Tethys
Journal of Mediterranean Meteorology & Climatology

Tethys 2012, **9**, 13–24
www.tethys.cat
ISSN-1697-1523
eISSN-1139-3394
DOI:10.3369/tethys.2012.9.02
Journal edited by **ACAM**

Climate change projections for Catalonia (NE Iberian Peninsula). Part II: Integrating several methodologies

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Received: 22-X-2011 – Accepted: 18-IV-2012 – **Translated version**

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Abstract

The publication of the fourth IPCC report, as well as the number of research results reported in recent years about the regionalization of climate projections, were the driving forces to justify the update of the report on climate change in Catalonia. Specifically, the new IPCC report contains new climate projections at global and continental scales, while several international projects (especially European projects PRUDENCE and ENSEMBLES) have produced continental-scale climate projections, which allow for distinguishing between European regions. For Spain, some of these results have been included in a document commissioned by the"State Agency of Meteorology". In addition, initiatives are being developed within Catalonia (in particular, by the Meteorological Service of Catalonia) to downscale climate projections in this area. The present paper synthesizes results of these and other previously published studies, as well as our own analysis of results of the ENSEMBLES project. The aim is to propose scenarios of variation in temperature and rainfall in Catalonia during the 21st Century. Thus, by the middle of this century temperatures could rise up to 2°C compared with that of the late 20th Century. These increases would probably be higher in summer than in winter, generalized across the territory but less pronounced in coastal areas. Rainfall, however, would not change much, but it could slightly decrease. Towards the end of the 21st Century, temperatures could rise to about 5°C above that of the last century, while the average rainfall could decrease by more than 10%. Increases in temperature would be higher in summer and in areas further from the coast. Rainfall would decrease especially during the summer, while it could even increase in winter in mountainous areas such as the Pyrenees.

Key words: climate change, projection, ENSEMBLES, Catalonia, downscaling

1 Introduction

The latest report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) states that the way the Earth's climate is changing now has not known precedents. This recent climate change is a global scale phenomenon, but it is also reflected locally. To take adaptive measures to the new climate, it is very important to have climate projections, i.e., estimates about how the future climate can be, in the appropriate scales.

Climate projections are obtained mainly as a result of the use of climate models. These are the current tools used to understand the climate system. So in using the factors that affect (or "force") the system as input data, the resulting information is the climate to be expected in the future (McGuffie and Henderson-Sellers, 1990). There are several types of climate models, but the ones that should be mentioned are the so-called Atmosphere-Ocean General Circulation Models (AOGCM). The AOGCM are computer codes that solve a set of equations (that describe the physics and chemistry of the processes occurring in the atmosphere, ocean, hydrosphere, cryosphere and lithosphere), and they must therefore employ a grid to make the calculations in it. Currently, most models available to the scientific community do not work with resolutions of less than a few degrees of latitude and longitude. Other differences between models come from parametrizations, for example, the simplified treatment of some phenomena (formation of convective clouds, radiative transfer in the atmosphere, ocean mixing) that are not explicitly described by the main equations of the model.

AR4 mentions as well that AOGCM have progressed in recent years (Randall et al., 2007), but in fact they have not experienced significant changes in the years between the third and fourth IPCC report. The debate on the need to improve climate models and their predictions is therefore present in the scientific community (Goddard and Baethgen, 2009). Thus, the global models are still limited when it comes to climate projections at regional scales. The AOGCM admittedly have limitations in simulating extreme events (heat waves, droughts, torrential rain, etc.). This is mainly due to the parameterizations and their low resolution, which is contradictory to the local nature of many of these phenomena (Sánchez et al., 2004).

Indeed, the AOGCM do not include a good description of the terrain, nor a good definition of the coastline, at least to the level that would be needed to describe the climate in regional areas such as Europe, the Iberian Peninsula (IP), or Catalonia. Obviously, a solution to this problem would be to increase the resolution at which these models work, but this is limited by the available computing power (and the structure of the computer code, which is not always scalable). There are some examples of attempts to increase the resolution of a global model: in Japan, a model has been implemented on grids of less than 50 km in a specially designed computer, called Earth Simulator (Ohfuchi et al., 2005). Closer to us, the Barcelona Supercomputing Center - National Supercomputing Center has been working to increase the resolution of a global model (Jiménez-Guerrero, 2007), namely the EC-Earth model, an AOGCM built on the basis of the seasonal prediction model of the European Centre for Medium-Range Weather Forecasts (ECMWF).

While global models cannot produce results on a high resolution grid, some regionalization or downscaling technique will be needed, i.e., some kind of methodology to obtain more spatial detail of climate projections. There are basically two regionalization techniques, respectively called dynamic and statistical, although others, which are variations or combinations of these, are also used. All of them depend on the results of the global models, which are actually projecting the climate evolution ahead, while these techniques convert the results to a more detailed scale.

Dynamic regionalization is based on the use of regional climate models (RCM) nested in global models. RCM are basically limited-area (mesoscale) weather forecasting models, which describe the behavior of the atmosphere over part of the Earth, using a finer grid than that of the global models. They are run using boundary conditions that are given by the results of a global model. More details on the foundations of regional climate modeling can be found, for example, in Gaertner (2009). The article that makes the first part of this study (Barrera-Escoda and Cunillera, 2011) presents the precise application of a technique of dynamic regionalization.

The technique of statistical regionalization consists in the use of multivariate statistical regressions between climatic variables on a specific point on land and the values obtained in one or more cells of a global model. These first regressions are obtained first of all relating values measured in the past (instrumental historical series) with the outputs of the global models when simulating these past moments. A basic premise of this technique is that the relationship between climatic variables will remain unchanged even in the context of climate change. In some cases, the relationships are not established between a point and the values in a cell, but between one point and some index that includes synoptic information. These indexes often refer to the behavior of a low frequency or teleconnection synoptic pattern, such as the North Atlantic Oscillation (NAO) or El Niño (ENSO), among others. In other cases (methodologies based on analogues), the different synoptic situations are limited to a subset of typical situations whose behavior is known at a local scale. Statistical regionalization presents several advantages over dynamic regionalization: it can produce projections for specific points, and does not require large computing resources. One of the disadvantages, apart from the aforementioned stationarity relations, is the need of sufficiently long historical series to establish these relationships (Ribalaygua et al., 2009).

Thus, a specific climate projection of regional scope is the result of combining: a) an emission scenario; b) the output of a global climate model forced with the selected emissions scenario, and c) a regionalization technique. It is therefore clear that the number of projections that can be obtained is very high, which justifies the present analysis of the studies thus far developed and the synthesis of the published results, always on the area of Catalonia. It is worth mentioning that each of these steps introduces uncertainty in regional projections.

As mentioned, the main factor when trying to estimate what may be the climate of the future is the evolution of the concentrations of greenhouse gases (GHGs) and aerosols of anthropogenic origin. These factors significantly affect the climate and depend almost exclusively on economic, social and technological aspects related to human beings, which are highly uncertain. Therefore, several hypotheses are assumed for these developments, when obtaining the so-called "scenarios" of emissions. The scenarios analyzed at the AR4 come from a report (Special Report on Emission Scenarios, SRES) of Nakićenović et al. (2000), where forty future evolutions are developed, grouped into four families, called A1, A2, B1 and B2. The A1 family includes the A1FI scenario (in which energy needs are still supplied mainly by fossil fuels) and A1B (which considers a variety of sources and an improvement of energy technologies). All scenarios provided show that GHG emissions will continue growing at least until mid-21st Century, specifically, from higher to lower emissions in 2050, the scenarios are ordered as fol-

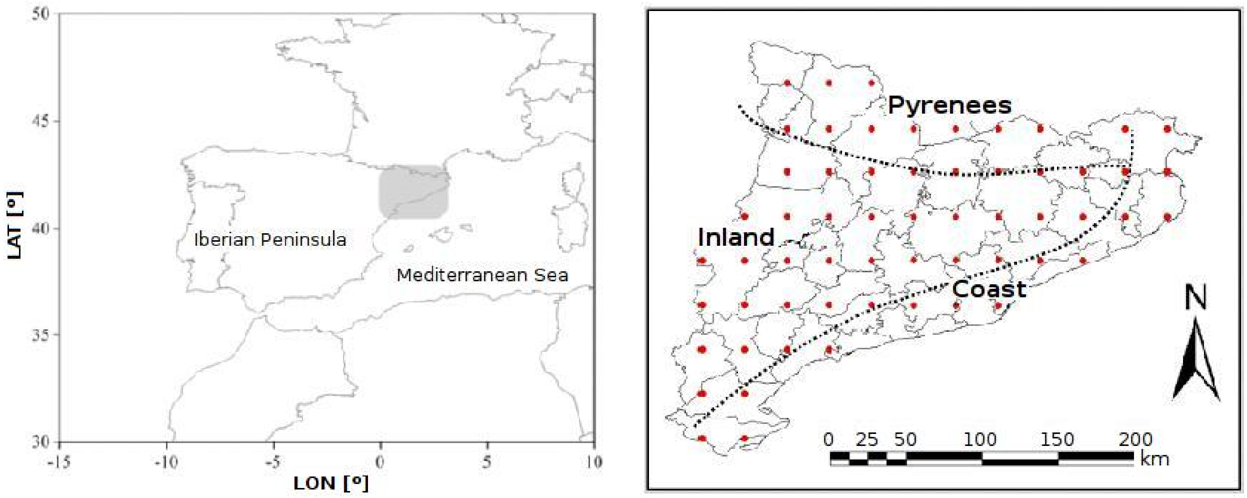

Figure 1. On the left, the shadowed area indicates the location of Catalonia regarding Europe, the Iberian Peninsula and the Mediterranean Sea. On the right we indicate the center of the cells used to analyze the results provided for the simulations of the RCM of the ENSEMBLES project. The three areas in which the region was approximately divided to synthesize the projections are indicated as well.

lows: A1FI, A2, A1B, B2, B1. Although in some scenarios emissions begin to decline towards mid-century, the concentration of these gases in the atmosphere continues to rise for several decades, as, for example, the time scale to reach a new equilibrium in CO_2 concentration is about 200 years.

This article aims to propose some projections of future climate in Catalonia (its situation in Europe and the Iberian Peninsula is shown in Figure 1), based on results obtained from a variety of previous investigations. The article first summarizes the results that appear in the AR4, at a global and continental scale. Then, different projects and works aimed at increasing the spatial resolution of the projections are presented: the European project PRUDENCE, and some of their results; the recent report done by the State Meteorological Agency (AEMET) and an analysis carried out based on simulations done in the framework of the European project ENSEMBLES. Finally, all the results presented above, together with those presented in the article that is the first part of this study (Barrera-Escoda and Cunillera, 2011), which correspond to a dynamic regionalization carried out by the Meteorological Service of Catalonia (SMC), are synthesized in two tables that show ranges of future variation of temperatures and rainfall in two time windows: mid and late 21st Century.

This work, including this article and its first part, summarizes, but also updates, chapter 6 of the recent Second Report on Climate Change in Catalonia (Calbó et al., 2010), and partially reproduces several recent publications that have the authorship or involvement of the first author (Calbó, 2009a; Calbó, 2009b; Calbó et al., 2009; Calbó, 2009c), where some additional details can be found.

2 Projections at a continental and global scale: what the IPCC report says

All projections indicate that the increase in the average temperature of the planet will continue. It must be highlighted that at the end of the 21st Century, and depending on the emissions scenario and the models used, the range of increase in global average temperature will be 1.1 to 6.4°C. The best estimates (among the set of models) are, for the lower emissions scenario (B1), of 1.8°C, and for the most pessimistic (A1FI), of 4°C. For the next decades, all scenarios project very similar increases: for example, for 2040, about 1.2°C. The temperature rise will not be uniform throughout the Earth: the increase will be higher in areas of high latitudes of the northern hemisphere, and lower on the oceans, particularly over the Antarctic (IPCC, 2007).

As for rainfall, most models indicate an increase (in global average), linked to a strengthening of the hydrological cycle. However, attending to the greater dispersion between models and the greater spatial and temporal heterogeneity of the changes of rainfall (compared with changes in temperature), the AR4 does not give global average values for this increase in rainfall. In general, the set of AOGCM give increases of rainfall in the intertropical zone and high latitudes of both hemispheres (especially during the corresponding periods in winter), and decreases in subtropical areas.

The third section of Chapter 11 of the AR4 (Christensen et al., 2007) is devoted to summarize the climate projections for the Southern European and Mediterranean regions (the area between the parallels 30°N-48°N and the meridians 10°W-40°E). The results are provided for the end of the century (2080-2099) and correspond to the simulations performed with 21 AOGCM included in the Program for Climate Model Diagnosis and Intercomparison (PCMDI), giv-

Table 1. Temperature (always positive) and rainfall variations for the end of the 21st Century (2071-2100) related to the average of the period 1961-1990, for the A2 scenario, as a result of the regional models used by PRUDENCE, for the northern area of Spain. The results are related to an increase of the global temperature by 1°C (Christensen, 2005).

	Temperature [°C]					Rainfall [%]				
	Year	DJF	MAM	JJA	SON	Year	DJF	MAM	JJA	SON
Average	1,3	1,0	1,1	1,9	1,4	-5,7	+1,9	-8,6	-14,4	-5,2
Est. Dev.	0,4	0,3	0,4	0,5	0,4	+1,6	+2,0	+2,7	+4,2	+2,7
Median	1,3	1,0	1,0	1,8	1,3	-5,7	+1,9	-8,5	-13	-5,1
p95	2,0	1,6	1,8	2,7	2,0	-3,1	+5,2	-4,1	-7,4	-0,7
p5	0,7	0,4	0,5	1,1	0,7	-8,4	-1,4	-13,1	-21,4	-9,7

ing rise to the "multimodel data set" (MMD). The simulations were done for the A1B scenario. Thus, for this large region in which Catalonia is located, (for the A1B scenario) an average temperature increase of 3.5°C [3.0 to 4.0] (the first value is the median, and the range between brackets corresponds to that given by the percentiles 25 and 75) is foreseen. The increase would be more pronounced in summer (4.1°C [3.7 to 5.0]) than in winter (2.6°C [2.5-3.3]).

The same publication presents some maps that allow a more detailed analysis. For example, we see that the yearly average temperature could rise between 2.5 and just over 3.5°C at the IP. This is an estimate which is equivalent to the one made for the whole globe and lower than that of the rest of Europe. All Catalonia is located within the boundary lines of an increase of 2.5-3°C. Seasonally, the behavior is quite different. In winter, the pattern resembles that of the whole year, with increases in the IP (and the Mediterranean in general) that are lower (2.5°C) than those of north-eastern Europe. However, in summer the increases in temperature in the Mediterranean area are clearly higher than in the rest of the continent, reaching values higher than 4°C for a big part of the IP.

As for rainfall, and according to Christensen et al. (2007) and for this region, average annual reductions of 12% [9-16] should be expected, a decrease that will be more marked in summer (24% [14-35]) than in winter (6% [1-10]). It must be said that the Mediterranean is one of the few regions among those considered in the AR4, where the estimated decrease in rainfall is the same in the majority of global models and throughout all seasons. However, the projected changes in rainfall present a marked latitudinal gradient in the area. Thus, in the southern Mediterranean (including Southern IP) the decline could exceed 20%. In Catalonia, decreases in rainfall of 10-15% on annual scale are expected. In summer, the decline would be even more remarkable in the IP (over 30% and even 50%), whereas in winter much of the peninsula is an area of little change (between 0 and -5%). These values may serve as reference for the other values that will be shown later, but we must keep in mind that the variability of rainfall in the Mediterranean region is very large. Therefore, it should not be surprising that after downscaling, projections become significantly different to this reference.

3 The results of the European project PRUDENCE

With the background of trying to bring order to the generation of regional climate scenarios and organize the research in this field in Europe, the European Union funded, between 2001 and 2004, the PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects). This project involved over 20 research groups, with the goal of providing high resolution climate scenarios for Europe and for the end of the 21st Century, through dynamic regionalization, and exploring the uncertainties of these projections.

The experiments conducted in PRUDENCE (Christensen, 2005; Déqué et al., 2005; http://prudence.dmi.dk) consist of a control simulation to represent the period 1961-1990 and another simulation of a future scenario (2071-2100), both performed with several regional climate models (10 RCM developed by institutions from 9 European countries). Most simulations were made for the A2 scenario, and using the output of the model HadAM3H initialized in turn with the HadCM3 global model outputs (to establish the boundary conditions). Other simulations were also done with the B2 scenario, and using other global models (ECHAM4/OPYC3). The analysis area covers all countries of Western Europe. All the models were run at resolutions around 50 km.

The project's final report (Christensen, 2005) presents values that try to summarize the results of the experiments by country. Table 1 has been elaborated from this information, it corresponds to the north of Spain (north of the parallel 40°N). Although this is the area where Catalonia is located, it also includes the Cantabrian coast, which has a clearly different climate. As mentioned in the report, the values are given relative to a global temperature rise of 1°C. This, which may seem reasonable for temperature, is somewhat surprising for rainfall, which does not respond linearly to increases in temperature. Based on these results, we can say that this region of the IP will suffer more warming than the global average, and it will be higher in summer than in winter. The rainfall will decrease in annual average, due to significant decreases in summer and spring, less important in fall, and insignificant increases in winter. It is needless to say that all these projections are compatible with those mentioned in the previous section, which resulted directly from the global models.

The revision work of Giorgi and Lionello (2008) also summarizes the results of the PRUDENCE project, defining various regions within the European continent. For the IP, it indicates that the range of temperature increase will be 2.4 to 4.1°C in winter and 4.1 to 7.6°C in summer. For rainfall, the given ranges are small increases in winter (from 0.01 to 0.04 mm dia^{-1}) and significant decreases in summer (between -0.13 and -0.80 mm dia^{-1}). The latter quantities are converted to percentage using approximate values of the average rainfall in Catalonia, representing increases of less than 2.5% in winter and decreases up to 50% in summer.

Also based on PRUDENCE, Beniston et al. (2007) find that all indexes related to heat waves (number, maximum length, maximum temperature, etc.) are clearly increased in Catalonia (10-25% depending on the index) at the end of the 21st Century under the A2 scenario. Sánchez et al. (2004), using only one model and the A2 scenario, find that the most extreme temperatures (90 percentile of temperatures) could rise between 5-7°C in summer and around 3°C winter. As for the lower minimum temperatures (percentile 10), they will increase some 3°C in winter and 4°C in summer. On the other hand, Kjellström et al. (2007) also found that extreme temperatures (95 percentile of the maximum and 5 percentile of the minimum) would increase in the IP 6 and 3°C respectively in summer and winter (scenario A2). Finally, Diffenbaugh et al. (2007) combined temperature and relative humidity to define a heat index, and obtained that for the A2 scenario and the end of the century, the days when the value of this index exceeds a certain danger threshold would be more than 30 in a year in some parts of the coast and the south of Catalonia. In the current climate these days are not more than 10 per year. Gao et al. (2006) analyze changes in the duration of periods without rainfall and intense rainfall (defined from the maximum rainfall accumulated in 5 consecutive days, 5DP) at the end of the 21st Century and for the A2 scenario. According to their results, and with regard to dry periods, these would tend to lengthen between 25-75% in the spring and more than 100% in summer, and would not change significantly in fall and winter. Regarding the 5DP, it would tend to decrease during the winter and spring (between 10-25%) but to rise up (up to 50%) on the coast in fall. On the other hand, Christensen and Christensen (2004) conclude that despite the decrease in total rainfall, some increase in heavy rainfall could be expected (A2, end of the century). However, Beniston et al. (2007) indicate that heavy rainfall would decrease in southern Europe, both in winter and in summer. We can deduce from the work of Sánchez et al. (2004) that there would be a clear reduction of days with heavy rainfall (over 10% decrease in winter and 25% in summer).

It is also relevant to highlight the work of Gaertner et al. (2007), who found, from the analysis of the results of regional models included in PRUDENCE and considering the A2 scenario, indications of a possible formation, in the western Mediterranean, of storms with characteristics of tropical cyclones in the latter part of the century. Another work (López-Moreno et al., 2008), evaluates what may be the rainfall in the Pyrenees at the end of the century and concludes that the importance of snow in the hydrologic cycle will be clearly diminished due in part to changes in rainfall (there will be a 5-10% decrease in winter in the eastern Pyrenees), but mostly due to temperature rise, which would mean a reduction in the area where snow is accumulated, an advance in the melting period and the consequent decrease of flows during the spring.

All these works, and some other that have been also published based on the results of the PRUDENCE project: Gibelin and Déqué (2003); Castro et al. (2005); Rowell (2005); Déqué et al. (2005, 2007); Rowell and Jones (2006); Petisco et al. (2006); and Tapiador et al. (2007), have been taken into account in the synthesis values given in section 6 of this work.

4 The report of AEMET

Under the "National Plan for Adaptation to Climate Change" and specifically in its first working program, the Spanish State Meteorological Agency (AEMET) was designated to coordinate the task of generating detailed climate scenarios for Spain, in order to evaluate the possible impacts. The first phase of this work was developed over the years 2006 and 2007, and has resulted in the publication (Brunet et al., 2009) mentioned here.

The approach presented in this report is based on the use of various regionalization techniques. On one hand, the results of global models are directly analyzed, using an appropriate method for this purpose, the scenarios generation MAGICC-SCENGEN (Wigley et al., 2000). On the other hand, the results of all regional models of the PRUDENCE project are used, analyzed at the IP scale. Finally, and as an interesting innovation to obtain the desired high spatial resolution, three statistical regionalization techniques are used. Two of them are methods that incorporate dynamic knowledge of the atmosphere (analogue methods), while the third one is a purely empirical method. Specifically, they are the analogue methods FIC (Foundation for Climate Research, Ribalaygua et al., 2009); analogue INM (operated by the National Meteorological Institute itself) and the SDSM (Statistical DownScaling Method) which is a multiple linear regression.

Several tables and figures of that report show the results. We have created Table 2 from a detailed inspection of the figures, where the projections are distinguished into three geographical areas, which we call coast, inland and mountains (Pyrenees). These areas are not defined exactly, but its approximate configuration is shown in Figure 1. In all cases there are ranges of values, since they come from the maps generated with the different techniques and also include the spatial variability that exists within the defined areas. Furthermore, the table also includes the expected ranges of tem-

Table 2. Increases of average temperature (°C) and variations in rainfall (annual and seasonal, for the case of the end of 21st Century), for three areas of Catalonia, for the A2 scenario and two time horizons, from the results of various regionalization techniques (Brunet et al., 2009).

			2071-2100				
		2011-2040	Year	Winter (DJF)	Spring (MAM)	Summer (JJA)	Fall (SON)
Increase temperature (°C)	Coast	0,2-1,3	3,5-5,0	2,5-3,5	3,0-4,0	5,0-6,5	3,5-5,0
	Inland	0,7-1,8	4-5,5,0	2,5-4,5	3,5-5,0	6,0-7,5	4,5-6,5
	Pyrenees	0,7-1,8	4-5,5,0	2,5-4,5	3,0-5,0	6,5-7,5	5,0-6,0
Variation rainfall (%)	Coast	-10 , 0	-20 , -10	-10 , 0	-10 , 0	-40 , -20	-15 , -5
	Inland	-5 , +5	-15 , -5	-5, +10	-15 , -5	-35 , -15	-15 , -5
	Pyrenees	0 , +10	-5 , +5	+5 , +15	0, +10	-15 , 0	-10 , 0

perature rise at seasonal level (only for the distant horizon of the end of the 21st Century). It must be said that in this case, the given increase corresponds to the maximum temperature. In fact, the results of the report show that increases in maximum and minimum temperatures are similar to the average, if anything, the maximum are slightly higher (0.2 to 0.4°C). Unlike the case of temperatures, the concordance between the different results for rainfall is elusive, because the values found vary widely. In particular, the results from PRUDENCE (forced with HadAM3H) present major reductions in rainfall compared with others in summer, and less significant in fall. Or the case of the analogue method of the INM, which forced with the same HadAM3 tends to show increases in rainfall in the cold half of the year for the area of Catalonia region.

5 Results for Catalonia from the European project ENSEMBLES

The Ensembles project (Hewitt, 2005; Van der Linden and Mitchell, 2009: www.ensembles-eu.org), financed between 2004 and 2009 by the European Union, aimed to develop a system for predicting climate change from sets of simulations, based on the main high-resolution regional models developed in Europe, to produce a probabilistic estimate of the uncertainty of future climate on scales that would go from seasonal to decennial. The ultimate goal of the project was to narrow the uncertainties in century predictions of climate change by integration with different emission scenarios, global models, regional models and statistical techniques of regionalization.

The data of the simulations performed under the ENSEMBLES project can be downloaded from their website, and the work presented here was done from the simulations of five RCM available, all based on the stage A1B and taking as boundary conditions the outputs of the global models HadCM3 and ECHAM5, with a spatial resolution of 25 km, converted to regular grids of 0.25°. Specifically, we have used the results of these models and cases:

- REMO (ECHAM5-r3), Max-Planck Institute, Germany.
- PROMES (HadCM3Q0), University of Castilla La Mancha, Spain.
- HadRM3Q0 (HadCM3Q0), Hadley Centre, England.
- RegCM (ECHAM5-r3), International Centre for Theoretical Physics, Italy.
- DMI-HIRLAM5 (ECHAM5-r3), Danish Meteorological Institute, Denmark.

All simulations are available for the period: 1951-2100, except those of the PROMES model, which are limited to 1951-2050.

The following variables have been downloaded, at monthly resolution, for each of the selected models: average temperature (°C), rainfall (mm), solar radiation (irradiance, W m^{-2}) and wind speed (m s^{-1}). From the entire grid available in Europe, all those cells that have their centroid on Catalonia were selected for further analysis. In total there are 59 cells that meet the above criteria (Figure 1).

To obtain the whole series for Catalonia for each climatic variable in the period 1951-2100, the average series were calculated at annual resolution, as well as for winter (December, January and February) and summer (June, July and August) for each of the models. Such series have become anomalies (in % for rainfall and wind speed) compared to the reference period 1971-2000, and finally the average series was calculated with the average value of the series of anomalies of all models. To smooth the time evolution of the series and improve the visualization of its interdecennial variability, we have implemented a low-pass Gaussian filter of 31 years. We have also calculated the linear trends for the period 2001-2100, and its significance ($\alpha \leq 0.05$) has been evaluated based on the Mann-Kendall non-parametric test.

Figure 2 shows the time evolution of the selected variables during the 1951-2100 period. The mean annual temperatures (Figure 2a) show a steady increase throughout the 21st Century, showing a significant increase of 0.40°C per decade. Trends are also significant at a seasonal level, presenting a higher rate of increase in the summer season (0.52°C decade^{-1}) than in winter (0.33°C decade^{-1}). In any case, the time evolution of the simulated temperatures during

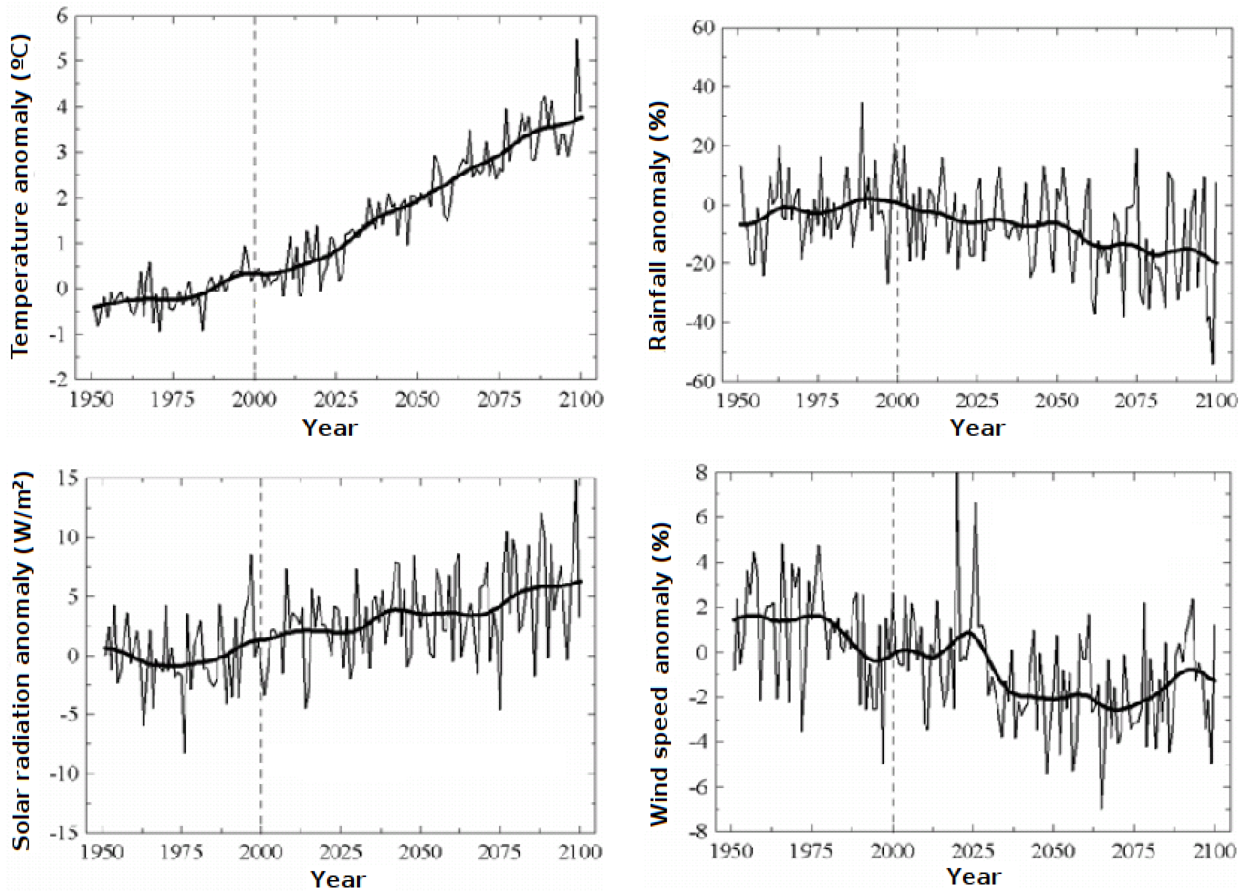

Figure 2. Time evolution (1951-2100) of the average annual series of different climate variables obtained using five RCM simulations of the ENSEMBLES project for Catalonia: (a, left above), average temperature (°C); (b, right above) rainfall (%); (c, left below) solar radiation (W m^{-2}); (d, right below) wind speed (%). The reference period is 1971-2000. The thick lines represent the 31-year Gaussian low-pass filters.

the 1951-2000 period does not show the decline or stabilization that occurs, as measured, between 1950 and the early 70's (SMC, 2011).

The simulated average annual rainfall (Figure 2b) show a progressive decrease during the analyzed period, although with a more pronounced decline during the last decades of the 21st Century. Overall, the series shows a significant decline of -1.8% per decade at annual resolution. At a seasonal level a clear seasonality is found, as they present a clear significant decrease in summer (-5.1% per decade) and a non-significant trend in winter.

Solar radiation (Figure 2c) shows a positive trend during the 21st Century, although two clear periods of increase can be seen during the first and last three decades. On a whole, for the period 2001-2010, the trend is positive and significant with 0.5 W m^{-2} per decade. Regarding wind speed, there is a decline during the 21st Century in annual resolution (Figure 2d), although during the first quarter of the century we see a stabilization period followed by a sharp decline until the early 2040 decade. Then there is a slight negative trend, ending with a spike in the last two decades of the century. The trend is negative and significant, with a value of -0.2% per decade.

Table 3 summarizes the mean anomalies recorded in the whole of Catalonia, for the selected variables and RCM, and in the periods 2021-2050 and 2071-2100 compared to the 1971-2000 reference period. The results confirm what has already been mentioned, an increase of 1.2°C and 3.4°C in the average annual temperatures for the first and second period, respectively, with an increase greater in summer than in winter. Regarding rainfall, a decrease of approximately -6% is observed for 2021-2050, both at annual and seasonal level. However, at the end of the 21st Century it seems that the annual escalation rate of decline is sharper (-16%), although the decline is concentrated in summer (-30%), while winter rainfall recovers up to levels close to the period 1971-2000.

Figure 3 shows the maps of projected changes in rainfall in Catalonia, based on the anomalies obtained in each of the grid points in the periods 2021-2050 and 2071-2100. A general decrease in rainfall at annual resolution can be seen for the period 2021-2050. However, in the most southern areas of Catalonia, slight increases are detected, which are

Table 3. Summary of the projections of the five selected RCM of the ENSEMBLES project, showing the changes between averages of different climate variables in all Catalonia for the periods 2021-2050 and 2071-2100 regarding the reference periods 1971-2000.

	2021-2050			2071-2100		
	Year	Winter	Summer	Year	Winter	Summer
Temperature (°C)	+1,35	+1,20	+1,73	+3,36	+2,69	+4,44
Raingall (%)	-5,68	-6,45	-6,87	-16,08	-1,20	-30,12
Solar radiation (W m^{-2})	+2,89	+1,48	+1,64	+5,47	-2,04	+7,52
Wind speed (%)	-1,67	-1,97	-1,51	-2,41	-1,92	-1,57

repeated in both winter and summer. The estimations for 2071-2100 show a general decrease in all regions of Catalonia, with a maximum of around -20% in the areas of the Pre-Pyrenees. However, in winter most of the territory does not show significant changes, and there are even increases of around 4% in Plana de Lleida, Empordà and the eastern Pyrenees. However, summer simulations predict a general decrease in rainfall over the whole Catalonia, showing declines that exceed -30% in inland areas that cover mainly the regions of Solsons and La Segarra, as well as the northeastern areas of El Maresme, La Selva, Girona and El Pla de l'Estany. The smaller declines are concentrated in sectors of the Pyrenees and southern points of Terres de l'Ebre, where minimum anomalies for all Catalonia are obtained, which are also significant (-21%).

6 Conclusions

In this section we have tried to summarize all projections discussed thus far in the previous sections. This is in order to show, for Catalonia and even with a certain distinction between geographical areas (coastal and inland areas, Pyrenees), a range of variation in temperature and rainfall that can be considered probable based on current knowledge, the modeling and regionalization techniques used by the researchers, and the considered scenarios.

Thus, in Table 4, we included the summary corresponding to the projections for the end of the 21st Century, which are those with most original works published. Note that the values of the table are not the result of a synthesis performed with a specific numerical or statistical methodology, but a rather qualitative integration of the different projections, obtained for different scales and with different methodologies. Among the difficulties encountered when making this table is the fact that the different results presented above show changes relating to slightly different periods (1971-2000, 1980-1999 or 1961-1990).

As shown, the expected ranges of temperature rise and changes in rainfall are given for the A2 scenario. This scenario was chosen because it is one of those that project higher GHG emissions. In addition, there are many more projections for this scenario than for any other. To make the values in Table 4, the results of the regional modeling carried out by the SMC for the period of the end of the century and A2 scenario (Barrera-Escoda and Cunillera, 2011) were also taken into account. As for the ENSEMBLES results (remember that this was the A1B scenario), the projections of changes in rainfall are very similar to those of Table 4, i.e., they remain within or close to the ranges shown. However, the increases in temperature suggest that the results of this project are lower, but show the same seasonal differentiation.

In summary, we observe that the average temperature in Catalonia could rise between 4 to 5.5°C by the end of the century, this increase being more significant in summer in the Pyrenees and inland areas (up to 7°C), and more moderate in winter for coastal areas (around 3°C). Regarding rainfall, for the whole of Catalonia and the annual average, it could decrease between 5-15%, with summer being the season that would suffer the greatest declines in rainfall (up to 40% less rainfall in some coastal areas). Fortunately, the area of the Pyrenees, and in the most rainy seasons (fall) the declines would be a little more moderate, similar to the annual average. In general, many projections indicate the possibility of a slight increase in rainfall during the winter.

A degree of confidence may be granted to the values presented in Table 4, since they come from many different analyses, carried out by different authors. It is true that most of these works are based on simulations of the PRUDENCE project, which, despite using several regional models, run them with the boundary conditions given by only two global models. However, some works that are independent of PRUDENCE (for example the summary for the Mediterranean region included in the AR4 of the IPCC and the simulations carried out by the SMC) appear to endorse the validity of these values.

For other scenarios and other time horizons, the projections become more difficult because, as we have seen, there are fewer published papers referring to them. However, it is also true that most scenarios begin to distinguish themselves in terms of emissions around 2030. In other words, the change that can be expected in the coming decades (say from the present until mid-century) should be almost independent of the trends that GHG emissions end up being. Therefore, even if based on fewer projects, we also provide a summary table of the climate projections in a closer time frame.

Specifically, for mid-century, we have summarized the results of the simulations analyzed of the ENSEMBLES project (several regional models for the A1B scenario and

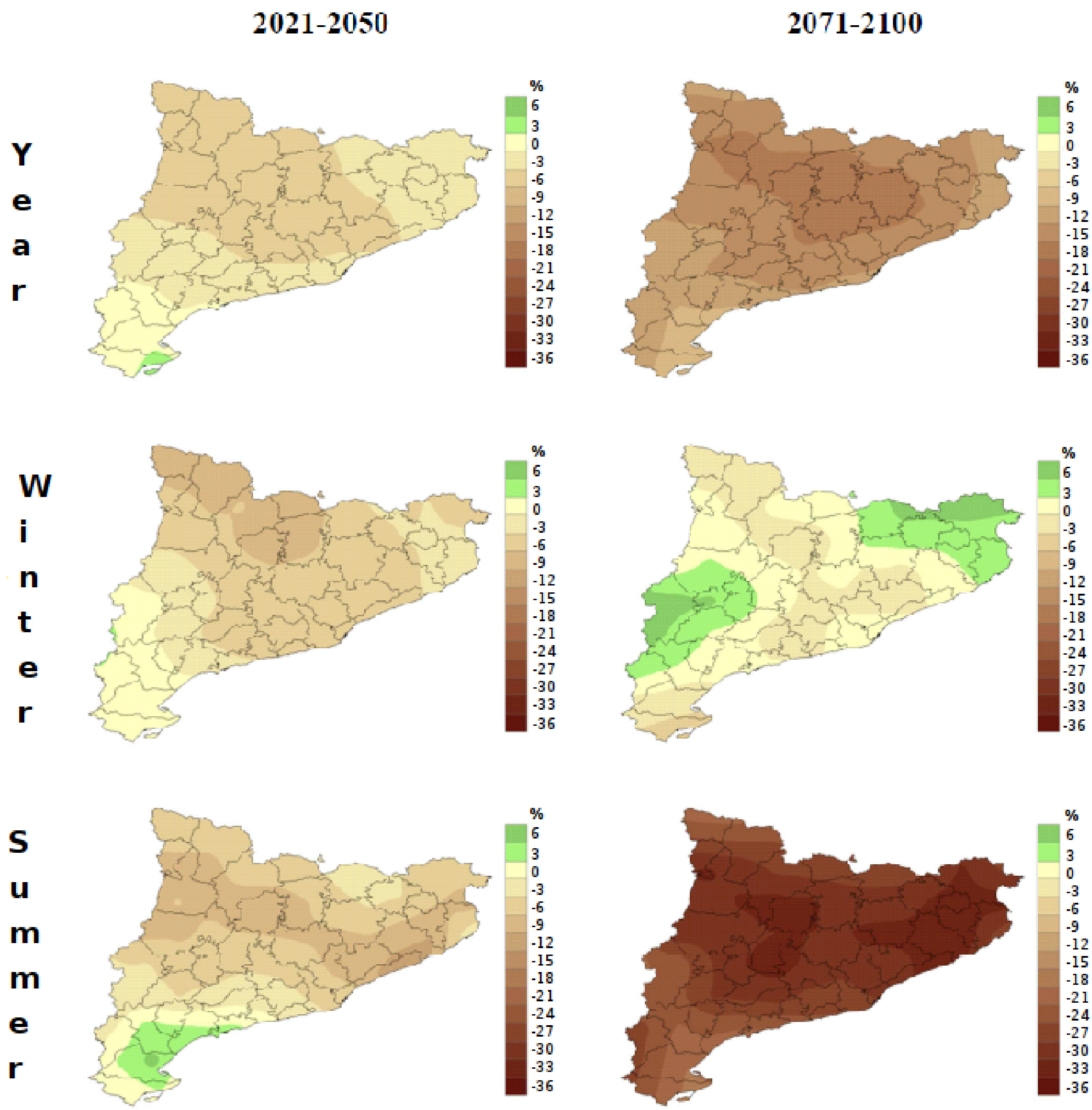

Figure 3. Changes in annual (above), winter (middle) and summer (below) rainfall (%) in Catalonia from the selected simulations of the ENSEMBLES project at 25 km resolution, for the emissions scenario A1B, and for the periods 2021-2050 (left) and 2071-2100 (right). Reference period: 1971-2000.

for the period 2021-2050) with the results obtained for the SMC with a regional model, two scenarios (A2 and B1) and the period 2041-2070 (see Barrera-Escoda and Cunillera, 2011). This diversity of models, scenarios, and periods, suggest that the summary of Table 5 contains a lot of uncertainty (which is the reason why some ranges are quite large) nevertheless indicates the main features of the change that can be expected for the middle of this century. The temperature increase could be around 1.5°C, and as for the other horizons, higher inland and in the Pyrenees than on the coast, and higher in summer than in winter and spring. Average annual rainfall in Catalonia would vary very little with respect to the present, as a result of possible increases in some areas (coast) and decreases in others (Pyrenees). Seasonally, the results are very significant, in the sense that the various methodologies and scenarios give results that may be even contradictory. Thus, in fall, and especially in summer, the A2 scenario shows clear decreases in rainfall, while the B1 indicates increases in it. The A1B scenario (ENSEMBLES results) is halfway, with moderate decreases. In winter, most results show minor changes, while spring is the season when the decrease in rainfall is shown more consistently.

Table 4. Temperature increases (high line in each square, in °C) and rainfall changes (low line in each square, in %), estimated from several works and documents checked. Changes projected (value ranges are given) for the end of the 21st Century, regarding the values of the end of the 20th Century.

	A2 scenario, period 2071-2100				
	Winter	Spring	Summer	Fall	Year
Coast	2,5;3,5	3,0;4,0	5,0;6,5	3,5;5,0	3,5;5,0
	-10;0	-15;0	-40;-20	-20;-5	-20;-5
Inland	2,5;4,0	3,5;5,0	6,0;7,0	4,5;6,5	4,0;5,5
	+5;+10	-15;-5	-35;-15	-20;-5	-15;-5
Pyrenees	2,5;4,0	3,0;4,5	6,5;7,5	5,0;6,0	4,0;5,5
	0;+15	-5;+10	-25;0	-15;0	-10;+5
Catalonia	2,5;4,0	3,0;4,5	5,5;7,0	4,0;5,5	4,0;5,5
	-5;+10	-10;0	-30;-10	-15;-5	-15;-5

Table 5. Average temperature increases (high line in each square, in °C) and changes in average rainfall (low line in each square, in %), estimated from several works and documents checked. Changes projected for mid-21st Century.

	Several scenarios, mid-century				
	Winter	Spring	Summer	Fall	Year
Coast	1,0;1,6	-	1,3;1,9	-	0,8;1,6
	-5;+15	-10;+5	-40;+30	-5;+20	-5;+10
Inland	1,0;1,6	-	1,6;2,2	-	1,4;2,2
	-5;+15	-10;0	-50;+20	-10;+20	-15;+5
Pyrenees	1,3;1,9	-	1,6;2,2	-	1,4;2,2
	-5;+5	-20;-5	-25;+20	-10;+20	-20;-5
Catalonia	1,1;1,9	0,9;1,7	1,3;2,3	1,3;1,9	1,2;1,9
	-5;+5	-10;-5	-30;+20	-5;+10	-5;0

However, as it has been said, climate projections are not exempt from uncertainty due to several factors. It has also been mentioned that some of these factors are related to the lack of data and information needed, while others are associated with a limited understanding of the functioning of certain components of the climate system, that affect the projections of future rainfall in a particularly significant way. Therefore, as provided by the AR4, climate projections and their impacts, especially if we go beyond 2050, very much depend on the scenario and the model chosen. For example, for the new IPCC report, there is work being done on a new definition of scenarios, which will include half (2035) and long term (2100), and will consider the consequences of mitigation and adaptation actions on the evolution of radiative forcing. For this reason, the ranges of temperature increase (and even more in the case of rainfall) provided in this article are quite large. The other way around, however, we noted that the projections for the next 2-4 decades are much more solid, almost regardless of the emission scenario and less dependent on the representation of feedbacks, since the latter tend to have an effect on longer time scales.

Acknowledgements. This work has been developed in the framework of the 2nd Report on Climate Change in Catalonia, promoted by the Advisory Council for Sustainable Development (CADS) and the Meteorological Service of Catalonia, both of them institutions of the Generalitat de Catalunya. We thank them for their support. The second author has a Post Doctoral scholarship financed by the Commissioner for Universities and Research of the Department of Innovation and Universities and Enterprise of the Generalitat de Catalunya (2009 BP-A00035).

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