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Climate change projections for Catalonia (NE Iberian Peninsula). Part I: Regional climate modeling

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Abstract

This work presents a dynamical technique of climate downscaling to generate projections for the 21st Century in Catalonia, based on the outputs of the atmosphere-ocean global coupled model ECHAM5/MPI-OM. This technique consists in long integrations (5 years) with the MM5 mesoscalar model through three one-way nested domains of 135, 45 and 15 km of horizontal resolution and 23 vertical levels. Two possible emission scenarios of the Special Report on Emissions Scenarios are used for the generation of downscaled projections: a severe one (A2) and a moderate one (B1). Only temperature at 2 m and precipitation are studied in detail, as they are the variables of greatest social interest and the ones that condition the water resources most directly. The general space-time characteristics of these two variables are correctly reproduced by the methodology used, except for the seasonal cycle of precipitation. The simulations performed show a significant cold bias for temperature, as well as a general overestimation of precipitation. The scenarios obtained project a sharp increase of temperature (up to 5°C at the end of the century) and a decrease in the annual mean precipitation during this century, but with a high spatial and temporal variability. This decrease is sharper during the warm period of the year (50% in some areas for summer at the end of the century). On the other hand, a slight increase is projected for the greater part of the cold period of the year. Regarding extreme values, a significant increase of warm months and a slight decrease of cold months is expected. About precipitation, a significant increase of dry periods is projected. However, an increase of extremely rainy months is also predicted. The projected changes are more marked for the A2 scenario than for B1.

Key words: climate change, projections, climate downscaling, MM5, Catalonia

1 Introduction

The typical resolution of general circulation climate models (GCCM), between 100 and 300 km, is not enough to study the characteristics of the climate on a regional or local level (in terms of Catalonia or its counties). Therefore, the projections obtained directly from GCCMs for the 21st Century are not useful to evaluate the impact at regional and local scale that will take place due to anthropogenic climate change. This is why the use of downscaling techniques is recommended for performing high-resolution future climate scenarios (IPCC, 2007). These techniques consist basically in finding the main meteorological variables with larger spatial detail. There are a large number of downscaling techniques, which can be divided into two groups: statistical and dynamical. The statistical techniques use empirical relations between large-scale climate variables (or predictors) and regional or local variables (predictands). On the other hand, dynamical techniques use limited-area meteorological models (mesoscale models) to obtain the same variables.

The need to downscale the GCCMs simulations, discussed above, is even more evident in areas with a complex orography such as Catalonia, which is also in the Mediterranean area and, therefore, under the influence of air masses of both polar and tropical origin. The complex orography of Catalonia implies that mesoscale processes, such as orographic precipitation or convective phenomena, play an important role in the climate of the country. These processes are not well resolved by GCCMs or not taken into account within these models, because of their low spatial resolutions.

The last IPCC report (2007) argues that one of the Earth's most vulnerable areas to climate change would be the Mediterranean area. An increase in annual-mean temperature (between 2-6°C) is projected for this area, which is higher than the mean value projected for the whole planet. A decrease in precipitation (10-15%) is also projected during this century. Specifically, according to this report, the environmental conditions are expected to worsen in a region that is already vulnerable to climate variability. Consequently, the availability of water could be reduced (20-40% reduction of water resources), as well as the potential for hydroelectric generation and, in general, crop yields. More risks for human health are also expected due to a higher frequency of heat waves and forest fires. Most of the ecosystems and organisms would find it hard to adapt to climate change. An increase in the variance of precipitation due to global warming is also pointed out. That is, an increase in both the episodes of intense precipitation as well as droughts. Thus, some recent studies show that dry periods and droughts could increase during this century in Catalonia (Altava-Ortiz, 2010).

There are few studies in the Catalan area or in the Western Mediterranean that have addressed the issue of climate downscaling at high spatial resolutions ($\leq$ 15 km). Basically, the works already published or currently under way are focused on the use of statistical downscaling techniques: Brunet et al. (2009) show projections for the entire Iberian Peninsula (IP) at a spatial resolution of about 50 km or Altava-Ortiz (2010) with projections of about 5 km of precipitation for the entire 21st Century at the NE of the IP. Other examples on a Spanish level are that of Gutiérrez et al. (2010) in Cantabria at only 1 km using statistical techniques or Montávez (2008) with a set of downscaled projections from the MM5 mesoscale model for the entire IP at 30 km and at 10 km for the Southeastern IP. Finally, the Spanish projects ESCENA (2008-2011, http://www.meteo.unican.es/en/node/72776) and ESTCENA (2008-2011, http://www.meteo.unican.es/en/projects/esTcena) must be mentioned, which are currently developing downscaled projections at about 25 km of the IP climate for the 21st Century with only dynamical or statistical downscaling techniques, respectively, whose results will be published soon. For the rest of the world, the European projects PRUDENCE (EVK2-CT2001-00132, 2001-2004, http://PRUDENCE.dmi.dk/) and ENSEMBLES (GOCE-CT-2003-505539, 2004-2009, http://ENSEMBLES-eu.metoffice.com/index.html) must be highlighted. In the first case, regional climate simulations were performed at 50-70 km across Europe with different models from European research centers (Christensen, 2005; Déqué et al., 2005). In the second case, an ensemble system of downscaled projections at 25-50 km was carried out for all Europe (Van der Linden and Mitchell, 2009). Currently, the project of the WCRP CORDEX (since 2009, http://cordex.dmi.dk/) must be also highlighted, which is the continuation of the previous projects. Several downscaled simulations are being developed and coordinated through it, many of them with the WRF mesoscale model for several areas on Earth at 20-50 km. Finally, in recent years many works with dynamical climate downscalings have been carried out in different parts of the world and from different mesoscale models, with Salathé Jr et al. (2008) as a good example, with projections at 15 km with the MM5 model for the NW Pacific of the USA.

The work presented in this study is the first done with such a high spatial resolution for Catalonia, taking into account dynamical downscaling techniques. However, this work represents only a starting point for the study area, as just some initial results are displayed, which may be useful to complement studies of impact analysis in Catalonia. Regional simulations of the climate for the 21st Century for all of Catalonia at a spatial resolution of 15 km are being carried out through the MM5 mesoscale model nested into the boundary conditions of the atmosphere-ocean global coupled model ECHAM5/MPI-OM. First, this paper presents the data used to develop such a study, then the methodology is explained and the most significant results in relation to the projections of the air temperature at 2 m and the precipitation in all of Catalonia are presented. Finally, we present the main conclusions as well as the future work to be developed to improve the simulations. To conclude, it must be noted that this work is the continuation and expansion of what was done for Chapter 6 (Calbó et al., 2010) of the *Second Report on Climate Change in Catalonia* (Llebot, 2010). A second part is in preparation, which will summarize the results of projections for Catalonia through various approaches, including those presented here.

2 Data used

The data used to prepare this study are:

- Reanalyses of the ERA40 (Uppala et al., 2005) from the European Centre for Medium-Range Weather Forecast (ECMWF) at 2.5° horizontal spatial resolution for the period 1971-2000 and available every 6 h (00, 06, 12 and 18 UTC). These data have been used to evaluate the ability of downscaled simulations to reproduce the main space-time characteristics of temperature and precipitation (http://data-portal.ecmwf.int/data/d/ERA40_daily/).
- Global climate simulations of the ECHAM5/MPI-OM model for the IPCC (2007) at 1.875° of horizontal spatial resolution, 19 vertical levels and available every 6 h (00, 06, 12 and 18 UTC): one for the climate of the 20th Century (Roeckner, 2005) and two for the 21st Century climate, respectively, forced by the emission scenarios defined at the Special Report on Emissions Scenarios

Table 1. Comparison of the average seasonal values of temperature (in °C) among the observations, the ERA40, the EHA5OM and the simulations MM5+ERA40 and MM5+EH5OM at 15 km for the reference period 1971-2000.

Season	OBS	MM5+ERA40	ERA40	MM5+EH5OM	EH5OM
DGF	7.3	6.7	5.8	6.5	7.1
MAM	12.8	10.3	11.2	9.9	8.8
JJA	22.0	16.5	20.3	15.4	18.6
SON	15.1	10.9	13.2	10.2	17.7
Annual	14.3	11.1	12.6	10.5	13.1

Table 2. Comparison of the average seasonal values of precipitation (in mm) among the observations, the ERA40, the EHA5OM and the simulations MM5+ERA40 and MM5+EH5OM at 15 km for the reference period 1971-2000.

Season	OBS	MM5+ERA40	ERA40	MM5+EH5OM	EH5OM
DGF	134.8	247.1	111.1	351.8	112.7
MAM	174.5	257.1	152.6	423.8	135.7
JJA	147.3	85.6	144.9	172.6	34.7
SON	195.7	132.9	138.9	264.5	140.4
Annual	652.2	722.8	547.4	1212.7	423.5

(SRES) by Nakićenović et al. (2000): SRES-A2 (severe scenario, Roeckner et al., 2006a) and SRES-B1 (moderate scenario, Roeckner et al., 2006b). They have been used to generate the downscaled scenarios in Catalonia (http://cera-www.dkrz.de/CERA/index.html).

- Precipitation grid of 5 km × 5 km at the NE of the IP calculated by Altava-Ortiz (2010) from about 1100 rain gauge stations of the Spanish Meteorological Agency and other institutions in this region (not simultaneous in time). It has been used to compare it with the simulated precipitation data.
- 17 homogeneous temperature series representative of the different climatic zones of Catalonia (Meteorological Service of Catalonia, SMC, 2010). They were used to compare them with simulated temperature data.

3 Methodology

This study proposes the use of the MM5 mesoscale model (Grell et al., 1994; Dudhia et al., 2005) with three one-way nested domains of 135, 45 and 15 km of horizontal resolution and 23 levels of vertical resolution into the boundary conditions provided on one hand by the ERA40 reanalyses, and on the other hand by the global coupled atmosphere-ocean model ECHAM5/MPI-OM. The ECHAM5 (Roeckner et al., 2003) is its atmospheric component, which was jointly developed by the ECMWF and the *Max Planck Institut für Meteorologie* in Hamburg (Germany), and the MPI-OM (Marsland et al., 2003) is its ocean component, entirely developed at the *Max Planck Institut*.

The MM5 model is one of the models used in the weather forecasting done every day by the SMC with good reliability (Sairouni et al., 2007). Further, it is one of the most widespread short-term prediction numerical models in the international community of atmospheric modeling, as it is freely distributed and easy to install and run on multiple platforms. On the other hand, the ECHAM5/MPI-OM model is one of the global models that best reproduces the current climate of the Earth under the known radiative forcings (Ulden and Van Oldenborgh, 2006), especially in the Mediterranean area (Altava-Ortiz, 2010). Therefore, it can be considered one of the best models for making future projections of the climate among all the models considered in the IPCC (2007) for the study area.

The first domain with the MM5 that has been defined (horizontal resolution of 135 km and 30×50 points), covers an area limited to 50°W to 50°E and 17°N to 58°N, and it is centered on 0°E and 40°N. The second domain (horizontal resolution of 45 km and 40×40 points) occupies an area limited to 12°W to 8°E and 32°N to 47°N. The third domain (horizontal resolution of 15 km and 25×25 points) has an area limited to 1°W to 4°E and 40°N to 43°N. It should be mentioned that the dimensions of the integration domains have been optimized in order to minimize the computing time and the storage space on the hard data output. A dynamic analysis nudging has been applied to the mother domain (135 km). This technique involves forcing the simulation to follow the boundary conditions provided by the global model throughout the integration. This ensures continuity of mass in the simulations (integration of limited area). This technique also allows to obtain large-scale patterns consistent with those present in the global simulation (Salathé Jr et al., 2008). In contrast, the second and third domains are integrated without dynamic forcing so the MM5 model freely reproduces the small scale phenomena in these two domains and so the downscaling technique used is really effective.

Table 3. Summary of the projected changes in temperature and precipitation for the whole of Catalonia according to the emission scenarios A2 and B1 and for each climatic season obtained with the downscaled simulations with the MM5 at 15 km. Reference period 1971-2000. Aver. is average, Max. maximum value and Min. minimum value. The latter two values indicate the maximum and minimum variation detected among all the cells that cover Catalonia.

SRES	Period	Season	Temp. variation (°C)			Precip. Variation (%)		
			Aver.	Max.	Min.	Aver.	Max.	Min.
		Annual	$+0,8$	$+0,9$	$+0,2$	$-8,0$	$-0,7$	$-15,9$
		DJF	$+0.7$	$+0.8$	$+0.0$	-3.5	$+7.1$	-13.3
	2011-2040	MAM	$+0.6$	$+0.8$	$+0.1$	-12.8	-4.6	-19.7
		JJA	$+0.9$	$+1.1$	$+0.4$	$+5.9$	$+25.7$	-20.6
		SON	$+0.8$	$+1.0$	$+0.2$	-11.9	$+8.9$	-23.9
		Annual	$+2.1$	$+2.3$	$+1.6$	-8.0	$+12.4$	-18.1
A2		DJF	$+2.0$	$+2.3$	$+1.5$	$+4.5$	$+37.6$	-18.6
	2041-2070	MAM	$+1.8$	$+2.0$	$+1.4$	-13.3	$+11.1$	-25.0
		JJA	$+2.5$	$+2.7$	$+2.0$	-23.2	-1.1	-47.3
		SON	$+2.1$	$+2.4$	$+1.6$	-10.6	$+9.6$	-24.0
		Annual	$+3.6$	$+4.0$	$+3.3$	-16.5	$+3.7$	-29.7
		DJF	$+3.2$	$+3.5$	$+3.0$	$+4.0$	$+37.1$	-20.8
	2071-2100	MAM	$+3.2$	$+3.5$	$+2.9$	-20.8	$+9.7$	-35.6
		JJA	$+4.3$	$+4.8$	$+3.6$	-39.2	-13.7	-61.6
		SON	$+3.9$	$+4.4$	$+3.3$	-25.3	-0.6	-37.4
		Annual	$+0.9$	$+1.0$	$+0.5$	-1.4	$+10.8$	-14.5
		DJF	$+1.0$	$+1.2$	$+0.7$	$+10.7$	$+40.4$	-17.0
	2011-2040	MAM	$+0.7$	$+0.8$	$+0.4$	-11.1	-1.2	-18.0
		JJA	$+1.0$	$+1.2$	$+0.7$	$+1.2$	$+27.0$	-26.0
		SON	$+0.8$	$+0.9$	$+0.4$	-2.1	$+6.0$	-15.0
		Annual	$+1.4$	$+1.5$	$+1.2$	-3.8	$+3.2$	-12.5
B1		DGF	$+1.3$	$+1.5$	$+1.1$	-1.2	$+20.6$	-12.5
	2041-2070	MAM	$+1.1$	$+1.2$	$+0.9$	-11.5	-1.1	-20.3
		JJA	$+1.7$	$+1.9$	$+1.4$	-0.7	$+21.7$	-25.8
		SON	$+1.5$	$+1.6$	$+1.2$	$+2.8$	$+17.4$	-11.9
		Annual	$+2.5$	$+2.8$	$+2.3$	-10.5	$+8.0$	-21.5
		DGF	$+2.2$	$+2.4$	$+2.0$	$+6.0$	$+35.2$	-19.2
	2071-2100	MAM	$+2.2$	$+2.5$	$+2.0$	-13.5	$+7.3$	-25.5
		JJA	$+3.0$	$+3.4$	$+2.5$	-23.0	$+4.0$	-47.3
		SON	$+2.6$	$+2.9$	$+2.3$	-21.6	-6.7	-37.1

The entire simulation process has been divided into continuous integrations of 5 years, independent from each other, and each of them is initialized with the initial conditions provided by the global models (ERA40 or EH5OM). To carry it out, we have chosen a set of simple physical parameterizations. This is because previous studies such as Fernández et al. (2007) conclude that there is no entirely appropriate combination to define the characteristics, on a regional scale, of the IP climate for long integrations (5 years) with the MM5 model. Therefore, a set of parameterizations that minimize computing time is recommended. Thus, we have chosen the Grell algorithm (Grell, 1993; Grell et al., 1994) for convection, the simple ice parameterization (Dudhia, 1989) for the microphysics, the cloud scheme (Dudhia, 1989; Grell et al., 1994) for radiation, the MRF scheme (Hong and Pan, 1996) for the planetary boundary layer, and finally, a simple 5-layer soil model(Dudhia, 1996) for soil parameterization.

4 Results

This section presents the main results of the developed simulations. Firstly, there is the evaluation of the methodology defined in reproducing the current space-time characteristics of temperature and precipitation for the control period (1971-2000). Secondly, we analyze the projections obtained for the 21st Century, with special emphasis placed on the

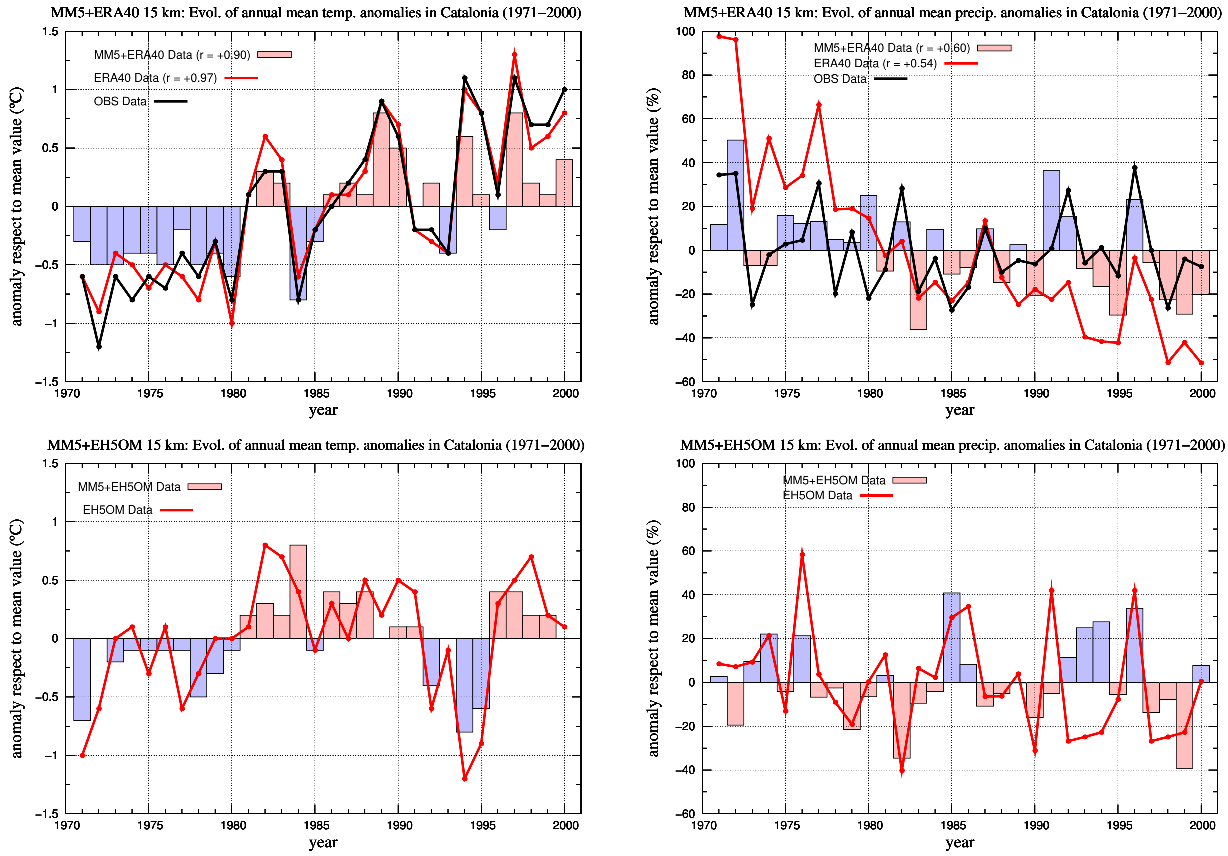

Figure 1. Temporal evolution of the annual mean anomalies of temperature (a, upper left, and c, lower left) and precipitation (b, upper right, and d, lower right) for the whole of Catalonia and the period 1971-2000 calculated from the downscaled simulations with the MM5 at 15 km (color bars), the observations (black lines) and the ERA40 (red lines, Figures a and b) or the global climate simulations of the EH5OM (red lines, Figures c and d).

analysis of three periods of 30 years: 2011-2040, 2041-2070 and 2071-2100.

4.1 Reproduction of the current climate

Figure 1a and 1b show the temporal evolutions of the annual mean anomalies of temperature and precipitation, respectively, for the whole of Catalonia for the simulation of the MM5 nested into the ERA40 (MM5+ERA40), those directly obtained from the ERA40 and the observations for the 1971-2000 period. It can be concluded that the range of variability produced by the model is similar to the observed one, and above all, the downscaling improves the results directly obtained from the global model. The latter can be seen significantly regarding precipitation (Figure 1b), where, while observations do not show any trend, the ERA40 data shows a significant tendency to decrease and the MM5+ERA40 only shows a slight decrease. This improvement is also observed with the linear correlation between the MM5+ERA40 simulation and the observations (r = +0.60) compared to the ERA40 correlation with the observations (r = +0.54).

On the other hand, Figures 1c and 1d show the same temporal evolutions as Figures 1a and 1b except for the simulation of the MM5 nested into the climate global simulation of the ECHAM5/MPI-OM (MM5+EH5OM). The downscaled simulation keeps the variability range, especially for temperature.

With respect to seasonal cycles (Tables 1 and 2), that of temperature is well reproduced by the downscaled simulations, better for the MM5+ERA40 simulation than for the MM5+EH5OM simulation. The cycle of precipitation, however, is not well reproduced, obtaining a very significant overestimation in winter and spring and an underestimation in summer and autumn. In general, then, this analysis shows a cold bias produced by MM5 (the cold bias is intrinsic to the MM5 model, as concluded in the technical note of the SMC of Sairouni et al. (2007). Moreover, a part of this bias could be due to the low density of series available for comparison with simulated values) and a general overestimation of the rain, much more marked in the MM5+EH5OM simulation (possibly the fact that the ERA40 and the EH5OM, the latter to a lesser extent, do not reproduce well the cycle of precipitation may be an important factor in not being properly

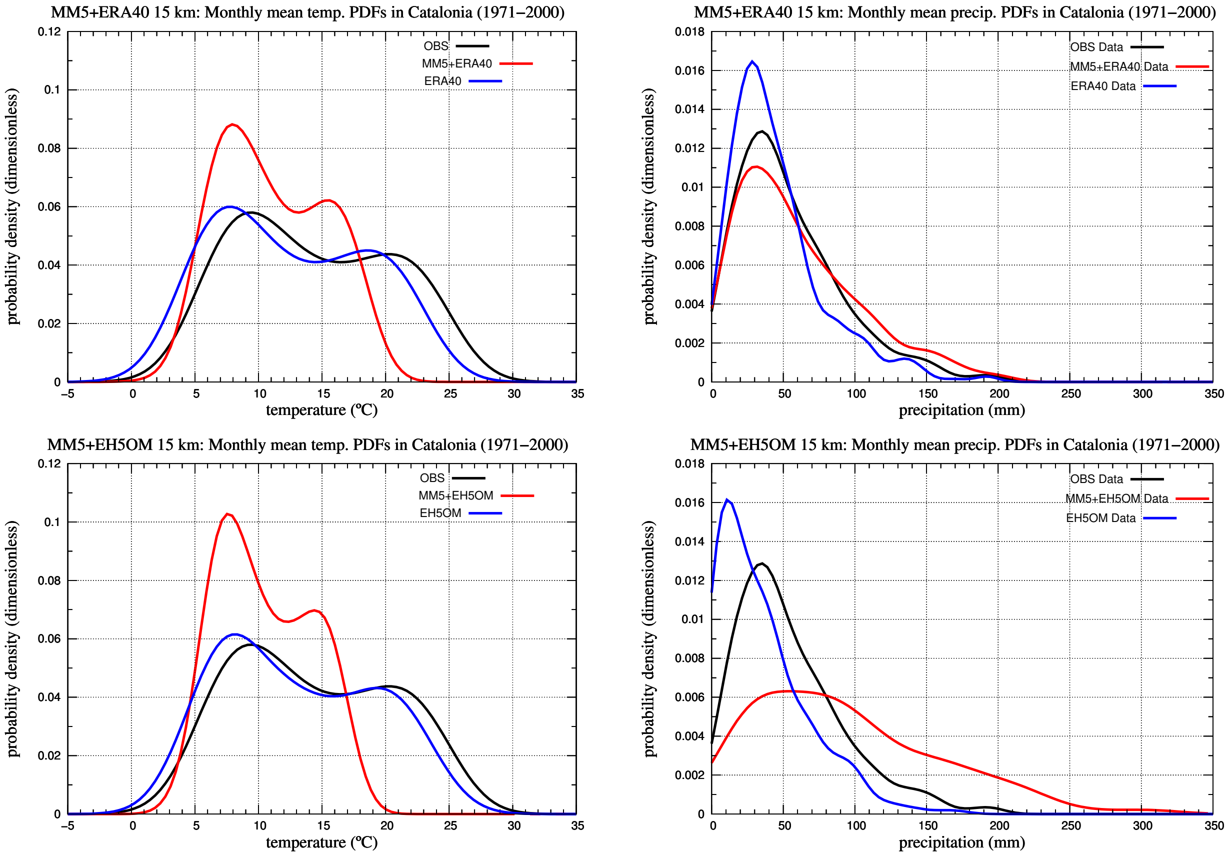

Figure 2. Probability density functions (PDFs) of temperature (a, upper left, and c, lower left) and precipitation (b, upper right, and d, lower right), monthly averages for the whole of Catalonia and the period 1971-2000 calculated from the downscaled simulations with the MM5 at 15 km (red lines), the observations (black lines) and the ERA40 (blue lines, Figures a and b) or the global climate simulations of the EH5OM (blue lines, Figures c and d).

reproduced it by the downscaled simulations. In addition, the different nests done together with the very tight dimensions of the domains are probably also responsible for this overestimation).

This behavior of simulations can be better seen in the analysis of frequency distributions of monthly mean temperatures and precipitation from their Probability Density Functions (PDFs, Figure 2). In general the typology of all simulated PDFs is similar to the PDFs observed: bimodal distribution for temperature and unimodal distribution with negative skewness in the case of precipitation. However, due to the cold bias produced by the MM5, as discussed for temperatures, neither of the two downscaled simulations correctly reproduces the PDF. Therefore, in this case the technique does not show an improvement regarding the global models whose PDFs are very similar to those observed. In the case of precipitation, the analysis is more complex, since for the MM5+ERA40 simulation the PDF obtained is closer to the PDF observed than to that obtained directly from the ERA40. In contrast, for the MM5+EH5OM simulation, due to the large overestimation that it produces, the shape of the simulated PDF is quite different from the one observed, although in this case it is not similar to the one observed for the PDF of the EH5OM.

Although the downscaled simulations have shown inaccuracies in such important characteristics as the seasonal cycle of precipitation and the frequency distribution of monthly temperature and precipitation values, the technique developed is now the only one that can reproduce the spatial variability of both variables with sufficient detail. Thus, Figure 3 shows a comparison between the annual mean precipitation fields for the control period obtained from the observations and those obtained from the global models and the two downscaled simulations. We can see how the MM5+ERA40 simulation (Figure 3d) reproduces the spatial pattern (match of the maximum and minimum precipitation, and total values) of the observations (Figure 3a) quite well. The MM5+EH5OM simulation (Figure 3e), although it significantly overestimates the precipitation field, has a spatial pattern that is also similar to the one observed. However, because the domain of interest (that of 15 km spatial resolution) has a too tight extension, in its contours there are areas with a significant overestimation of precipitation (especially in the northern strip of Figure 3d). Finally, mention that with the mean fields ob-

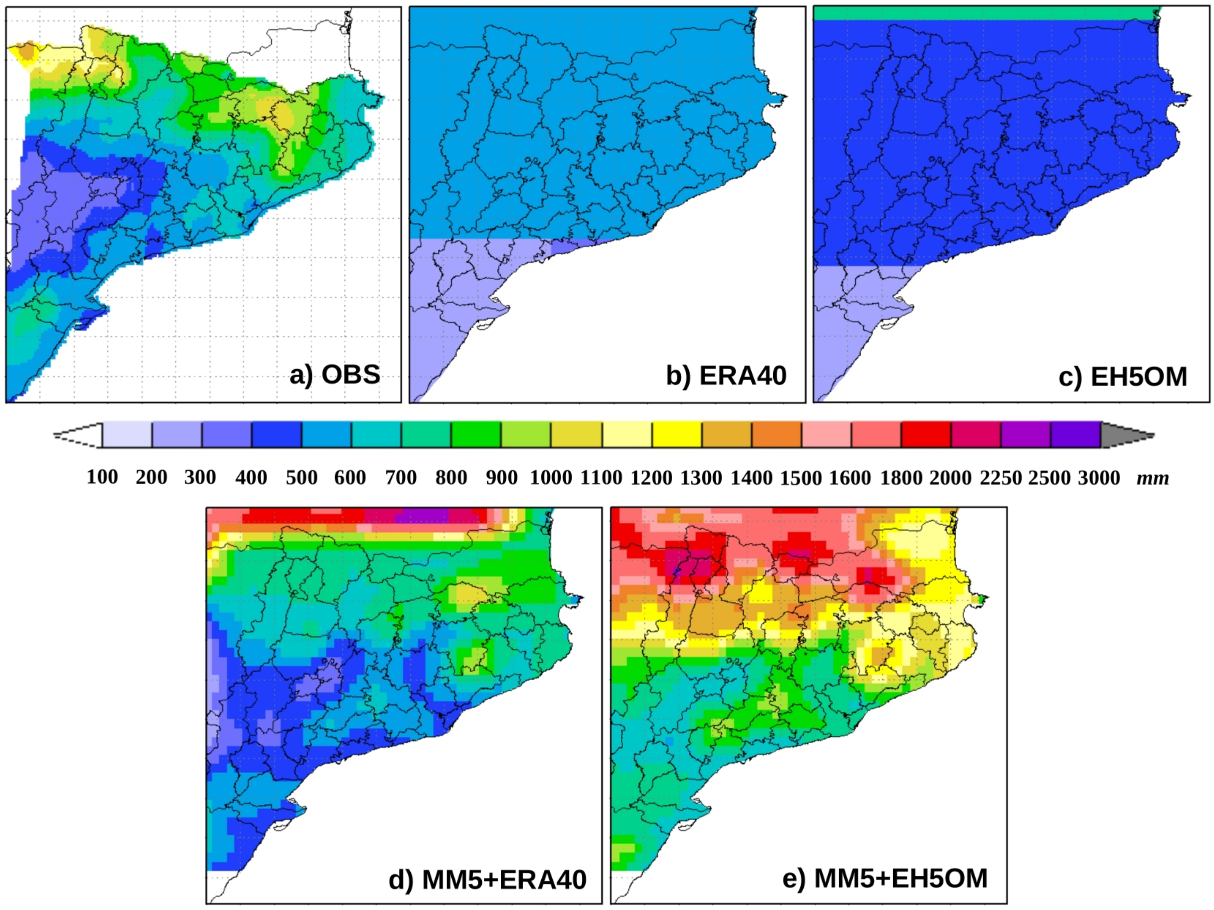

Figure 3. Comparison of the annual mean precipitation field for the period 1971-2000 calculated from the observations (a), from the ERA40 (b), from the EH5OM (c) and from the simulations MM5+ERA40 (d) and MM5+EH5OM (e) at 15 km.

tained from ERA40 (Figure 3b) and EH5OM (Figure 3c) it is not possible to reproduce the large spatial variability of precipitation in Catalonia.

4.2 Analysis of the projections

To evaluate the projected changes in precipitation and temperature for the three analysis periods (2011-2040, 2041-2070 and 2071-2100) we proceed as follows: first, the mean values of these variables were calculated by the MM5+EH5OM simulation at 15 km for the control period (1971-2000). Then, the mean values of the variables from the MM5+EH5OM for the three periods of the 21st Century were calculated, but considering two different emission scenarios (A2 and B1). Finally, the variations of the variables, such as the difference between the mean values of the two forced simulations with the corresponding emissions and the reference simulation, are calculated. By making this difference it is assumed that most of the errors and biases, produced by the methodology used, will be cancelled. However, they are not fully eliminated because generally biases are not linear, even if the errors that the model shows are always present.

Table 3 shows a summary of the projected changes in temperature and precipitation for the whole of Catalonia (box set by 0.15°-3.35°E and 40.5°-42.9°N). It gives the average, maximum and minimum values of the projected variations in these two variables with respect to the average values of the reference period 1971-2000 for each period, scenario and season. These values have been calculated from all grid points of the high-resolution domain (15 km) located on land and within the box defined above. In short, we can say that an increase of the annual mean temperature for the two emission scenarios is projected for this century. This increase would be closer to 1°C for the first period, about 1.8°C for the second period and the order of 3°C by the end of the century. We also observed an increase in temperature during all seasons, being more pronounced in summer and especially for the A2 scenario. Regarding precipitation, an average reduction of precipitation by 5% is obtained for the first and second periods and 14% by the end of the century. The seasonal behavior of precipitation is less regular and the range of variation much larger than in the case of temperature. In addition, there are notable differences between the results obtained for each scenario in the seasonal scale, es-

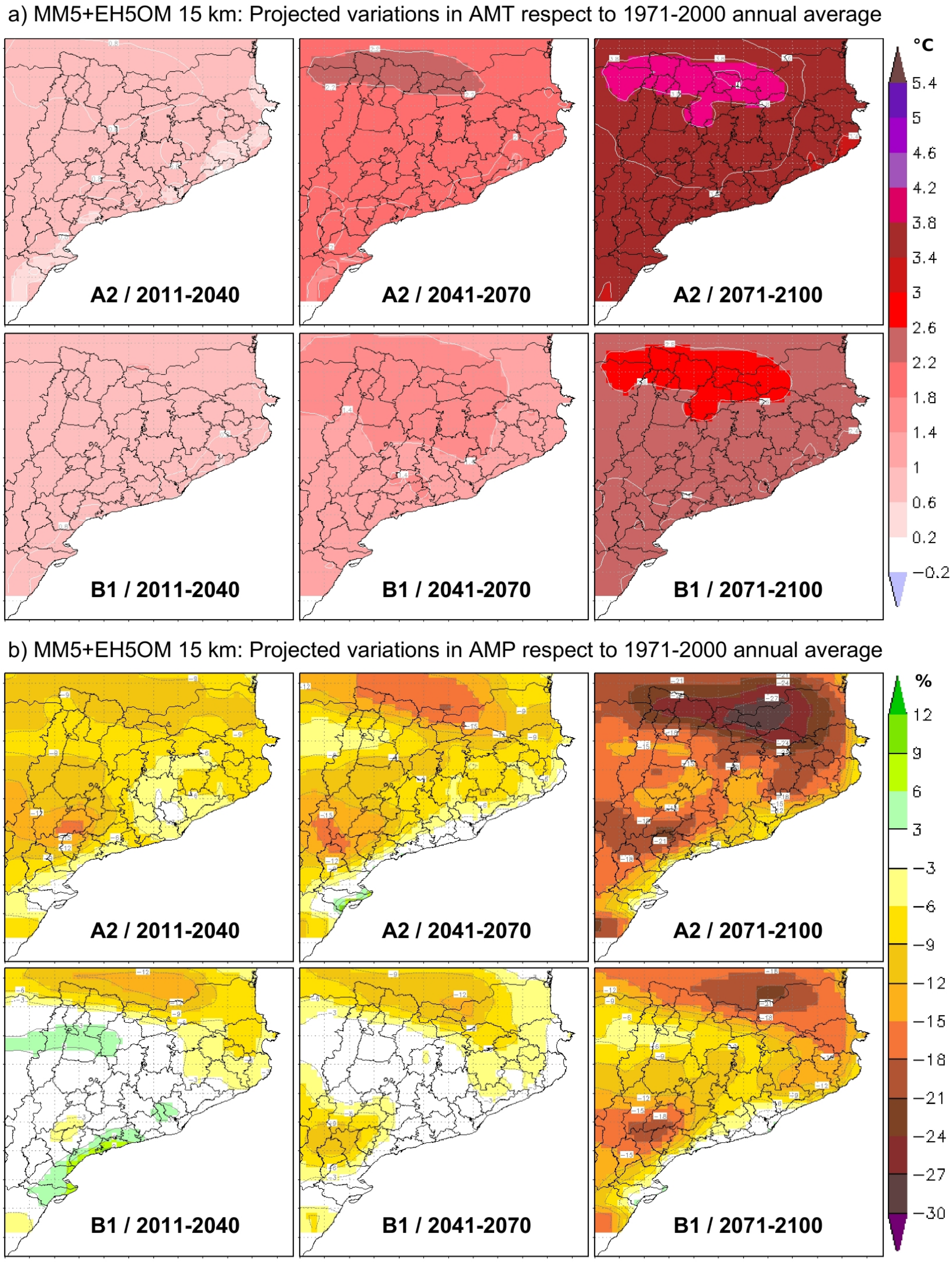

Figure 4. Maps of the annual mean temperature (a) and precipitation (b) variation fields, obtained with the downscaled simulation with the MM5 at 15 km for the emissions scenarios A2 and B1 and for the periods 2011-2040, 2041-2070 and 2071-2100. Reference period 1971-2000. The temperature variation contour lines are represented each at 0.2°C while those of precipitation are represented according to the values scale on the left.

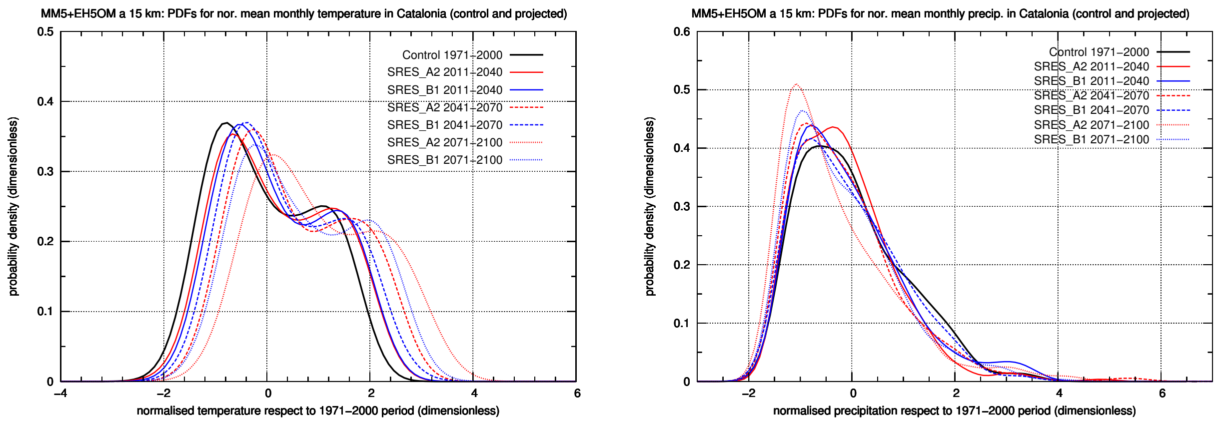

Figure 5. Probability density functions (PDFs) of temperature (a, left) and precipitation (b, right), monthly normalized averages for the whole of Catalonia calculated from the downscaled simulations with the MM5 at 15 km: control simulation (1971-2000, black lines), simulations according to scenario A2 (red lines) and B1 (blue lines) for the periods 2011-2040, 2041-2070 and 2071-2100.

pecially for the mid-century. Although towards the end of the century both scenarios tend to converge on the sign of the projected variation both annually and seasonally. Thus, the projected decrease in precipitation is not a result as robust as the projected temperature increase.

Figure 4 shows the maps with projected annual changes in temperature (Figure 4a) and precipitation (Figure 4b) for the three study periods. It is possible to see that the projected increase in temperature will not be of the same magnitude for all Catalonia, being much more important in the Pyrenees than at the coast, of the order of 1°C. The interior of the country would behave as a transition zone between the coast and the Pyrenees, in reference to projected variations. Regarding precipitation, it is observed that the general decline in precipitation would not be constant during the 21st Century and would not occur with the same intensity throughout Catalonia. In fact, in a large area of the coast only a slight decrease or virtually no appreciable change in the annual totals is projected. In some coastal points precipitation could even slightly increase ($\sim 5\%$). If we analyze the areas of the country that could suffer a more significant reduction of precipitation in detail, the Pyrenees would be the area that suffers the highest annual reduction followed by the Western area. For the Pyrenees, there is a projected reduction close to 30% for A2 scenario by the end of the century, and higher than 20% for Terres de Ponent. Although for the first two periods the differences between both scenarios are significant, at the end of the century these differences are minor, projecting a more generalized and more marked decrease in precipitation that would affect almost the entire country (except the south coast), with reductions in precipitation of 10-15% in most of the country.

Figure 5 shows the projected PDFs of normalized monthly mean temperature (Figure 5a) and precipitation (Figure 5b) for the control period and the three periods of study for the whole of Catalonia. All monthly data on temperature and precipitation that have been used to calculate the PDFs were standardized according to the following mathematical expression:

$$z = \frac{x - x_m}{s} \qquad (1)$$

where z is the normalized variable, x is the original variable, x_m and s are respectively the arithmetic mean and standard deviation for all months of the year of the analysis period.

For temperature, the most important thing to be highlighted of the projections obtained is an increase in the probability of occurrence of very warm months ($z > 2$), which would be more significant as the 21st Century progresses. This result is more pronounced for the A2 scenario than for B1. Moreover, for the months of extreme cold ($z < -2$) a decrease in their frequency is projected during this century, which is less marked than the increase in warm months. For precipitation, we can conclude that a transfer of probability towards the end of the PDF of the monthly precipitation for the next 100 years could happen, which would increase its interannual variability in Catalonia. Therefore, this suggests that the frequency of hydric extremes (droughts and floods) might be increased during this century, but have not yet been detected (Barrera-Escoda, 2008).

Finally, Figure 6 shows the temporal evolutions of the projected annual mean anomalies in temperature (Figure 6a) and precipitation (Figure 6b) for all Catalonia for 1971-2100. The evolution of annual temperatures during the 21st Century clearly shows a positive trend (increase), and increase values close to +5°C could be reached at the end of the century for the A2 scenario in relation to the mean values for the period 1971-2000. The linear trend in temperature for this century is projected at +4.5°C in 100 years for the A2 scenario and +2.4°C in 100 years for B1. It is also interesting to mention that until mid-century the annual evolution of temperature is projected in quite a similar way for both scenarios

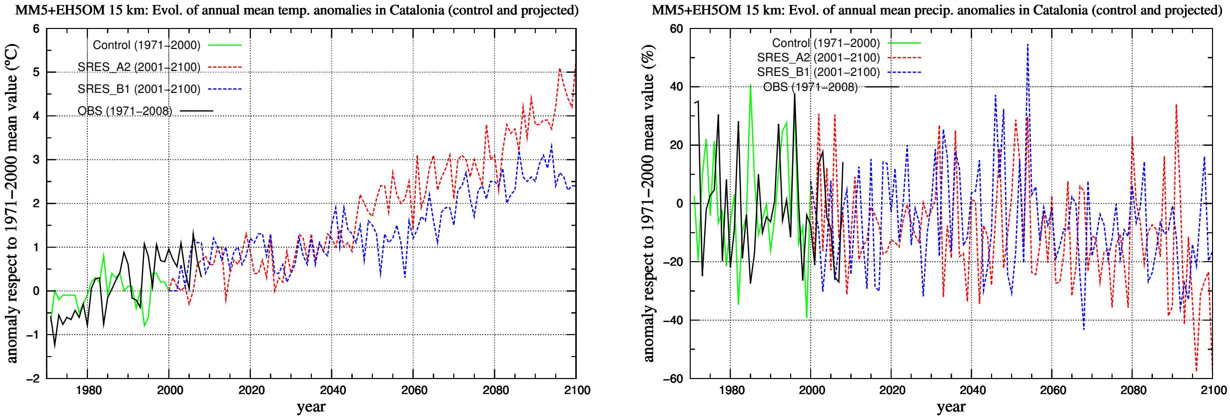

Figure 6. Projected temporal evolutions of the anomalies of temperature (a, left) and precipitation (b, right) for the whole of Catalonia calculated from the downscaled simulations with the MM5 at 15 km for the period 1971-2100. The data of the control simulation (1971-2000) downscaled with the MM5 at 15 km are in green, the data of the simulation with the scenario A2 are in red and those of the B1 scenario are in blue. The data of the observations (1971-2008) are in black.

Table 4. Summary of the application of the Monte Carlo method in the evaluation of trends in downscaled annual precipitation projections with the MM5 at 15 km for the 21st Century. The linear trends are expressed in emission scenario of reference, t is the linear trend calculated, $T_{2.5}$, T_5, T_{95} and $T_{97.5}$ are the percentiles 2.5, 5, 95 and 97.5 of the random linear trends calculated with the Monte Carlo method, respectively.

SRES	t	$T_{97.5}$	T_{95}	T_5	$T_{2.5}$	Sig.? $\rightarrow t > \|T\|$?
A2 (2001-2100)	-17.0	-12.31	—	—	+12.33	Yes
B1 (2001-2100)	-8.7	-11.49	-9.59	+9.58	+11.50	No

and it is not until the end of the century when the two projections are quite different. Broadly speaking, the projections for B1 scenario are lower than those for A2, especially at the end of the century. The annual evolution of precipitation does not present such a clear trend as that obtained for the annual mean temperature. It can be seen how until the middle of this century the simulations carried out give a great variability in precipitation without a clear trend, although generally negative values predominate over positive values. For the second half of the century, the projected annual precipitation shows a much clearer trend towards a reduction, which could become very significant at the end of the century and the A2 scenario, reaching reductions of over 40%. The analysis of trends in annual precipitation projections (Table 4) using a Monte Carlo method to evaluate their statistical significance (Livezey and Chen, 1983; Kunkel et al., 1999; Liebmann et al., 2004) only results in a decreasing linear trend, statistically significant with a confidence level of 95%, of the annual mean precipitation considering the A2 scenario. In this case, the linear trend projected for this century is -17.0% in 100 years. However, for the B1 scenario there is no statistically significant trend, since the linear variation of -8.7% in 100 years falls within the range of randomness of the Monte Carlo method used (Table 4).

5 Conclusions

The downscaled simulations developed correctly reproduce both the range of interannual variability as the sign of the observed trends, but not the seasonal cycle of rain (they do reproduce the cycle of temperature). However, a general overestimation and cold bias of the mean fields of annual precipitation and temperature are observed, respectively. The projections show a significant and robust increase in temperatures, of up to +4°C at the end of the century with respect to the period 1971-2000, with a significant increase of warm months and a decrease of the coldest months. Regarding precipitation, the projected trends are not so robust. An annual decrease of precipitation (up to 17% in 100 years) is projected, but not a monotonous one. It should be noted that there are great differences at a seasonal scale according to the emission scenario considered. More variability is also projected, so an increase in extreme precipitation and dry episodes should be expected. For the A2 scenario (severe) major and more significant changes are projected than for the B1 (moderate), with the Pyrenees being the area of the country with the greatest changes and the coastal areas where these changes are lesser. The interior of the country would behave as a transition zone between the two areas.

It is worth mentioning that the general results obtained are in line with those found in similar works for the study area but with lower spatial resolutions, such as Brunet et al. (2009) and the European projects PRUDENCE and ENSEMBLES (see references in the introduction). However, the fact of having done the simulations with high spatial resolution has allowed us to analyze in detail how the projected changes are not uniform throughout the country. More information about the results is in preparation in the second part of this work.

The results shown in this paper represent a starting point for the study area, as there are a number of issues to improve, such as the reproduction of the rain seasonal cycle, its general overestimation and the cold bias of temperatures, as seen in section 4.1. Therefore, for future work, the integration domains should be redefined to cover a wider area, especially for the higher resolution domain. It would also be necessary to use more complex parameterizations so that the physical processes are better represented and the results could be more robust. To get a more complete vision of the projections, downscaled simulations considering other emission scenarios of the SRES, such as the A1B, intermediate scenario of emissions between the A2 and B1, should be performed. On the other hand, other global climate models that have also demonstrated success in reproducing climatic conditions in the North Atlantic and Europe (Ulden and Van Oldenborgh, 2006) should be used, such as the CCC63 (Flato, 2005), the MIROChi (Hasumi and Emori, 2004), HadGEM (IPCC, 2007), CCC47 (Kim et al., 2003) and GFDL2.1 (Delworth et al., 2006) in decreasing order of quality, respectively. Finally, together with the considerations exposed, other models of limited scale should be used besides the MM5, such as WRF (Skamarock et al., 2005). The combination of these options would offer a wide range of results from which we could analyze in detail the robustness of the projections obtained, and the evaluation of their uncertainties.

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