. As Fig. 6 but for scenario B2.

Figs. 8 and 9 show also the same pattern as Figure 6 but for the daily maximum (Tmax) and minimum temperatures (Tmin) respectively. It is worth noting that the average rise is slightly larger for Tmax than for Tmin. In the figures, this is particularly evident in the Iberian Peninsula.

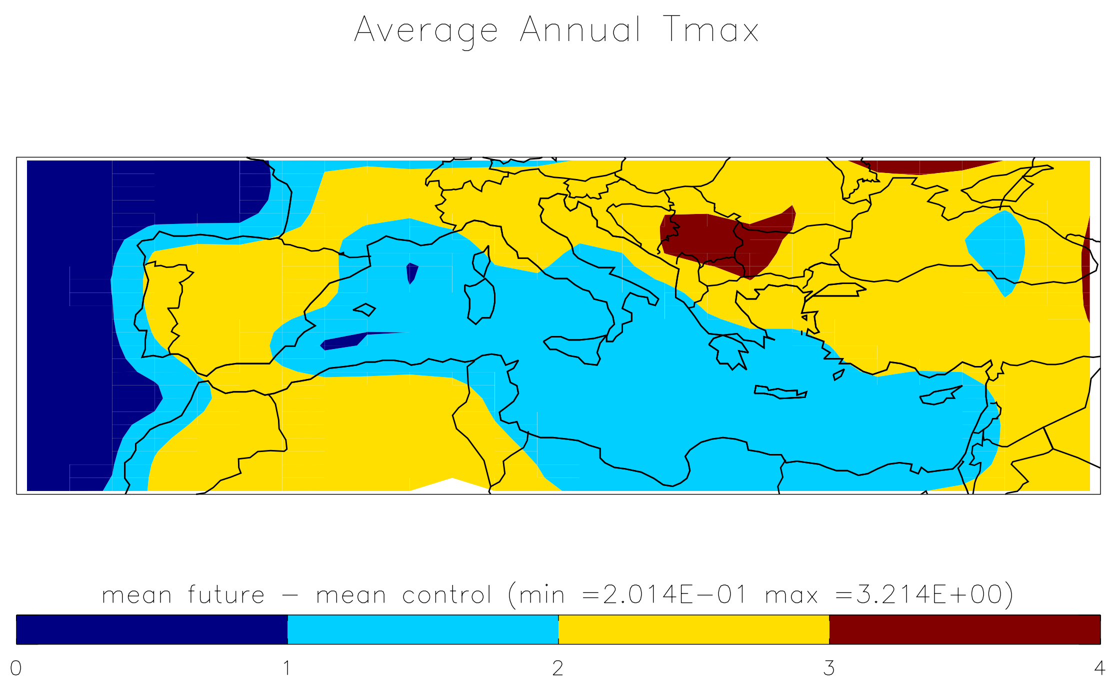


Figure 8. As Fig. 6 but for the daily maximum temperature.

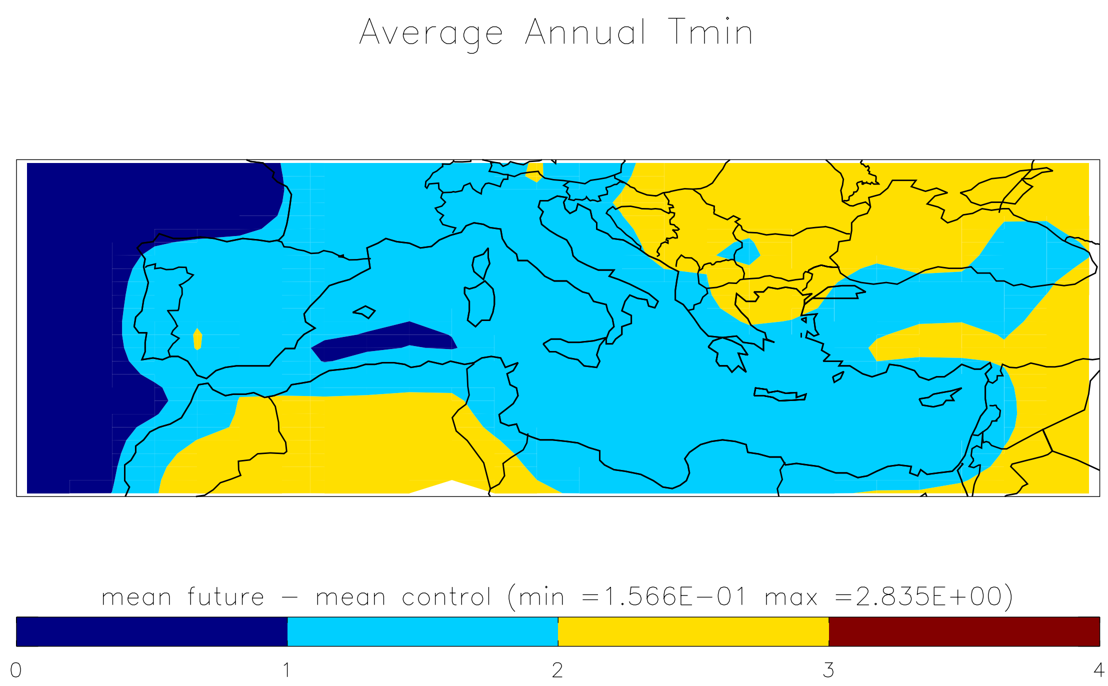


Figure 9. As Fig. 6 but for the daily minimum temperature.

5.1.2 Seasonal changes

Figs. 10, 11 & 12 present the variations in mean (Tmean), maximum (Tmax), and minimum (Tmin) temperatures, respectively, for each of the four seasons, as projected under the A2 scenario.

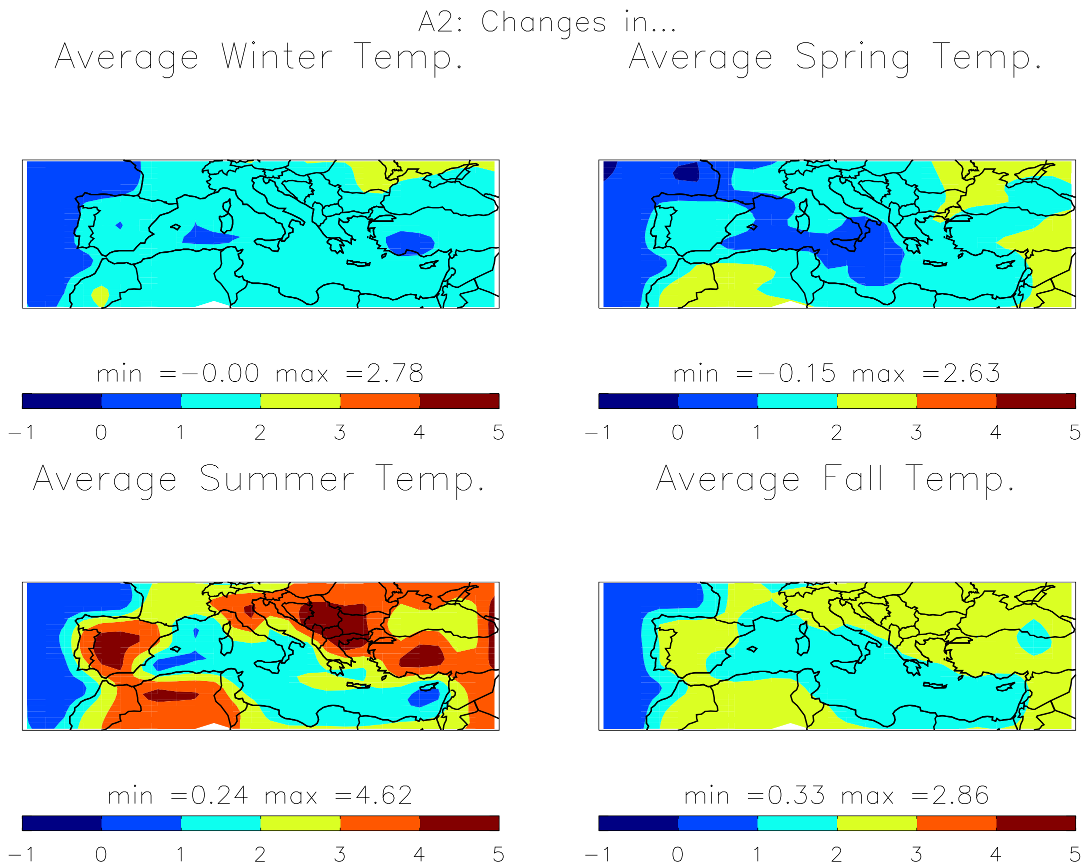


Figure 10. As Fig. 6 but for each season (Winter=DJF, Spring=MAM, Summer=JJA, Fall=SON).

For **Tmean** (Fig. 10), the rise occurs mainly in summer, when it reaches 4 °C inland on average. Fall is the second season to get warmer, with temp rises above the 2 °C average. Winter is likely to be uniformly warmer by 1-2 °C. Spring experiences the average 2 °C increase, except in the north-western part of the region, where the warming is less.

Tmin (Fig. 11) features the same seasonal variation, with a slightly smaller increase in summer than Tmean.

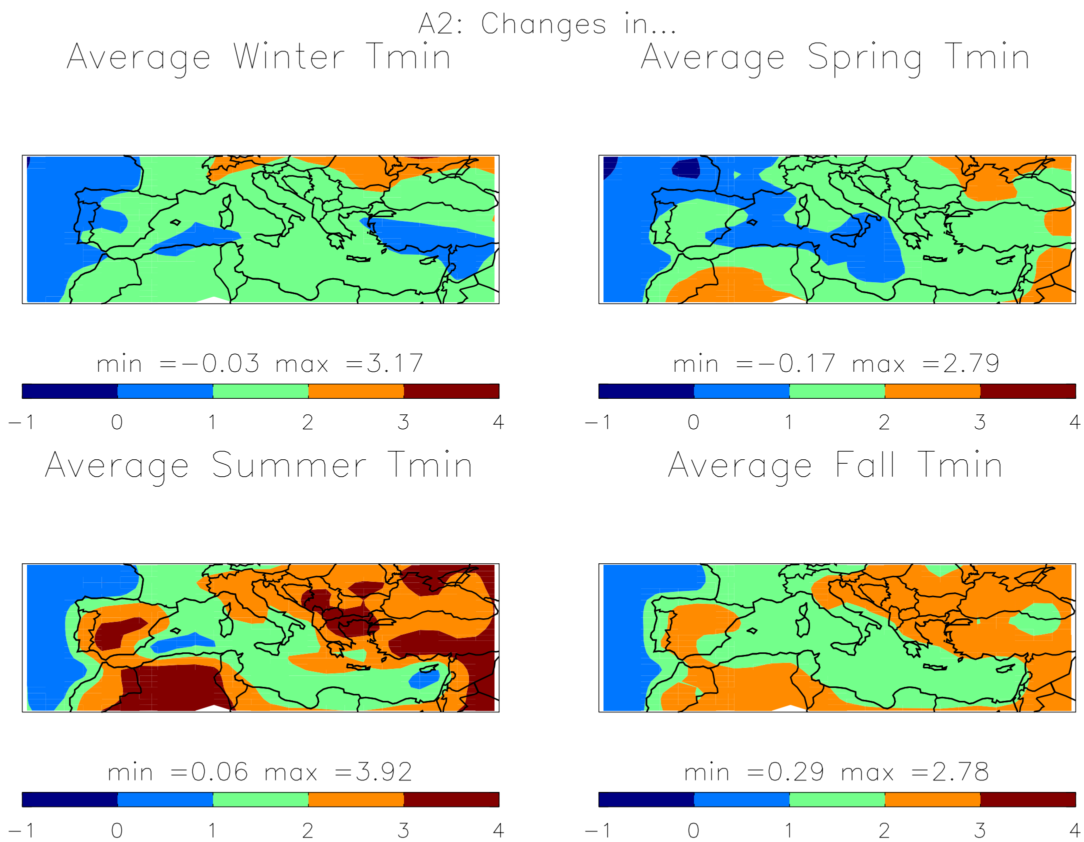


Figure 11. As Fig. 10 but for the daily minimum temperature.

Tmax (Fig. 12) features the same seasonal variation, with a rise notably larger than Tmean in summer and slightly larger in fall.

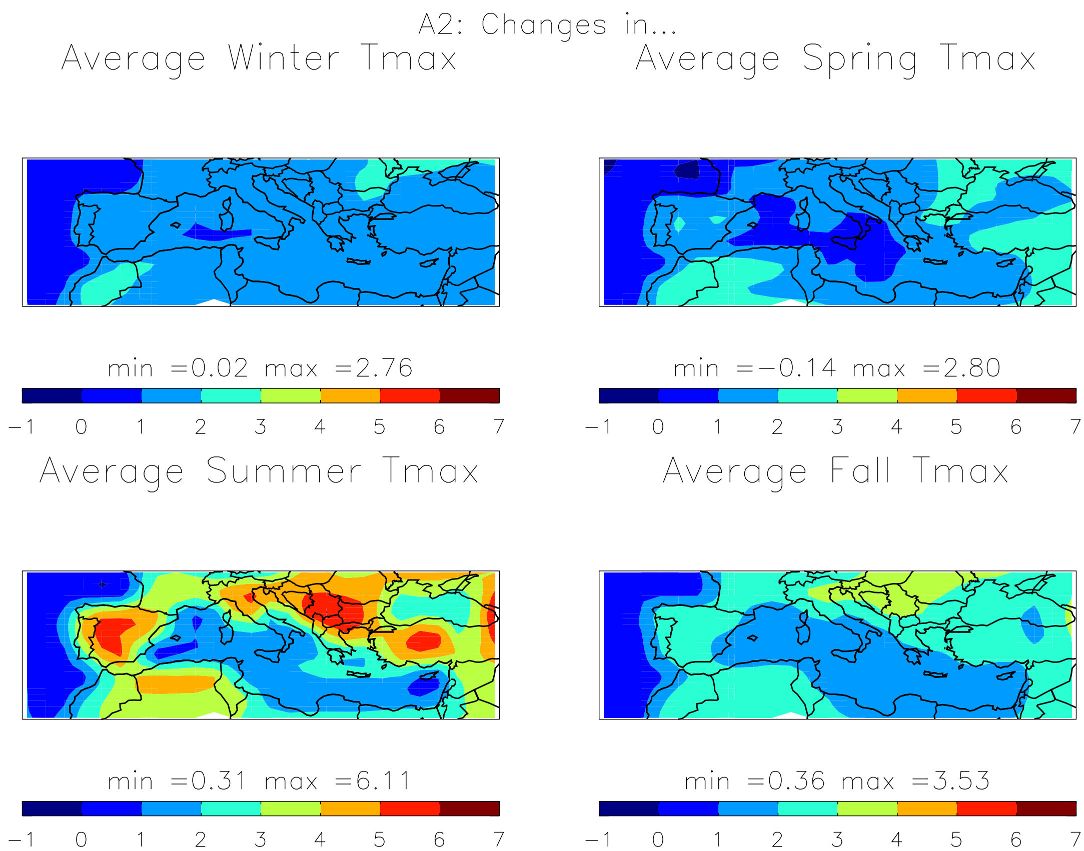


Figure 12. As Fig. 10 but for the daily maximum temperature.

5.1.3 Summary

The global 2 °C temperature rise is expected to be seasonally and spatially translated in the Mediterranean region by:

- Largest increase in summer, and inland: Tmean by 4 °C and Tmax by 5 °C, on average.
- Second largest increase in fall: 2-3 °C everywhere.
- Spring temperatures could rise by about 2 °C.
- Winter and spring temperatures could rise less than 2 °C.
- Although less pronounced, thanks to the sea, the rise in coastal region temperature is expected to be in the 1-2 °C range on average, and a bit more than 2 °C in summer for Tmax.
- Tmax is expected to rise more than Tmin.

5.2 High temperatures

5.2.1 Summer days

The increase in the **number of summer days**, defined as the number of days when T_{max} exceeds 25°C, is from 2-to-6 weeks (Fig. 13 top). This is translated to about one additional month of summer days on average.

- Large increases are found in Central Mediterranean Region (i.e. Crete, Peloponnese, South Greece, Sicily), North Adriatic, and inland (within Maghreb, Spain, Turkey, South of France and the Balkans). In this group, the largest increase seems to occur in Crete with an additional 7 weeks of summer and the smallest in the Maghreb with an additional 3-5 weeks of summer.
- On the other hand, the coastal regions of the western Mediterranean, the Black Sea and the Middle East is expected to have the smallest increases with only 2-3 additional weeks of summer.
- It is expected that there will be, on average, one additional summer month everywhere inland, as well as in the central Mediterranean coastal region, and about half a month on all other coastal regions except the central Mediterranean Region.

5.2.2 Hot days

The pattern in **the number of hot days**, defined as the number of days with T_{max}> 30 °C (Fig. 13 bottom) is somewhat different from the pattern of the number of summer days. The increase is from 2 weeks along the coast to 5-6 weeks inland (within Spain, Turkey, South of France, the Balkans and in the Maghreb) indicating the role the Mediterranean Sea exerts in preventing too hot days.

5.2.3 Summary

According to our study, there exist four types of regions:

- Inland: on average one additional month of hot days, and also one additional month of summer days.
- Along the coasts outside Central Mediterranean region: 1-3 weeks of additional hot days, and 2-3 weeks of additional summer days.
- The coastal regions in Central and Eastern Mediterranean region are expected to have only few additional hot days (like the other coastal regions), but one additional month of summer days, as in the continental part of the Mediterranean. Crete is the

perfect example: no change in the number of hot days, but an average of 7 additional weeks of summer days.

It looks as if the Mediterranean Sea moderates temperature increases in the coastal areas so while more summer days are forecast, few of these days will be on the hot side.

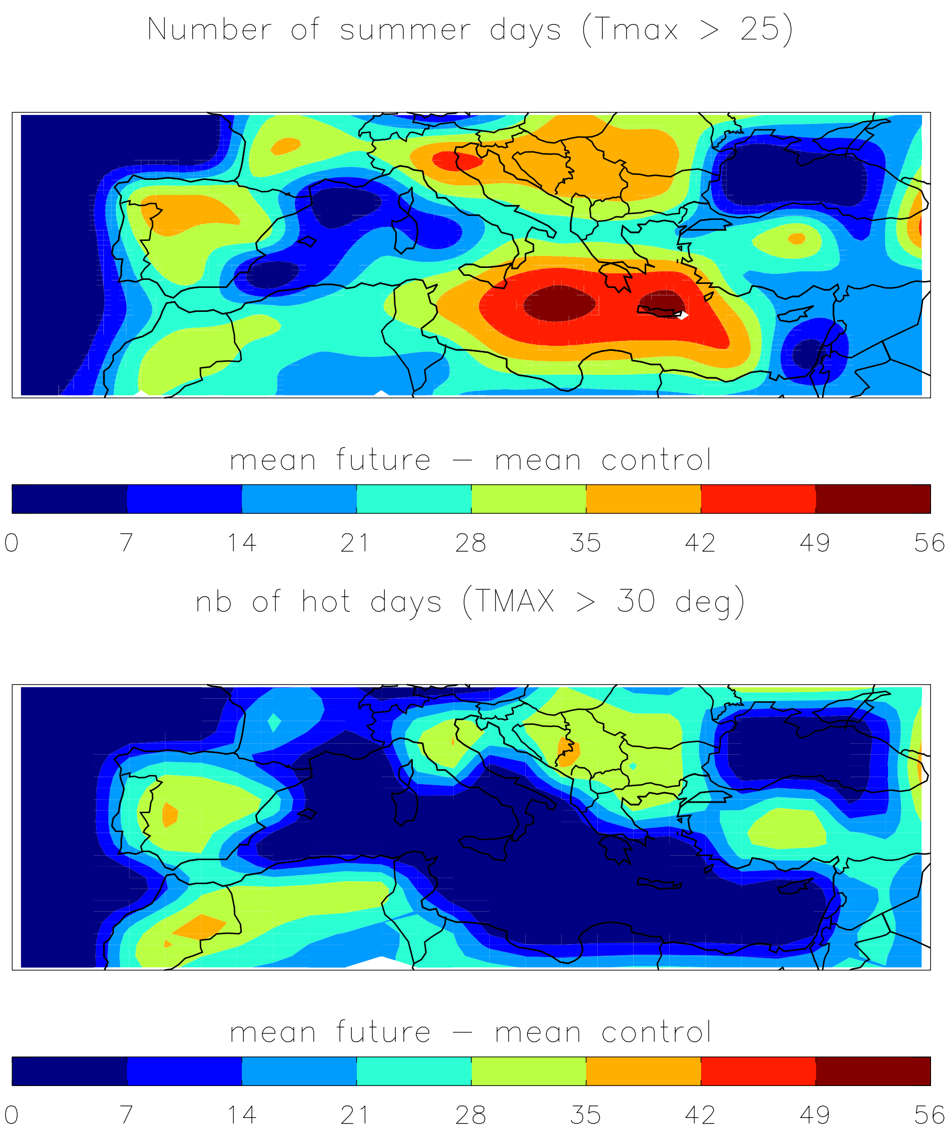


Figure 13. Differences in the number of summer (top) and hot (bottom) days between control and future period for scenario A2.

5.2.4 Tropical nights

The **number of tropical nights**, defined as the number of nights with Tmin > 20 °C (fig.14) increases by about a month almost everywhere. Only regions well within land are expected to keep their night fresh, with only 1-2 weeks per year of additional tropical nights. A larger increase in tropical nights than in summer days is expected to be seen in the South Eastern Mediterranean Region (SEMR). The SEMR extends from the Israeli/Syrian coast to Egypt. The opposite is likely to occur inland (South of France, Spanish interior and Turkey, the Balkans and North Adriatic).

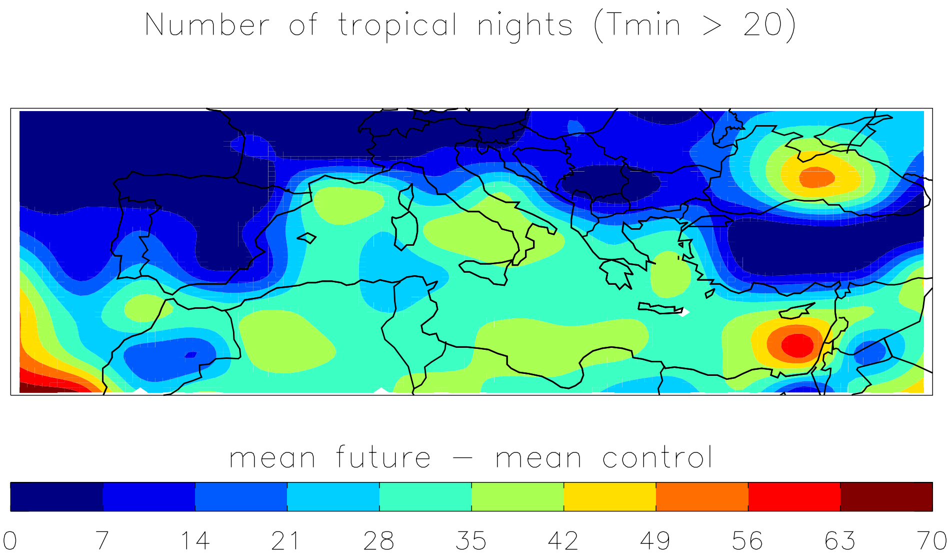


Figure 14. Difference in the number of tropical nights (scenario A2).

5.2.5 Extremely hot days

Fig. 15 shows the percentage of days with temperatures in the future period (2031-2060) above the value that is exceeded by 10% of the days in the reference period (1961-1990). This value is also called the 90th percentile of the reference period, and changes with location. In other words, Fig. 15 (top and bottom) gives the percentage of days in the future period that fall within the range of the 10% hottest days of the reference period. It can be seen that the temperature range of the 10% hottest reference days and nights will be reached or exceeded by 20% of the future days and nights on average. This is a doubling, which is associated with the increase in the number of summer and hot days.Note that the lowest increases are found near the Atlantic Ocean, and in Cyprus (in contrast to Crete), while the sharpest increase is in the SEMR hot spot.

Figure 16 shows the changes in the number of heatwaves in the future period, defined as the change in the number of weeks per year with temperatures exceeding 35^{o}C. The changes are about the same for both scenarios. Continental areas in Spain, the Middle East, Turkey, the Balkans, North Africa and North Italy are expected to experience an increase of 3-5 weeks of heatwave days. Areas under the moderating influence of the Mediterranean sea are likely to see very small or no changes. Such areas are all the islands, South Italy, and Peloponese. The sole exception occurs in the islands in the North Aegean Sea, which are expected to experience more heatwaves (4 weeks more) in the future period.

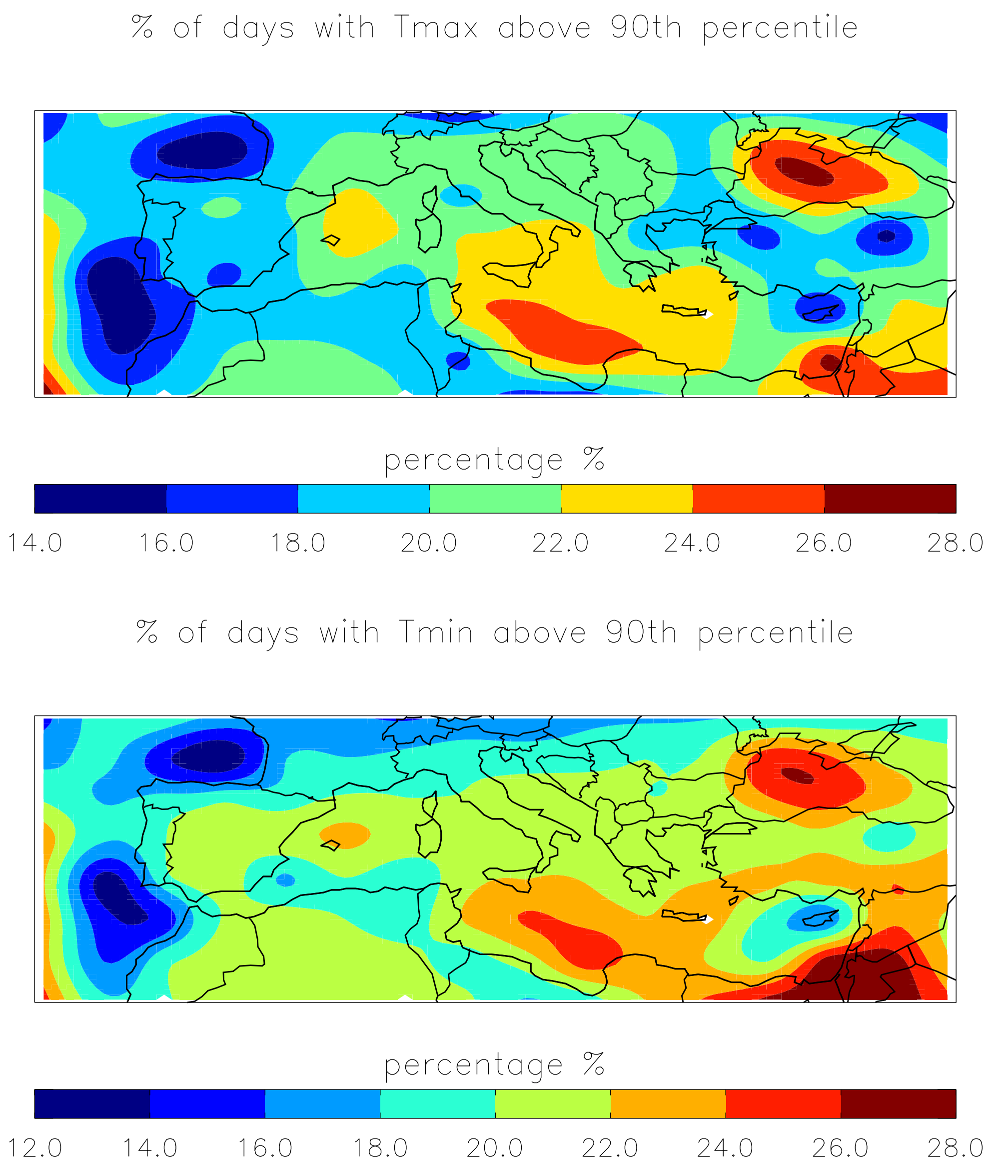


Figure 15. Percentage of days (top) and nights (bottom) nights with Tmin above the 90th percentile of the reference period (scenario A2).

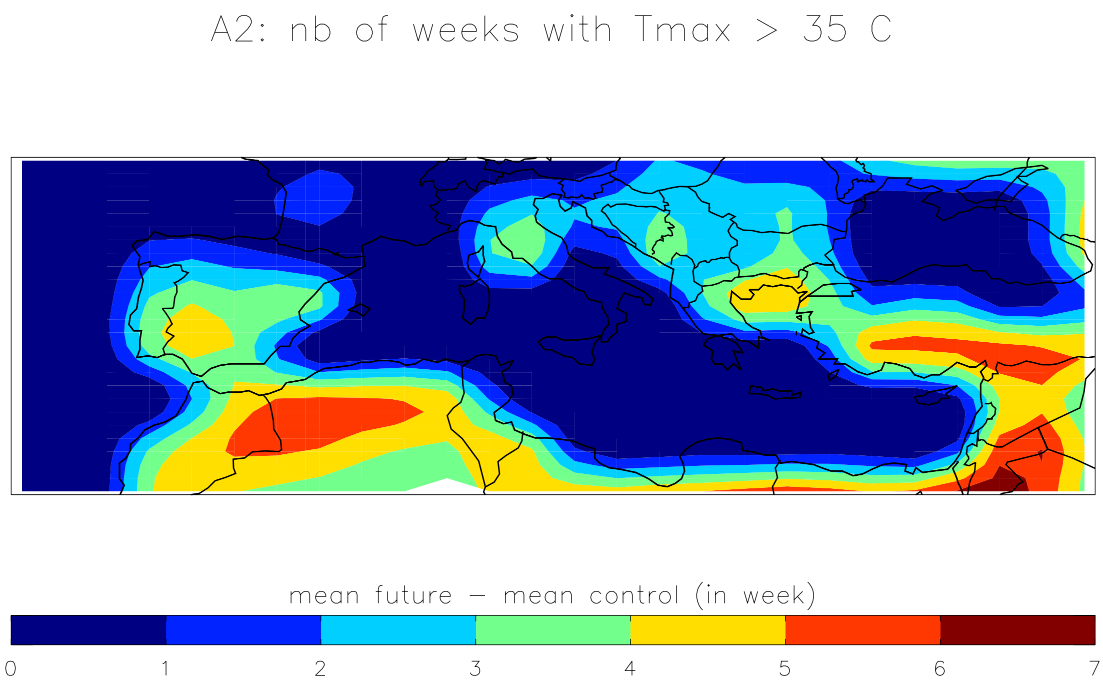


Figure 16. Difference in the number of heatwaves (i.e. weeks with Tmax>35°C) under A2 scenario between the two periods.

5.3 Low temperatures

Fig. 17 reveals that the **number of frost nights**, defined as the number of nights with Tmin < 0 °C, falls by 1-2 weeks along the coast, and up to a month inland. **The number of very cold nights** (Tmin < -5 °C) is not shown but it also has a decreasing trend (though not as strong).

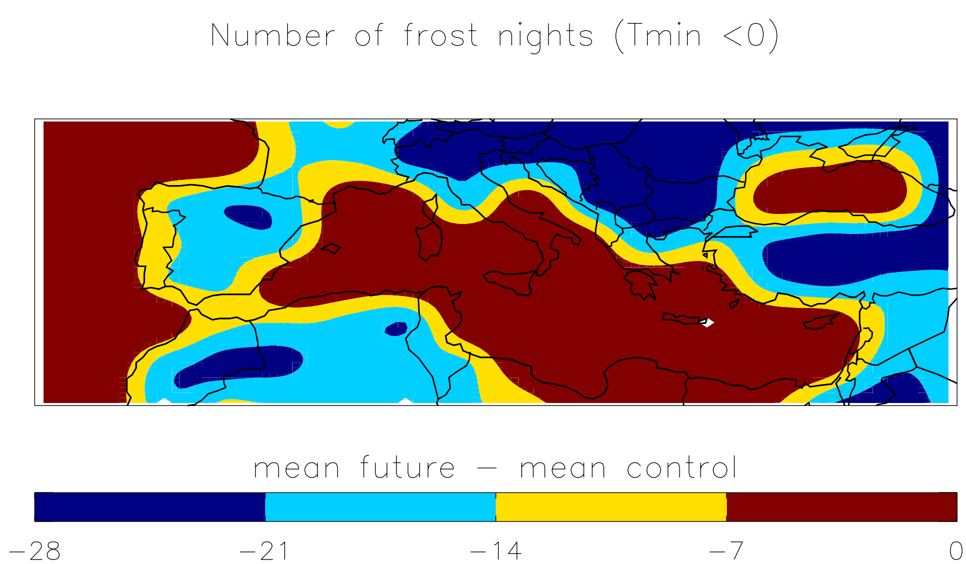


Figure 17. Difference in the number of frost nights (scenario A2).

Finally, in symmetry with the 10% hotter days and nights examined above, we examine the 10th percentile of the coldest days and nights in relation to the reference period. The percentage of days and nights reaching these ranges is shown in Fig. 18 for both scenarios. The ranges of the reference period are expected to be reached by only 5% of the future days and nights. A 50% decrease in the number of coldest days is therefore evident. The drop is larger in the SEMR, both during night and during day, and a little bit more under B2 scenario.

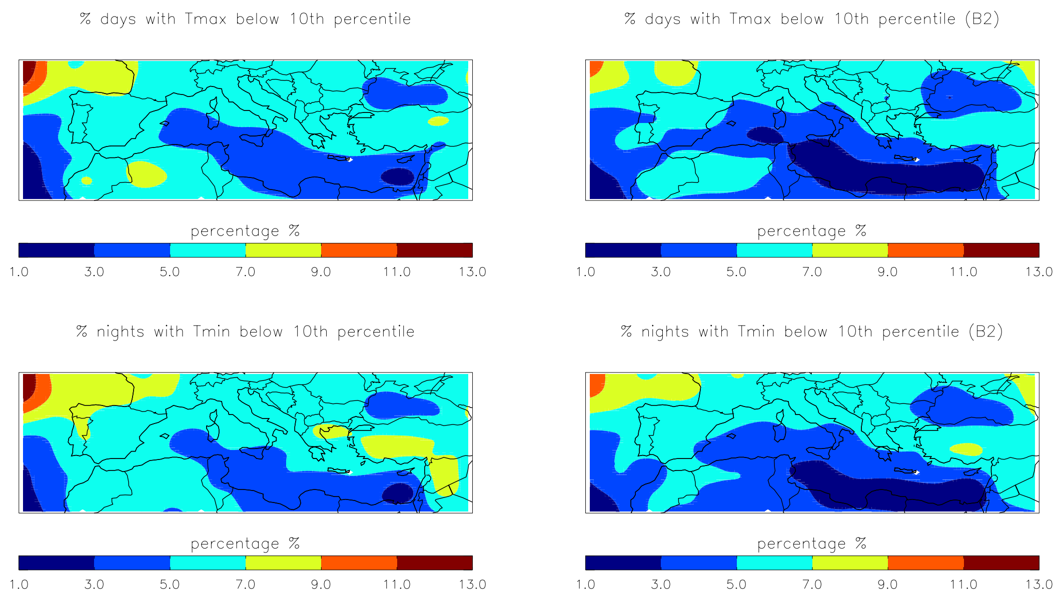


Figure 18. Percentage of days (top row) and nights (bottom row) with temperature below the 10^{th} percentile of the control years, under scenario A2 (left column) and B2 (right column).

5.4 Precipitation

5.4.1 Annual rainfall changes

Figs. 19 & 20 give the variations in the mean total yearly rainfall for both scenarios. Under scenario A2, a drop in precipitation seems to be the dominant feature of the future precipitation regime. Under B2, some rainfall increases are expected in the northern part of the region. Compared to temperature, precipitation exhibits larger differences between the two scenarios .

Under A2, we can roughly identify two main areas:

- 0-10% drop in precipitation relative to the 1961-1990 values in the northern part
- 10-20% drop in precipitation relative to the reference period values in the southern part including Spain.

Under B2, the northern part is expected to experience both increases and decreases in total yearly rainfall while a 0-20% drop is evident in the southern part.

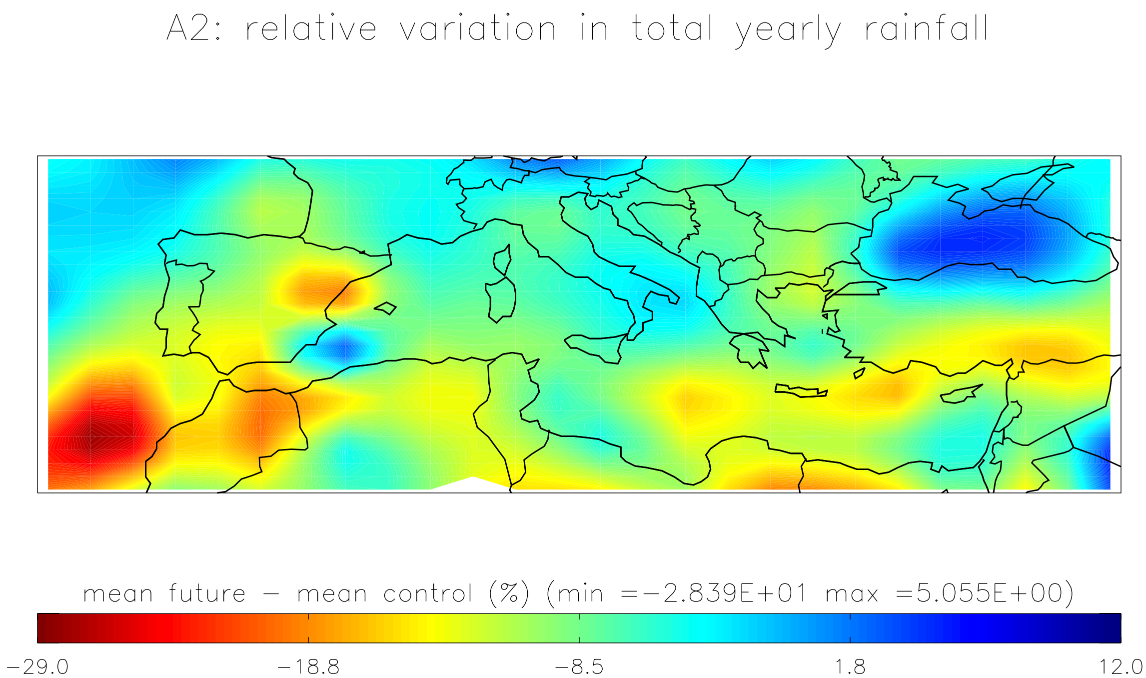


Figure 19. As Fig. 6, but for precipitation under A2 scenario.

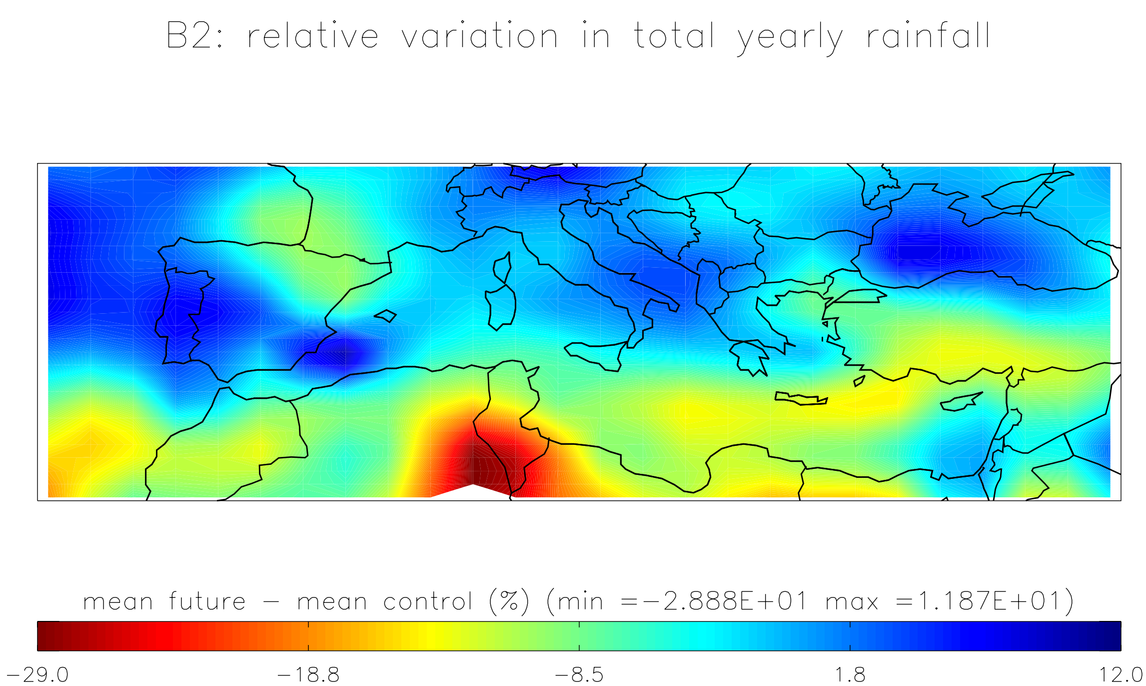


Figure 20. As Fig. 6, but for precipitation under B2 scenario.

5.4.2 Seasonal rainfall changes

Figs. 21 and 22 represent the relative changes in precipitation between the two periods and for scenarios A2 and B2 respectively. From these two figures it becomes evident that:

- Spring and summer rainfall regime exhibits no differences between the two scenarios.
- Fall seems to experience a little bit more rain under B2 scenario.
- Winter exhibits the main differences between the two scenarios, with more rainfall under B2, especially in France and Spain.

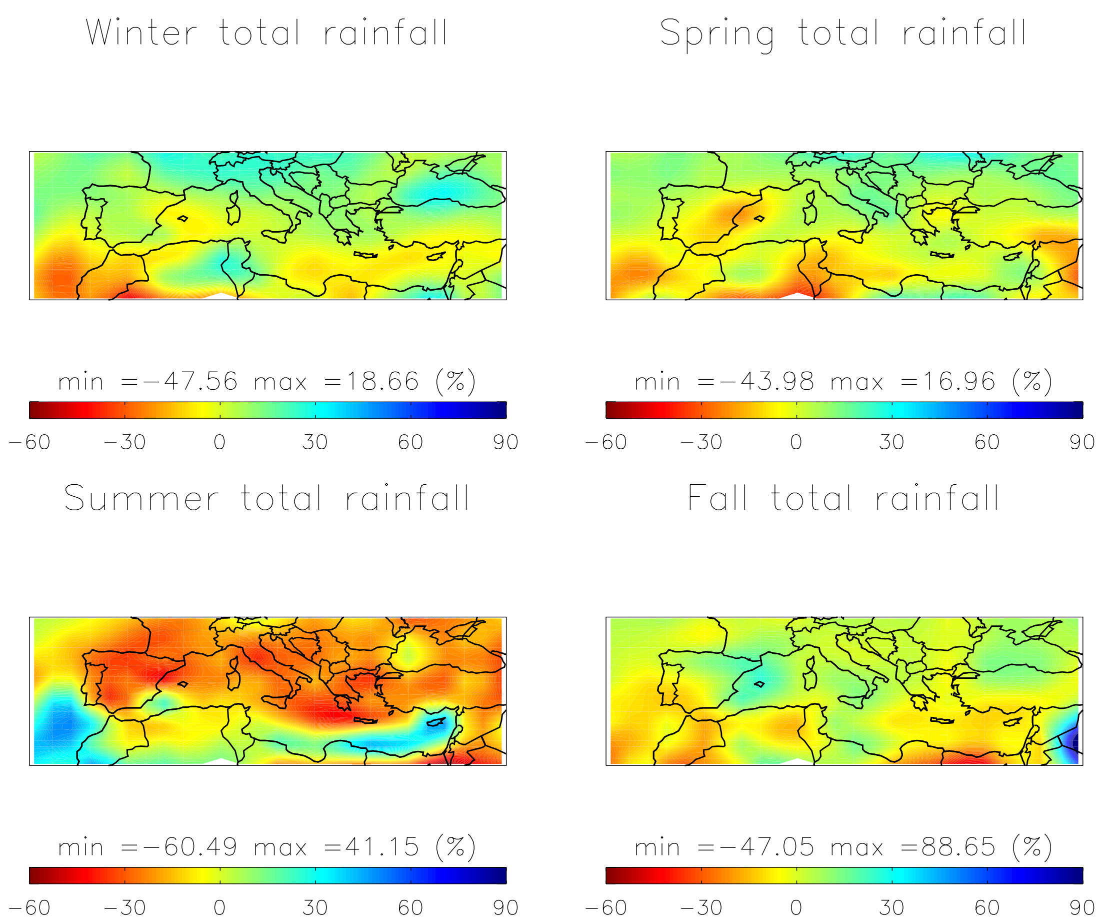


Figure 21. As Fig. 10, but for percentage precipitation changes in relation to 1961-1990 amount under A2 scenario.

The main feature of the seasonal variations in precipitation is the contrast between the North - South and winter- summer:

- A summer drop in the total rainfall over the northern region is expected, only partially balanced by an increase in winter.
- The opposite pattern is evident in SEMR (including the southern part of Turkey): small increase in autumn rainfall, slightly larger decrease in spring.
- All other parts of the Mediterranean (south European and North African countries) are expected to see a decrease in the summer precipitation and a small decrease or no change in the other seasons (mainly under B2 scenario).

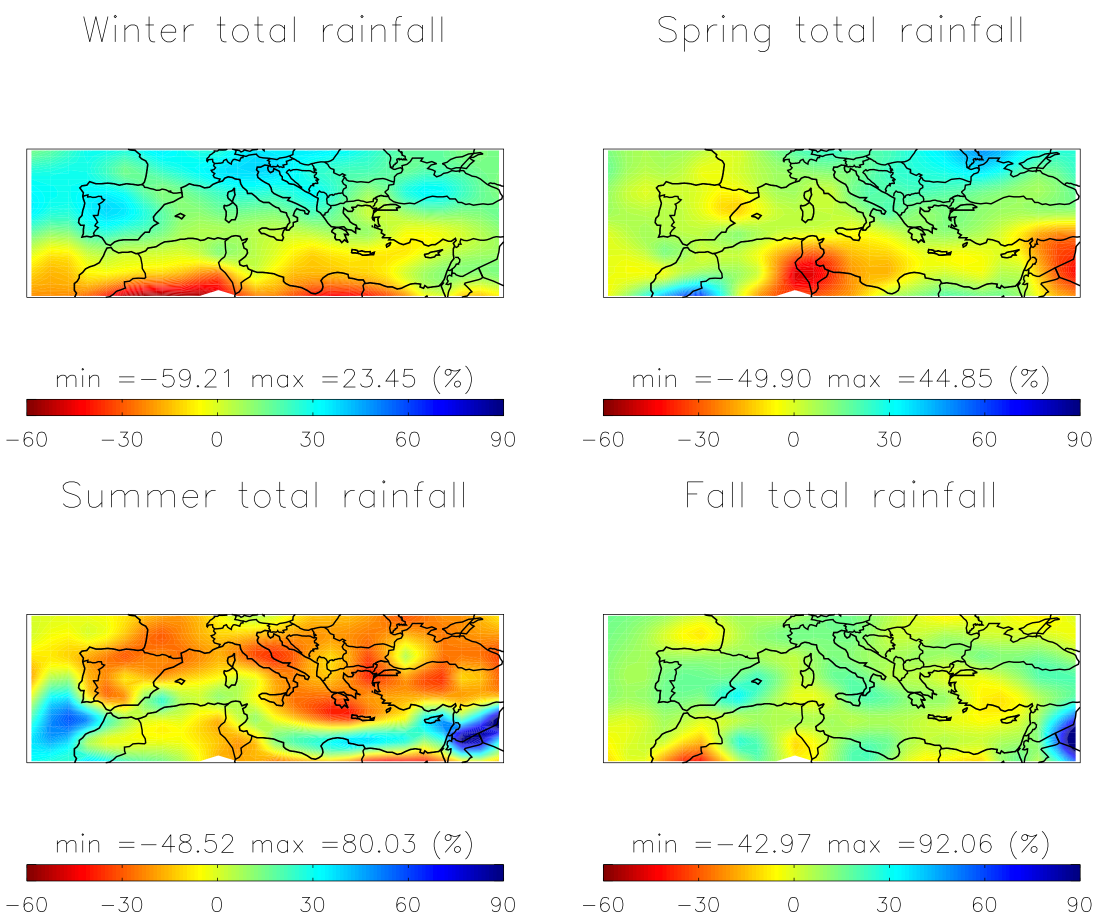


Figure 22. As Fig. 10, but for percentage precipitation changes in relation to 1961-1990 amount under B2 scenario.

5.4.3 Number of dry and wet days

Figure 23 describes the differences in the yearly **number of dry days** between the two examined periods. The dry days are defined when the daily precipitation amount (RR) is less than 0.5mm. On average, the Mediterranean is expected to feature more dry days. The increase is expected to be about 2 to 3 weeks in the Northern MR and in the Maghreb (Algeria/Morocco).

The increase is likely to be lower along the coast (~2 weeks), but higher inland (3 weeks in the south of France, the Balkans, Turkey, and Italy, and almost a month in the Iberian peninsula and in Bulgaria).

This increase is balanced by the situation in the greater SEMR (Libya-Egypt-Israel-Lebanon-Cyprus) where no significant change or even a slight decrease will be experienced (between -4 and +5 dry days).

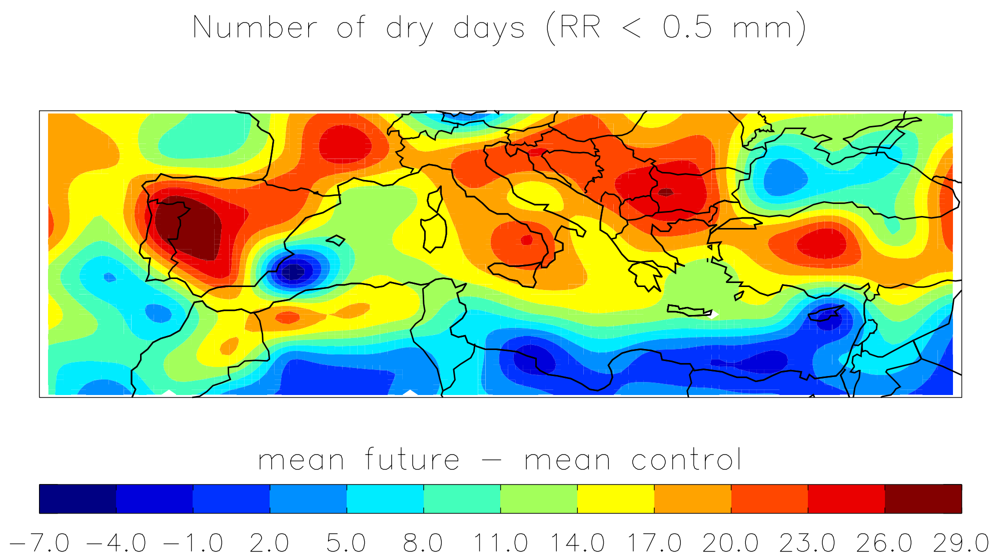


Figure 23: Difference between the average yearly number of dry days in the future and in the control years. RR <0.5 mm defines dry days. Future scenario is A2.

Note that under the B2 scenario, fewer dry days are expected everywhere, which is not a significant difference between the two scenarios. The results are also very similar if RR <1mm is used to define dry days (not shown here).

To summarise, we have an increase in general in the number of dry days, ranging from ~1 month more dry days within the Iberian peninsula to just few extra dry days in the SEMR or even a slight decrease in Cyprus.

The **number of wet days** was also examined. One may ask if a dry day increase is associated with a decrease in the very or extremely wet days or simply in the wet days. The number of very wet days (RR > 10 mm) does not change much (+/- <3 days on average, not shown). No change is also seen in the **number of extremely wet days** (RR > 20 mm, not shown).

Finally, variation of rainy days that fall in the 1-10 mm range is shown in Fig. 24. This corresponds to the middle range of precipitation. It is expected to drop by 2 weeks in the North Med, and by a less than a week in the southern Mediterranean (except in the

Maghreb where the drop will be closer to 2 weeks). This decrease in the middle range is associated with the increase in dry days, as clearly seen by comparing Figs. 24 and 23, and taking into account that no change in the number of very wet days is expected.

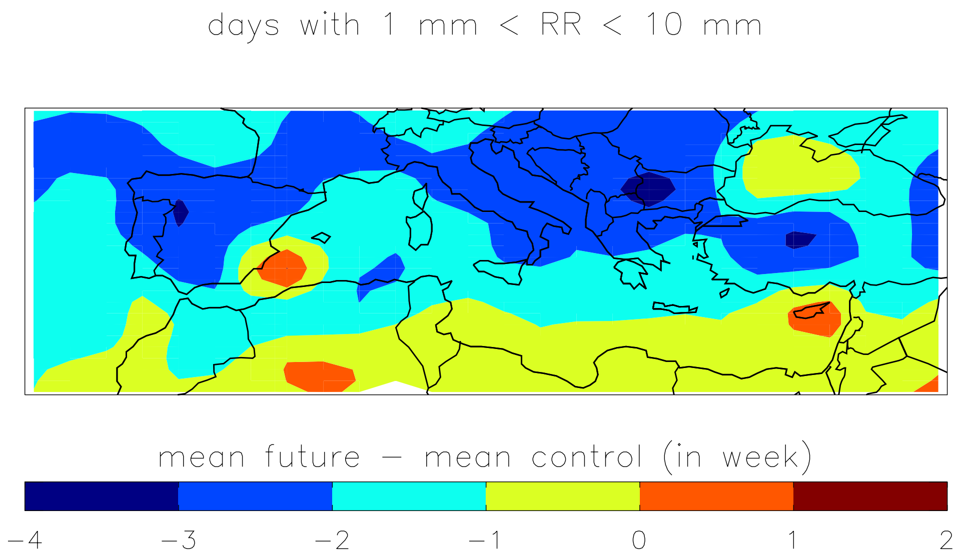


Figure 24: Variation in the number of days with precipitation between 1 and 10 mm.

5.4.4 Precipitation intensity

Figure 25 shows the annual maximum amount of total rainfall over 3 days. It is worth noting that some areas in the North Mediterranean are likely to see this parameter increasing while their total annual precipitation actually decreases and the number of wet days remains unchanged. This can imply that when it rains it will rain more intensely and strongly. This is particularly true in Italy, Western Greece, South of France, and the northwestern part of the Iberian Peninsula. On the contrary, rainfall is likely to become less intense over the Southern Mediterranean.

5.4.5 Spells

Changes in the length of wet spells and dry spells (also referred to as droughts) are examined. Our results show little change in the **length of wet** (RR> 0.5 or 1mm) or **extremely wet** (RR> 10 or 20mm) spells (not shown). This is in accordance with our results under Section 4.4.3 which show little change in the number of days associated with these ranges of precipitation.

Greater variations are seen in **dry spells**. Longer dry spells are likely to be common. The biggest changes for RR<1mm, shown in Figure 26, are likely to be 2 to 4 weeks increase in the south of Italy and the Peloponese region in Greece, from the south of Iberian Peninsula to Morocco, and in Libya.

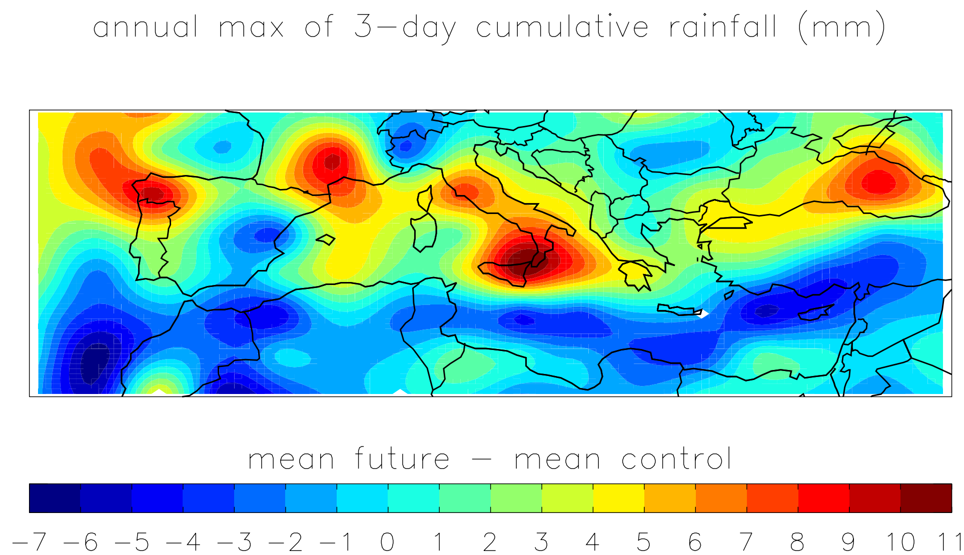


Figure 25. Difference in the annual maximum 3-day cumulative rainfall.

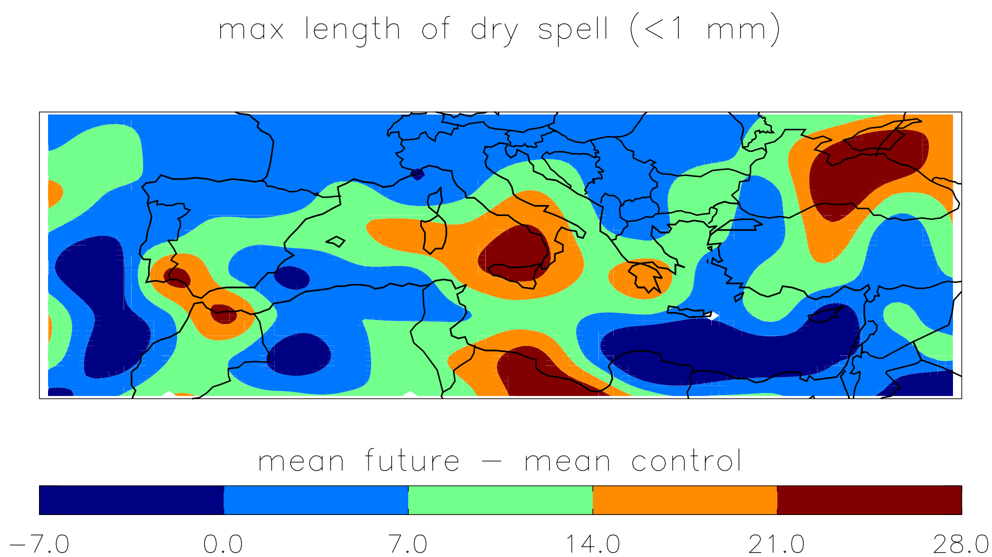


Figure 26. Difference in the length of the longest dry spell (RR<1mm defines dry spells, scenario A2).

Other areas in the SEMR and the Cartagena-Algiers axis do not feature longer dry spells. On the other hand, the northern part of Algeria, which is expected to have more dry days, is not expected have longer dry spells. The extra dry days are scattered in time.

The start and the end of these longest dry spells are also of interest since these are expected to affect agriculture. Fig. 27 (Fig. 28) shows the shift in the end (start) of the drought.

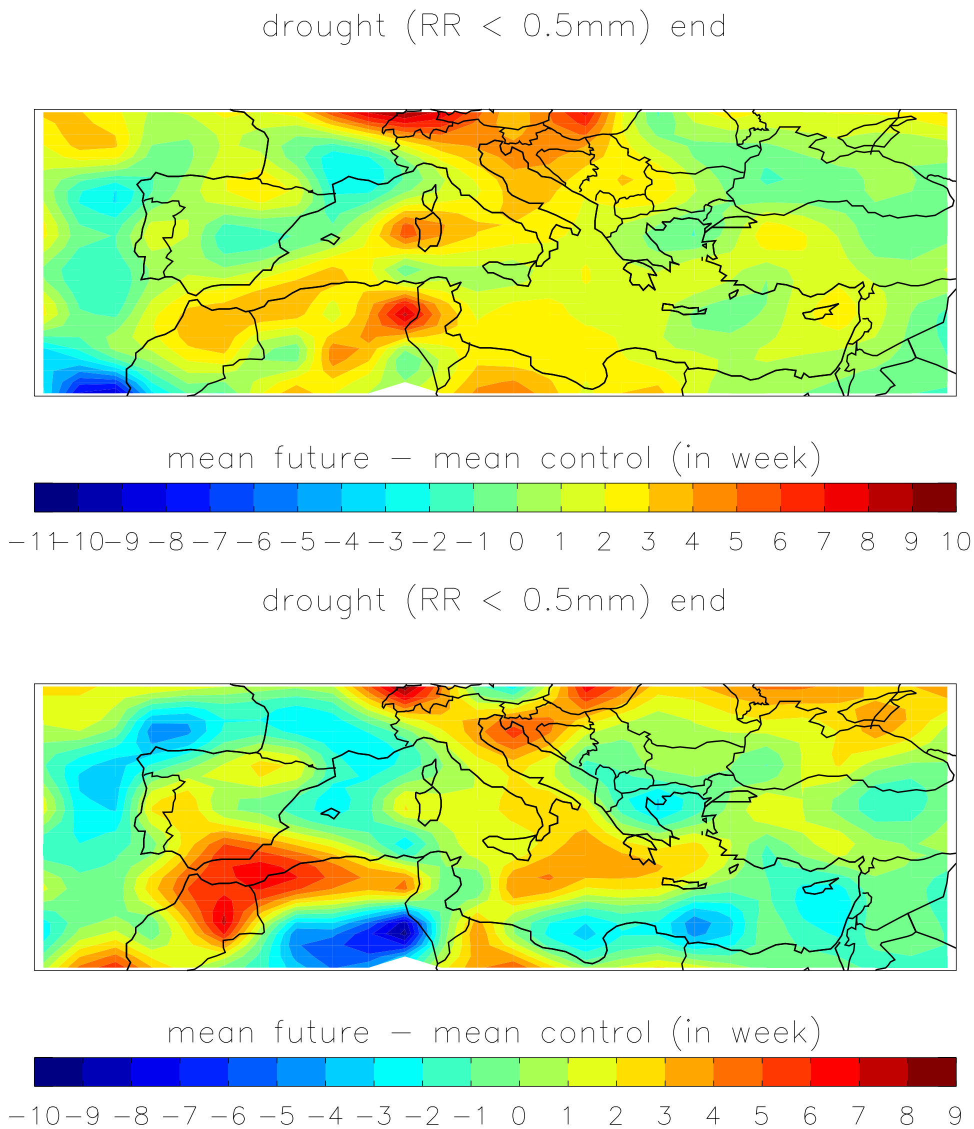


Figure 27. Difference in end of longest drought, for both scenarios (top=A2, bottom=B2).

We note the following noticeable shifts:

- In the South of France and Central Spain, drought starts 3 weeks earlier and ends 2 weeks earlier. This is a shift of the dry season towards spring.
- North Adriatic (Italy –except far south- and western Balkans), Maghreb: a general shift of 2-4 weeks later.
- Sicily: no major change.
- Sardinia sees its driest season shifted towards fall by a month.
- Greece and the area east of Greece, see its dry season getting longer towards fall: no big change for start, but drought end shifts to a later date by 2 weeks or so.

- It is noteworthy that the droughts of the Maghreb/South of Spain region shift towards fall under the B2 scenario. The opposite holds true in Tunisia, but with less amplitude. Continental Greece and Peloponese also show the opposite pattern.

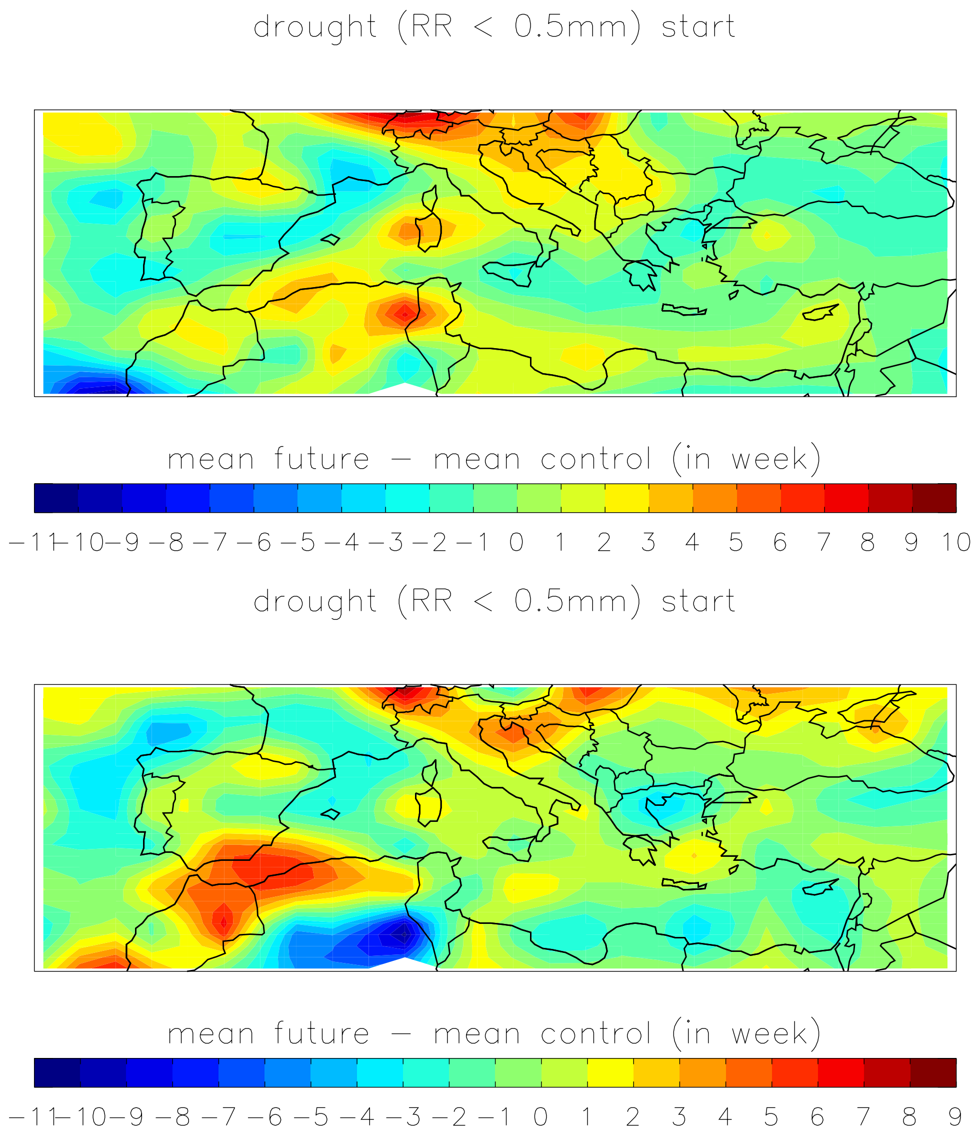


Figure 28. As Fig. 27 but for the longest drought start (top=A2, bottom=B2).

5.5 Summary table

	High Temperatures					Low Temperatures			Precipitation				
	Summer Days	Hot days	Tropical nights	Days > 90th-quantile	Nights > 90th-quantile	Frost nights	Ice days	(1) Days < 10th-quantile	Relative Precip. Var.	Dry days	Rainfall between 1-10mm	Max 3-days Rainfall	Longest dry spell
NW Iberian Peninsula	1	1		1	1	-1		-2		2	-2	3	
South of France (inland)	3	1	1	2	2	-1		-2	-1	3	-2	3	
Coast of South of France	1		2	2	2	-1		-2	-1	2	-2	3	1
Corsica	1	1	2	2	2	-1		-2	-1	2	-1	2	1
Sardegna	1		3	2	2			-3		2	-1	1	2
Sicily/ South Italy	3		3	3	2 3			-3		3	-1	3	3
North Adriatic	3	3		2	2	-2	-1	-2	-1	3	-2	1 2	1
Central Balkans	3	3		2	2	-2	-1	-2		3	-3		
Central Greece	2	1	2	2	2	-1		-2	-1	2	-2	1	1
Peloponnese	3		3	2	2			-3	-1	2	-1	2	2
Crete	3		3	3	3			-3	-1	2	-1		1
Coastal Turkey	1 2	1	1 2	2	2	-1		-2	-1	2	-1	-1 2	1
Turkey Inland	3	3		2	2 3	-2	-1	-2		3	-2		2
Cyprus	1		3	1	1			-3	-1	1	1		-1
Lebanon-Israel-Nile Delta	1	1	3	3	3	-1		-3	(2)	1	-1		
E. Egypt – E. Libya	3	1	3	2	3			-3	(2)		-1		-1
W. Libya	3	1	3	2	3			-3	-3		-1		3
E. Maghreb	2	3	3	2	2	-2		-2	-3	2	-2		
W. Maghreb	3	3	3	2	2	-2		-2		2	-2	-1	3
South Iberian Peninsula	2	2	2	2	2	-1		-2	-1	2	-2		3
Central Spain	3	3	1	2	2	-2		-2	-1	3	-2	-1	1

Synoptic Table. Red = Large change=3, Yellow = Moderate change=2, Grey = Small change=1, White = No change, (-)=decrease. Notes: (1) very similar results for nights; (2) depend on scenario. Typical temporal values: Big is about 1 month or more; Moderate is about 2-3 weeks; Small is about 1 week (few days).

6. Impact analysis

6.1 Energy demand

Energy demand is linked to climatic conditions (Giannakopoulos and Psiloglou, 2005) and the relationship of energy demand and temperature is non-linear. The variability of ambient air temperature is closely linked to energy consumption, whose maximum values correlate with the extreme values of air temperature (maximum or minimum). In the Mediterranean region, during January, the maximum values of energy consumption are related to the appearance of the lowest temperatures. During the transient season of March-April, energy consumption levels are nearly constant until about May, while air temperatures are constantly rising. From about mid-May onwards, and throughout the summer period, any increase in air temperature translates to an increase in energy consumption mainly due to the extensive use of air conditioning. The exception is August since most people in the Mediterranean region tend to take their summer holidays. Another transient period exists in the months of September and October where energy demand and consumption are at constant levels. This transient period is followed by a period of continually increasing energy demand with a peak before the Christmas festive period. Therefore, it is expected that with warmer weather decreased demand should be typical in winter and increased demand should be typical in the summer (Giannakopoulos and Psiloglou, 2005, Valor et al., 2001). Moreover, the effect of higher temperatures chiefly in the summer is likely to be considerably greater on peak energy demand than on net demand, suggesting that there will be a need to install additional generating capacity over and above that needed to cater for underlying economic growth unless adaptation or mitigation strategies are put into place.

Since the energy-temperature relationship is non-linear and has distinct winter and summer branches, it would be more convenient to separate these two branches. The easiest way to achieve this is to use the idea of Degree-Day, which is defined as the difference of mean daily temperature from a base temperature.

Base temperature should be the temperature where energy consumption is at its minimum. If this temperature is chosen, then the degree-day index is positive in the summer branch and negative in the winter branch. Instead of having both positive and negative values for this index, the definition of two indices is used: heating (HDD) and cooling degree days (CDD).

For the calculation of the HDD and CDD indices, the following equations were used:

HDD = max (T* - T, 0) (Eq. 1)

CDD = max (T - T**, 0) (Eq. 2)

where T* and T** are the base temperatures for HDD and CDD respectively, which can be either the same or different and T is the mean daily temperature as this is calculated from the daily data of HadCM3 for both the reference and the future periods.

HDD (CDD) is a measure of the severity of winter (summer) conditions in terms of the outdoor bry-bulb air temperature, an indication of the sensible heating (cooling) requirements for the particular location. Kadioğlu et al. (2001) used different base levels of 15^{o}C and 24^{o}C for the calculations of HDD and CDD in Turkey, respectively. In our study we use 15^{o}C for the calculation of HDDs and 25^{o}C for the calculation of CDDs. We identify the changes in energy demand levels by showing differences in the cumulative numbers of CDDs and HDDs between the reference (1961-1990) and the future period (2031-2060).

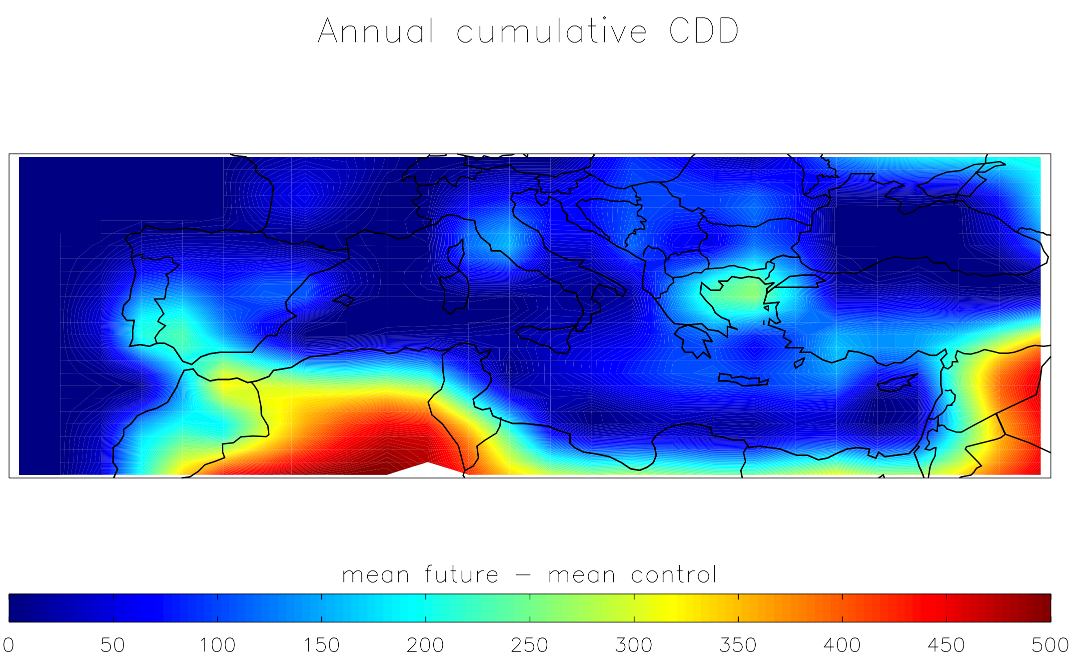


Figure 29. **C**hange in average yearly cumulative CDD between the future and control period.

6.1.1 Cooling energy requirements

In general, more cooling will be required.

Over the year (Fig.29), the increase in CDD will be large in South Mediterranean (from Gibraltar to Lebanon), i.e., in the Middle East and the North African part of

Mediterranean Region. In northern side, the main increase will be in the South Iberian Peninsula, North-Italy-Balkans-Greece, and South Turkey.

Fig. 30 shows the seasonal changes in CDDs. As expected the main contribution is from summer, with no increase in winter, and a very small increase in fall and spring. The only regions to escape any significant increase in cooling requirements are: south Italy (including Sicily and Sardinia), south of France, Cyprus, northern part of Turkey (because of Black Sea), and the North Western tip of Spain.

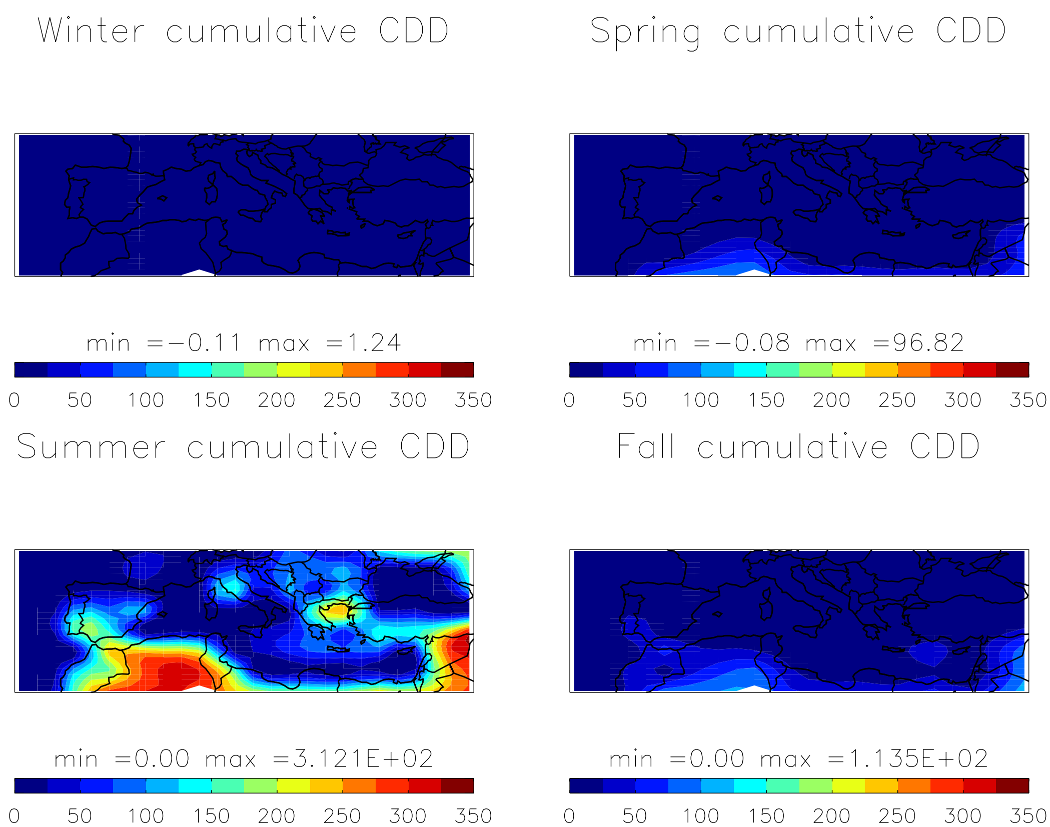


Figure 30. As Fig.29 but for each season.

Fig. 31 presents another view on the increase of energy demand by showing the number of days when this requirement will be needed to cool more than 5^{o}C. In the south side of the Mediterranean Sea, from the southern part of Iberian Peninsula and the North African coast to Syria, an additional month of heavy cooling will be required. The 2-3 week increase in the north Aegean area is also worth mentioning.

6.1.2. Heating energy requirements

In general, less heating will be required. Fig. 32 shows the spatial distribution of the general decrease in HDDs. It can be emphasised that:

- The largest decrease occurs in the northern side of the region, from Turkey to North Italy.
- Spain and France will see a smaller but still noteworthy decrease,

- The SEMR exhibits the lowest decrease, mainly because it is already a warmer region.

Note also the cooling effect of the sea along the coasts.

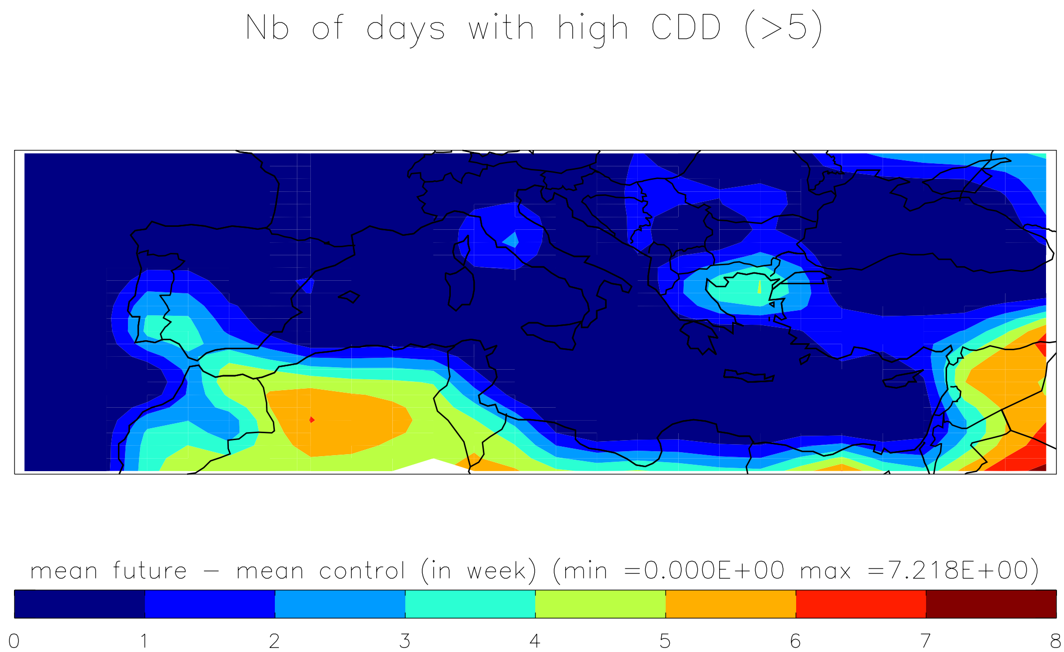


Figure 31. Changes in the number of days with large cooling demand (CDD >5) between the future and control period.

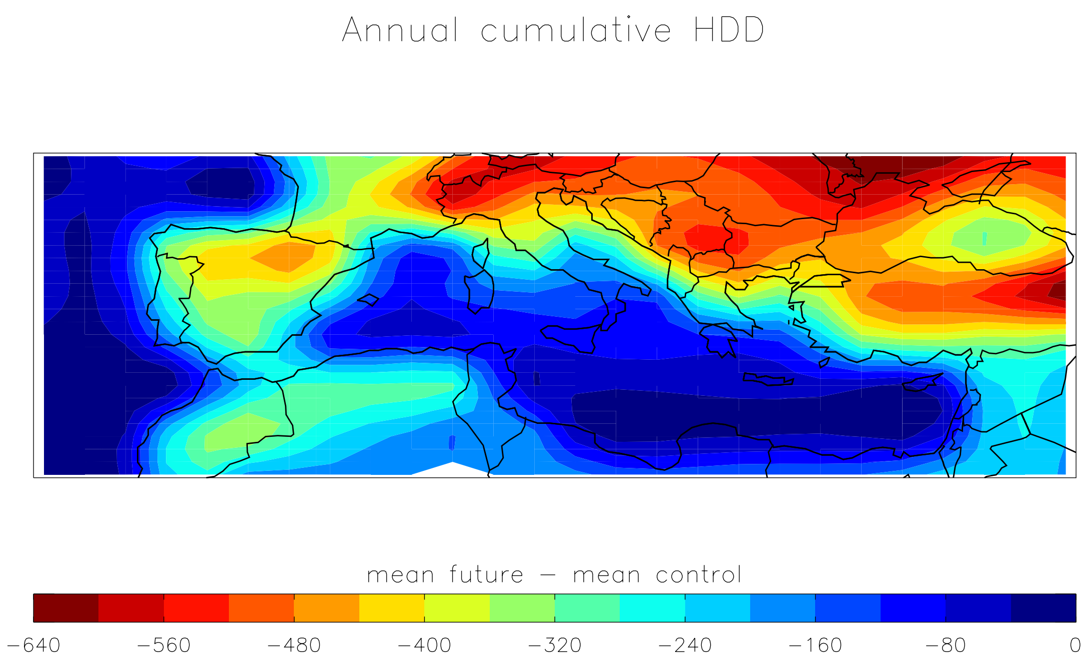


Figure 32. Changes in average yearly cumulative HDDs between the future and control period.

Unlike the CDD rise, the HDD decrease is spread over the year (Fig. 33), although this probably depends to some extent on the choice of base temperature.

Of course, winter will be the season that will require much less heating. The largest changes will happen along and above the axis North-Italy-Balkans-Greece-Turkey.

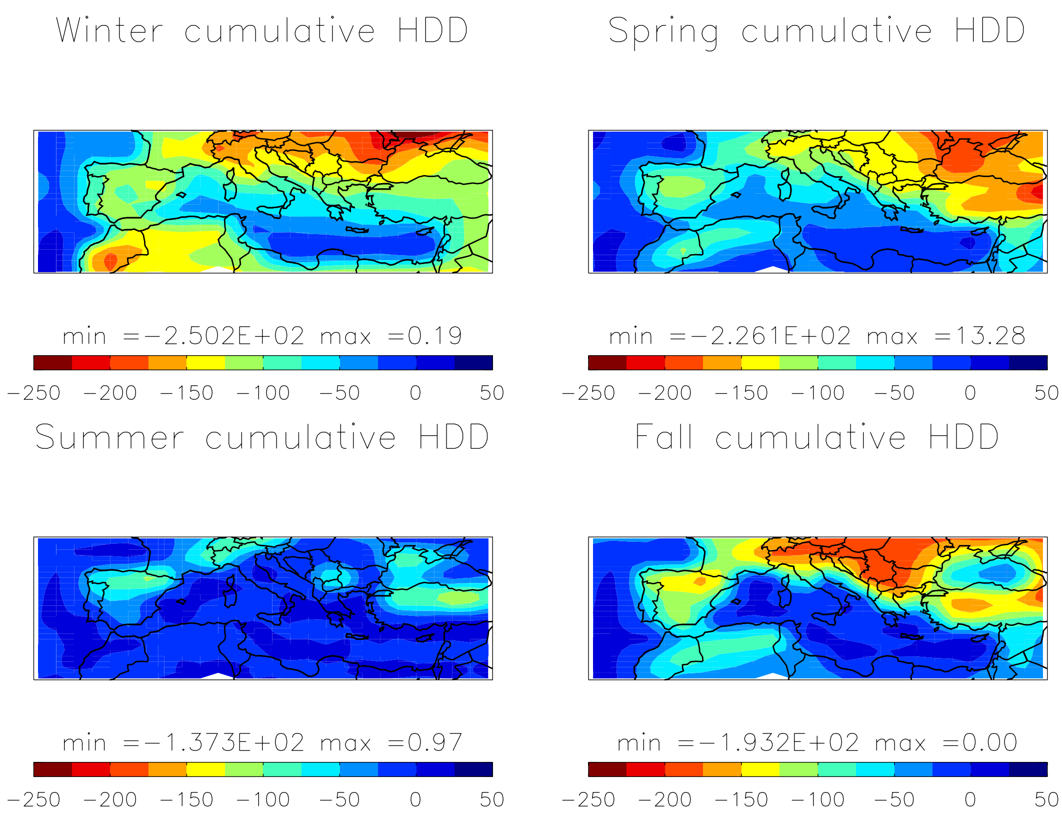


Figure 33. As Figure 32, but for each season.

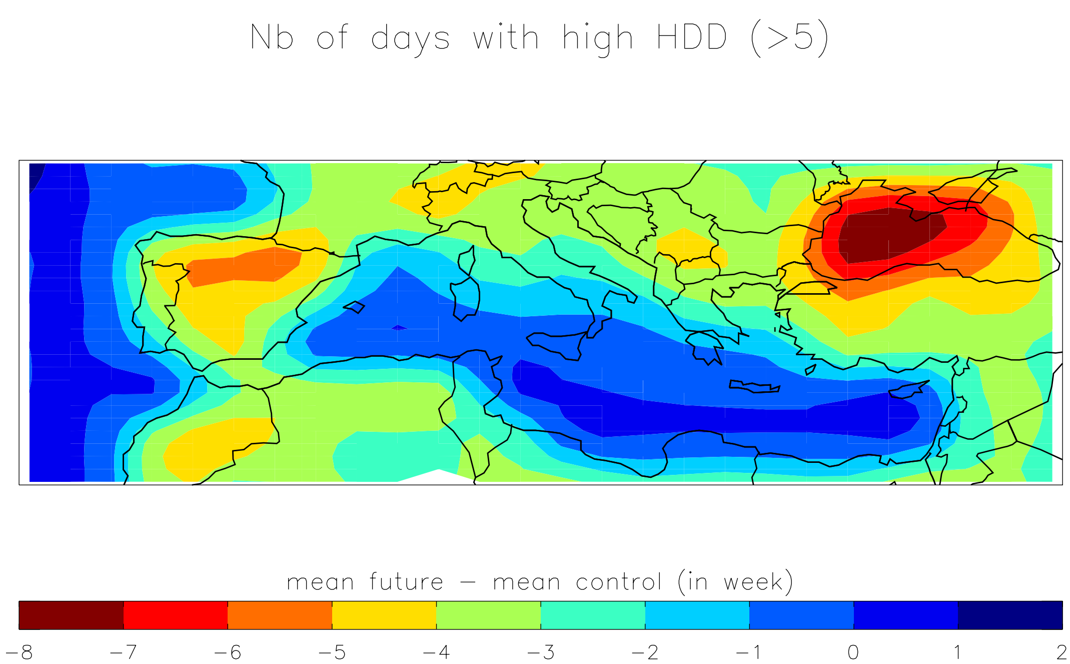


Figure 34. Changes in the number of days with large heating demand (HDD >5) between the future and control period.

As shown in Fig.34, the decrease in the number of days that require warming more than 5°C (HDD>5) varies from about 2 weeks along the coast to a month inland.

6.1.3 Summary of impacts on energy demand and supply

Summarising about the CDDs and the HDDs, three areas can be identified:

- South Side of the Mediterranean (North Africa to Syria): very large rise in CDD, small drop in HDD
- North Side of the Mediterranean (Italy-to-Turkey): small rise in CDD, very large drop in HDD
- Atlantic Side (Spain / France): small rise in CDD, large drop in HDD

As expected, the northern Mediterranean region is likely to reduce energy use in the winter due to reduced heating needs. However, during summer, substantial increases in energy demand are expected everywhere and especially in the south. The peak in energy demand hence falls in the dry season, which is expected to become even drier in the future (Section 5.4). A low water supply reduces energy production from hydroelectric plants, as well as from conventional power plants, which require water for cooling and for driving the turbines. As a result, energy demands may not be able to be met in the warm period of the year. Additional capacity may need to be installed unless adaptation or mitigation strategies are to put into place. On the other hand, conditions for renewable energy production, such as solar power, may improve under climate change.

Data in Spain show that the response of mean daily demand for electricity to an increase of 1°C has steadily increased over the past 30 years (Rodriguez et al., 2005). The energy demand for per degree of cooling is likely to continue to rise as a society becomes richer and increased incomes allow the population to afford more comfort. More air conditioning facilities could be installed. In turn, the heat generated by air conditioning units could raise temperatures further and further increase the demand for cooling.

6.2 Forest fire risk

6.2.1 About the Fire Weather Index (FWI)

One of the many possible detrimental impacts of anthropogenic climate change is increased wildfire occurrence. Mediterranean Europe, in particular, has been identified as likely to suffer hotter, drier summers towards the end of the century (IPCC, 2001a), and hence potentially increased fire risk (e.g. Pinol et al., 1998, Moriondo et al., 2005). The contribution of meteorological factors to fire risk is simulated by various non-dimensional indices of fire risk. Viegas et al. (1999) validated a number of such indices in the Mediterranean against observed fire occurrence, with the Canadian Fire Weather Index (FWI, van Wagner, 1987) amongst the best performers. Viegas et al. (2001) demonstrated that in summer, the slow response of live fine fuel moisture content to meteorological conditions is well described by the Drought Code sub-component of the FWI system. FWI is also one of the most widely used indices of fire risk. Hence, it is natural to use output from climate model simulations (here of HadCM3) of the coming decades (here 2031-2060) as input to the FWI model to suggest how Mediterranean fire risk may change.

The Canadian Fire Weather Index system is described in detail in van Wagner (1987). Briefly, it consists of six components that account for the effects of fuel moisture and wind on fire behaviour. These include numeric ratings of the moisture content of litter and other fine fuels, the average moisture content of loosely compacted organic layers of moderate depth, and the average moisture content of deep, compact organic layers. The remaining components are fire behaviour indices, which represent the rate of fire spread, the fuel available for combustion, and the frontal fire intensity; their values rise as the fire danger increases.

Fire risk is low for FWI<15, and increases more rapidly with FWI>15 (Good et al., 2005). A threshold of FWI>30 was selected as a measure of increased fire risk.

6.2.2 FWI results

Fig. 35 shows the monthly changes of average FWI from May till October between the future and the control period. We note that:

- The increase is higher during the summer, with maximum increase in August in the North Mediterranean inland.
- Balkans, Maghreb, North Adriatic, Central Spain, and Turkey are the most affected regions.
- South of France is as strongly affected as Spain, but only in August and September.
- The SEMR (from Lebanon to Libya) sees no increase or decrease.
- The same seems to hold for the islands of Crete, Sardinia, Sicily (southernmost Italy too), Peloponnese, and Cyprus. Cyprus may even see a small decrease every month.
- The results are very similar under scenario B2 (not shown).

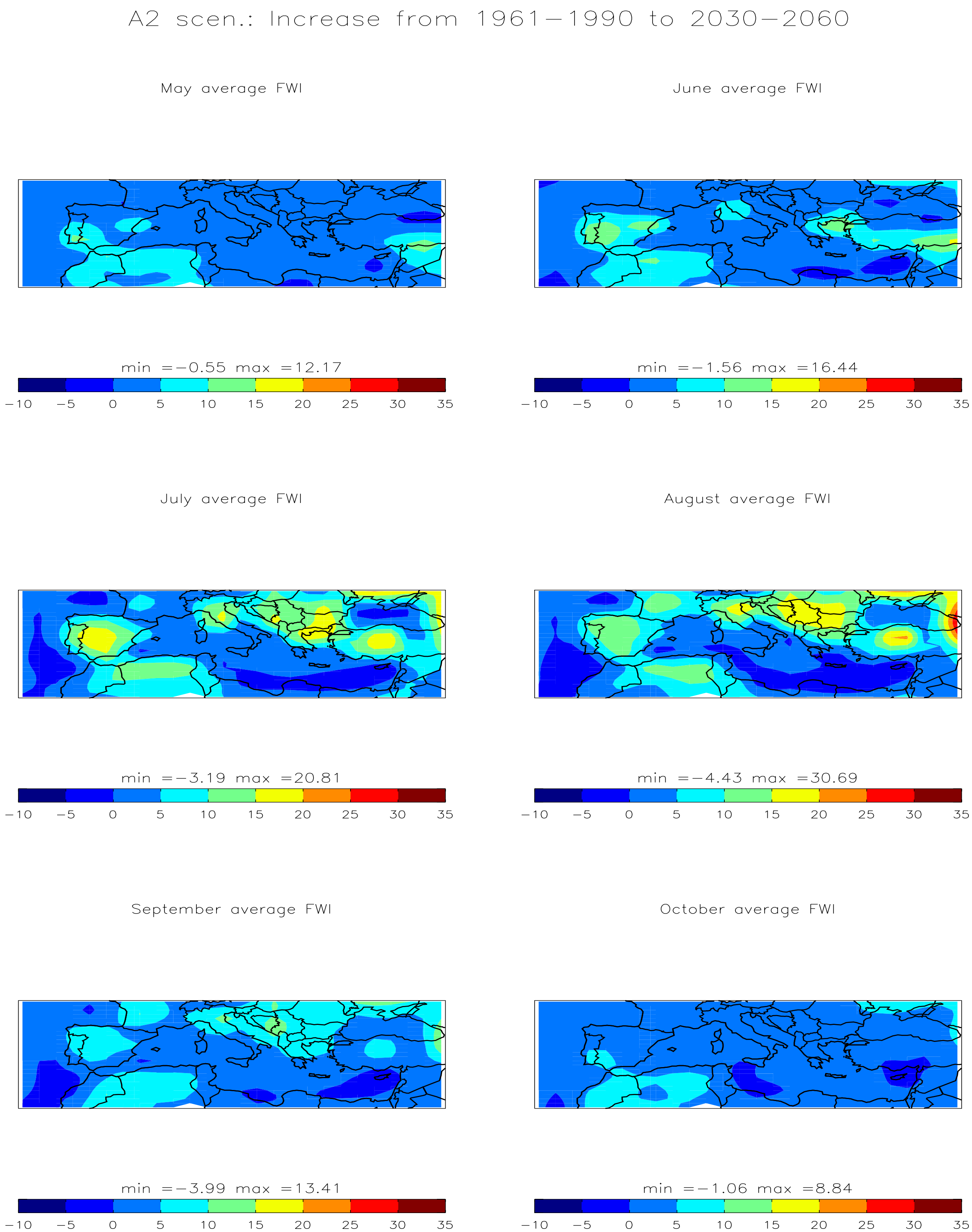


Figure 35. Monthly changes of average FWI from May till October between future and control period.

Fig. 36 shows the increase in the number of days with fire risk (top) and extreme fire risk (bottom). According to this figure, the increase in the mean FWI is translated into:

- 2 to 6 additional weeks of fire risk everywhere, except south Italy and Cyprus and the SEMR.
- The maximum increase is again inland (Spain, Maghreb, Balkans, North Italy, and Central Turkey), where at least an additional month with risk of fire has to be expected.
- A significant proportion of this increase in fire risk is actually extreme fire risk (FWI>30).
- South of France, Crete, and the coastal area of the rest of Mediterranean Region: significant increase in the number of days with fire risk (1-4 weeks), but not in the number of extreme fire risk.

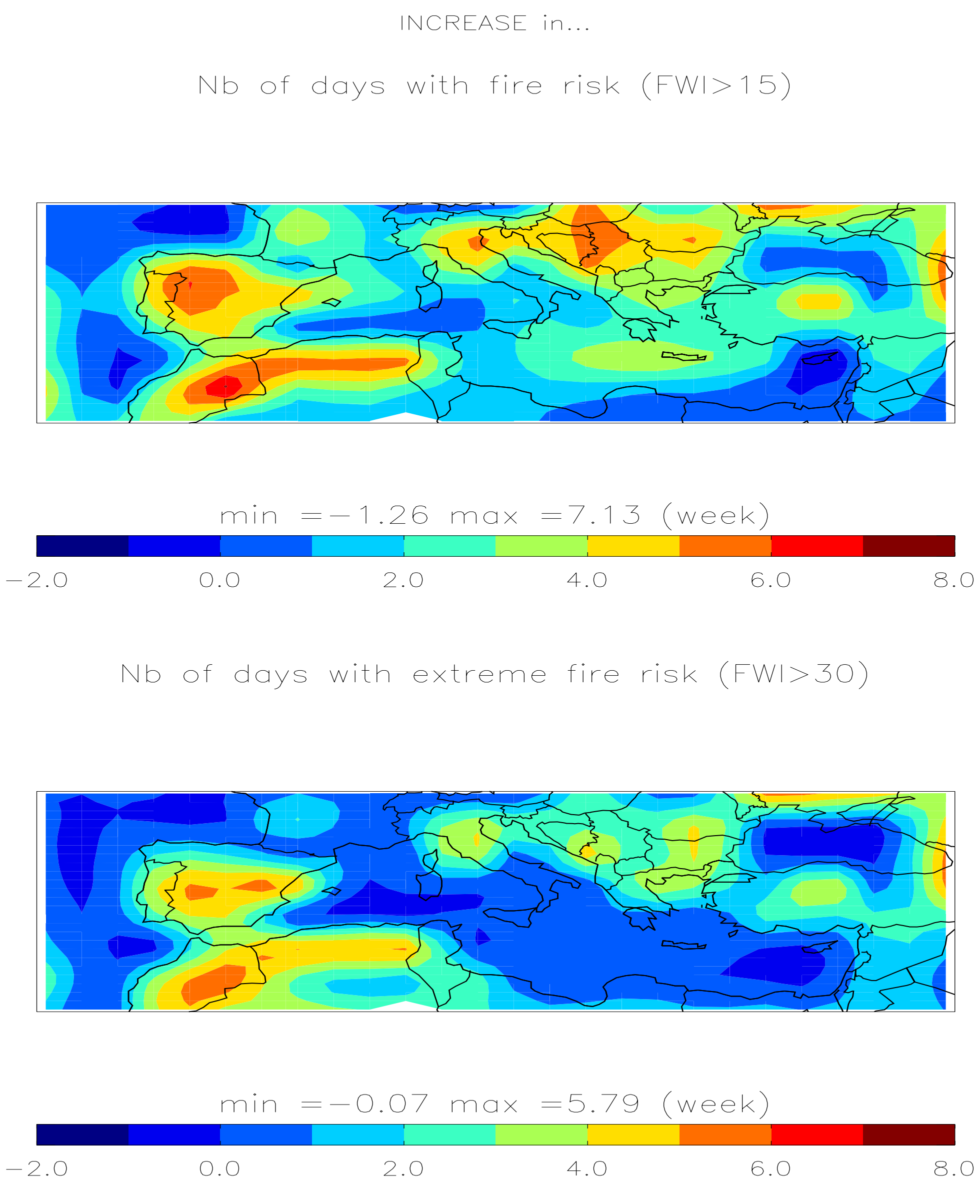


Figure 36. Changes in the number of days with fire risk (top) and extreme fire risk (bottom)between the future and the control period.

To conclude, Fig. 37 shows the number of weeks with fire risk in the future. In the south part of the Mediterranean, practically the whole year is expected to be a period of fire risk.

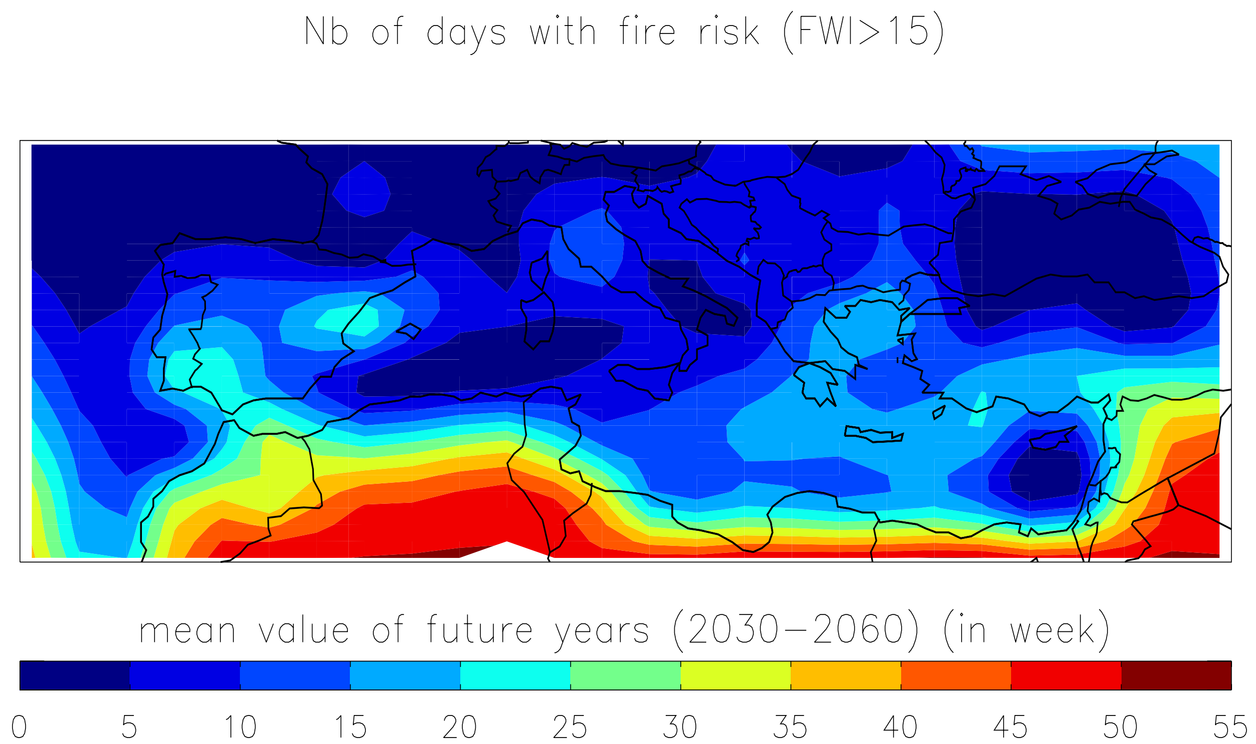


Figure 37. No of weeks with fire risk (FWI>15) in the future period (2031-2060).

6.3 Impacts on tourism

As some measure of the economic importance of summer tourism to the Mediterranean, 147 million international tourists visited the Mediterranean in 2003 (this is 22% of the international tourism market) and generated US$113 billion for the region. 70% of these tourists visited just two countries, Italy and Spain. It is very difficult to model the potential response of tourists to climate change. However, by discussions with experts at the MICE regional workshop entitled "Impacts of climate extreme events on Mediterranean tourism and beach holidays", (which took place in June 2004 in Crete), it was possible to identify some of the impacts climate change may have on the tourism industry (Table 1).

Rising temperatures over the Mediterranean region in 2031-2060 will certainly affect the thermal comfort of tourists and their ability to acclimatise to a region prone to high temperatures and heatwaves. Rainfall is also projected to decrease, leading in turn to shortages in the public water supply and more widespread desertification, which may affect the aesthetics of the region. Water shortages due to extended droughts will also affect tourism flows especially in the SE Mediterranean since the water use has a strong seasonal cycle. The maximum demand coincides with the minimum availability. Perry (2001) reports that a tourist in Spain uses 4 times as much water as a Spanish city dweller, so tourists are not water conscious. He also states that in Crete water shortages could be experienced in 5 years out of 6 by 2010. As noted earlier in this report, the decreased rainfall and increased temperatures in combination will lead to a greater frequency of forest fires. Intense rainfall events in winter may increase especially in the Northern part of the region, leading to greater erosion rates and a higher risk of flooding. Greater heat is also likely to repel at the same time the important old age population and the residents of Mediterranean regions, in France, Italy or Spain. Thus mountainous regions could become appreciated for their relative coolness and the shade of their forests (Ceron and Dubois, 2000).

Table 1: Summary of climate changes and their probable impact on major travel flows in the Mediterranean.

MAJOR TOURISM FLOW	ORIGIN MARKET CLIMATE CHANGE	DESTINATION REGION CLIMATE CHANGE	IMPLICATIONS FOR DESTINATION REGION	POSSIBLE MARKET REACTIONS
NORTHERN EUROPE TO MEDITERRANEAN	-Much warmer, wetter winters -Warmer, drier summers -More reliable summers	-Warmer winters -Much warmer, drier summers - Increased heat index -More heatwaves -More arid landscape -Small tidal range means greater sea level rise impact	-Greater drought and fire risk -Increased water shortages -Greater personal heat stress -Beach degradation and habitat loss due to sea level rises -Vulnerability to more tropical diseases (e.g. malaria) -More flash floods -Poor urban air quality in cities	*Overwhelmingly a leisure travel market* -Improvement of Northern European summers triggers more domestic holidays -Decreased incentive for Mediterranean summer holidays -Increased incentive for shoulder month Mediterranean holidays -Increased incentive for southerners to go north

It is not, however, just the change in climate over the Mediterranean that will impact on the region's tourism. Improvements in the climate of the source regions of the tourists visiting the Mediterranean will also affect the popularity of the area. Warmer, drier and more reliable summers in Northern Europe will encourage tourists to take domestic holidays and will even encourage those in the Mediterranean region to holiday further north, away from the high temperatures and water deficits likely in the south during summer. It is also likely that the Mediterranean holiday season will split into two seasons, in the spring and the autumn, when climate conditions will be more comfortable.

In conclusion:

- Warmer northern European summers encourage an increase in domestic holidays.
- In a warmer future, there is an increased likelihood of people from the Mediterranean holidaying in the north.
- More frequent and more intense heat waves and drought are likely to discourage Mediterranean summer holidays.
- There is likely to be a shift in the Mediterranean holiday season to spring and autumn.

6.4 Impacts on water resources

One of the greatest potential impacts of climate change on human society is through its effect on water resources. The Mediterranean is already a region, experiencing moderate to high water stresses and climate change has the potential to exacerbate further these stresses.

The implications of climate change for water resources stress in the Mediterranean were assessed by the UK Meteorological Office (Arnell, 1999). First, river runoff was simulated with a macro-scale hydrological model. Then changes in national water resource availability were computed (taking into account imports from upstream), and the estimated volume of water available for use was compared with the amount withdrawn by water users. For the period in question in this report (2031-2060), it was projected that runoff decreases substantially in the Mediterranean Europe, North Africa and the Middle East. The North Mediterranean will see a 50mm/year reduction in runoff while the South (already dry) will experience a 25mm/year decrease or less. However, these changes can be very large in percentage terms.

The rise in temperature is expected to also affect the timing of streamflow through the year with particularly large changes in the North Mediterranean, where the higher winter temperatures mean that a much smaller proportion of winter precipitation falls as snow to be stored on the land surface until the spring melt. In these areas winter flows might increase but it is highly likely that spring flows will decrease.

One measure of national water resource stress is the ratio of water used to water available (although this hides within-country variations and the risk of stress during drought conditions), and countries using more than 20% of their total annual water supply are generally held to be exposed to water stress. Using this measure, all countries around the Mediterranean are expected see an increase in water stress.

The sole exception can be Egypt where river runoff from the Nile may actually increase due to floods in the Central African Nile springs.

Some countries have conducted further studies to illuminate the impact of such changes on their countries. In the northern Mediterranean, the Spanish Government estimates that a 1°C increase in the mean annual temperature is likely to lead to a reduction of 5-14% in water yields in the country. In the extreme case of a 4°C increase, water yields could reduce by as much as 22% in some regions (Rodriguez et al., 2005). In the southern Mediterranean, the Algerian Government estimates that a 1°C rise in mean annual temperature would lead to decreases in precipitation by 15% and in influx of surface waters by 30%. Subsequently, water demand would exceed available water resources by 800 million m3 (Government of Algeria, 2001). In the southeastern Mediterranean, the Lebanon Government estimates that by 2050, climate change would be responsible for nearly doubling the water shortage to 350 million m3 of water (Khawli, 1999).

6.5 Impacts on sea level rise

Results from the HadCM3 give a projection of a global rise in sea level of 21cm by the 2050s due to rise in greenhouse gases from human activities (IPCCa, 2001). This estimate includes direct prediction of thermal expansion combined with estimates of land-based ice-melt.

However, global mean sea level rise does not manifest itself uniformly around the world. Regional variations in atmospheric circulation, ocean circulation and warming rates and the interactions between them have led to significant deviations of regionally sea level change from the globally averaged trend.

Model projections of regional sea level patterns show very little agreement. For the Mediterranean, the values range from 1 to 2cm of regional sea level rise per 1 cm of global sea level rise (IPCCa, 2001). This is due to the low tidal range in the Mediterranean combined with the limited potential for wetland migration. The most vulnerable region seems to be the Southern Mediterranean from Turkey to Algeria where flooding impacts can occur particularly in deltaic countries (such as Egypt).

6.6 Impacts on biodiversity

Climate change over the past 30 years has produced numerous shifts in the distributions and abundances of species. Recent studies have tried to quantify future changes under different warming scenarios. Thuiller et al. (2005) shows that a 3.6°C global warming could lead to a loss of over 50% of plant species in the northern

Mediterranean and the Mediterranean mountain region, while species loss is likely to exceed 80% in northcentral Spain and the Cevennes and Massif Central in France. These results are in the direction of earlier studies (e.g., Thomas et al., 2004) although estimates of the magnitudes extinction risks are lower than earlier predictions. Climate change may also have indirect effects on the ecosystem. Grigulis et al. (2005) shows that increased fires due to climate change could increase the spread of invasive grass species which in turn, could lead to more frequent and more intense fires.

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Impact of a 2° C global temperature rise on the Mediterranean region: Agriculture analysis assessment.

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Summary
The climate change impact analysis on agriculture showed that the expected changes in temperature and precipitation for SRES-IPCC scenarios A2 and B2 in the time-slice 2031-2060 determined a general reduction in yield of agricultural crops (e.g. C3 and C4 summer crops, legumes, cereals, tuber crops). Reductions in yields are more severe in the southern Mediterranean than in the northern Mediterranean, even when the fertilizing effect of increased CO_2 is taken into account. The southern Mediterranean is likely to experience an overall reduction of crop yields due to climate change. In some locations in the northern Mediterranean, the effects of climate change and its associated increase in CO_2 may have little or small positive impacts on yields, provided that additional water demands can be met. The adoption of specific crop management options (e.g. changes in sowing dates or cultivars) may help in reducing the negative responses of agricultural crops to climate change. However, such options could require up to 40% more water for irrigation, which may or may not be available in the future.

Materials

Climate data. The daily climate data used for this study was obtained from the simulation results of the HadCM3 model developed by the UK Meteorological Office Hadley Centre. In particular, in order to reproduce the impact of a 2° C global temperature rise on the Mediterranean region, two time-slices 1961-1990 and 2031-2060 were considered to represent present and future climate, respectively. Further, two emission scenarios were selected among those proposed by the Special Report on Emissions Scenarios (SRES) (IPCC 2000): i) scenario A2, characterised by medium-high greenhouse gas emission; ii) scenario B2 characterised by medium-low greenhouse gas emission.

Statistical yield data. In order to select the most important crops for the different areas of the Mediterranean basin and to evaluate the capacity of the selected crop simulation model (i.e. CropSyst) to reproduce crop yields, the data reported in the FAOSTAT database (http://faostat.fao.org/) has been collected for Mediterranean countries.

Crop simulation model. CROPSYST is a multi-year, multi-crop, daily time step crop growth simulation model (Stockle et al, 2003). The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, phenology, dry matter production, yield, residue production and decomposition, and erosion. The model allows the user to specify management parameters such as sowing date, cultivar genetic coefficients (photoperiodic sensitivity, duration of grain filling, maximum leaf area index, etc.), soil profile properties (soil texture, thickness), fertilizer and irrigation management, tillage, atmospheric CO_2 concentration etc. The capability of the model to simulate crop yields has been evaluated in numerous field studies conducted in the Mediterranean, United States and Australia (Stockle et al., 2003). In general, the agreement between simulated and measured yields was good. When properly calibrated and applied, CropSyst has proved to be a suitable tool for simulating cropping systems.

Methods: ***Selection of the hot spots.*** Following the results of the climate analysis assessment performed in Section 5, by C. Giannakopoulos, thirteen grid cells (called 'hot spots') of the HadCM3 has been selected (Fig. 1). More specifically these grid cells (2.5° latitude by 3.75° longitude) were selected to provide an homogenous cover of the study area and to study the areas where changes in precipitation and temperature patterns are expected to be substantial, according to HadCM3 model simulations.

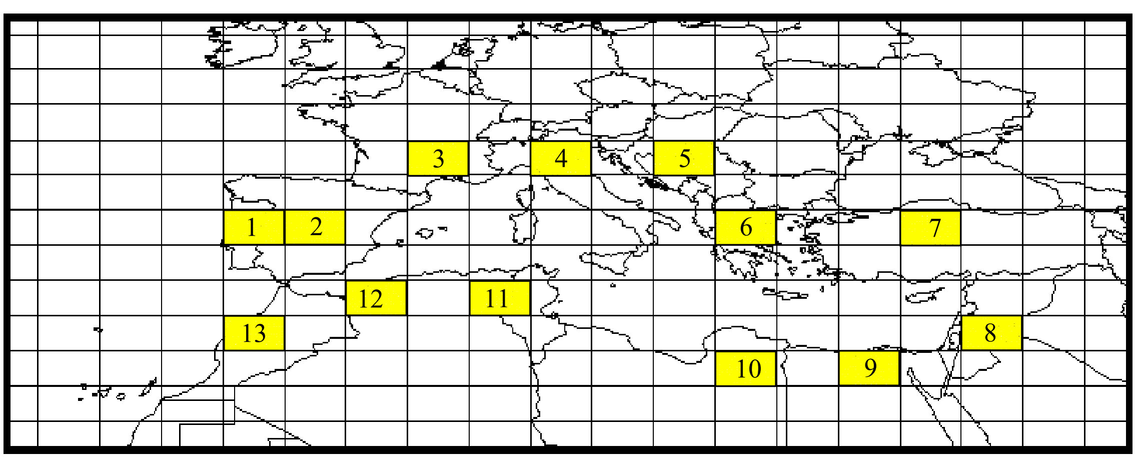

Figure 1 – Grid cells of Had CM3 selected for impact assessment on agriculture

Selection of the crops. The data reported on the FAOSTAT database was used to select the agricultural crops for each 'hot spot'. In particular, the selection of the species was based on the different characteristic of agricultural crops: i) photosynthesis pattern (C3 and C4 crops)[1], ii) growing period (winter an summer seasons), iii) food composition (protein, e.g. legumes and carbohydrates, e.g. tuber crops); and on the basis of the extension of the cultivated area in the countries that are included the grid cells (Tab. 1). No account has been taken of the introduction of new crops which may becomes suitable in these regions.

Table 1 – Type of crop simulated in each of the selected grid cell

Grid cell number	Country	C4 summer crop	C3 summer crop	Legumes	Tuber crops	Cereals
1	Portugal	maize	sunflower	bean	potato	wheat
2	Spain	maize	sunflower	lentil	potato	barley
3	France	maize	sunflower	soybean	potato	wheat
4	Italy	maize	sunflower	soybean	potato	wheat
5	Serbia	maize	sunflower	soybean	potato	wheat
6	Greece	maize	sunflower	bean	potato	wheat
7	Turkey	maize	sunflower	lentil	potato	wheat
8	Jordan	maize	sunflower	lentil	potato	barley
9	Egypt	maize	sunflower	bean	potato	wheat
10	Libya	maize	sunflower	bean	potato	wheat
11	Tunisia	maize	sunflower	bean	potato	wheat
12	Algeria	maize	sunflower	bean	potato	wheat
13	Morocco	maize	sunflower	bean	potato	wheat

Impact analyses. First of all the CropSyst model (Stockle et al. 2003) was calibrated to fit as much as possible the data reported on the FAOSTAT database (http://faostat.fao.org/). Then, for each 'hot spot' and crop type the annual values of development stages and yields were calculated for the two time-slices (1961-1990 and 2031-2060). In particular, for the present climate the simulation runs were done setting the atmospheric concentration of CO_2 at 350 ppm; whilst the simulation runs for the future climate scenarios were done without and with the effects of increasing CO_2 (470 ppm scenario B2 and 520 ppm scenario A2). The crop responses to increasing CO_2 was introduced in the simulation runs following the results obtained in the Free Air CO_2 Enrichment (FACE[2]) experiments (Kimball et al. 2002; Ainsworth and Long 2005). In general, results from FACE experiments show, as under field conditions, the effect of

[1] Almost all plant life on Earth can be broken into two categories based on the way they assimilate carbon dioxide into their systems. C3 plants include more than 95 percent of the plant species on earth (e.g. trees, wheat, sunflower). C4 plants include such crop plants as sugar cane and corn. During the first steps in CO_2 assimilation, C3 plants form a pair of three carbon-atom molecules. C4 plants, on the other hand, initially form four carbon-atom molecules. It turns out that under present CO_2 concentration (≈ 360 ppm) C4 plants are more economical in the use of water and have a much higher yield potential than C3 plants. However, it is expected that C3 plants can respond readily to higher CO_2 levels, and C4 plants can make only limited responses. Thus, increased CO_2 likely will mean that some plant species will be stronger, more prolific, and may overwhelm those less able to benefit.

[2] In FACE experiments, jets of CO2 are released over vegetation plots in the open-air through an array of pipes. Natural wind and diffusion disperse the CO_2 across the experimental area.

CO_2 on crop yields is significantly lower than that obtained in controlled environmental studies.

Finally, the CropSyst model was rerun introducing adaptation management strategies (e.g. changes in sowing dates, cultivar, etc.) that may reduce the negative impact of climate change or enhance positive impacts. In all the simulation runs the C4 summer crops (i.e. maize) and tuber crops (i.e. potato) were considered as "irrigated crops", whilst the rest of the crops were considered as "rainfed crops". Moreover, all the crops were considered fully fertilised (i.e. no nitrogen stress).

Results:

Crop yields under present climate The simulated crop yields for the present climate obtained by calibrating CropSyst model on the basis of the FAO data were reported in Fig. 2. The results showed a pattern of crop yields in rainfed crops (C3 summer crop, legumes, cereals) that is strongly correlated to the precipitation regimes of the different grid cells. Hence, lower crop yields were seen in regions of Northern Africa which is expected to have lower water availability. Whilst for the irrigated crops (C4 summer crops and tuber crops) the differences in crop yields among the grid cells were less evident and these were mainly driven by the temperature regimes.

In order to provide a quantitative estimate of the uncertainties related to the capacity of CropSyst to simulate crop yields, Mean Absolute Errors (MAEs) were calculated for each crop type in four main regions in the Mediterranean (Table 2). Mean absolute error is the average of the difference between modeled and observed value in all test cases and can be considered as the average prediction error for CropSyst simulations for ths study. MAEs also include inherent errors that arise from the comparison of model output with observed data. Simulated values from CropSyst are calculated for individual grid cells while the statistical data from FAO has been collected at the nation level. The climate conditions of the grid cells cannot completely represent the average condition over a nation, and the statistical data also include sources of variability (e.g. technological trend, pest and disease stresses, etc.) that cannot be reproduced by the model.

Table 2. Mean Absolute Error (MAE, %) between observed and simulated crop yields for the main Mediterranean regions: N-W = Portugal, Spain, France and Italy, N-E = Serbia, Greece and Turkey, S-E = Jordan, Egypt and Libya, S-W = Tunisia, Algeria and Morocco

	Mean Absolute Error (MAE, %)				
Region	**C4 summer**	**Legumes**	**C3 summer**	**Tuber crops**	**Cereals**
N-W	9.3	4.6	10.8	8.7	9.8
N-E	4.4	1.4	2.1	6.7	4.3
S-E	12.1	13.8	4.4	11.7	1.3
S-W	13.4	0.9	2.7	3.3	6.4

Table 2 shows that CropSyst results match quite closely with the statistical data collected by FAO, with MAEs ranging from less than 1% to under 14%. The MAEs can also be used as a measure of the uncertainties of crop yield estimates due to the bias between observed and simulated yields. The total uncertainty is likely to be larger due to the uncertainties cascaded from the emission scenarios and the global climate model (see Section 4.4 for a discussion of uncertainty cascades).

Changes in crop yields without the effect of CO_2

The results of the CropSyst simulation runs (without including the effect of CO_2) for present and future climate scenario were reported in Fig. 3. On the basis of the different crop types these are the main results:

- ***C4 summer crops.*** C4 summer crops showed an almost systematic reduction of yields with the exception of a few grid cells located in the EU-Mediterranean countries (e.g. Italy, France, Spain and Portugal). More specifically, these ranges from -15% (Morocco) to + 10% (France) in A2 scenario and from -13% (Morocco) to +9% (France) in B2 scenarios (Fig. 3a).
- ***Legumes.*** Legumes showed a general reduction of yields in all the grid cells with the exception of that on Spain, where, however, the increase was very small. More specifically, these changes ranges from -44% (Morocco) to -13% (Turkey) in A2 scenario and from -45% (Egypt) to +3% (Spain) in B2 scenarios (Fig. 3b).
- ***C3 summer crops.*** C3 summer crops showed a general reduction of yields in all the grid cells with the exception of that on Spain, where, however, the increase was very small. More specifically, these changes ranges from -32% (Portugal) to -6% (Jordan) in A2 scenario and from -23% (Morocco) to +1% (Spain) in B2 scenarios (Fig. 3c).
- ***Tuber crops.*** Tuber crops showed a general reduction of yields in all the grid cells with the exception of those on Jordan and Spain. More specifically these changes ranges from -35% (Morocco) to -1% (Jordan) in A2 scenario and from -31% (Egypt) to +15% (Spain) in B2 scenarios (Fig. 3d).
- ***Cereals.*** Cereals showed a general reduction of yields, even if in a few grid cells the yields increased (Turkey, Greece and Spain). More specifically these changes ranges from -23% (Morocco) to -2% (Turkey) in A2 scenario and from -24% (Libya) to +8% (Turkey) in B2 scenarios (Fig.3e).

The general picture showed a substantial reduction for all the crop types in all the ‘hot spots’ grid cells. This was due to the increases in temperature and reduction in precipitation predicted for both future climate scenarios (A2 and B2), that determined a reduction of the length of the growing period (i.e. higher rate of crop development) (Tab. 3) and the water available for crop growth, respectively. These decreases were higher in summer and not irrigated crops (e.g. C3 summer crops, legumes), since the reductions in precipitation are expected to be higher during the summer periods. Moreover, in general the reductions were higher in A2 scenarios, since for this scenario larger changes in temperature (increase) and precipitation (reduction) regimes were expected. However, the results from the two scenarios agree closely in terms of maximum decreases in yields.

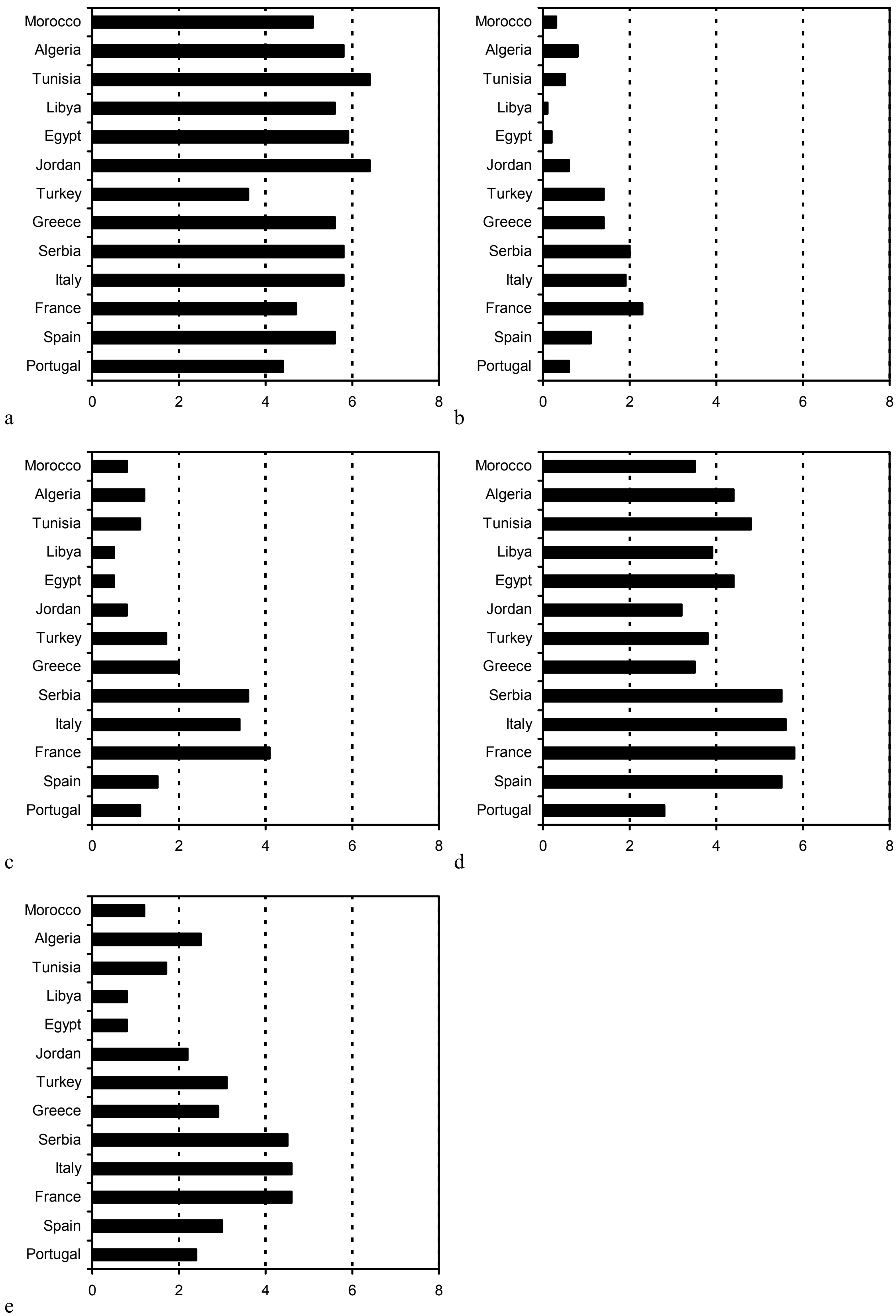

Figure 2- Crop yields (t ha^{-1}) in the selected 'hot spots' grid cells: a) C4 summer crop, b) legumes, c) C3 summer crop, d) tuber crops, e) cereals.

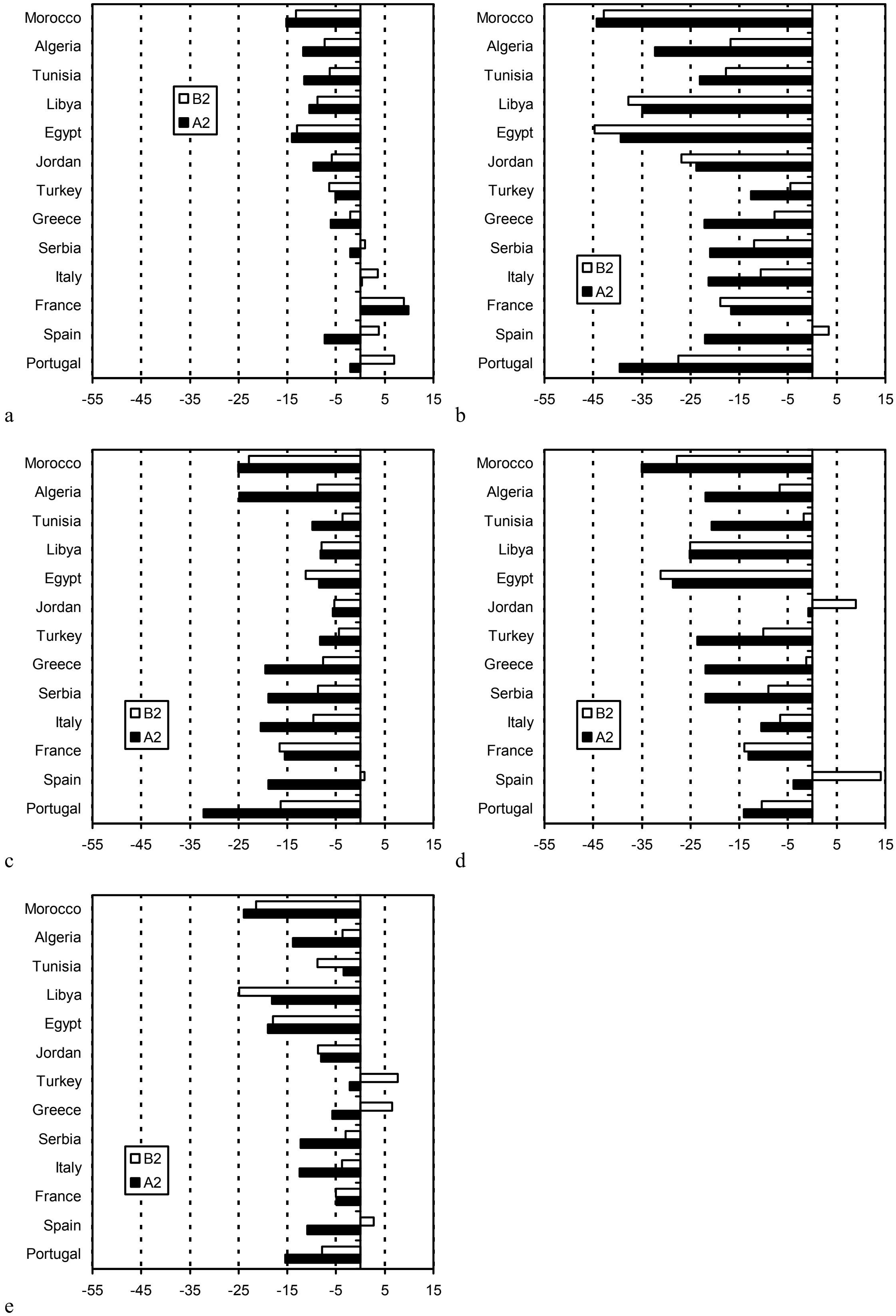

Figure 3- Impact of climate change on crop yields without CO_2 effect: a) C4 summer crop, b) legumes, c) C3 summer crop, d) tuber crops, e) cereals. The changes reported in the figures were expressed as % and obtained as differences between the mean yields of the two futures and the present yields.

Table 3 – Mean length of the growing season for the different crop types under the present climate scenario and mean percentage changed under future scenarios

Crop type	Length (days)	A2 (% change)	B2 (% change)
C4 summer crop	126.3	-8.0	-7.5
C3 summer crop	131.2	-6.7	-6.4
Legumes	108.0	-5.9	-5.7
Tuber crops	170.4	-5.5	-4.7
Cereals	214.0	-1.7	-1.8

Changes in crop yields with the effect of CO_2

The results of the CropSyst simulation runs (including the effect of CO_2) for present and future climate scenario were reported in Fig. 4. On the basis of the different crops types these are the main results:

- ***C4 summer crops.*** C4 summer crops showed a prevalent reduction in yields in the grid cells located in the African and Asian Mediterranean countries (e.g. Morocco, Tunisia, Jordan, etc.); whereas on the European grid cells yields showed a consistent increase. More specifically, these changes ranges from -12% (Morocco) to + 16% (France) in A2 scenario and from -11% (Egypt) to +13% (France) in B2 scenarios (Fig. 4a).
- ***Legumes.*** Legumes showed a general reduction of yields in all the grid cells with the exception of those on Spain, Turkey and Greece. More specifically, these changes ranges from -39% (Morocco) to +2% (Turkey) in A2 scenario and from -41% (Egypt) to +15% (Spain) in B2 scenarios (Fig. 4b).
- ***C3 summer crops.*** C3 summer crops showed a general reduction of yields in the grid cells located on Northern and South-western shores of the Mediterranean basin; whereas in the grid cells located on the Southern or Eastern shores, yields were substantially unchanged. More specifically, these changes ranges from -21% (Portugal) to +6% (Turkey) in A2 scenario and from -16% (Morocco) to +11% (Spain) in B2 scenarios (Fig. 4c).
- ***Tuber crops.*** Tuber crops showed an inconsistent response among selected grid cells, with a general reduction of yields in those on the African shores of the basin, and prevalent increase in the rest. More specifically these changes ranges from -25% (Morocco) to +16% (Jordan) in A2 scenario and from -27% (Egypt) to +30% (Jordan) in B2 scenarios (Fig. 4d).
- ***Cereals.*** Cereals showed a prevalent increase in yields. More specifically these changes ranges from -15% (Morocco) to +13% (Tunisia) in A2 scenario and from -19% (Libya) to +19% (Turkey) in B2 scenarios (Fig. 4e).

The general picture showed that the effect of climate change on agriculture in tropical areas are likely to be more severe than in temperate areas, even when the fertilizing effect of increased CO_2 is considered (Table 4). In the warmer southern Mediterranean, increases in CO_2 help to reduce the loss in yield arising from a warmer and drier climate, but is not able to completely offset the losses. In the cooler northeastern Mediterranean, CO_2 increase and the associated climate change result in little net effect on most crops, provided that the increase in water demands, especially for irrigated crops, can be satisfied (Table 4). Similarly in the northwestern Mediterranean, yields of irrigated crop may increase if water demands can be met. However, rainfed summer crops are likely to experience a net reduction in yield, even when the fertilizing effect of CO_2 is considered.

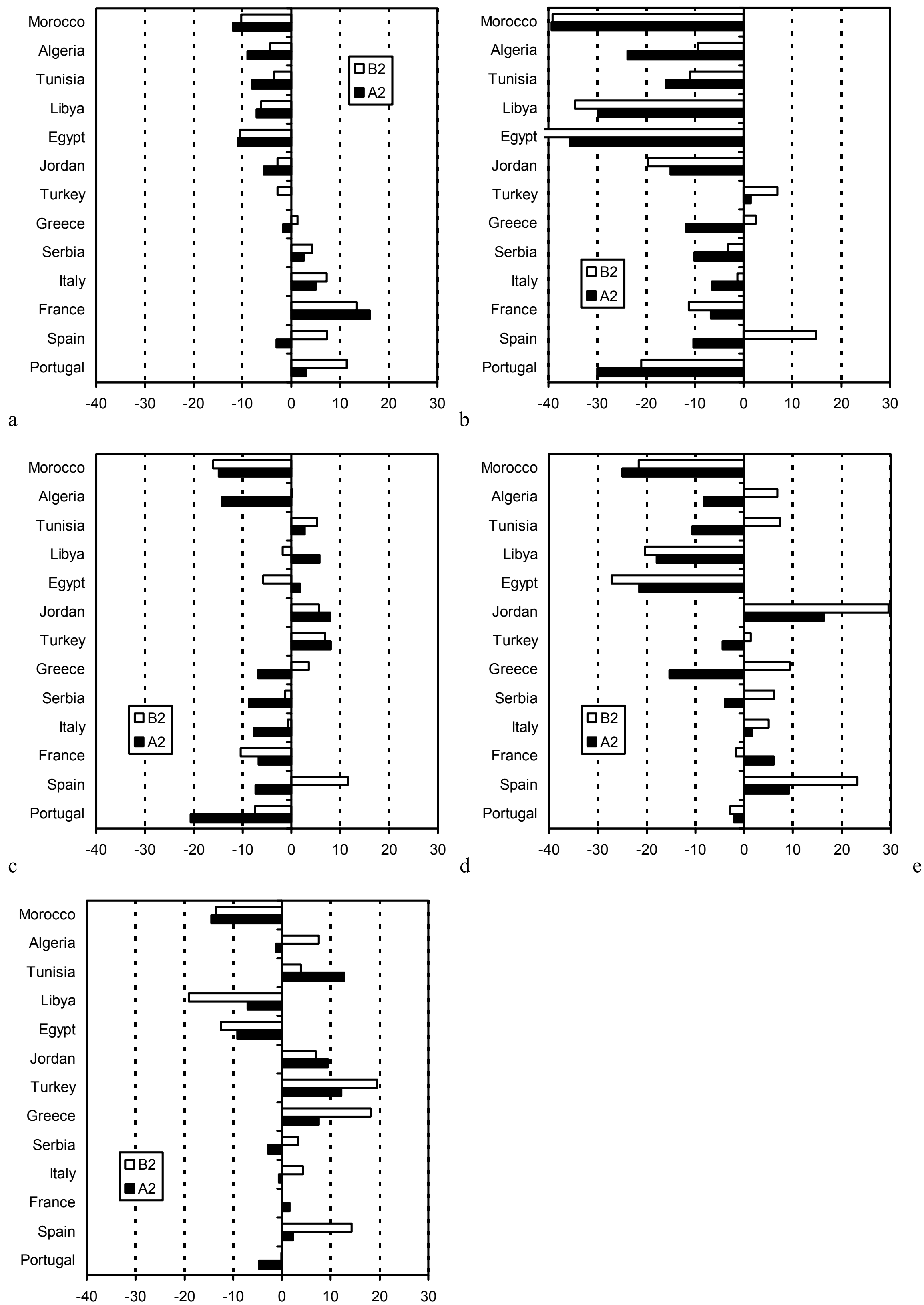

Figure 4- Impact of climate change on crop yields with CO_2 effect: a) C4 summer crop, b) legumes, c) C3 summer crop, d) tuber crops, e) cereals. The changes reported in the figures were expressed as % and obtained as differences between the mean yields of the two futures and the present yields.

Table 4 – Percentage changes of crop yields for the main Mediterranean regions: N-W = Portugal, Spain, France and Italy, N-E = Serbia, Greece and Turkey, S-E = Jordan, Egypt and Libya, S-W = Tunisia, Algeria and Morocco

		Without CO_2		**With** CO_2	
		A2-A	**B2-A**	**A2-A**	**B2-A**
C4 summer	N-W	0.19	5.80	4.19	8.78
	N-E	-4.43	-2.54	-0.60	0.21
	S-E	-11.44	-9.26	-7.89	-6.70
	S-W	-12.87	-8.94	-9.38	-6.37
Legumes	N-W	-24.90	-13.42	-14.38	-4.86
	N-E	-18.59	-8.11	-7.19	0.97
	S-E	-32.72	-36.43	-23.30	-30.15
	S-W	-33.26	-25.81	-23.92	-18.48
C3 summer	N-W	-21.79	-10.44	-12.41	-2.85
	N-E	-15.57	-6.92	-5.44	0.96
	S-E	-7.44	-8.19	3.66	-0.41
	S-W	-19.94	-11.81	-10.33	-4.34
Tubers	N-W	-10.37	-4.24	4.87	7.53
	N-E	-22.50	-6.80	-9.33	4.39
	S-E	-18.22	-15.77	-4.31	-5.66
	S-W	-25.88	-12.10	-13.28	-1.55
Cereals	N-W	-10.97	-3.49	-0.29	4.68
	N-E	-6.79	3.71	4.39	12.49
	S-E	-15.08	-17.17	-4.88	-10.15
	S-W	-13.77	-11.29	-3.42	-3.77

Impacts of adaptation options

The results of the CropSyst simulation runs (including adaptation strategies) for present and future climate scenarios were reported in Fig. 5. On the basis of the different crops types these are the main results:

- ***C4 summer crops.*** C4 summer crops showed that the introduction of cultivars with a longer growing cycle or the early sowing of standard cultivars determined positive effects on crop yields. More specifically, the average changes of yields passed from – 1% with standard cultivar to +1% and +9% with an early sowing and cultivar with longer growing cycles, respectively (Fig. 5a).
- ***Legumes.*** Legumes showed that the introduction of an early sowing of standard cultivars determined positive effects on crop yields. More specifically, the average changes of yields passed from – 15% with standard cultivar to -10% and +4% with an early sowing and cultivar with longer growing cycles, respectively (Fig. 5b).
- ***C3 summer crops.*** C3 summer crops showed that the introduction of an early sowing of standard cultivars determined positive effects on crop yields. More specifically, the average changes of yields passed from – 3% with standard cultivar to +5% and -1% with an early sowing and cultivar with longer growing cycles, respectively (Fig. 5c).
- ***Tuber crops.*** Tuber crops showed that the introduction of cultivars with a shorter growing cycle or the early sowing of standard cultivars determined positive effects on crop yields. More specifically, the average changes of yields passed from – 3% with

standard cultivar to +16% and +6% with cultivars with longer growing cycles an early sowing, respectively (Fig. 5d).
- ***Cereals.*** Cereals showed that the introduction of cultivars with a longer growing cycle or the early sowing of standard cultivars determined positive effects on crop yields. More specifically, the average changes of yields passed from +1% with standard cultivar to +8% and +9% with cultivars with longer growing cycles and early sowing, respectively (Fig. 5e).

The introduction of adaptation strategies showed the possibility to reduce the negative effects determined by the changes in climate conditions. Anticipation of the sowing date may allow the crops to escape the water stress during the late period of the growing cycle. Cultivars with longer growing period may increase the length of the filling of reproductive organs that under future climate is expected to be shorter for the increasing temperature. Both options, however, would require additional water for irrigation. In particular, the effective use of long cycle cultivars can demand 25 – 40 % more water (Table 5), which may or may not be available in the future.

Table 5 - Mean percentage changes of water supply for irrigated crops under future scenarios for different adaptation options

Crop type	**Scenario A2**			**Scenario B2**		
	Standard (%)	Early sowing (%)	Long cycle (%)	Standard (%)	Early sowing (%)	Long cycle (%)
C4 summer crop	2.9	3.6	25.1	2.6	2.6	26.5
Tuber crops	7.0	9.6	43.7	7.8	8.3	41.0

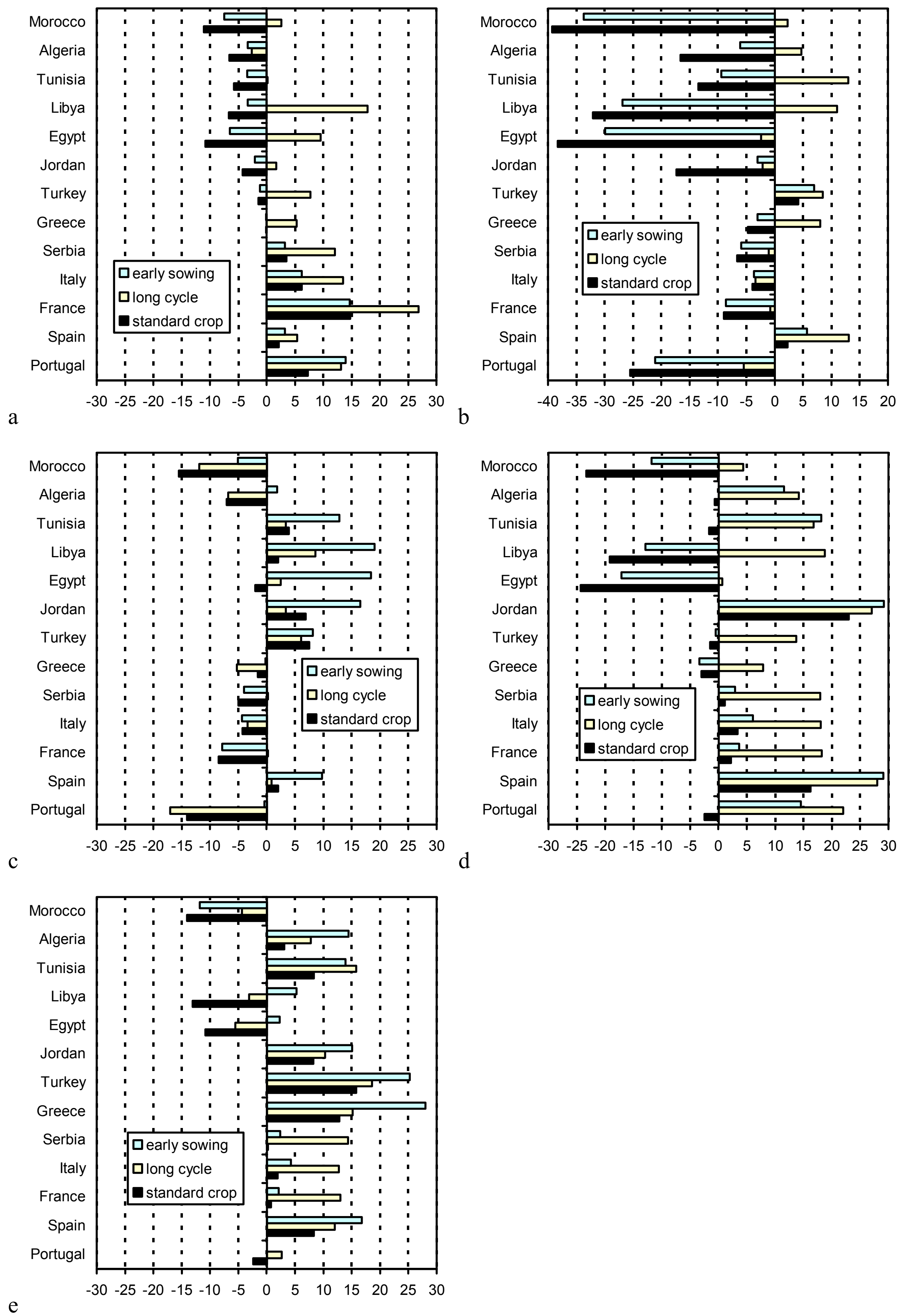

Figure 5 - Impact of different crop adaptation options on crop responses under climate change: a) C4 summer crop, b) legumes, c) C3 summer crop, d) tuber crops, e) cereals. The changes reported in the figures were expressed as % and obtained as differences between the mean yields of the two futures and the present yields.

Discussions and Conclusions

Our study showed that the increases in temperature and reduction in precipitation predicted for both future climate scenarios (A2 and B2) lead to a substantial reduction of yields for all the crop types in all the 'hot spots' grid cells, through the reduction of the length of the growing period and the water available for crop growth. Reductions in yields are more severe in the warmer southern Mediterranean than in the cooler northern Mediterranean, even when the fertilizing effect of increased CO_2 is taken into account. The southern Mediterranean is likely to experience an overall reduction of yields due to climate change. In some locations in the northern Mediterranean, the effects of climate change and its associated increase in CO_2 may have little or small positive impacts on yields, provided that additional water demands can be met.

Strategies such as early sowing dates or cultivar with slower development rates may be considered as helpful options to reduce some of the reductions in crop yield determined by the changes in climate conditions. However, such options could require up to 40% more water for irrigation, which may or may not be available in the future.

Moreover, according to recent studies on the effects on crop yields of tropospheric pollutants such ozone, there is reason to believe that our estimates of yield losses under a future scenario may be conservative. Current and increased concentrations of ground level ozone have been shown to lead to decreases in plant biomass and yield (Morgan et al., 2003; Gitay et al., 2001). Independently of climate change, but exacerbated by it, surface ozone concentrations are expected to increase globally. Thus, if the effects of ozone are to be included in an assessment of crop yields in the Mediterranean under a future climate scenario, the results are likely to greater yield reductions than presented in this report.

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