Tellus
SERIES A
DYNAMIC
METEOROLOGY
AND OCEANOGRAPHY
PUBLISHED BY THE INTERNATIONAL METEOROLOGICAL INSTITUTE IN STOCKHOLM

Tellus (2009), 61A, 57–71

TELLUS

Exploiting an ensemble of regional climate models to provide robust estimates of projected changes in monthly temperature and precipitation probability distribution functions

By FRANCISCO J. TAPIADOR*, ENRIQUE SÁNCHEZ and RAQUEL ROMERA,
Institute of Environmental Sciences University of Castilla-La Mancha (UCLM), Avda. Carlos III s/n. 45071 Toledo, Spain

(Manuscript received 28 March 2008; in final form 24 September 2008)

ABSTRACT

Regional climate models (RCMs) are dynamical downscaling tools aimed to improve the modelling of local physical processes. Ensembles of RCMs are widely used to improve the coarse-grain estimates of global climate models (GCMs) since the use of several RCMs helps to palliate uncertainties arising from different dynamical cores and numerical schemes methods. In this paper, we analyse the differences and similarities in the climate change response for an ensemble of heterogeneous RCMs forced by one GCM (HadAM3H), and one emissions scenario (IPCC's SRES-A2 scenario). As a difference with previous approaches using PRUDENCE database, the statistical description of climate characteristics is made through the spatial and temporal aggregation of the RCMs outputs into probability distribution functions (PDF) of monthly values. This procedure is a complementary approach to conventional seasonal analyses. Our results provide new, stronger evidence on expected marked regional differences in Europe in the A2 scenario in terms of precipitation and temperature changes. While we found an overall increase in the mean temperature and extreme values, we also found mixed regional differences for precipitation.

1. Introduction

The European Union project PRUDENCE (Christensen et al., 2002) was a multinational effort to establish uncertainty limits in climate modelling, providing high-resolution (50 km) estimates from present (1961–1990) and future (2071–2100) climate (Christensen et al., 2007a) using an heterogeneous set of regional climate models (RCMs). Studies using PRUDENCE data span from boundary layer dynamics (Sánchez et al., 2007b) to regional precipitation analysis (Tapiador et al., 2007) through comprehensive analyses of the ensemble means using three–dimensional fields (Christensen and Christensen, 2007; Christensen et al., 2007a; Déqué et al., 2007; Jacob et al., 2007). PRUDENCE results have also been used as a part of the 2007-IPCC Scientific report (Christensen et al., 2007b).

Among the downscaling methods used to provide insight on climate description at regional scales, RCMs forced by GCMs have become a widely used tool for regional climate studies (e.g Giorgi and Mearns, 1999). Crucially in terms of new insights, results from improved resolution RCM estimates do not necessarily agree with the values of the GCM used for forcing. Since new information is added to the RCM by modelling GCM-subgrid processes, the RCMs' fields may have different statistical properties that those of the original GCM (Mearns et al., 1999). Even for large-area studies such as hydrological analysis of catchments (Ekström et al., 2007; Graham et al., 2007), RCM outputs significantly depart from GCM's. This is specially apparent with highly anisotropic fields such as precipitation (Machenhauer et al., 1998).

Climate change numerical projections present many sources of uncertainty (Räisänen, 2007). Chiefly among them lays our still limited knowledge on cloud microphysics (Khain et al., 2000) and other physical parametrizations (radiative processes, soil–atmosphere exchanges, precipitation, etc.), as the results from PRUDENCE have shown (Beniston et al., 2007; Christensen and Christensen, 2007; Christensen et al., 2007a; Déqué et al., 2007; Jacob et al., 2007; Kjellström et al., 2007; Lenderink et al., 2007; Sánchez et al., 2007a; Van Ulden et al., 2007). Other uncertainty sources include sensitivity to initial conditions, those arising from the global model used to

*Corresponding author.
e-mail: francisco.tapiador@uclm.es
DOI: 10.1111/j.1600-0870.2008.00374.x

force the regional models, incomplete knowledge of greenhouse gases emissions scenario and unknown feedbacks in the climatic system (Christensen, 1999; Giorgi and Bi, 2000; Vidale et al., 2003).

In this research, we have concentrated our analysis in the uncertainties arising from model formulation. PRUDENCE project presents an excellent opportunity to analyse the outcomes of many RCM forced with the same GCM for the same emissions scenario. While several studies have already analysed climatic characteristics, using seasonal or annual means to analyse interannual variability for temperature and precipitation (Christensen and Christensen, 2007; Christensen et al., 2007a; Déqué et al., 2007; Jacob et al., 2007), here we use a different statistical perspective to complement those analyses. Thus, instead of seasonal or annual values, monthly results are analysed and compared for the two simulations (present and future climates). Another difference over previous studies using PRUDENCE data is the explicit use higher order statistics from the probability distribution function (PDFs) that we have used to compare climates (Fowler et al., 2007; Tapiador et al., 2007). This choice gives us a different perspective on climate changes and uncertainties in the estimation (Murphy et al., 2004; Ferro et al., 2005; Perkins et al., 2007). As in previous studies, a regional approach will be followed to derive the PDFs. Specifically, we will use the same regionalization done in Giorgi

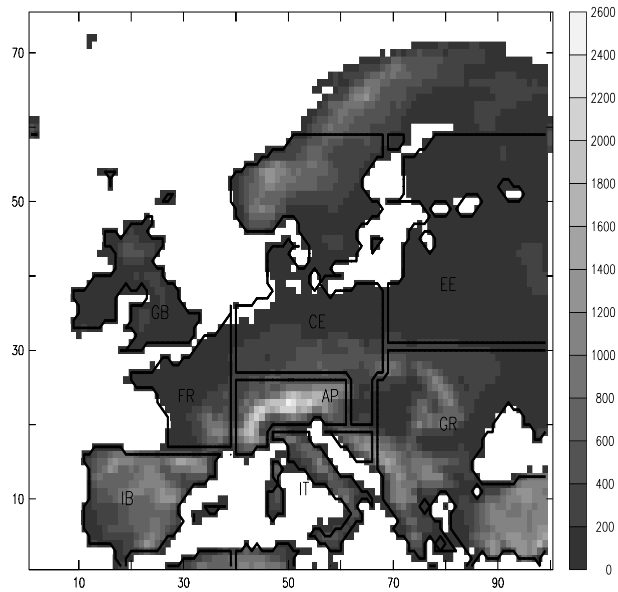

Fig. 1. Simulation domain, regionalization used and topography. Colour scale is in metres above sea level. The eight regions used are: the Iberian Peninsula (IB), the British Isles (BI), the Alps (AP), Italy (IT), France (FR), Eastern Europe (EE), Central Europe (CE) and the Balkan Countries (BC).

Table 1. Regional *r*-squared correlation of the RCMs and the GCM compared with CRU, for precipitation (top) and 2 m temperature (bottom) over the regions defined in Fig. 1. Values in bold are the best (in average) models for precipitation and 2 m temperature. Values in bold italics correspond with plots in Fig. 2

					Precipitation						
	HIRHAM	CHRM	CLM	HadRM3H	RegCM	RACMO	REMO	RCAO	PROMES	GCM	avgd RCMs skill
IB	0.67	0.80	**0.83**	0.57	0.68	0.57	0.80	0.61	0.83	**0.56**	0.71
IT	0.36	0.45	0.25	0.35	0.51	0.35	0.32	0.37	0.36	0.49	0.37
AP	0.21	0.39	0.04	0.53	0.47	0.62	0.31	0.59	0.55	0.13	0.41
BC	0.47	0.42	0.36	0.49	0.65	0.49	0.56	0.57	0.57	0.49	0.51
BI	0.49	0.47	0.60	0.63	0.40	0.36	0.56	0.41	0.62	0.47	0.51
CE	0.58	0.67	0.73	0.58	0.55	0.42	0.74	0.48	0.77	0.48	0.61
EE	0.15	0.36	0.33	0.16	0.24	0.24	0.20	0.31	0.16	0.02	0.24
FR	0.26	0.18	0.20	0.23	0.17	0.18	0.23	0.22	0.29	0.09	0.22
Region avg	0.40	0.47	0.42	0.44	0.46	0.40	0.47	0.45	**0.52**	0.34	0.45
					2 m temperature						
IB	0.96	0.95	0.93	0.97	0.89	0.96	0.98	0.95	0.96	0.95	0.95
IT	0.94	0.83	0.89	0.92	0.85	0.91	0.93	0.91	0.90	0.87	0.90
AP	0.94	0.93	0.93	0.95	0.82	0.95	0.96	0.91	0.97	0.95	0.93
BC	0.92	0.92	0.90	0.95	0.90	0.95	0.95	0.94	0.95	0.95	0.93
BI	0.84	0.73	0.92	0.84	0.79	0.91	0.89	0.93	0.81	0.76	0.85
CE	0.95	0.94	0.94	0.95	0.91	0.96	0.95	0.96	0.86	0.93	0.94
EE	0.95	0.88	0.94	0.96	0.91	0.95	0.96	0.97	0.82	0.93	0.93
FR	0.84	0.83	0.75	0.90	0.78	0.90	0.93	0.90	0.90	0.81	0.86
Region avg	0.92	0.88	0.90	0.93	0.86	0.94	**0.94**	0.93	0.90	0.89	0.91

et al. (2004a), Sánchez et al. (2007a), Christensen and Christensen (2007).

2. Data and experimental setup

The standard procedure to estimate the reliability of a future climate simulation is to compare present-climate simulations against an observational database using monthly or seasonal means (Giorgi et al., 1994). In our case, we have used monthly precipitation and temperature station data for 1961–1990 from the Climate Research Unit (CRU) gridded dataset (0.5° × 0.5°) as our present-climate empirical basis. Climate Research Unit data is described in Hulme et al. (1995), New et al. (2002). This database has become a reference for present-climate modelling validation (Christensen et al., 1998; Giorgi et al., 2004a; Sánchez et al., 2004, 2007a; Jacob et al., 2007).

As mentioned above, the RCMs results used correspond to nine RCMs involved in the PRUDENCE project (Christensen et al., 2007a). All the nine models were forced with the GCM, namely the UK Met Office HadAM3 (Pope et al., 2000). Fields were forced every 6 h. Grid size was 1.875° × 1.25° for the GCM and 0.5° × 0.5° for the RCMs. Sea surface temperatures (SSTs) from the HadISST database (Rayner et al., 2003) were used in the current climate simulations. For the future, forcings were obtained from the HadCM3 coupled atmosphere–ocean GCM (Rowell, 2005). The reasons for this particular setup are described in detail in Christensen and Christensen (2007).

To generate climatically homogeneous areas, subregions inside the model domain are used (Giorgi et al., 2004a; Sánchez et al., 2007a; Christensen and Christensen, 2007). Here, we have selected eight subregions as shown in Fig. 1. To calculate the PDFs for each region, monthly values for both present and future 30 yr periods were used. The resulting density functions provide a robust and integrated representation of climatic conditions over a region both in space and in time; artefacts that may appear linked with likely early/late seasons in future climates are removed using the PDF. Moreover, even with this rather broad analytical approach the PDF remains informative of present-day climate and its potential changes in the future.

The analysis of climatic characteristics in terms of the statistical distribution structure can be regarded as a complementary approach to the more usual of seasonal first-order statistics and interannual variability comparisons (Giorgi et al., 2004a,b; Christensen and Christensen, 2007; Déqué et al., 2007; Jacob et al., 2007). While RCM simulations may compare well in terms of mean values, this does not ensure that other key characteristics are correctly reproduced (Zwiers and Zhang, 2003).

The PDF encompasses most of the uncertainties in both present- and future-climates simulation, while the use of monthly aggregations may mask known seasonal errors in the circulation patterns (Van Ulden et al., 2007) and in surface energy budgets (Lenderink et al., 2007). Therein, the use of the whole distribution as characterized by the PDF will provide insight on how well RCMs simulate, for example, those extreme (rare) values for present climate, which are likely to be more common in future climates conditions (Perkins et al., 2007).

Our variables of interest in this paper are 2 m temperature, maximum and minimum temperatures and precipitation. Empirical PDFs characterize the climatologies of those variables in terms of the shape of the distribution, which can be quantitatively described by its statistical moments up to a desired order (usually four, Von Storch and Zwiers, 2001). We have chosen to describe the PDF using four empirical distribution moments instead of fitting the data to a parametric curve because either the method of the moments, maximum likelihood or maximum

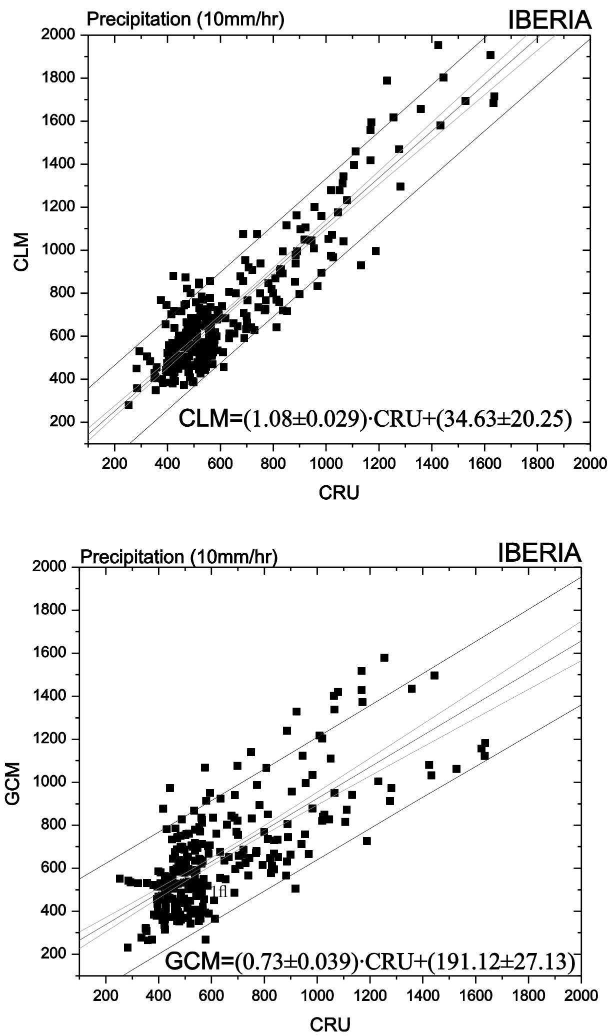

Fig. 2. An example of the best and worse correlations of all the RCMs against CRU data for precipitation (CLM model, top and the GCM, bottom) for Iberian Peninsula (IB) region. Lines indicate the linear fit to the data (inner line), and the lower and upper 80% and 90% confidence bounds (outmost line pairs). Equations indicate the best linear fit and the errors for the abscissa and the ordinate.

entropy introduce an unavoidable error in the parameter estimation Singh et al. (1986). Additional information from the empirical PDF is in the form of percentiles. We have used the correlation coefficient (r^2) statistics instead of the bias as this is a stronger requirement for goodness of fit between models and validation data. Also, the non-dimensional character of r^2 can be helpful to compare results of different magnitudes in terms of their better or worse agreement with observations or with the forcing GCM results.

The structure of the results is as follows: first, we compare the simulations with the observations. Then, we analyse the RCM consensus for both present and future climate (SRES-A2 scenario). The next section is devoted to analyse both climates in terms of PDFs.

3. Results: validation and RCMs consensus

3.1. Present-day (1961–1990) climate simulations analysis

Table 1 shows an overview of RCMs performances for present climate. There, each RCM monthly estimate for each region is compared against CRU observational database in terms of the correlation coefficient (r^2). As the RCMs are driven by the

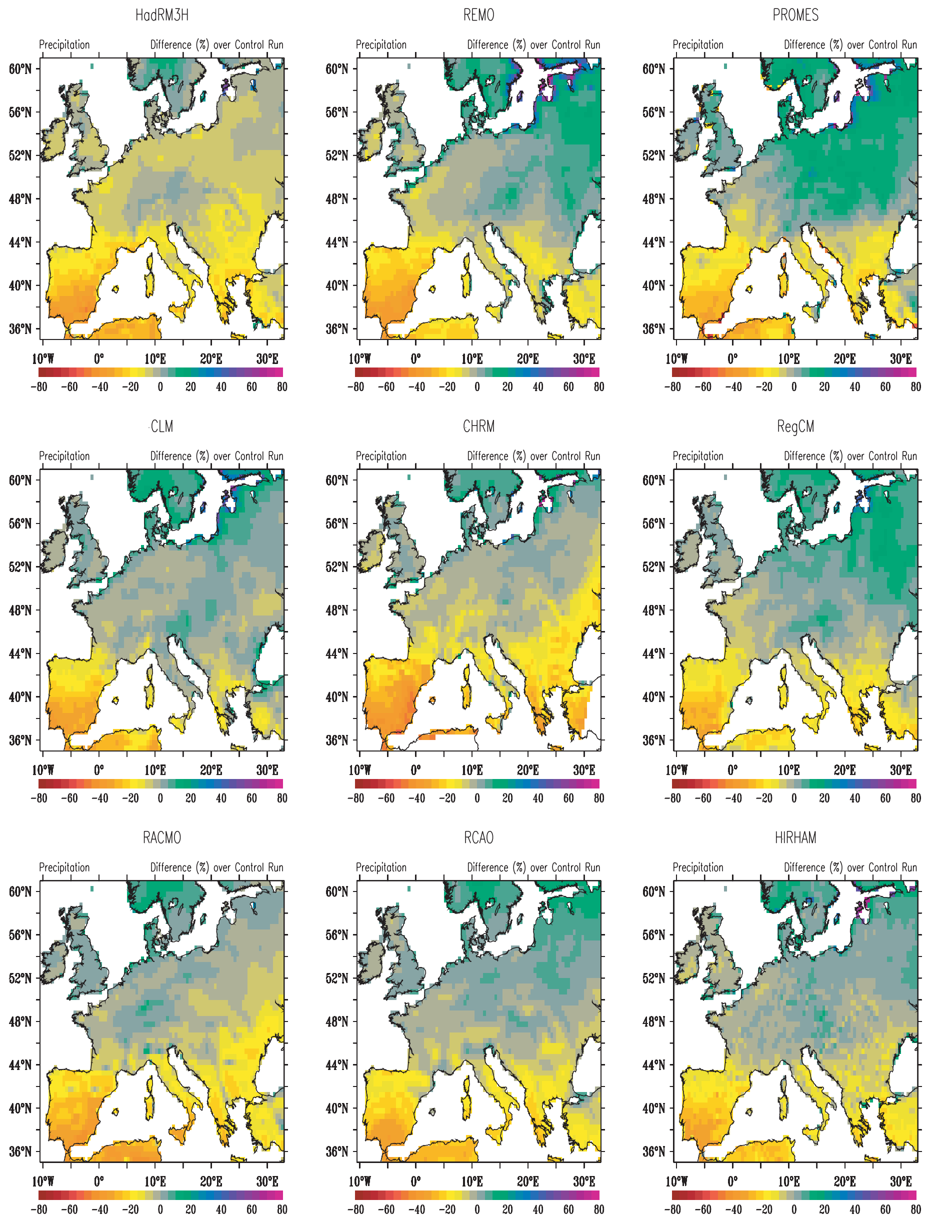

Fig. 3. Annual precipitation changes: differences (% over 1961–1990 climate) in the A2 scenario for the nine RCMs.

boundary data from a GCM, this comparison has to be done using monthly means, as regionally done by Giorgi et al. (1994) (eq. 3 there). The results show that the performances of individual RCMs are comparable among them (small spread of the results), and also that the RCMs compare favourably with observations. Statistics shown in Table 1 are for both precipitation (upper part of the table) and 2 m temperature (bottom).

3.1.1. Precipitation. In the case of precipitation, there is a large variability in the performances of the models. While most the models improve over the GCM they are nested in, there are large discrepancies between models and also between regions. A model such as HIRHAM ranges from $0.14r^2$ for the Eastern Europe (EE) region to a 0.67 for the Iberian region whereas some other models such as the RCAO present a lower spread in their regional behaviour. In average however, the correlation for simulated precipitation does not exceed $0.51r^2$ with an average of 0.44 (compare with 0.34 for the GCM) for all models/all regions comparison.

The overall RCMs performance is higher than the GCM in terms of correlation coefficient even if we take into account the variability among the regional models: the RCM nine-models-mean minus the standard deviation has better correlation with observational CRU data than the GCM for the Iberian Peninsula (IB), Alps (AP), Central Europe (CE), EE and France (FR)

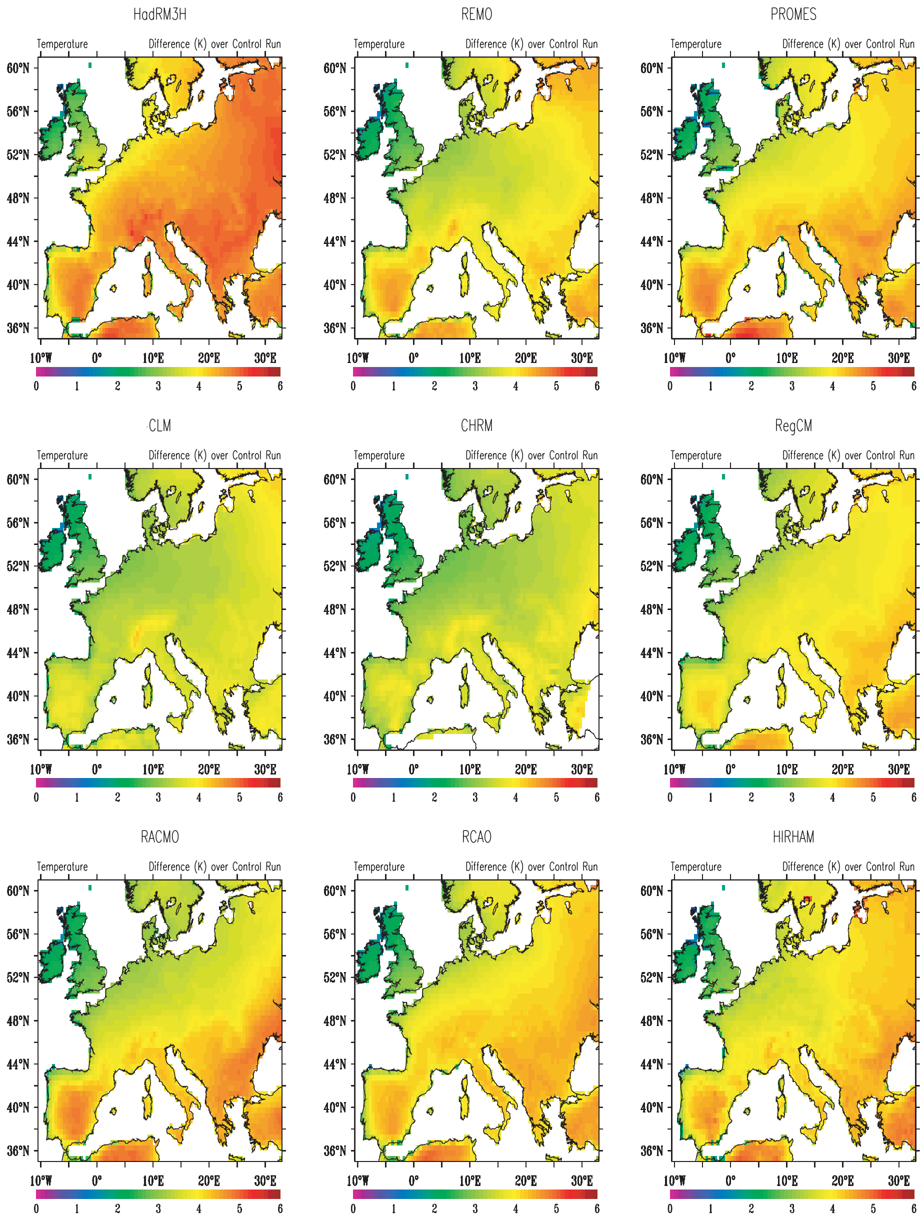

Fig. 4. Annual temperature (2 m temperature) changes: difference (over 1961–1990 climate) in the A2 scenario for the nine RCMs.

regions (last column of upper half of Table 1). Only for the Italy (IT) region does the GCM present higher correlation values. This can be attributable to the complex topography of this region which leads to important local differences in the rainfall of orographically enhanced precipitation, as each model uses their native grid and a slightly different topography.

Nevertheless, one point to notice when analysing current climate results is about the reliability of CRU observational data reference, specially when dealing with precipitation values. From the results in New et al. (2002) (table 1 there), up to 32% deviations in the square root of the generalized cross validation can be expected between actual rain gauge estimates and the interpolation domain mean (compare with the temperature maximum error of 1.1 K for the same area in their table 4). Those large uncertainties due to the inherent spatial variability of precipitation induce us to take the model/CRU validation results with some caution.

As an example of the correlation results for precipitation, Fig. 2 graphically depicts the scatterplots with the upper and lower correlation bounds (80% and 90%) for the Iberian (IB) region. In this figure, the best and the worse correlations are shown: the best RCM for this region (the CLM model) has a $0.83r^2$ correlation when compared with CRU. Those graphs show that the RCM has not only less dispersion than the GCM, but also is more capable of dealing with high extremes: the GCM truncates values of 170 to about 110 mm, whereas the CLM model provides a better estimate of about 170 mm. The best-fit regression equations in both plots also show that the best RCM has lower bias than the GCM.

3.1.2. Temperature. The results for 2 m temperature estimate are quite different. Here, correlations are far higher than in the precipitation case, with RACMO model achieving a $0.94r^2$ top-overall performance and the lowest value being a $0.86r^2$ (RegCM). This illustrates that models better simulate

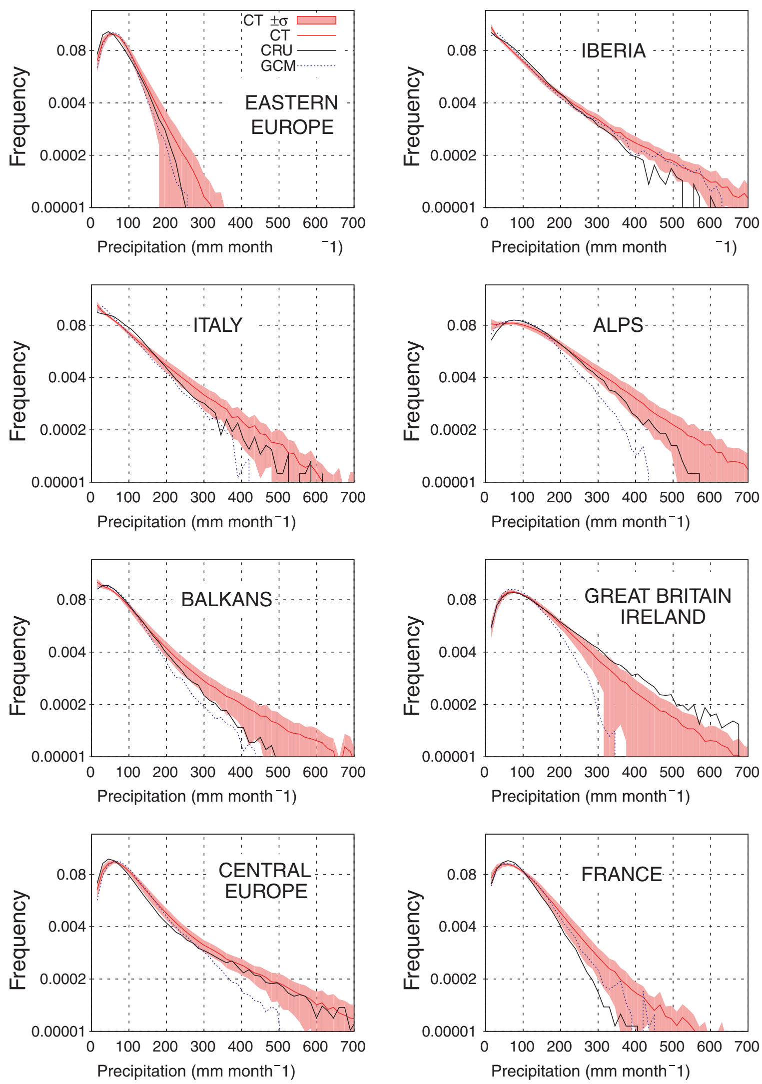

Fig. 5. Present climate precipitation probability density functions (PDFs), showing the $\pm\sigma$ and the mean of the nine RCMs, CRU database and the forcing GCM.

temperature than precipitation, which is not surprising given the anisotropy of the precipitation fields and the smoother nature of surface temperature, as can be expected from kinetic theory. Errors in the interpolated validation data are also lower (New et al., 2002), making temperature validation a good estimate of the RCMs performances when compared with GCMs.

3.2. *Future climate (2071–2100) climate simulations analysis*

Figures 3 and 4 map the differences observed between present-day and future-climate RCMs simulations in terms of percentage of change to present-day climate for annual mean precipitation (Fig. 3) and annual mean 2 m temperature (Fig. 4) . These plots are aimed to provide just a visual, geographical framework of the PDF characterization that follows, as there are several detailed studies on seasonal or even annual scales from an ensemble of PRUDENCE regional models (Déqué et al., 2005, 2007; Christensen and Christensen, 2007) or from single RCMs (Christensen and Christensen, 2003; Giorgi et al., 2004b; Räisänen et al., 2004; Sánchez et al., 2004; Semmler and Jacob, 2004). As reported there, uncertainties associated with precipitation are larger than those for temperature. A Student's t-test for the data in Figures 3 and 4 yields that the changes in temperature are 100% statistically significant ($|t| > 2$) for all the grid boxes. For precipitation, however, only 36% of the cases were significant, indicating a weak significance of this variable. This should be taken into account in the following sections.

3.2.1. Precipitation. In terms of annual means all the RCMs show a decrease of precipitation in the south of Europe. An especially strong decrease (up to 70%) is observed in the south of Spain and Northern Africa, meaning that under the A2 scenario those areas will found exacerbated their semi-arid characteristics. In CE slight changes in both directions appear, while for

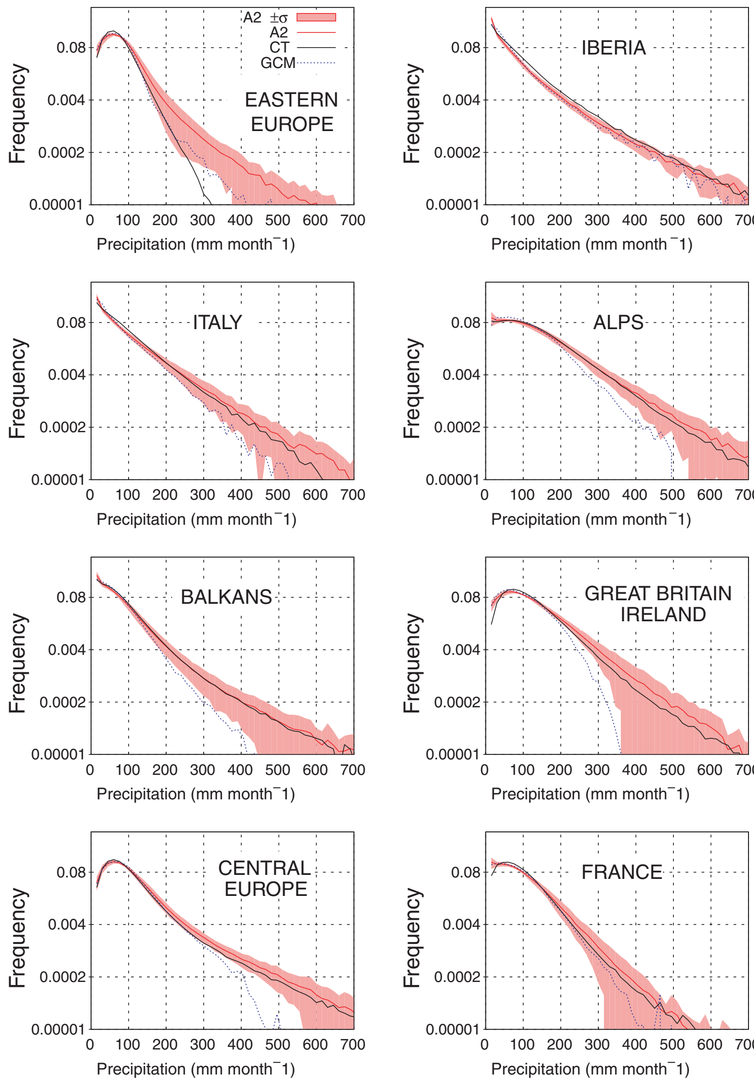

Fig. 6. As Fig. 5, but for the A2 scenario. Mean ensemble of RCM models together with the $\pm\sigma$ area is shown, and mean RCMs present climate (CT) values to inspect changes between both periods, and the forcing GCM A2 results.

the north of Europe region most RCMs agree in an approximate 20% increase in precipitation. This north–south gradient has been noted by Christensen and Christensen (2007). When compared with the GCM results, the more important discrepancies are obtained in the north of Europe, where the GCM model does not exhibit a clear increase in precipitation. This is also the case of HadRM3H regional model, but this can be explained as it shares convection (Gregory and Rowntree, 1990), radiation (Edwards and Slingo, 1996) and land surface (Cox et al., 1999) parametrizations with the GCM, and differs from other RCM models parametrizations.

3.2.2. Temperature. Temperature changes are mapped in Fig. 4. All the regional models agree in an increase in the annual mean temperature for all the regions. As in the precipitation case, the HadRM3H's results are the closest to the GCM's from all the regional model results. It presents an overall 2% increase with the exception of the British Isles (BI) where a 1% increase is predicted, meanwhile the other RCMs exhibit a smaller percentage annual temperature increase. Although with local differences, a northwest–southeastern gradient is observed for temperature in all the models, and also coastal gradient structures, specially over the Iberian Peninsula (Sánchez et al., 2007b). The CHRM, the

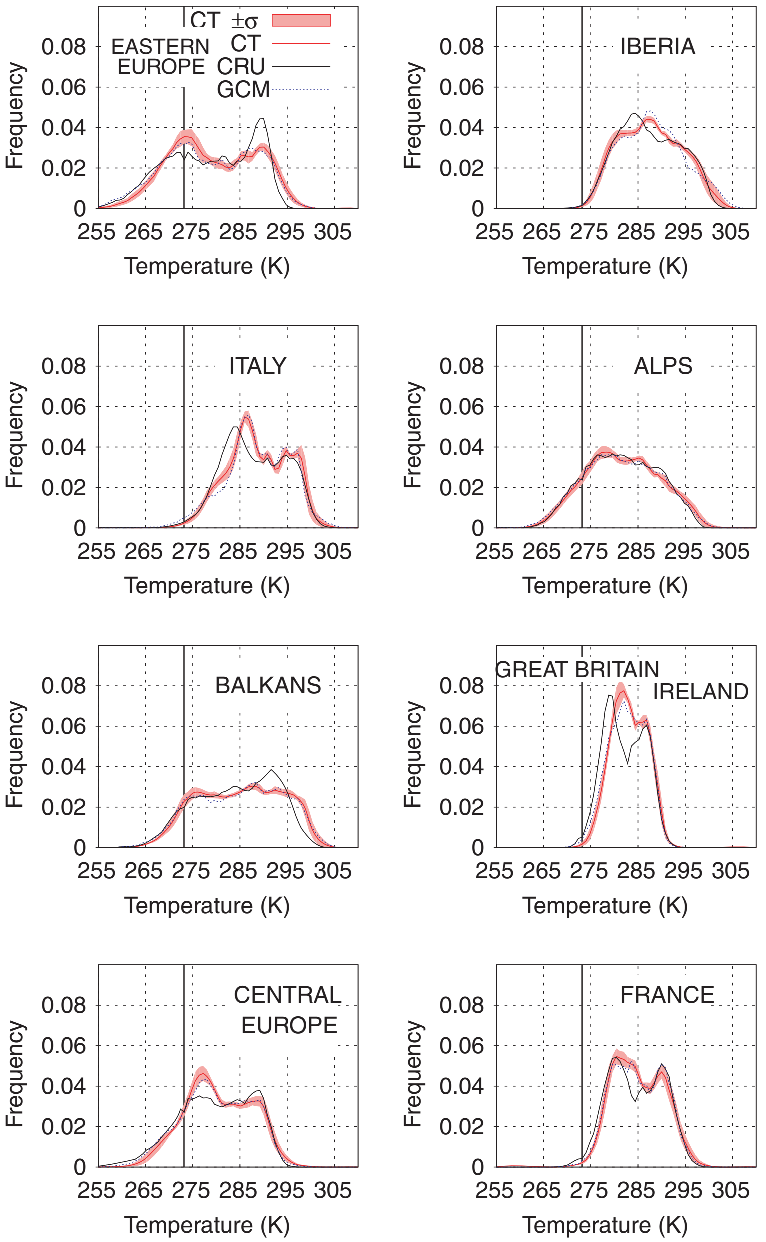

Fig. 7. As Fig. 5, but for 2 m temperature. Freezing point (0 °C) is indicated with a vertical solid line.

CLM and REMO models clearly singularize the Alpine region from the neighbouring areas. The CHRM and the CLM models use the same convection (Tiedtke, 1989), microphysics (Kessler, 1969; Lin et al., 1983) and radiation (Ritter and Geleyn, 1992) parametrizations.

4. Discussion

4.1. PDF results

The probability density functions of monthly values over the selected regions are shown in Figs. 5 and 6 for present climate and future scenario precipitation, respectively, and Figs. 7 and 8 for temperature results.

4.1.1. Present climate (1961–1990). Both temperature and precipitation PDFs present a good correlation between models (RCMs and GCM) and CRU data, with CRU data lying well between the $\pm\sigma$ of the RCMs for light and moderate precipitation amounts. Large fluctuations for high precipitation values of RCM ensemble appear, as can be expected, as sparse and infrequent high rainfall rates are major contributors to high monthly mean rates. Another important RCMs adequately differentiate between exponential and lognormal precipitation PDFs (which may be linked to the dominance of frontal/convective

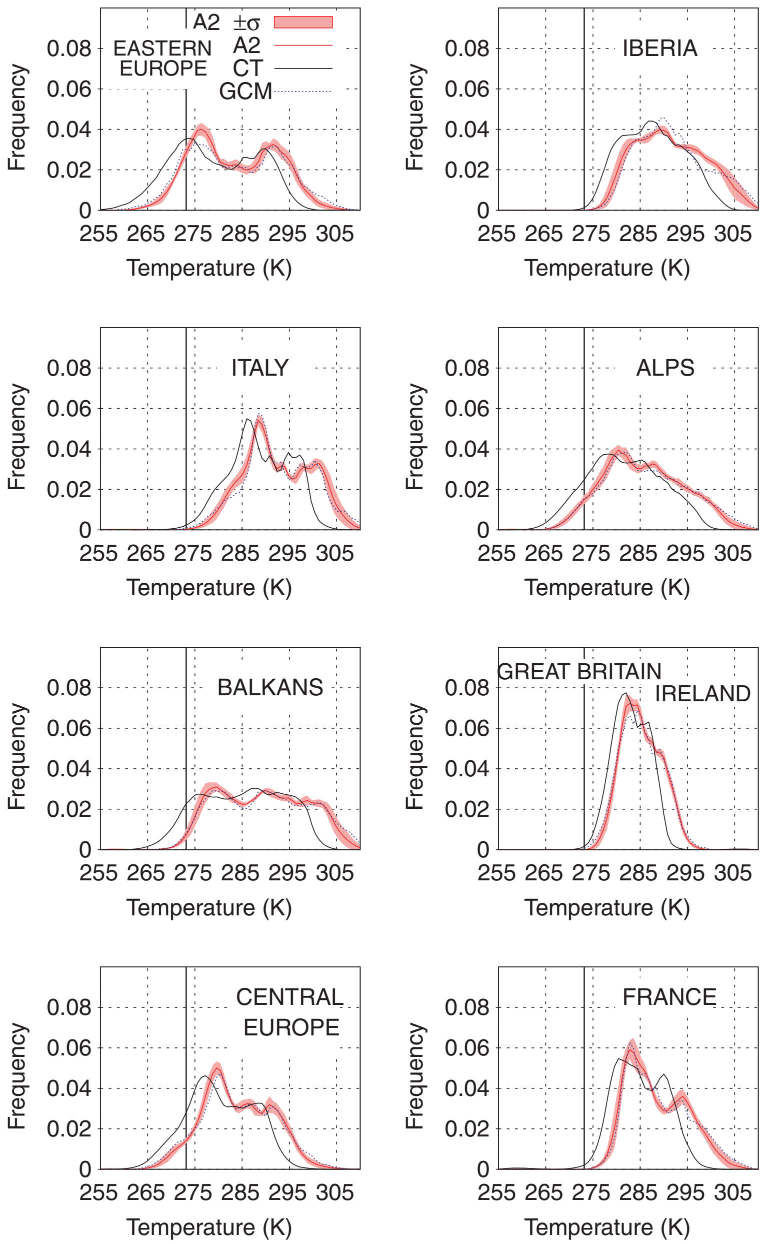

Fig. 8. As Fig. 6, but for 2 m temperature. Freezing point (0 °C) is indicated with a vertical solid line.

processes, Tapiador et al., 2007) and also between the locations of the peaks corresponding with the unimodal/bimodal (winter/summer) PDFs of monthly temperature in Europe (Fig. 7). Nevertheless, some discrepancies on temperature peaks are sometimes obtained, when comparing RCMs and CRU data, both in the intensity (EE or first peak for CE, FR or IB), or in the value (first peak of IT or GB, or second of Balkan Countries, BC). This qualitative agreement builds up the confidence in the future-climate RCMs simulations, despite the low spatial correlations for precipitation obtained in Table 1.

These results provide further empirical evidence for this case of a general feature of RCM/GCM comparison, which is the

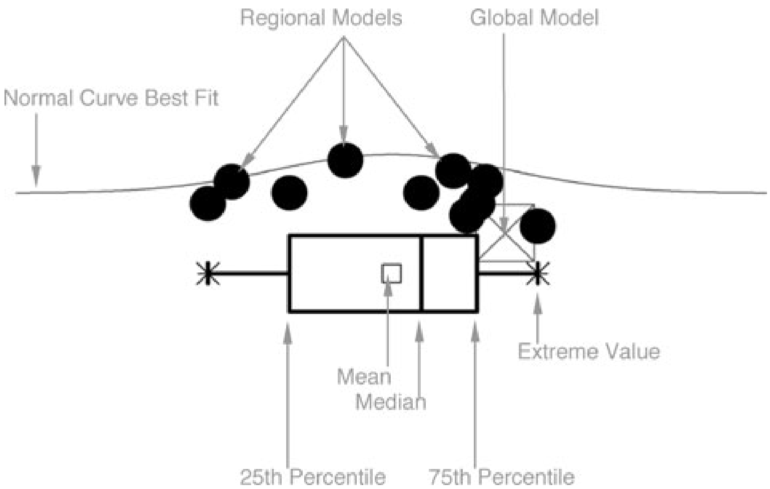

Fig. 9. Boxplots key for Figs. 10–13.

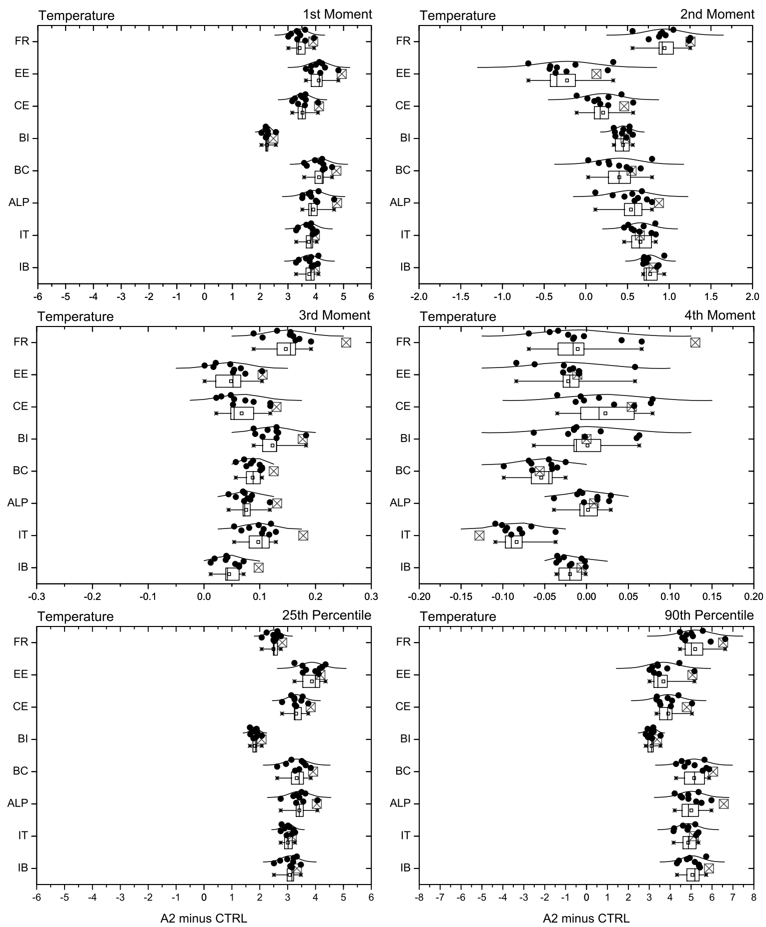

Fig. 10. First four moments – mean, standard deviation, skewness and kurtosis – and 25th and 90th percentiles of the regional changes in the 2 m temperature PDF between 2071–2100 and 1961–1990 (regional climatology change) under the SRES-A2 scenario.

underestimation of high precipitation in the GCM. This is an expected result due to the local characteristics of extreme precipitation events, which are likely to be better reproduce as RCMs have better spatial resolution. This effect can be seen in Fig. 5 for the BC, GB and AP regions, where the GCM estimates are below the RCM $\pm\sigma$ area. In those cases, RCMs compare favourably with CRU data.

4.1.2. Future climate (2071–2100). The PDFs for the A2 scenario period are shown in Figs. 6 and 8. The precipitation structure slightly change from a lognormal (Atlantic and continental climates) to an exponential shape (corresponding to Mediterranean influence regimes) over FR and partially over GB regions, both for the ensemble RCMs and the GCM. High precipitation values are increased also over some regions (EA and GB), while GCM values again underestimate RCM ensemble results over many regions (AP, IT, BC, CE and GB), even taking into account the $\pm\sigma$ band.

Temperature changes show a clear shift of the whole distribution to high values, for all the regions, both for the ensemble of RCMs, and the GCM. The shape of the distribution (unimodal/bimodal) is maintained. Nevertheless, there is some indication of a broadening of the PDF, in for instance FR, GB, AP or IT regions.

4.2. *Climate changes in the high-order statistics of the PDF*

While the PDFs in Figs. 5–8 visually illustrate the changes, a quantitative estimate is needed to fully appreciate the extent of the variations in the A2 scenario. Statistically, a PDF can be characterized by its statistical moments (Von Storch and Zwiers, 2001). Standard names for the first four moments are mean (1st), standard deviation (2nd), skewness (3rd) and kurtosis (4th moment). We have compared present-day climate with future climate in terms of changes in those high-order statistics, and also those in the 25th and 90th percentiles to account for changes in the extremes of the distributions.

Figure 9 gives the key of the box plots used to show the variations in the 2 m temperature (Fig. 10), minimum and maximum temperatures (Figs. 11 and 12) and precipitation (Fig. 13). All these plots depict the difference between future (SRES-A2 scenario) and present-day climate in terms of monthly means, so

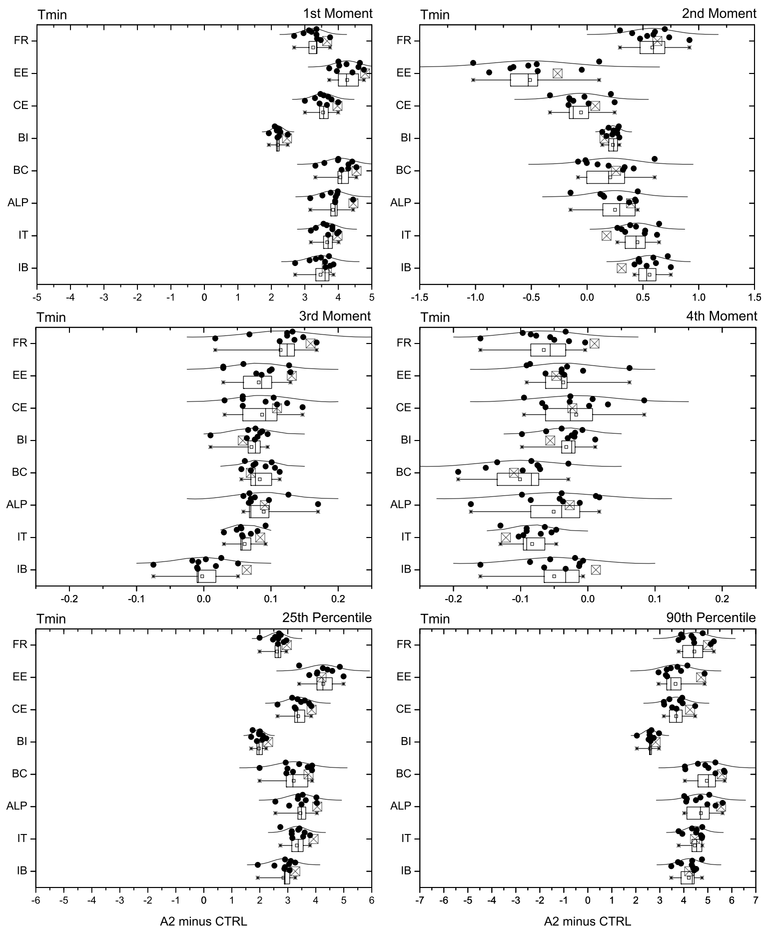

Fig. 11. As Fig. 10, but for minimum temperature.

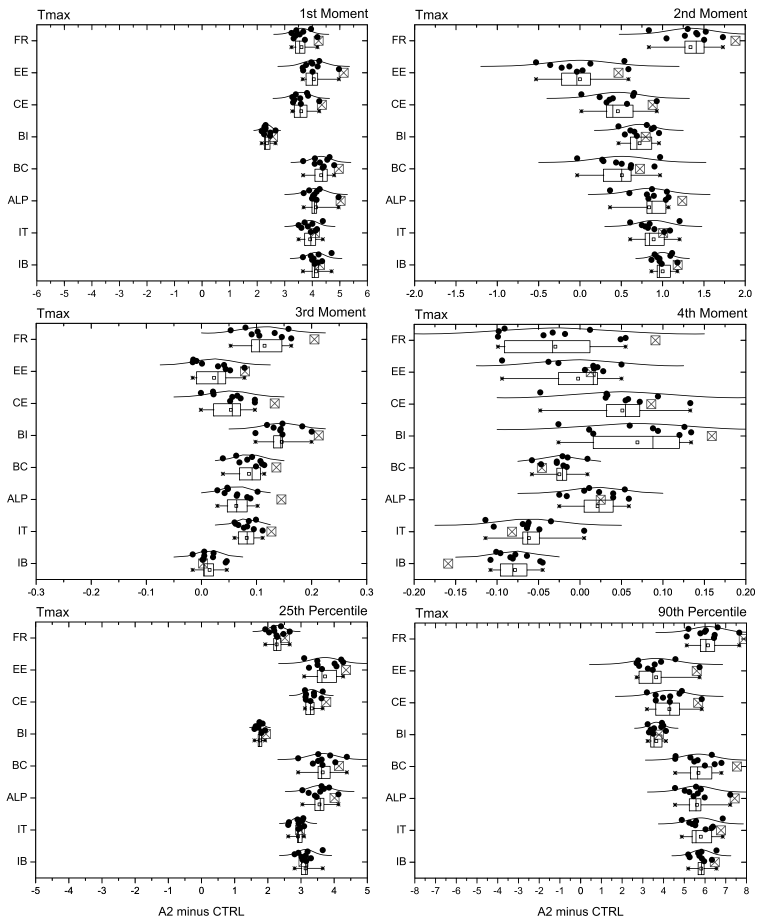

Fig. 12. As Fig. 10, but for maximum temperature.

zeroes indicate no change and positive values future increases of the corresponding statistical moment. The plots gather information on the PDFs for each one of the RCMs and for the GCM, also indicating the best-fit gaussian curve to the RCMs (as a representation of the RCM ensemble) and a boxplot (as in Fowler et al., 2007 or Tapiador et al., 2007) including the location of the extreme values, mean, median and 25th and 75th percentiles for the RCM ensemble distribution. Little spread in the boxplots indicates a consensus among the RCMs estimate while a large spread means an uncertain value of the moment in that region. Scattered RCMs values in both sides of the *x*-axis indicate discrepancies even in the sign of the change.

4.2.1. Precipitation. As expected, Fig. 13 shows that the discrepancies between the RCMs are greater for precipitation than for temperature (see below) for all the moments. The same applies for the two percentiles. In some cases, the RCMs do not agree even in the sign of the changes, thus indicating a highly uncertain situation. Nevertheless, there are some points that can be made. The variability of monthly precipitation (2ndnd moment) increases over most of the regions (FR, EE, CE and PA), and decreases over IB, with comparable results of the GCM in relation with mean RCM distribution values. Skewness also increases over four regions (IB, IT, AL and BC).

The 90th percentile is particularly important in precipitation as it reflects the probability of severe weather episodes (Christensen and Christensen, 2003). This percentile can be used as a surrogate for the occurrence of extreme precipitation events; even at monthly scale, the footprint of large storms providing the bulk of monthly precipitation is apparent when values are aggregated, as noted by Frei et al. (2006). What the plots in Fig. 13 show is an increase in the extremes for the FR, EE, CE and the BI regions, with inconclusive estimates for the AP and the Balkans and a decrease for the IT and the IB regions.

Quite revealing, the most uncertain estimates are for mountain areas, while decreases affect the two more Mediterranean regions. The marked decrease in the mean and the 25th and 90th percentiles for the Iberian region indicates a deepening in the Mediterranean climate character of the area, which is characterized by a long dry season and sparse, summer showers that provide most of the high monthly precipitation values in the annual share. The BI case is also interesting. Here, there is almost no change in the mean, but the 25th and 90th percentiles move

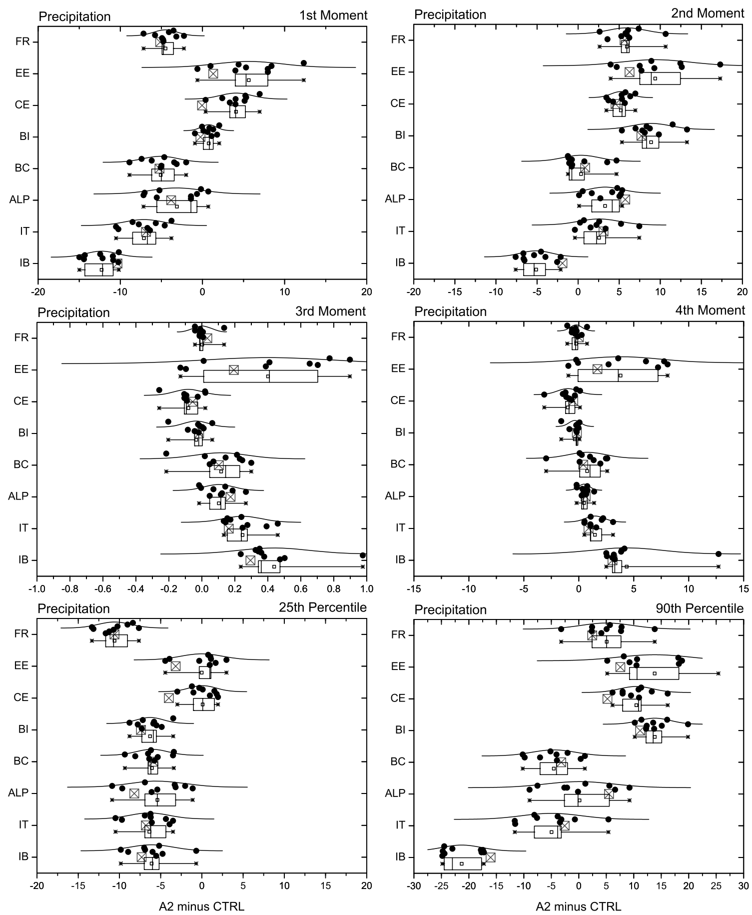

Fig. 13. As Fig. 10, but for precipitation.

towards both extremes. This fact, together with the behaviour of the 2nd, 3rd and 4th moments indicates the mean is conserved by a broadening of the PDF, a change that is apparent in Fig. 6; both low and high monthly precipitation frequencies increase whereas there is a net zero change in the mean.

4.2.2. Temperature. For mean monthly 2 m temperature (Fig. 10), all the simulations show and increase in the mean for all the European regions (top-left plot). The spread of the models is at most 2 K, which indicates a strong RCM consensus. Differences between the RCMs and the GCM are also noticeable, illustrating an overall stronger increase of mean temperature by the GCM, as shown by Christensen and Christensen (2007) for seasonal results. Variations in the second moment (top-right plot) are indicative of an overall increase in the variance of the monthly temperature, except for the EE area where the wide boxplot reveals large differences between models. Christensen and Christensen (2007) analysis already showed that interannual seasonal variability was increased, specially for summer. The 3rd moment (middle-left plot) shows a consistent increase in the skewness of all the regions, indicating a change in the climate signal.

The 4th moment (middle-right plot) is inconclusive except for the IT region, where a marked reduction appears. Both the 25th (bottom-left plot) and the 90th percentiles (bottom-right plot) appear clearly changed in the future climate scenario, thus providing stronger evidence of an overall decrease in the left-hand side of the PDFs (milder low temperatures) and in the right-hand side (increased high temperatures).

The boxplots for the minimum temperature ($T_{\min}$ hereafter, Fig. 11) and the maximum temperature ($T_{\max}$, Fig. 12) provide additional information on expected changes in temperature characteristics in Europe. There is regional and model consensus in an increase both in the mean of the minimums (Fig. 11, upper-left plot) and maximums (Fig. 12, same place), which indicates a warmer climate. These results are coherent with increases in heat waves and days with high temperatures described in Beniston et al. (2007). Again, as with mean 2 m temperature, GCM increases are higher than the ensemble of RCMs over almost all the regions. The 2nd moment also presents an overall increase, except for the EE region, similar to mean temperature variance changes. Also, skewness is increased for minimum and maximum temperature, comparable to the mean temperature increases. For all the regions the 25th percentile increases less for $T_{\min}$ than for $T_{\max}$, while the 90th increases more for $T_{\max}$ than for $T_{\min}$. This is an indication that $T_{\max}$ extreme events would increase more than $T_{\min}$ ones, a confirmation of extreme temperature changes (Beniston et al., 2007). The $T_{\max}$ 90th percentile also presents a smaller increase for the RCMs than for the GCM.

5. Conclusions

Ensembles of several RCMs are used to analyse the effects of different paramterizations (Christensen et al., 2002) and dynamical cores, one basic idea being that the spread of the ensemble would provide an indication of the predictability of the simulation due to model description by the RCMs, while the actual values would indicate the major features of the future climate (Collins, 2002). This strategy stems from the need of embracing the probabilistic nature of climate simulations and accounting for errors and limitations in the numerical models, including the need of parametrize physical processes at subgrid resolution.

Using a PDF approach to build up a estimate from RCMs ensemble simulation can be a valuable statistical tool to describe many aspects of climate change characteristics. In this paper, we have analysed changes in the SRES-A2 scenario (Nakicenovic et al., 2000) derived from the PRUDENCE project results (fully described in Beniston et al., 2007; Christensen et al., 2007a; Déqué et al., 2007). The aim of this analysis is to provide aggregated but more robust estimates of changes in the future climate, encompassing as much uncertainty as possible by sacrificing spatial and temporal resolutions but without renouncing to the insight provided by the RCMs. The simulations show marked regional differences in Europe in terms of precipitation and temperature changes, with an overall increase in the mean temperature and extreme values, but mixed regional patterns for precipitation. As those characteristics are apparent even in such an aggregated estimate as the PDFs is, our results provide stronger evidence of those changes not been due to modelling error, but being an inherent feature of the future climate.

6. Acknowledgments

This work has been funded through projects CGL2006-03611 (MEC), PAI06-0101 (JCCM) and the PRUDENCE project (EVK2-CT-2001-00132).

References

Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, C. and co-authors. 2007. Future extreme events in European climate: an exploration of regional climate model projections. *Clim. Change* **81**(Suppl.1), 71–95.

Christensen, O. B. 1999. Relaxation of soil variables in a regional climate model. *Tellus* **51A**, 674–685.

Christensen, J. H. and Christensen, O. B. 2003. Severe summertime flooding in Europe. *Nature* **421**, 805–806.

Christensen, J. H. and Christensen, O. B. 2007. A summary of the PRUDENCE model projections of changes in European climate during this century. *Clim. Change* **81**(Suppl.1), 7–30.

Christensen, O. B., Christensen, J. H., Machenhauer, B. and Botzet, M. 1998. Very high-resolution regional climate simulations over Scandinavia-Present climate. *J. Clim.* **11**, 3204–3229.

Christensen, J. H., Carter, T. and Giorgi, F. 2002. PRUDENCE employs new methods to assess european climate change. *EOS* **83**, p. 147.

Christensen, J. H., Carter, T. R., Rummukainen, M. and Amanatidis, G. 2007a. Evaluating the performance and utility of regional climate models: the PRUDENCE project. *Clim. Change* **81**(Suppl.1), 1–6.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X. and co-authors. 2007b. Regional climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (eds. A. Solomon, D.Qin, M. Manning, Z. Chen, M. Marquis, and co-editors), Cambridge University Press, Cambridge, UK and New York, NY, USA .

Collins, M. 2002. Climate predictability on interannual to decadal time scales: the initial value problem. *Clim. Dyn.* **19**, 671–692.

Cox P. M., Betts R. A., Bunton C. B., Essery R. L. H., Rowntree P. R. and co-authors. 1999. The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Clim. Dyn.* **15**, 183–203.

Déqué, M., Jones, R. G., Wild, M., Giorgi, F., Christensen, J. H. and co-authors. 2005. Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from PRUDENCE results *Clim. Dyn.* **25**, 653–670.

Déqué, M., Rowell, D. P., Lüthi, D., Giorgi, F., Christensen, J. H. and co-authors. 2007. An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. *Clim. Change* **81**(Suppl.1), 53–70.

Edwards, J. M. and Slingo, A. 1996. Studies with a flexible new radiation code. *Quart. J. R. Meteorol. Soc.* **122**, 689–719.

Ekström, M., Hingray, B., Mezghani, A. and Jones, P. D. 2007. Regional climate model data used within the SWURVE project 2: addressing uncertainty un regional climate model data for five European case study areas. *Hydrol. Earth Syst. Sci.* **11**, 1085–1096.

Ferro, C. A. T., Hannachi, A. and Stephenson, D. B. 2005. Simple nonparametric techniques for exploring changing probability distribution of weather. *J. Clim.* **18**, 4344–4354.

Fowler, H. J., Ekström, M., Blenkinsop, S. and Smith, A. P. 2007. Estimating change in extreme european precipitation using a multimodel ensemble. *J. Geophys. Res.* **112**, D18104, doi:10.1029/2007JD008619.

Frei, C., Schöll, R., Fukutome, S., Schmidli, J. and Vidale, P. L. 2006. Future change of precipitation extremes in Europe: intercomparison of scenarios from regional climate models. *J. Geophys. Res.* **111**, D06105, doi:10.1029/2005JD005965.

Giorgi, F. and Mearns, L. O. 1999. Regional climate modeling revisited. An introduction to the special issue. *J. Geophys. Res.* **104**, 6335–6352.

Giorgi, F. and Bi, X. 2000. A study of internal variability of a regional climate model. *J. Geophys. Res.* **105**, 29 503–29 522, doi:10.1029/2000JD900269.

Giorgi, F., Brodeur, C. S. and Bates, G. T. 1994. Regional climate change scenarios over the United States produced with a nested regional climate model. *J. Clim.* **7**, 375–399.

Giorgi, F., Bi, X. and Pal, J. S. 2004a. Mean, interannual variability and trends in a regional climate change experiment over

Europe: I. Present-day climate (1961–1990). *Clim. Dyn.* **22**, 733–756.

Giorgi, F., Bi, X. and Pal, J. S. 2004b. Mean, interannual variability and trends in a regional climate change experiment over Europe: II. Climate change scenario (2070–2100). *Clim. Dyn.* **23**, 839–858.

Graham, L. P., Hagemann, S., Jaun, S. and Beniston, M. 2007. On interpreting hydrological change from regional climate models. *Clim. Change* **81**(Suppl.1), 97–122.

Gregory, D. and Rowntree, P. R. 1990. A mass flux convection scheme with representation of cloud ensemble characteristics and stability-dependent closure. *Mon. Wea. Rev.* **118**, 1483–1506.

Hulme, M., Conway, D., Jones, P. D., Jiang, T., Barrow, E. M. and co-authors. 1995. Construction of a 1961–1990 European climatology for climate change modelling and impact applications. *Int. J. Climatol.* **15**, 1333–1363.

Jacob, D., Barring, L., Christensen, O. B., Christensen, J. H., Castro, M. and co-authors. 2007. An inter-comparison of regional climate models for Europe: model performance in present-day climate. *Clim. Change* **81**(Suppl.1), 31–52.

Kessler, E. 1969. On the distribution and continuity of water substance on the atmospheric circulation. *Meteorol. Monogr.; Amer. Meteorol. Soc.* **32**, 84pp.

Khain, A., Ovtchinnikov, M., Pinsky, M., Pokrovsky, A. and Krugliak, H. 2000. Notes on the state-of-the-art numerical modeling of cloud microphysics. *Atmos. Res.* **55**, 159–224.

Kjellström, E., Bärring, L., Jacob, D., Jones, R., Lenderink, G. and co-authors. 2007. Modelling daily temperature extremes: recent climate and future climate changes over Europe. *Clim. Change* **81**(Suppl.1), 249–265.

Lenderink, G., Van Ulden, A., Van der Hurk, B. and Van Meijgaard, E. 2007. Summertime inter-annual temperature variability in an ensemble of regional model simulations: analysis of surface energy budget. *Clim. Change* **81**(Suppl.1), 233–247.

Lin, Y., Farley, R. D. and Orville, H. D. 1983. Bulk parameterization of the snow field in a cloud model. *J. Appl. Meteorol.* **22**, 1065–1092.

Machenhauer, B., Windelband, M., Botzet, M., Christensen, J. H., Déqué, M. and co-authors. 1998. *Validation and Analysis of Regional Present-day Climate and Climate Change Simulations Over Europe*. Max-Planck Institut für Meteorologie, **275**, 60pp.

Mearns, L. O., Bogardi, I., Matyasovsky, I. and Palecki, M. 1999. Comparison of climate change scenarios generated from regional climate model experiments and statistical downscaling. *J. Geophys. Res.* **104**, 6603–6621.

Murphy, J. M., Sexton, D. M. H., Barnett, D. N., Jones, G. S., Webb, M. J. and co-authors. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature* **430**, 768–772.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J. and co-authors. 2000. *IPCC Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, UK and New York, NY, USA .

New, M., Lister, D., Hulme, M. and Makin, I. 2002. A high-resolution data set of surface climate over global land areas. *Clim. Res.* **21**, 1–25.

Perkins, S. E., Pitman, A. J., Holbrook, N. J. and McAneney, J. 2007. Evaluation of the AR4 climate models' simulated daily maximum temperature, minimum temperature, and precipitation over Australia using probability density functions. *J. Clim.* **20**, 4356–4376.

Pope, V., Gallani, M., Rowntree, P. and Statton, R. 2000. The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3. *Clim. Dyn.* **16**, 123–146.

Räisänen, J. 2007. How reliable are climate models? *Tellus* **59A**, 2–29.

Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L. P. and co-authors. 2004. European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Clim. Dyn.* **22**, 13–31.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V. and co-authors. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**, doi:10.1029/2002JD002670.

Ritter, B. and Geleyn, J. F. 1992. A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. *Mon. Wea. Rev.* **120**, 303–325.

Rowell, D. P. 2005. A scenario of European climate change for the late twenty-first century: seasonal means and interannual variability. *Clim. Dyn.* **25**, 837–849.

Sánchez, E., Gallardo, C., Gaertner, M. A., Arribas, A. and Castro, M. 2004. Future climate extreme events in the Mediterranean simulated by a regional climate model: a first approach. *Global Planet. Change* **44**, 163–180.

Sánchez, E., Gaertner, M. A., Gallardo, C., Padorno, E., Arribas, A. and co-authors. 2007a. Impacts of a change in vegetation description on simulated European summer present-day and future climates. *Clim. Dyn.* **29**, 319–332.

Sánchez, E., Yagüe, C. and Gaertner, M. A. 2007b. Planetary boundary layer energetics simulated from a regional climate model over Europe for present climate and climate change conditions. *Geophys. Res. Lett.* **34**, doi:10.1029/2006GL028340.

Semmler, T. and Jacob, D. 2004. Modeling extreme precipitation events–a climate change simulation for Europe. *Global Planet. Change* **44**, 119–127.

Singh, V., Rajagopal, A. K. and Singh, K. 1986. Derivation of some frequency distributions using the principle of maximum entropy (POME). *Adv. Water Resour.* **9**, 91–106.

Tapiador, F. J., Sánchez, E. and Gaertner, M. A. 2007. Regional changes in precipitation in Europe under an increased greenhouse emissions scenario. *Geophys. Res. Lett.* **34**, doi:.

Tiedtke, M. 1989. A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Wea. Rev.* **117**, 1779–1800.

Van Ulden, A., Lenderink, G., Van der Hurk, B. and Van Meijgaard, E. 2007. Circulation statistics and climate change in central Europe: PRUDENCE simulation and observations. *Clim. Change* **81**(Suppl.1), 329–341.

Vidale, P. L., Luthi, D., Frei, C., Seneviratne, S. I. and Schär, C. 2003. Predictability and uncertainty in a regional climate model. *J. Geophys. Res.* **108**, doi:10.1029/2002JD002810.

Von Storch, H. and Zwiers, F. W. 2001. *Statistical Analysis in Climate Research*. Cambridge University Press, UK .

Zwiers, F. and Zhang, X. 2003. Towards regional-scale climate change detection. *J. Clim.* **16**, 793–797.