

# Possible Climate Change Scenarios with Specific Reference to Mediterranean Regions

Josep Calbó

**Abstract** The Mediterranean basin is one of the most sensitive areas of the world regarding possible consequences of the present, anthropogenic-induced climate change. Besides temperature increase, most models consistently project rainfall decreases both on annual basis and for all seasons. On the basis of results from general circulation models (as presented in the recent Fourth Assessment Report of the IPCC) and also from results of several downscaling studies applied to Europe and the Mediterranean areas, some quantitative projections are summarized in this chapter. On average for the region, temperature is projected to increase about 3.5°C on an annual basis by the end of this century, with remarkable differences among specific areas. Precipitation could be reduced more than 10% (annual and regional average), the decrease being larger in summer and in the southern areas of the region. There are many uncertainties involved in these projections; basically, they derive from the unknown future emissions of greenhouse gases and aerosols, from the knowledge gaps of the complex climatic system, and from limitations of models and downscaling techniques. Despite these uncertainties, it is highly probable that water availability will be reduced in the Mediterranean areas as a consequence of increased temperatures and decreased and more variable precipitation. This result should be taken into account by water management agencies, concerned stakeholders and society in general.

**Keywords** Climate change, Climate projections, Downscaling, Mediterranean, Uncertainties

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J. Calbó

Department of Physics and Institute of the Environment, Universitat de Girona, EPS-II, Campus de Montilivi, 17071 Girona, Spain  
e-mail: josep.calbo@udg.edu

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## 1 Introduction

Recent climatic change is a phenomenon of planetary scale, which has its effects at regional and local scales also. Given the dimension of the phenomenon and its causes, that is the introduction into the atmosphere of greenhouse gases as a result of the human activities, the study of climatic projections needs to derive from this same global scale. The recent Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) presents its conclusions first, on the global scale projections, followed by regional projections [1]. In discussing about climate projections, it should be understood that they are estimations about the future climate, in the next decades. These projections depend mainly on three factors: first, the future emissions of greenhouse gases (which depend on demographical, economical, and technological evolutions, and on future regulatory efforts that might be implemented); second, the understanding of the climate system, which continuously improves as a result of basic research efforts; third, the ability of numerical models in reproducing this climate system, in close connection with the capabilities of computation technologies.

Climate projections are mostly obtained as a result of climate models, in particular the so-called Atmospheric Oceanic General Circulation Models (AOGCM). These models are numerical tools that incorporate most of the knowledge about the climate system to produce climate scenarios depending on factors that affect the climate (i.e., climate “forcings”). These forcings are one of the main sources of uncertainty in climate projections, and are strongly linked with the emissions of greenhouse gases and aerosols; the diversity of possible future evolution of emissions is addressed through the use of the so-called emission scenarios.

Indeed, the most important factor that affects the future estimates of climate is the (anthropogenic) emissions of greenhouse gases and all kind of aerosols. The amount of these products released into the atmosphere depends upon the socio-economical and technological development of humankind. Thus, different hypotheses about these evolutions are assumed, resulting in several emission scenarios. The scenarios used in the IPCC AR4 derive from a Special Report on Emission Scenarios (SRES) published earlier [2]. All these scenarios can be grouped in four families (storylines) that are named A1, A2, B1, and B2.

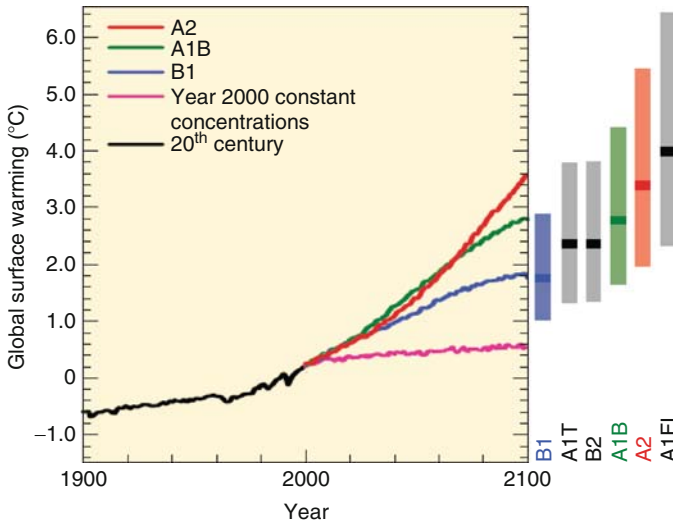
All predicted scenarios show that greenhouse gases emissions will keep growing, at least until the middle of the present century. Among these scenarios, A2 produces the maximum emissions along the twenty-first century, while B1 is the most optimistic, i.e., forecasts the lowest emissions. In general, most climate projections are based on intermediate scenarios, such as B2 or A1B (a particular case within the A1 scenarios that assumes that energy will be obtained from a variety of sources, including fossil fuels and renewable). Despite the assumption that emissions would start to decrease by the middle of the century in some scenarios, atmospheric concentrations would increase further, in all cases, until reaching a new equilibrium state. In scenario B1, CO<sub>2</sub> concentration reaches 500 ppm by 2100; in scenario A1, this concentrations is reached by 2050, and by 2100 the concentration is more than 800 ppm, i.e., far more than double the preindustrial amount of 280 ppm.

This chapter summarizes climate projections presented by the recent Fourth Assessment Report (AR4) of the IPCC, both for the global scale and for the so-called European and Mediterranean region. Besides the IPCC projections, other results regarding the Mediterranean area will be reviewed as well. The emphasis will be mostly placed on temperature and precipitation projections, while other variables, such as wind, solar radiation, or sea level, will not be commented in depth. Some attention will be paid to methodologies used to develop projections, and the corresponding uncertainties will be commented. In general, projections will be given for the end of the current century.

## 2 Global Projections After the IPCC AR4

As a consequence of the continuous increase in concentration of greenhouse gases, global mean temperature will increase in the future [3], as it has been doing in recent years. Figure 1 shows this projected increase, for several emission scenarios and relative to the period 1980–1999 (recall that the average temperature in this period is at least 0.5°C higher than the mean temperature by the end of the nineteenth century). Depending on the emission scenario and on the model used, the temperature increase ranges between 1.1 and 6.4°C by the end of the twenty-first century. The best estimate for the most optimistic scenario included (B1) is an increase of 1.8°C, and the best estimate for the most pessimistic scenario (A1FI) is an increase of 4.0°C. For the most immediate decades, all scenarios show very similar temperature increases: for example, about 1.2°C by 2040.

Most models indicate a global increase of precipitation. Nevertheless, given the great disparity among models, and the great heterogeneity and variability of precipitation across the Earth, the AR4 does not produce global average values of precipitation changes. In general, most AOGCM generate precipitation increases within the intertropical area, and also at higher latitudes of both hemispheres, as well as precipitation decreases at subtropical latitudes. On the other hand, the AR4 indicates that an increase in the frequency of heavy precipitation events is very



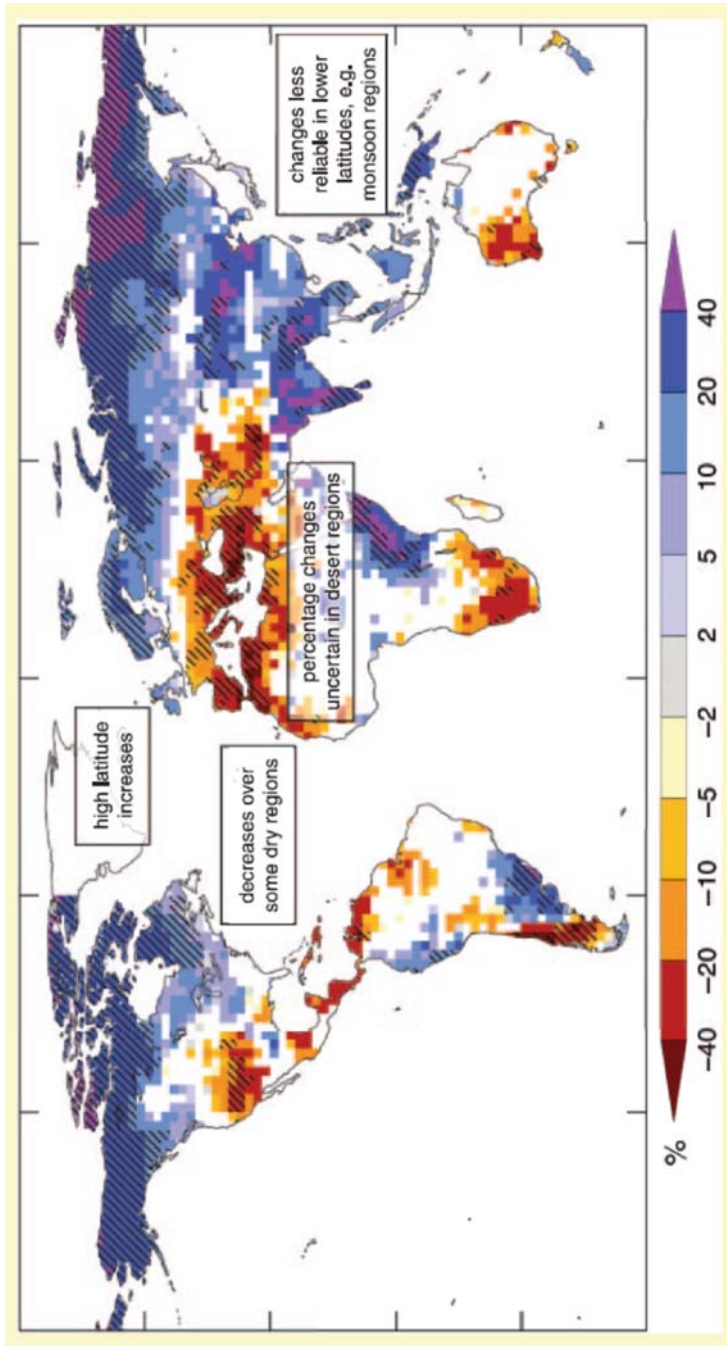
**Fig. 1** Global mean surface temperature evolution during the last century (observed) and projected for the next century. Bars on the right show the possible range of temperature increases from different AOGCM, and also from Simple Climate Models (SCM) and Earth Models of Intermediate Complexity (EMIC). Figure taken from IPCC [1]

likely over most areas, while the length and frequency of dry spells may likely increase in areas where they are currently usual.

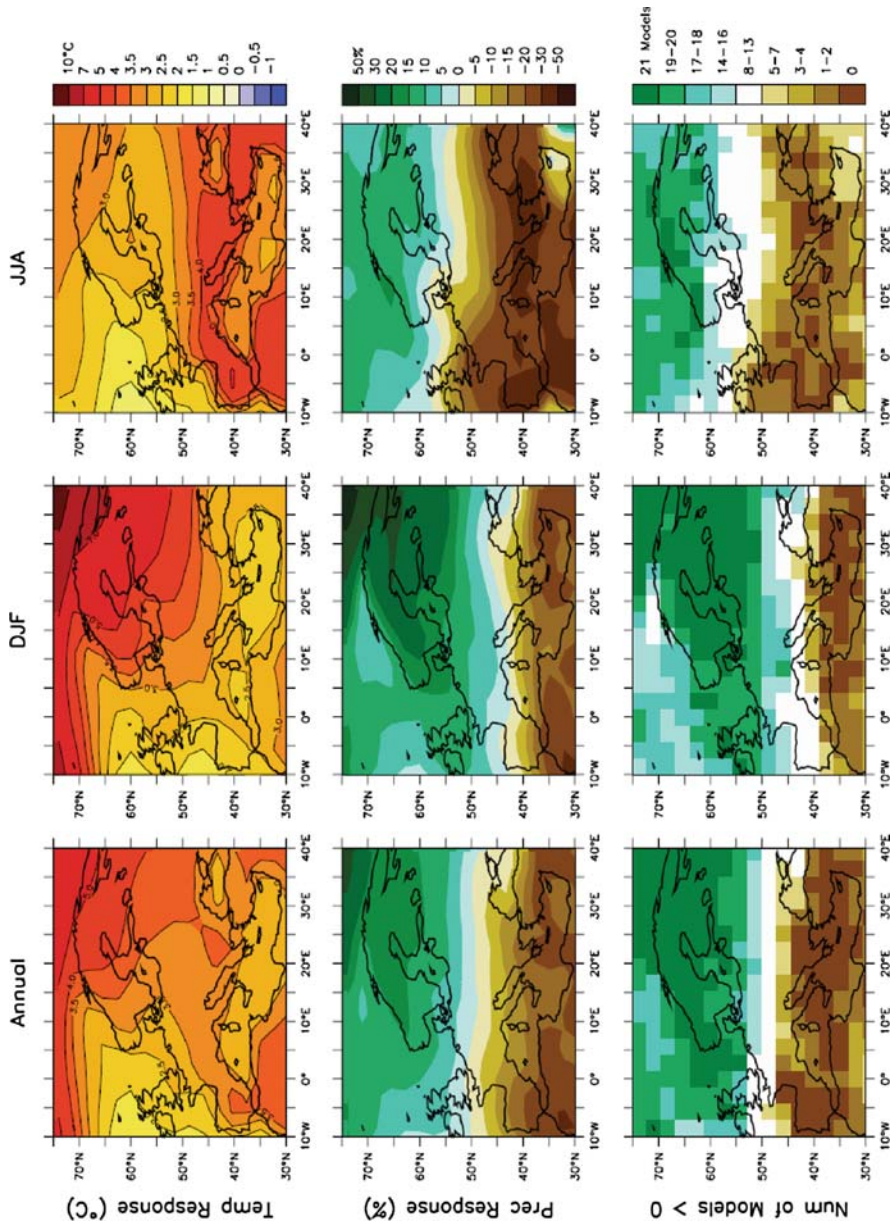
According to the AR4, it is very likely that some currently semiarid areas will suffer a clear decline of water availability. Among these areas, the Mediterranean region is particularly highlighted. To illustrate this fact, Fig. 2 shows changes in surface runoff as a result of changes in precipitation and temperature (that induce evapotranspiration increases). It is apparent that the Mediterranean regions may suffer a significant decline of between 20 and 40%. These results, however, are not particularly robust: surface runoff models deviate from measurements in the present climate, so these projections must be taken with caution.

Figure 3 shows temperature and precipitation changes for Europe and the Mediterranean, according to the results of 21 global models included in the Program for climate models diagnostic and intercomparison (PCMDI) that produced the so-called “multimodel data set” (MMD). These results correspond to the A1B emission scenario and are given for the end of this century (2080–2099) with respect to the end of the previous century (1980–1999); values plotted are calculated as the average of the variations produced for each model. Results are presented both for the annual basis and for seasonal basis (summer, June–July–August; and winter, December–January–February).

On an annual basis, temperature increase will be between 2.5 and 3.5°C for this scenario, lower on the sea itself and in coastal areas, higher in the interior of Iberian and Balkan peninsulas and in Northern Africa. These increases are slightly lower in winter, and remarkably higher in summer, when temperature increases of more than



**Fig. 2** Relative changes (between 2080–2099 and present, 1980–1999) of annual surface runoff on the globe, from results of several climate models forced by emissions of scenario A1B. Dashed areas indicate that more than 90% of models agree with the sign of change. Taken from IPCC [1]



**Fig. 3** Temperature changes (top) and precipitation changes (middle) in Europe and the Mediterranean, from the simulations performed by 21 global models, for the A1B scenario. Values are differences between 2080–2099 and 1980–1999. Left column, annual mean; middle column, winter mean; right column, summer mean. An assessment of the uncertainty of precipitation changes is given in the bottom row, by indicating the number of models that give the same sign of change. Taken from Christensen et al. [4]



4°C are projected for most land areas in the Mediterranean region. Regarding precipitation, there is a clear latitudinal gradient within the analyzed area. Thus, in the South of the Mediterranean region (including part of the Iberian Peninsula and most of Northern Africa), the average precipitation decline in annual basis might be as large as 20%. All Mediterranean countries would suffer this or even stronger precipitation declines in summer, while in winter the change is lower, particularly in the northern half of the Mediterranean. Although these results carry some uncertainty, the Mediterranean region is one of the few areas in the World where most models, for all seasons, agree in the decreasing trend in rainfall [4].

### 3 Downscaling Projections to Mediterranean Regions

#### 3.1 *Downscaling Techniques*

Global models used so far to estimate climate projections such as those presented above, are based on numerical computations on a grid that typically has sizes of 2–3° both in latitude and longitude. Therefore, global models do not include a good description of orography or coastal lines, at least, not at the level required to obtain a reliable climate description for Europe or the Mediterranean. A possible solution for this issue would be to increase resolution of global climate models, but this is limited by the computing capabilities in practical applications. Therefore, as long as global models cannot work at finer resolutions (about 50 km or better), some technique for “regionalization” or “downscaling” is required to obtain more spatial detail of climate projections. Researchers have already established several downscaling methodologies in recent years; all of them, however, rely on results of global climate models, since downscaling methods do not really project the climate into the future, but convert global results into higher resolution results.

Broadly speaking, there are two main downscaling techniques, and some methodologies that are variations or combinations of these two. Firstly, dynamical downscaling consists in the use of regional climate models nested within global models. That is, a high resolution model is applied in a limited area of the world, while low-resolution AOGCM is applied globally and supplies the necessary boundary conditions to the former. Secondly, statistical downscaling consists in multivariable statistical regressions (or other statistical techniques) between climatic variables at a particular point (or small region) and the values obtained in one or several cells of a global model. Sometimes, the relationship is established between a particular point and some index that summarizes the synoptic state of the atmosphere. For example, several indices relative to the behavior of a low frequency synoptic pattern or a teleconnection mechanism are commonly used: the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the El Niño-Southern Oscillation (ENSO), the Western Mediterranean Oscillation (WeMO) indices, among others. The analogue methodology is still a statistical technique,

which is founded upon the clustering of all possible synoptic situations in a few typical cases; knowing the frequency (that might be changing) of each of these cases and the local behavior of the weather for each situation allows estimating the local climate.

Whatever is the methodology used, a regional climate projection is the result of combining a) an emission scenario, b) the output of a global model forced with these emissions, and c) a particular downscaling technique. Therefore, note that the number of uncertainties involved is huge: some arise from the human behavior (emissions), some from limitations in knowledge (for example, cloud physics) and due to the chaotic nature of the climate system, and some are a result of computing limitations or of the statistical method (for example, it is assumed that current relations between synoptic state and local weather will remain valid in the future). In this sense, some authors advocate for recognizing the fundamental, irreducible uncertainties that limit the accuracy of climate predictions [5].

As an attempt to provide climate projections for Europe and to assess the implicated uncertainties, the PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects, Christensen [7]) involved, during 2002–2005, more than 20 European research groups. The specific goal of the project was to obtain climate scenarios with high resolution, for Europe and for the end of the twenty-first century, by using dynamical downscaling. Experiments performed in the frame of PRUDENCE consisted of a control simulation for the period 1961–1990 (which was used to evaluate the ability of the regional models, i.e., to validate them) as well as other simulations for the future period 2071–2100. Most simulations were performed for the A2 scenario, and used the output of an atmospheric model (HadAM3H) which in its turn was initialized by the output of the HadCM3 AOGCM. Other simulations were performed for the B2 scenario or forced by the output of another global model (ECHAM4/OPYC3) [6]. Regarding the regional models, PRUDENCE used ten different models developed at several European institutions. All of them were run with a resolution of around 50 km, and applied for an area that covered most of Western Europe. The project produced a number of reports and peer-reviewed papers that may be considered the state-of-the-art regarding climate projections for Europe ([7–9]). More recent projects, however, are producing new results. In particular, the ENSEMBLES project deals with developing an ensemble prediction system for climate change based on the principal state-of-the-art, high resolution, global and regional Earth System models developed in Europe. The goal is to produce for the first time an objective probabilistic estimate of uncertainty in future climate at the seasonal to decadal and longer timescales [10].

### **3.2 Results for the Mediterranean Area**

On the basis of results from GCM (Fig. 3) the AR4 summarizes the projected changes for the Mediterranean region (Table 1, regarding temperature changes; Table 2 for precipitation), the moderate emission scenario A1B having been



**Table 1** Summary of projections from the 21 models included in the *MultiModel Data set*, for the Mediterranean region (30°N, 10°W–48°N, 40°E) and the A1B emission scenario. Temperature differences (°C) between 2080–2099 and 1980–1999. The table shows the minimum, maximum, median (50%), and 25 and 75% quartile values. The frequency of extremely warm, averaged over the models, is also shown. From Christensen et al. [4]

Season	Min.	P25	P50	P75	Max.	Warm seasons (%)
DGF	1.7	2.5	2.6	3.3	4.6	93
MAM	2.0	3.0	3.2	3.5	4.5	98
JJA	2.7	3.7	4.1	5.0	6.5	100
SON	2.3	2.8	3.3	4.0	5.2	100
Annual	2.2	3.0	3.5	4.0	5.1	100

**Table 2** As in Table 1, but for precipitation differences (%)

Season	Min.	P25	P50	P75	Max.	Wet seasons (%)	Dry seasons (%)
DGF	-16	-10	-6	-1	6	3	12
MAM	-24	-17	-16	-8	-2	1	31
JJA	-53	-35	-24	-14	-3	1	42
SON	-29	-15	-12	-9	-2	1	21
Annual	-27	-16	-12	-9	-4	0	46

considered in both cases. On annual basis, the temperature is projected to increase in the range of 2.2–5.1°C (median of the 21 models, 3.5°C). Note that unlike most areas in the world, in the Mediterranean, the largest temperature increment is expected in summer. The average precipitation projected decrease, for the whole area and on annual basis, is in the range -16%, -9% (median of the 21 models, -12%); summer is the season with the largest expected precipitation decreases.

Combining an analysis of these results from GCM with results from the PRUDENCE project, the AR4 also [4] presents some clear facts about the future climate in Europe and the Mediterranean:

- Annual mean temperatures in Europe are likely to increase more than the global mean. Seasonally, the largest warming is likely to be in northern Europe in winter and in the Mediterranean area in summer.
- Maximum summer temperatures are likely to increase more than the average in southern and central Europe.
- It is very likely that the mean annual precipitation will decrease in most of the Mediterranean region. The annual number of precipitation days is very likely to decrease in the Mediterranean area.
- It is likely that the risk of hydrological drought (as a result of precipitation and evaporation trends) will increase, in particular in summer in Southern Europe and the Mediterranean.
- It is very likely that the snow season will shorten in most of Europe. It is also very likely that the winter accumulation of snow will decrease.

Besides the IPCC AR4, several specific works make reference to climate projections for Europe and/or the Mediterranean, some being related with the PRUDENCE project also. One particular study is that of Sánchez et al. [11] where

they use one regional climate model (PROMES) to analyze and show changes of temperature and precipitation and their related extreme events by the end of this century for the scenario A2. They conclude that it is convenient to use a set of diagnostic indices for a correct analysis of climate extreme events, trends and changes, since frequency or intensity parameters separately cannot represent all the aspects of extreme processes. Intensity of extreme daily maximum temperatures will increase more than the average maximum temperatures. On the other hand, extreme daily minimum temperatures will increase less than the average of minimum temperatures. In terms of temperature ranges in the projected climate for the Mediterranean region, daily temperature range will be greater than current climate values. Changes in precipitation extremes are much more varied than maximum and minimum temperature extremes. Though a moderate to high decrease of annual precipitation in most of the Mediterranean region is projected, important seasonality changes are also possible [11]. An increasing trend in projected extreme precipitation events is expected in many Mediterranean areas. That increase of extreme events is mainly expected in the warmest seasons (summer and early autumn).

Gao et al. [12] utilized a regional model with a resolution of 20 km to analyze the changes of periods without precipitation (dry spells, DS) and with intense rainfall (defined as the maximum accumulated precipitation in five consecutive days, 5DP). They also used scenario A2 and gave results for the end of the twenty-first century. They found substantial (and seasonally dependent) fine scale topographically-induced structure in the climate change signal over a number of regions of the Mediterranean area (i.e., the Alpine and Balkan regions, the Iberian, Italian and Hellenic peninsulas, and the Northern African coastal regions). Similar to the changes in mean precipitation, the changes in extreme events also exhibit topographically induced fine scale structure. Gao et al. [12] also indicated that an increase in maximum 5DP and a decrease in maximum DS length over western and central European areas are to be expected in winter, implying stronger and more frequent storms. In summer and intermediate seasons, as well as in winter in some Mediterranean areas, increases in maximum DS length and areas of both increase and decrease for maximum 5DP can be expected. In general, the areas of increased maximum 5DP are more extended than the areas of increased mean precipitation, and the areas of increased DS length are more extended than those of decreased mean precipitation. This implies a widening of the precipitation distribution, with increased probability of both flood and drought events.

Beniston et al. [13] presented an overview of changes in the extreme events that may affect Europe in next decades, on the basis of regional climate model simulations produced by the PRUDENCE project. They concluded that the frequency, intensity and duration of heat waves will increase over Europe. They also found that in both winter and summer, intense precipitation may decrease in south Europe, while Mediterranean droughts may start earlier in the year and last longer. Diffenbaugh et al. [14] combined temperature and relative humidity to define a heat index, and assess the probability that a certain warming threshold be reached in the future climate. Diffenbaugh et al. [14] determined that days with high values (dangerous

or extremely dangerous heat index) are projected to increase under an A2 emission scenario, in particular in the coastal areas of northern Africa, the Iberian Peninsula and south Italy. Christensen and Christensen [15] analyzed the summer precipitation, and concluded that a decrease of mean precipitation may be compatible with an increase in extreme precipitation events. Lehner et al. [16] analyzed the risk of both droughts and floods, and obtained reduced return periods for both phenomena in many areas in Europe, from simulations of global models (HadCM3 and ECHAM4) and the scenario A1B.

## 4 Discussion and Conclusions

Climate projections, in particular regarding mean or extreme precipitation over limited areas of the World, carry remarkable uncertainty. This is reflected in some contradictory results mentioned in the previous section. The uncertainty has many different causes, the future evolution of the climate forcings (greenhouse gases emissions, land use changes, ...) being the most relevant. There are, however, several physical mechanisms of the climate system that are not yet fully understood. Most of them concern feedback mechanisms, which are processes that may amplify or reduce the response of the climate system for a given forcing. The main positive climate feedback is the water vapor feedback: when temperature increases, water vapor content also increases in the atmosphere, which produces an enhanced greenhouse effect. This mechanism is nowadays much better understood than in previous IPCC reports. Contrarily, feedbacks involving clouds and aerosols are still poorly described, and mean an important cause of uncertainty in the climate projections by global models.

Therefore, as it is mentioned in the AR4, climate projections for the end of the century depend on the scenario and the particular model used to develop them. Temperature changes, and especially precipitation changes, show, for such temporal horizon, a broad range of values. On the other hand, projections for the next 2–4 decades are quite robust, since they depend less on long-term feedbacks and also on future greenhouse gases emissions. In fact, the climate of the next few years is tightly determined by past and recent emissions (climate commitment).

Regional climate models use high resolution grids (20–50 km) to simulate the evolution of the atmosphere in a particular region of the Earth by applying the output of a global model as boundary condition. This methodology, however, increases the number of uncertainties involved; besides the already mentioned emission scenario and global model uncertainty, regional models carry their own issues related with the parameterization physical processes and other approximations. For example, the PRUDENCE project has shown that several regional models, even if forced by the same global model and by the same emission scenario, produce quite diverse results. This is an interesting fact, since the range of results may be understood as a measure of the uncertainty over the significant signal [17]. In fact, the European project ENSEMBLES, still under development, is trying to

perform climate projections of a probabilistic nature, based upon an ensemble of simulations obtained by combining several scenarios, global models, and regional models and downscaling techniques. This methodology is expected to produce a remarkable improvement in the regional climate projections. In fact, there is a general consensus among the scientific community that a step further in climate modeling is necessary, particularly for regional scales [18].

Despite the uncertainties discussed in previous paragraphs, it is highly probable that water availability can be reduced in the Mediterranean areas as a consequence of increased temperatures and decreased and more variable precipitation. Specifically, besides the lowered precipitation, higher temperatures will enhance evaporation rates from reservoirs and the potential evapotranspiration rates from land areas in general, thus further reducing available water for human uses. This result is confirmed by the recent IPCC technical paper on climate change and water [19], where it is stressed that many semiarid and arid areas (e.g., the Mediterranean Basin, among others) are projected to suffer a decrease of water resources due to climate change. These projections are to be taken into account by the water management agencies, the concerned stakeholders and the society in general.

**Acknowledgments** This contribution derives from a previous work [20]. Additional parts have been developed in the frame of an assessment report requested by the Catalan Water Agency (ACA); some colleagues contributed to that report: Jordi Cunillera (Servei Meteorològic de Catalunya), Carme Llasat (Universitat de Barcelona), Josep Enric Llebot (Universitat Autònoma de Barcelona) and Javier Martín-Vide (Universitat de Barcelona). Rosana Rel also contributed to the bibliographic search.

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