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Climate change and the Portuguese precipitation: ENSEMBLES regional climate models results

Pedro M. M. Soares · Rita M. Cardoso ·
João Jacinto Ferreira · Pedro M. A. Miranda

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Abstract In Portugal, the precipitation regimes present one of the highest volumes of extreme precipitation occurrence in Europe, and one of the largest mean precipitation spatial gradient (annual observed values above 2,500 mm in the NW and under 400 mm in the SE). Moreover, southern Europe is one of the most vulnerable regions in the world to climate change. In the ENSEMBLES framework many climate change assessment studies were performed, but none focused on Portuguese precipitation. An extensive evaluation and ranking of the RCMs results addressing the representation of mean precipitation and frequency distributions was performed through the computation of statistical errors and frequency distribution scores. With these results, an ensemble was constructed; giving the same weight to mean precipitation and distribution model skills. This ensemble reveals a good ability to describe the precipitation regime in Portugal, and enables the evaluation of the eventual impact of climate change on Portuguese precipitation according to the A1B scenario. The mean seasonal precipitation is expected to decrease substantially in all seasons, excluding winter. This reduction is statistically significant; it spans from less than 20 % in the north to 40 % in the south in the intermediate seasons, and is above 50 % in the largest portion of mainland in summer. At a basin level the precipitation diminishes in all months for all the basins with exception of December. Total precipitation PDFs reveal an important decrease of the contribution from low to moderate/high precipitation bins, and a striking rise for days with extreme rainfall, up to 30 %.

Keywords Climate change · Regional climate modelling · Precipitation · PDFs · Extremes · Basins · Portugal

1 Introduction

Several studies have suggested that global warming will lead to an intensification of the hydrological cycle with an increase in the global mean precipitation, and a greater amplification in the frequency and intensity of precipitation extremes (Meehl et al. 2007; Palmer and Räisänen 2002; IPCC 2013). Such changes are, however, expected to be very heterogeneous, with an overall increase in mean precipitation being accompanied by its decrease in some regions, leading to the strengthening of key climate gradients. Indeed, the analyses of climate change scenarios, from regional climate models (RCMs), in northern Europe consistently suggest a rise in both mean and extreme precipitation (Semmler and Jacob 2004; Frei et al. 2006; Nikulin et al. 2011), whereas most RCMs suggest a reduction in mean precipitation in the Mediterranean sector with an increase in extreme values (Alpert et al. 2002; Sánchez et al. 2004; Gao et al. 2006; Rajczak et al. 2013), but with significant differences between models (Christensen and Christensen 2007; Tapiador et al. 2007; van der Linden and Mitchell 2009). Because of that, and also for being already a region where water is seasonally limited, the Mediterranean area was identified as one of the world's most vulnerable region to climate change (Giorgi 2006; Giorgi and Lionello 2008).

P. M. M. Soares (✉) · R. M. Cardoso · P. M. A. Miranda
Instituto Dom Luiz, Faculdade de Ciências,
Universidade de Lisboa, Campo Grande, Ed. C8 (3.26),
1749-016 Lisbon, Portugal
e-mail: pmsoares@fc.ul.pt

J. J. Ferreira
Instituto Português do Mar e da Atmosfera,
Rua C do Aeroporto, 1749-077 Lisbon, Portugal

The use of multi-model ensembles is increasingly used for climate change assessment, from global (IPCC 2013) to regional scales (Christensen and Christensen 2007; van der Linden and Mitchell 2009; Giorgi et al. 2009). RCM ensembles enable the understanding and characterization of uncertainties which have different origins, from the future scenario, to the forcing data and the regional model physics, and therefore, reduce uncertainties and increase confidence in future projections (Tebaldi and Knutti 2007; Déqué et al. 2007; Hawkins and Sutton 2009). Nevertheless, two important issues arise: the distinction between the GCMs and the RCMs errors (Déqué et al. 2005; Diaconescu et al. 2007) and the controversial selection and weighting of ensemble members for climate change assessment (Perkins and Pitman 2009; Christensen et al. 2010). A broad view of the ability of RCMs to reproduce the European precipitation probability distribution and its changes was carried out by Boberg et al. (2009, 2010), respectively for PRUDENCE (Christensen and Christensen 2007) and ENSEMBLES (Hewitt 2005; van der Linden and Mitchell 2009) datasets. In the latter, the improved ability of ENSEMBLES RCMs to reproduce the daily precipitation probability density functions (PDFs) was associated to a finer resolution and to the models used. That study suggested that the contribution of light to moderate precipitation to the total precipitation consistently decreases in the future climate, with an increase of the contribution of high to extreme precipitation. These changes, however, are regionally dependent, as expected. Puzzling was that the only regions in Europe not having a clear PDF change in all XXI century decades were Iberia and the Mediterranean region. Moreover, Boberg et al. (2010) found that the PDF skill scores for Iberia were amongst the lowest, suggesting that the discrepancies between PRUDENCE and ENSEMBLES results were attributable to small-scale convective precipitation. Additionally, they found the largest discrepancies for low precipitation, and large spreads in the 95th precipitation percentile, as Tapiador et al. (2007) for monthly precipitation values. This large spread in high ranking percentiles for Iberia, when compared with other European regions, may be related to the precipitation regime in this region, where fewer days with moderate precipitation and more days with more intense precipitation occur (Martin-Vide 2004).

In Boberg et al. (2010) the ENSEMBLES RCMs generally underestimate extreme precipitation, which may also be due to the evaluation with a very scarce number of local observational stations. A fairer comparison would have been against a high resolution gridded dataset based on a large number of local stations with the same kind of spacing (Soares et al. 2012b; King et al. 2013). All these shortcomings emphasize the particularities of the Iberian precipitation in the European context, and the common difficulties that RCMs experience in its description (Boberg et al. 2010; Kjellström et al. 2010; Herrera et al. 2010).

In the western edge of the Iberian Peninsula (IP), Portugal displays a very large precipitation gradient, from the southeast regions, with less than 400 mm per year, to the northwest mountains, which is one of the wettest places in Europe and where precipitation annual amounts can be over 3,000 mm (Soares et al. 2012a). This study revealed the benefits of higher resolution simulations to describe the present Portuguese climate, either the mean daily values or the extremes. However, to present-day, the largest set of high resolution simulations available and validated comprehending Portugal is the ensemble of RCM simulations from the EMSEMBLES project. The ability of the ENSEMBLES RCMs forced by ERA-40 (Uppala et al. 2005) to describe the precipitation variability and extremes over Portugal was evaluated by Soares et al. (2012b), where a large model spread with an overall good representation of precipitation was found. Nevertheless, with the exception of the northern mountains, a general negative bias was prevalent all over. The underestimation was related to an underrepresentation of most of the light to moderate daily precipitation bins, which was alleviated with the basin level aggregation. Yet, there was a good description of the higher ranking percentiles related to the precipitation extremes for Portugal.

The comparison of the ENSEMBLES RCMs results for Portugal (Soares et al. 2012b) with the ones for Spain (Herrera et al. 2010) reveals a different behaviour of the RCMs for the two Iberian countries. It shows a precipitation overprediction in Spain, and an underprediction in Portugal. Interpretation of the regional differences in RCM behaviour is complicated by the fact that the peak of annual precipitation in Iberia is spatially and temporally very heterogeneous. The western IP is dominated by a single absolute winter peak, whereas the highest values in the central and eastern Iberian regions are more spread throughout the year, often characterized by two maxima occurring in spring and autumn (Rios-Entenza and Miguez-Macho 2013; Rios-Entenza et al. 2014). The latter authors showed that, relatively to the north-western Iberia dominated by the winter frontal precipitation, recycling processes are crucial to explain the Iberian spring precipitation, particularly over the eastern and north-eastern sectors.

Unfortunately, there aren't many studies assessing Portuguese precipitation climate change, except for a relatively outdated study by Miranda et al. (2002) and the works of Jerez et al. (2012, 2013). The latter use the MM5 model to assess the climate change signal on Iberian temperature and precipitation, based on multi-physics ensembles. These illustrate the sensitivity of seasonal regional climate change projections to the model physics, and the evaluation, not focused in Portugal, relies only on the E-Obs dataset. Consequently, a thorough study addressing the changes of Portuguese precipitation mean and PDF is highly desirable to support the decision making on impacts on diverse economy sectors associated to water, namely, hazard mitigation, water public supply, hydropower energy, forest, agriculture, tourism, etc. This is precisely the main goal of the present study.

In the current work, a comprehensive evaluation of the historic reference simulations for Portugal is developed, taking advantage of a high spatial resolution gridded dataset (Belo-Pereira et al. 2011). This evaluation is focused on the spatial and temporal structures of the mean precipitation and also on PDFs. In this manner, we can evaluate the suitability of the RCMs results for the regional precipitation variability and assess, with higher confidence, the changes in precipitation mean and extremes recurring only to the best models. The reduction of the ensemble size, selecting only the best performing models, produces a decrease in the spread (i.e., uncertainty) while driving the ensemble mean closer to the observed values (Herrera et al. 2010). For PDFs, Boberg et al. (2010) matches historic reference simulations results with a very small number of local station observations, 11 in Portugal, and 18 in Spain. This small number of observations carries important caveats. Additionally, the grid-box model results should be compared with areally averaged precipitation to conserve consistency (Osborn and Hulme 1997). Boberg et al. (2010) refers clearly that station observations are not optimal for the use in an assessment of model distribution data due to its spatially heterogeneous distribution within each sub region. Sun et al. (2006) also highlights that models are expected to have a shift in the precipitation intensity spectrum towards lower intensities and an underestimation of higher intensities. Nonetheless, the comparison against regular gridded datasets also carries difficulties, since these grids are often built with a small number of stations which are spatially heterogeneous distributed. The apparent high resolution comes largely from interpolation, leading to over smoothed precipitation fields, with possibly dramatic effects in extreme values (Hofstra et al. 2010). Furthermore, Gómez-Navarro et al. (2012) stresses the dependence of model evaluation and ranking on the selected observational dataset, showing that uncertainties in the observations are comparable to the uncertainties within RCMs. The Portuguese regular grid (Belo-Pereira et al. 2011) offers the best precipitation dataset at 0.2° spacing, comparable to the 25 km of the ENSEMBLES RCMs, since it is based on a much larger number of rain gauges, above 400.

The main goals of the present study are: to assess the quality of the ENSEMBLES RCMs historic reference simulations to describe the mean precipitation and the precipitation PDFs relying on a quality gridded dataset; to build a simple but high quality ensemble of the best performing models based on their description of both the mean and precipitation PDFs; and, finally, to characterize the climate change signal on the mean annual and seasonal precipitation and on the PDFs.

In Sect. 2 of this paper, the details of the methods, datasets and models are presented. Results are shown in Sect. 3, where the historic reference simulations results are thoroughly explored, regarding mean seasonal and daily precipitation and extreme events, followed by the portrayal of its changes resulting from global warming. The main conclusions are drawn in Sect. 4.

2 Data and Methods

2.1 RCMs

The overall aim behind ENSEMBLES project (http://www.ensembles-eu.org) was to establish a multimodel ensemble prediction system based on state-of-the-art RCMs to study climate change in Europe and estimate its uncertainty (van der Linden and Mitchell 2009). The RCM simulations used in the present study were performed in this framework, and are forced by different GCMs, both the historic reference and future simulations (Table 1). This amounts to 16 historic reference and 16 future simulations with daily precipitation data. The RCM historic reference simulations cover the period 1961–2000, and the future ones, performed under the A1B SRES scenario (Nakicenovic et al. 2000), encompass the period 2071–2100. The historic reference simulations are herein designated as control runs. Model domains are slightly different, but share a common minimum domain. The horizontal resolution of the models is similar, of the order of 25 km, with subtle differences associated with the map projection. More details can be found in the ENSEMBLES project website http://ensemblesrt3.dmi.dk (Christensen et al. 2010).

2.2 Observations

The evaluation of the control simulations results was carried out against the regular gridded precipitation dataset developed by Belo-Pereira et al. (2011). This dataset (ObsPT_0.2 hereafter) presents a horizontal spacing of 0.2° and was generated based on more than 400 rain gauges with daily precipitation data. This dataset spans from 1950 to 2003, and is based on much more rain gauges than other observational datasets, like the Climate Research Unit (Mitchell and Jones 2005) dataset, containing monthly precipitation at 0.5° resolution or version 9 of the ENSEMBLES observational gridded dataset for Europe (E-OBS) (Klein Tank et al. 2002; Haylock et al. 2008; Klok and Klein Tank 2009), which includes daily precipitation values at 0.25°. The ObsPT_0.2 dataset was not corrected

Table 1 ENSEMBLES regional climate models and forcing GCMs

Institution	Reference	Model	Forcing model	Acronym
Abdus Salam International Centre for Theoretical Physics	Pal et al. (2007)	REGCM3	ECHAM5_r3	ICTP
Danish Meteorological Institute	Christensen et al. (2006)	HIRHAM5	ARPEGE	DMI1
			ECHAM5_r3	DMI2
			BCM	DMI3
Swiss Institute of Technology	Jaeger et al. (2008)	CLM	HadCM3Q0	ETHZ
Hadley Center—UK Met Office	Collins et al. (2006)	HadRM3Q3	HadCM3Q3	HadC1
		HadRM3Q16	HadCM3Q16	HadC2
		HadRM3Q0	HadCM3Q0	HadC3
Koninklijk Nederlands Meteorologisch Instituut	van Meijgaard et al. (2008)	RACMO2	ECHAM5_r3	KNMI
Max Planck Institute for Meteorology	Jacob et al. (2001)	REMO	ECHAM5_r3	MPI
Met Eireann	Samuelsson et al. (2011)	RCA3	HadCM3Q16	MetEi
Norwegian Meteorological Institute	Haugen and Haakenstad (2005)	HIRHAM	BCM	MetNo
Swedish Meteorological and Hydrological Institute	Samuelsson et al. (2011)	RCA3	HadCM3Q3	SMHI1
			ECHAM5_r3	SMHI2
			BCM	SMHI3
Universidad de Castilla la Mancha	Sánchez et al. (2004)	PROMES	HadCM3Q0	UCLM

for undercatch since the correction factors for Portuguese annual precipitation are smaller than 5 % (Weedon et al. 2011).

2.3 Methods

For climate change assessment it is vital to perform an extensive evaluation of the control simulations and to build an ensemble model. Soares et al. (2012b) carried out a thorough analysis of the hindcast simulation results, for Portugal, using the same set of RCMs forced by the ERA-40 reanalysis, which was based fundamentally on standard statistical errors. A similar methodology is adopted here, but with important developments to respond to the need of generating a high quality ensemble in a simple way, and subsequently assess the climate change signal in the spatial distribution of precipitation. This procedure is based on a common and widely accepted assumption that RCMs revealing improved skills in describing present climate are also likely to have higher reliability for downscaling future climate (Liang et al. 2008). Nonetheless, Jerez et al. (2013) interestingly showed significant changes in the relevance of model parameterized processes with global warming, that may greatly affect the model ranking between present and future climate.

Here, the representation of mean precipitation and PDFs was equally weighted; therefore the control simulations evaluation is also extended to measure the quality of the RCMs in the representation of the full PDFs. The control RCMs results were interpolated to the observational grid.

The assessment of the quality of RCMs in the spatio-temporal representation of mean precipitation is performed through grid-point standard statistical errors at time scales, from monthly to yearly, namely, the percentual bias (BIAS), the mean absolute percentual error (MAPE), the root mean square error (RMSE) and the standard deviation (SD). For each grid point the multi-year monthly, seasonal and yearly mean values are computed, for observations and RCMs, and afterwards the referred errors are calculated for mainland Portugal. A simple bootstrapping technique (von Storch and Zwiers 1999, page 93ff) using 10,000 random samples was used to estimate the 95 %

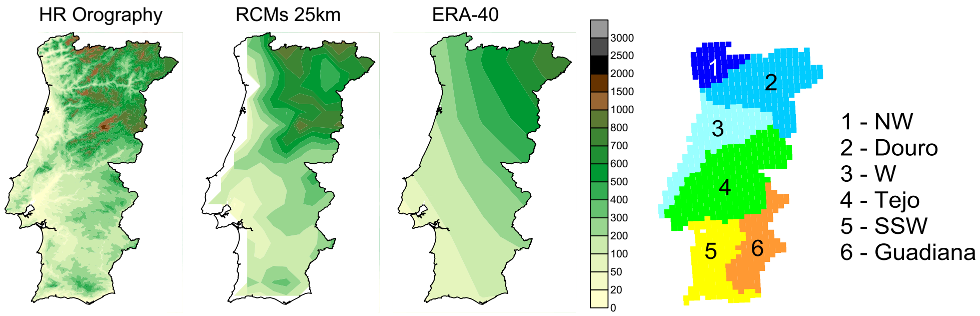

Fig. 1 Portuguese orography (m) according to Gtopo 30 dataset (30″ resolution), ENSEMBLES RCMs (25 km resolution) and ERA-40 reanalysis (1.125° resolution). Main Portuguese river basins

confidence interval of the different error statistics. For each model, the spatial–temporal series is transformed into a one dimensional vector. Then, the daily precipitation values were picked randomly from it until the length of random sample equals the length of the vector. The sample errors are subsequently calculated. This is repeated 10,000 times and the 2.5th and 97.5th percentiles of the error population represents the lower and upper bound of the 95 % confidence interval.

The precipitation can be characterized by histograms of daily precipitation, or also known as probability density functions (PDFs). For daily values of precipitation over land, 17 separate PDFs were built from the OBS_IM0.2 grid and the 16 RCMs following Boberg et al. (2009, 2010). The precipitation PDFs refer to normalized precipitation and only take into account wet days, i.e. days with precipitation ≥ 1 mm. PDFs are computed by binning the data into bins of 1 mm/day width and then multiplying the bin frequency by the bin mean value to calculate the precipitation amount. Lastly, the binned data is normalised by dividing each bin value by the total wet day precipitation amount for the 30 year period. For the future scenario, a similar method was followed to construct future PDFs.

The models ability to describe the observed PDFs is evaluated through the computation of two PDFs scores proposed by Perkins et al. (2007) and used in Boberg et al. (2009, 2010). The PDF skill scores are based on the common overlap of the model and observed PDFs. Firstly, the full PDF skill score (S) measures the full PDF common area (Boberg et al. 2009), second, a segmented skill score is calculated where the PDF is divided in two intervals and then averaged out to give an extra weight to the PDF tail, related to extreme precipitation. Boberg et al. (2010) divided the full PDF in two segments, first from 1 mm to the precipitation corresponding to the 90th percentile, and second, from the 90th to the 100th percentile. The two parts are then re-normalized separately and the degree of PDF overlap is calculated for each part. The final skill score (S90) for each RCM is calculated by averaging the two distinct partial scores. Both skill scores, S and S90, have values ranging from zero, for no overlap, and one, for a perfect overlap. This procedure is followed here.

For the assessment of the future changes in Portuguese precipitation, the control simulations results are compared with the future scenario results, firstly, by evaluating the changes in mean precipitation, secondly by juxtaposing the changes on the precipitation PDFs and thirdly by computing the changes on the precipitation quantiles.

The scenario change for mean precipitation, yearly and seasonal, is characterized by the relative anomalies (differences) between future and control results. The PDF changes are simply the difference between future and control normalized precipitation PDFs.

Finally, the evaluation of the changes in the PDF tails is investigated through adjusted quantiles following Ferro et al. (2005). The aim is to determine if the tail changes may be explained by shifts in scale (interquartile range) and/or shape (skewness) through normalised quantiles. Since the precipitation PDF is by nature always positive, the logarithm of each quantile is determined before the normalisation is performed, for both control and future scenarios. Following Ferro et al. (2005), the scale-adjusted quantile ratio is then calculated and the shape-adjustment is not performed since these authors show the smaller effect of this parameter.

All the previous modifications are computed for the best performing models and for a synthetic model ensemble produced from them. The synthetic ensemble model building is presently a rather controversial topic on the climate community. The simplest method is to equally average all available models, and rely in the finding that the ensemble mean performs better than individual ensemble models, regarding the mean value, but not the variances (Gleckler et al. 2008; Pincus et al. 2008; Reichler and Kim 2008; Pierce et al. 2009). Some authors have proposed more sophisticated ensemble weighting techniques (Giorgi and Mearns 2003), however with only minor improvements (Christensen et al. 2010; Räisänen and Ylhäisi 2012). Other studies focused on issues concerning the selection of ensemble members questioning the advantage of discarding models with weaker performance (Perkins and Pitman 2009). The critical issues of model independency (Knutti 2010; Bishop and Abramowitz 2013) and how to define the number of simulations required to reproduce various statistics of a full multi-physics ensemble was addressed by Evans et al. (2013).

In this context, a simple method to achieve a best performing ensemble is followed here. This method is based on the ranking of the different RCMs through the error measures and skill scores mentioned; more precisely, BIAS, MAPE, S and S90. After this grade, the two best performing RCM in each of the chosen measures are selected for the ensemble. In this way, and emphasizing that the main purpose of this ensemble is to have a best synthetic ensemble model for both mean precipitation and daily precipitation PDFs, an ensemble is built trying not to add more subjective constrains to its construction. The syntactic model ensemble PDF is computed from the full aggregation of the selected RCMs daily precipitation.

Soares et al. (2012b) showed that Portuguese precipitation is very diverse from basin to basin, and that ENSEMBLES RCMs have distinct skills in wetter and dryer basins. To illustrate the potential changes related to the A1B scenario, the description of the changes in the basin precipitation is also analysed, for mean monthly precipitation and for quantiles changes. The considered basins, the Portuguese orography, according to Gtopo 30 dataset

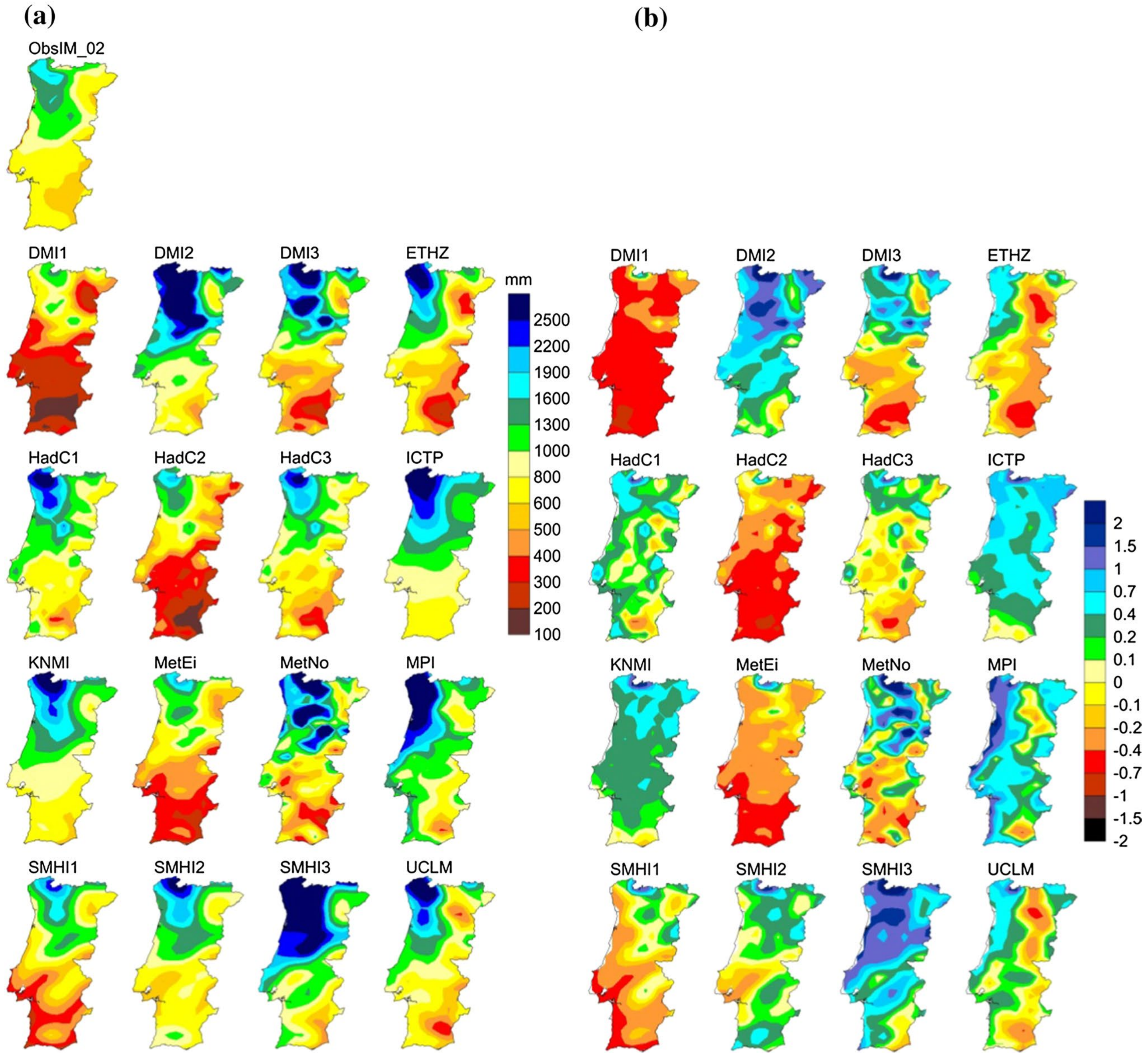

Fig. 2 **a** Yearly mean precipitation (1971–2000) from gridded observations (ObsIM_0.2) and ENSEMBLES RCMs control runs (interpolated to the ObsIM_0.2 grid); and, **b** relative differences of yearly mean precipitation between RCMs control runs and gridded observations (fraction)

(30″ resolution), ENSEMBLES RCMs (25 km resolution) and ERA-40 reanalysis (1.125° resolution) are illustrated in Fig. 1.

3 Results

3.1 Assessment of the control simulation

The evaluation of the RCMs control simulations enables the identification of the best preforming models for mainland Portugal. Figure 2a, depicts the annual mean precipitation for the period 1971–2000, and Fig. 2b, the relative differences to the high resolution regular gridded dataset ObsIM_0.2. Some of the overall statistical errors of the RCMs are shown in Fig. 3: the percentual bias and the mean absolute percentual error (further details in Cardoso et al. 2013), for the monthly, seasonal and yearly precipitations.

Generally, RCMs show a reasonable ability to describe the spatial distribution of the annual mean precipitation, with a large regionally dependent spread and a tendency

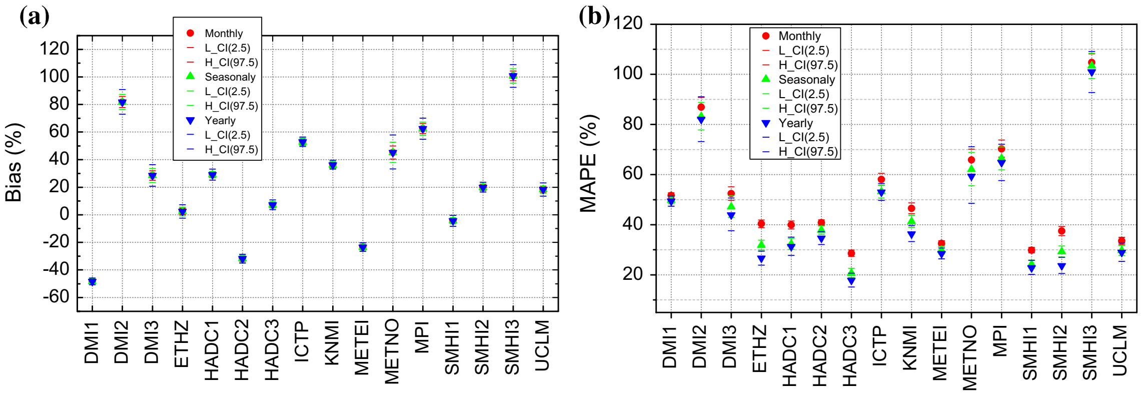

Fig. 3 Global error measures of the ENSEMBLES RCMs precipitation against the observational grid (ObsIM_0.2) for the Portuguese mainland. The error measures are **a** normalized bias (Bias %) and **b** mean absolute percentage error (MAPE). The errors are computed for different accumulation periods of precipitation (monthly, seasonally and yearly), pooling all data together

to overestimate precipitation. This positive bias is generally found in the north and west of Portugal, whereas most RCMs underestimate precipitation in the southern drier regions. These features were also found in Soares et al. (2012b), but the overestimation covered less land extensions of the northwest regions and was focused only in the north-western border mountains. Some model deficiencies are very much constrained by the forcing GCMs. DMI was identified as the drier model when forced by ERA-40, and the same applies when it is forced by ARPEGE, but this deficiency is largely corrected when forced by BCM, whereas when forced by ECHAM it shows a strong overestimation. Also generally drier are the RCMs MetEi and HadC2, both sharing the forcing model HadCG3Q16. This dryness seems to be related to the HadCG GCM Q16 version since the others RCMs, HadC1 and HadC3 forced, respectively by Q3 and Q0, don't show the same deficiency. Moreover, all RCMs forced by ECHAM, ICTP, DMI2, KNMI, MPI, and SMHI2 in a less degree, generally overestimate precipitation (see also Fig. 3). This feature is clearer in the case of the KNMI model, the best performing when forced by ERA-40 (Soares et al. 2012b) and here revealing a strong positive bias, over 40 %. Inspecting the spatial pattern of the relative difference between RCMs and observations three model stand out, HADC3, SMHI1 and ETHZ, by the overall agreement, with the exception of some overestimation in the mountainous regions, where they seem to over represent the orographic enhancement of precipitation, or reveal in some degree the known problems of precipitation grids in complex mountains (Frei et al. 2003).

The RCMs showing smaller percentual bias are ETHZ, HADC3 and SMHI1, with values within 10 %. It should be kept in mind that bias is an error measure with spatial compensation that is not present in MAPE or RMSE. However, these models are still in the group of smaller MAPEs, as the SMHI2 model. The overall percentual bias spans from −50 to 100 %, and the MAPEs between less than 20 % to more than 100 %, for both the seasonal and the yearly temporal scales. The large spread on these measures show that RCMs have very distinct performances in describing the present climate of Portugal. And, that for ensemble building this fact should be taken in account, because of the negative effect of building ensembles based on very different model skills for the region of interest (Perkins and Pitman 2009).

Not surprisingly, RCMs standard deviations (not shown) show an overestimation the spatio-temporal variability. This overestimation is in the opposite sense of the underestimation seen when the models were forced by ERA-40, and so associated to the different model forcings. As expected, the drier models show variability closer to observations, e.g. DM1, HADC2 and MetEi.

As seen before, most RCMs overestimate yearly and seasonal grid point precipitation, but to evaluate if models are able to describe correctly the daily precipitation regimes in Portugal, in spite of spatial and phase problems, it is interesting to compare the normalized distribution of daily precipitation for the control run and the observations. Figure 4 shows the normalized empirical distribution of daily normalized precipitation for both the observations and the RCMs control results. Again the RCMs spread is very large and the vast majority underestimate the normalized precipitation frequency related to light to moderate precipitation (to around 20 mm/day), and largely overestimate the moderate to high precipitation bins. Some models show discrepancies of more than one order of magnitude in the normalized frequency of extreme daily precipitation events, e.g. DM2 and MPI above 80 mm. Models show difficulties to accurately describe the normalized precipitation frequencies, particularly related with moderate to extreme precipitation. As previously seen, this renders these models very wet, nevertheless those frequencies are obviously much rarer than light to moderate ones.

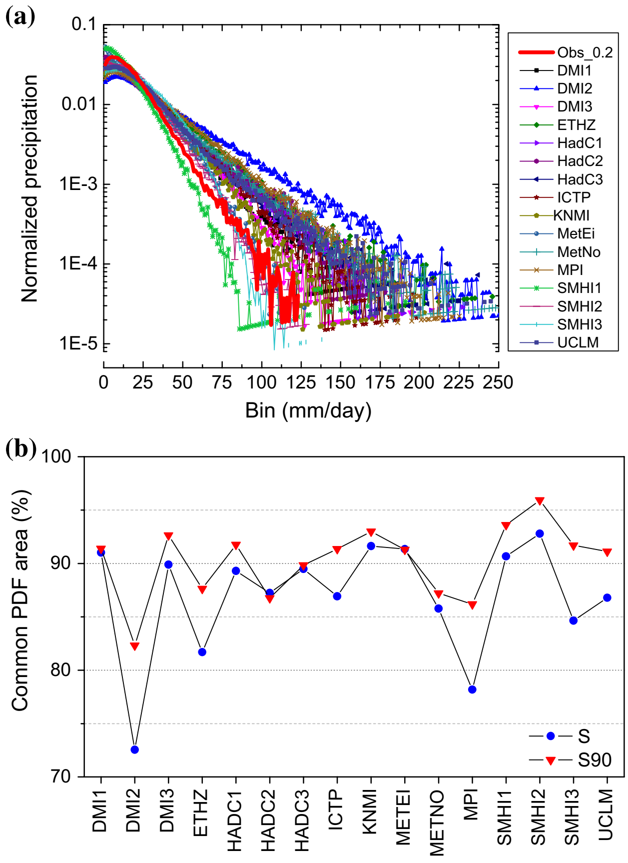

Fig. 4 **a** PDFs of daily precipitation from gridded observations (Obs_0.2, *red*) and 16 RCMs (*colored symbols*) for the period 1971–1990. **b** S and S90 scores (Boberg et al. 2010), comparing daily precipitation PDFs for 16 RCMs control runs against observations, for Portuguese mainland in the 1971–2000 period

To objectively assess the match between the empirical PDFs of RCMs and observations, the S and S90 skill scores computed accordingly to Boberg et al. (2009, 2010) are shown in Fig. 4. S gives a match metric for the full empirical PDF and S90 is an equal weighted measure between the similarity between the PDFs under the 90th percentile and above. The integral vision of the common empirical PDF areas, S, presents a large spread with values spanning between 72 and 93 %, but the majority of RCMs have S values between 85 and 90 %, revealing an overall reasonable skill in reproducing the daily precipitation bins. The best RCMs with respect to the full empirical PDF are: DMI1, KNMI, MetEi and SMHI2. The S90 skill score is larger and in general gives a similar ranking of the RCMs. Both versions of SMHI model, SMHI1 and SMHI2, and KNMI show the best behaviour.

The distinct model skill measures presented are clearly showing the different abilities each model has to reproduce present climate precipitation; i.e. the spatial structure of the mean precipitation, the spatial and temporal properties and the daily precipitation distributions. If we want to assess the climate change signal on precipitation, all these features should be accounted for. A simple rationale will be followed for the selection of the best models as members of a smaller ensemble, and more importantly the definition of criteria determining which models should be disregarded to mitigate their negative effect on the ensemble. In Table 2 we summarize the values of the selected performance measures (BIAS, MAPE, S and S90). It can be seen that in spite of the large spread, there are models that behave very well in more than one of the criteria, e.g. SMHI1 and SMHI2.

The need of evaluating the ENSEMBLES RCMs results only for Portugal, separately from Spain in Iberia, as defended before, is confirmed by the PDF ranking here and in Boberg et al. (2010) study. There, the worst PDF skill score (S) is linked to the SMHI model, and in here it appears as the best model, in two out of the three versions, SMHI1 and SMHI2 (Table 2). Additionally, two out of the three best Ss of Boberg et al. (2010), MPI and ETHZ, are among the three worst for Portugal. Finally, Boberg et al. (2010) identified the DMI HIRAM model as the best performing model in PDF matching, and for Portugal the DM1 is the 4th best.

As previously mentioned, we intended to build a simple ensemble, relying on a small number of members to characterize the precipitation change in Portugal. For that, we select the best two RCMs in the 4 statistical measures (bold in Table 2). It turns out that only 5 RCMs are able to fulfil this requirement, and consequently are considered as the constituent members for the ensemble. All the others are discarded.

The control run seasonal precipitation from the RCMs and the ensemble mean (ENSEM) can be observed in Fig. 5 next to the gridded observations. Overall, the ensemble mean does a good job describing the spatial seasonal precipitation patterns, with higher precipitation in the northwest mountains and much less precipitation in the northeastern and southern regions, in close agreement with observations. In winter the ensemble mean, and all members, overestimate the precipitation in the northwest mountainous regions when compared with the gridded dataset. Nevertheless, the values of regular gridded dataset should be looked at with some caution in complex orographic regions due to the poor sampling of rain gauges (Soares et al. 2012b, Cardoso et al. 2013). Elsewhere in Portugal, the precipitation fields given by the ensemble are quite remarkable, depicting the low amounts of precipitation in the northeast and the southeast, around 200 mm. Local features related to the mountains in the centre and southern Portugal, are well captured. The main characteristics mentioned for the winter precipitation can be extended to the other three seasons, but with much reduced values of rainfall. Table 3 summarises the ensemble improved performance when compared to the individual models. The ensemble synthetic model spatial correlations

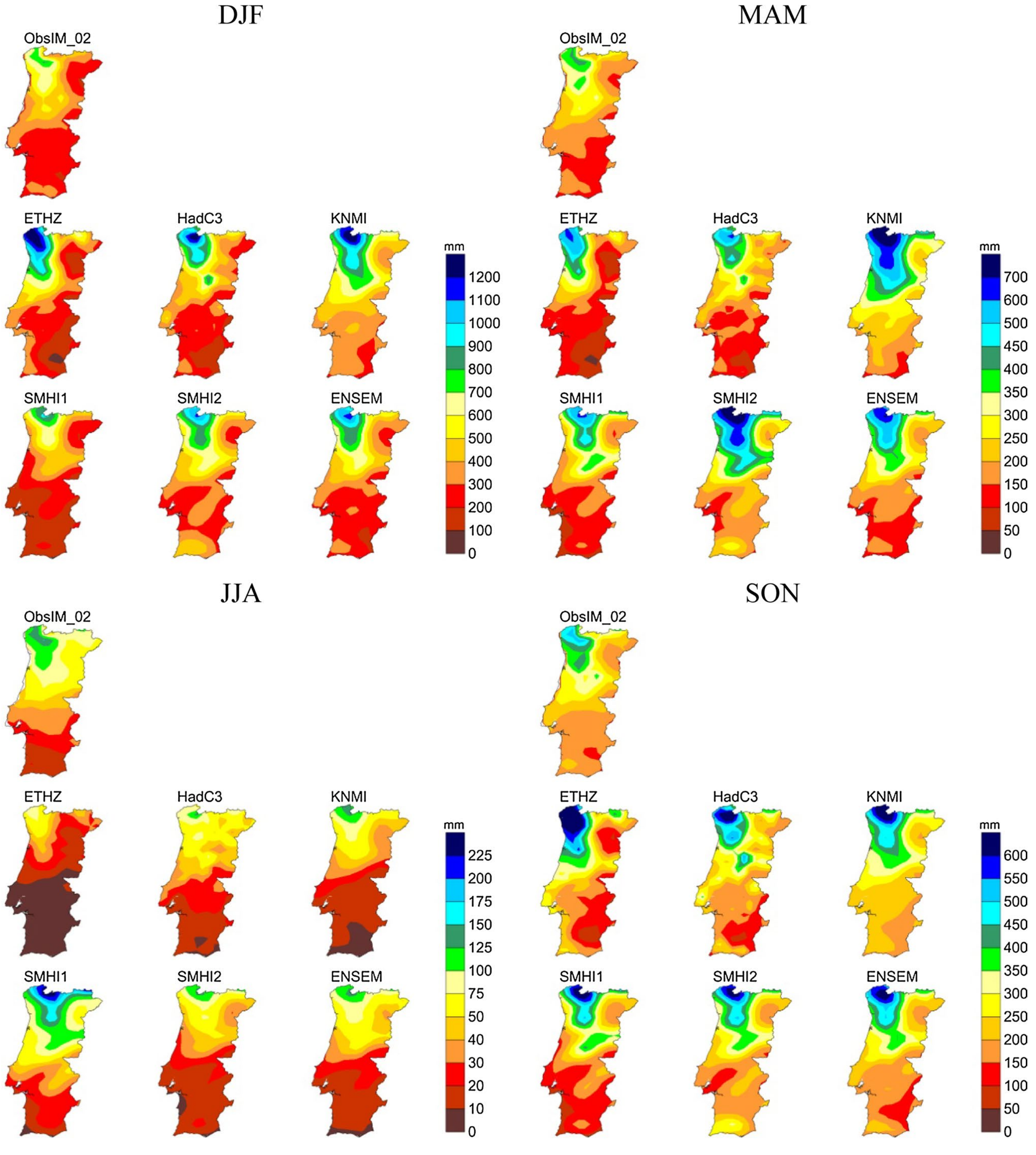

Fig. 5 Seasonal precipitation of Observations (ObsIM_02), of the 5 best performing RCMs (control runs) and the ENSEMBLE, for the period 1971–2000

for the yearly and seasonal scales are always higher than the constituent members, with values between 0.92 and 0.94. Generally, the ensemble synthetic model's MAPE reveals lower values than model members, with the exception of the HadC3 case in spring and SMHI2 in summer.

3.2 Climate change assessment for Portugal

The annual and seasonal amounts of rainfall are important for many economic sectors and the assessment of the potential change in response to global warming is a key

Table 2 Seasonal percentual bias, MAPE, and S and S90 scores for daily precipitation, which enable the RCM ranking

RCMs	Bias%	MAPE	S	S90
DMI1	−48.30	0.50	91.02	91.39
DMI2	81.75	0.83	72.55	82.32
DMI3	28.50	0.47	89.90	92.64
ETHZ	**2.44**	0.32	81.70	87.63
HadC1	29.10	0.32	89.30	91.76
HadC2	−31.86	0.38	87.25	86.76
HadC3	7.20	**0.21**	89.49	89.85
ICTP	52.87	0.53	86.92	91.37
KNMI	36.18	0.41	**91.63**	93.00
MetEi	−23.52	0.30	91.35	91.30
MetNo	45.19	0.62	85.77	87.22
MPI	62.42	0.66	78.18	86.18
SMHI1	**−4.38**	**0.24**	90.68	**93.60**
SMHI2	19.89	0.29	**92.79**	**95.94**
SMHI3	100.74	1.03	84.65	91.70
UCLM	18.31	0.30	86.80	91.13

The two best performing RCMs in each error/score are in bold

issue in climate change studies. The anomalies of annual mean precipitation, future climate minus control climate (2071–2100 minus 1971–2000) are shown in Fig. 6, for the five retained members and the associated ensemble synthetic model.

As expected, single RCMs display a more heterogeneous change pattern than the ensemble mean, but with some common features, like the severe reduction of rainfall values in the south, where decreases spanning between 20 and 50 % are projected. The areas which show a small change, less than 10 %, are not common to all models and this variation is not statistically significant, whereas the areas registering a strong difference, the change is statistically significant. The ensemble mean reveals a rainfall reduction in the north between 10 and 20 %, and a decrease within 20 and 35 % in the south. This is in agreement with the rainfall reductions found for the Mediterranean (Giorgi and Lionello 2008; Mariotti et al. 2008), for Iberia (Jerez et al. 2012, 2013) and for Spain (Argüeso et al. 2012) due to global warming, where decreases of annual mean precipitation, ranging from 20 to 40 %, were found. All values are statistically significant.

The wet days (not shown) consistently decrease in all RCMs, being the SMHI2 the one with smaller reductions and less spatial structure. For this model, the wet days diminishes around 20 %. The ensemble mean reveals a clear north–south gradient of wet days reduction, from 20 % in the extreme north to 30 % in the southeast. These findings are in agreement with Jerez et al. (2013).

The seasonal precipitation changes can be seen in Fig. 7, and they confirm the highly seasonal dependency of these changes found in other studies (Mariotti et al. 2008; Argüeso et al. 2012). In winter the individual RCMs predict small changes, positive and negative, on the accumulated precipitation, with some tendency for diminished precipitation in the south. It is worth noting that these small values are not significant. The ensemble mean reveals small changes in the north and centre of Portugal, and a decrease of seasonal rainfall above 10 % in the south, which is statistically significant. Since winter is the season with the greatest contribution to the total annual rainfall (see Fig. 9), this reduction could undermine the water availability of this area. This decline appears much intensified in the intermediate seasons, both spring and autumn experience larger reductions of rainfall from the north to the south. Only SMHI1 displays a different signal in the spring but like in winter, these values are not significant. In the autumn these decreases span from around 10 % in the north to values above 40 % in the extreme southeast, and in the spring are above 30 % and can reach approximately 50 % in the south. Like in spring, the ensemble mean introduces significance and there are no areas statistically insignificant. In the summer, a large portion of the north and centre are affected by a precipitation decline beyond 50 %, and in the south around 40 %. The individual RCMs in the summer even point out for reductions above 80 % in some regions next to the Spanish border. The same kind of values was found

Table 3 Spatial correlations and MAPEs for the 5 best performing RCMs and ensemble mean

Model	Yearly		Seasonally							
			DJF		MAM		JJA		SON	
	Corr	MAPE%	Corr	MAPE%	Corr	MAPE%	Corr	MAPE%	Corr	MAPE%
ETHZ	0.91	27	0.90	32	0.90	29	0.91	67	0.92	26
KNMI	0.92	38	0.90	48	0.92	63	0.92	40	0.92	18
HadC3	0.90	18	0.90	24	0.89	16	0.91	32	0.89	17
SMHI1	0.87	24	0.88	26	0.88	50	0.86	41	0.86	17
SMHI2	0.84	23	0.84	23	0.83	25	0.87	31	0.82	24
ENSEMBLE	0.94	16	0.93	20	0.93	26	0.92	32	0.94	12

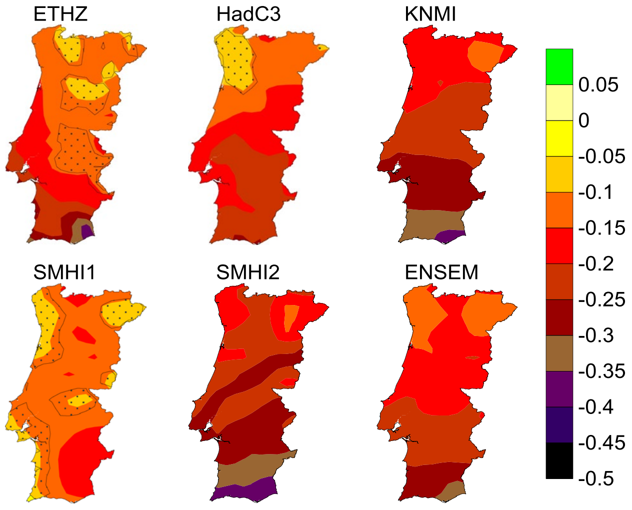

Fig. 6 **a** Selected RCMs and ensemble (ENSEM) climate change signal on yearly mean precipitation (2071–2100 minus 1971–2000), in fraction. *Areas with dots* specify changes not statistically significant using a Student's *t* test at the 90 % confidence level

for Spain by Argüeso et al. (2012), where the intermediate seasons register decreases of −20 to −50 %, and the summer precipitation shrinkages between −32 and 72 %. These common drops are extremely disturbing since Portugal and Spain share most of the river catchments, and the reduction of intermediate season precipitation is extremely concerning for agriculture, forest and water management.

These results emphasise the tendency of an increased gap between winter and the intermediate seasons precipitations, and the enlargement of the dry season into these seasons, which is particularly dramatic in the southern region.

Regarding the future changes on the precipitation distributions, Fig. 8a–c shows the ensemble PDFs of normalized precipitation for present (1971–2000) and future (2071–2100) climates, the correspondent changes for the ensemble synthetic model and each of the members, and finally the evolution of the normalized precipitation PDF changes for each climatological period (30 years periods) of the XXI century. The ensemble normalized precipitation PDF reveals, in spite of the logarithmic scale, a decrease of precipitation amounts related to bins of light to moderate precipitation, a relatively important increase of the ones associated with stronger precipitation, and the appearance of very extreme precipitation, above 250 mm, in future that are absent in present climate. The future distribution moves towards higher values. This is further emphasised in Fig. 8b where differently to what Boberg et al. (2010) obtained for the IP, there is a clear decrease in the light to moderate/high precipitation bins. The crossover bin between decreasing and increasing relative contributions to the total, occurs typically between 20 and 30 mm per day, which corresponds to the 90th, 95th percentiles. This illustrates the increase in contribution from the very high-intensity daily precipitation to the total and the reduction from nearly all low to moderate/high intensity. The scatter of the crossover point between models is also indicative of the difficulties the models have in representing Portugal's diverse climate in which heavy precipitation days are relatively frequent in the total number of wet days, and thereby the tails of the PDFs are sensitive to the individual model differences and to their internal variability. The temporal evolution of the PDF change is illustrated in Fig. 8c where 100 year run is divided into overlapping 30 year periods each 10 years apart. The ensemble PDFs of each period was calculated and then the control (1971–2000) was subtracted to obtain the PDF change. As the century progresses, the reduction of the moderate/high precipitation increases, with the inverse occurring for the heavy precipitation, and as in Boberg et al. (2010) there is no significant change with time of the crossover point. The latter is consistent with Gutowski et al. (2007) where the climate change signal does not imply a change in the PDFs shape. Ferro et al. (2005) also refer that the scale-adjusted quantile ratios were adequate to describe the changes in the precipitation distributions. The scale adjusted quantiles were calculated following Ferro et al. (2005) and are shown in Fig. 8d. The largest change is observed in the last quartile, with the lowest quantiles exhibiting a small reduction, corroborating the PDF changes estimated in the previous figures. In three out of five models, there's an increase greater than 25 % in extreme precipitation (P99.9), which can have a significant impact in terms of the probability of occurrence of floods. The higher ranking percentiles also increase by more than 15 %. SMHI2 and KNMI share the same GCM and have similar behaviour with almost no changes in the lower quantiles and significant rise in heavy precipitation. Only ETHZ doesn't show any substantial changes and only HadCM3 displays higher reductions in the low quantiles. The ensemble synthetic model signals an amplification of precipitation above the median, increasing from 5 to 20 % in the last quartile, and immaterial reductions in the lower quantiles.

3.3 Basin Analysis

Projections of basin precipitation changes are crucial to assist, for example, on water and energy management. The ensemble mean monthly basin precipitation for present and future climate for the main Portuguese basins can be seen in Fig. 9.

Unlike in Soares et al. (2012a), one cannot identify, in the present climate, the relative maximum of precipitation in April (related to the consistent low rainfall values recorded in March in recent decades (Paredes et al. 2006;

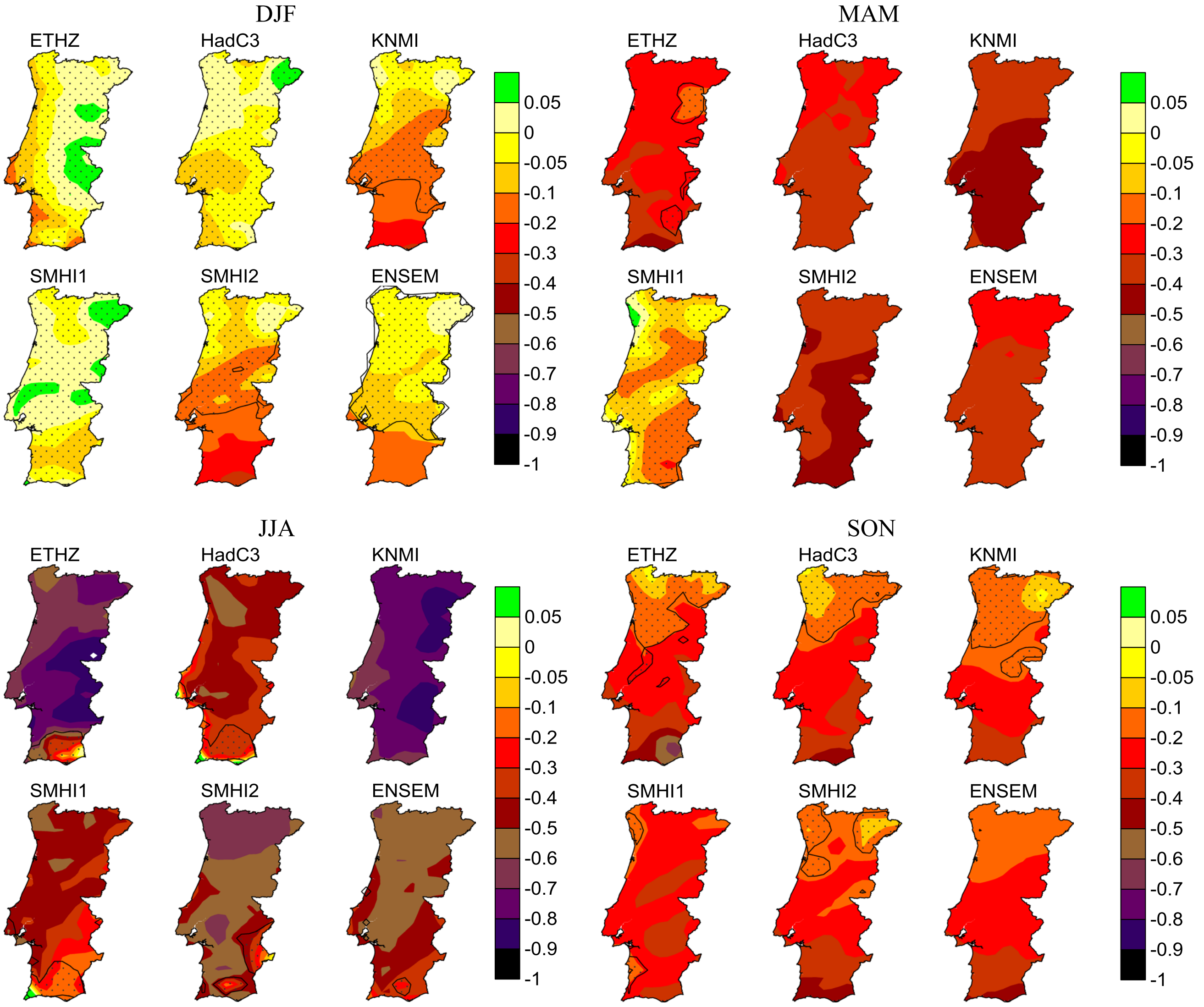

Fig. 7 As Fig. 6 but for seasons

Herrera et al. 2012) that can be seen in the observations and in the RCMs when forced by ERA-40. This is partially due to the inability of the forcing models to capture this well-known feature of the west Iberian precipitation (Soares et al. 2012a; Cardoso et al. 2013; Rios-Entenza et al. 2014).

The annual cycle of the main Portuguese basins reflect the dominant north–south and east–west precipitation gradients of the present climate, and its intensification in a future climate. The monthly precipitation appears reduced in every basin and in every month, with the single exception of December when all the basins have a small increase of the rainfall amounts. In agreement with the seasonal changes (Fig. 7) there are significant decreases on monthly precipitation in summer in North, Douro and W basins, and throughout the annual cycle in southern basins, SSW and Guadiana.

As shown in Fig. 10, there is a tendency for an amplification of heavy precipitation in all basins, with larger increases in the southern regions. From the rainiest basin (North) to the driest (Guadiana) the linear increase of the high quantiles change evolves into an almost exponential shape, denoting the striking difference in the extreme precipitation in the southern basin. In absolute values this changes are quite equivalent for the 99.9th percentile, 10 % change in the ensemble synthetic model in the North is similar to the 21 % in Tagus and to 30 % in Guadiana, i.e. ~15 mm of change, but relatively very meaningful. In the basins near the coast, north of river Tagus the changes in the quantiles bellow the median also have different behaviours from the inland and south of the Tagus basins. In the North and W basins the model spread is higher and there is

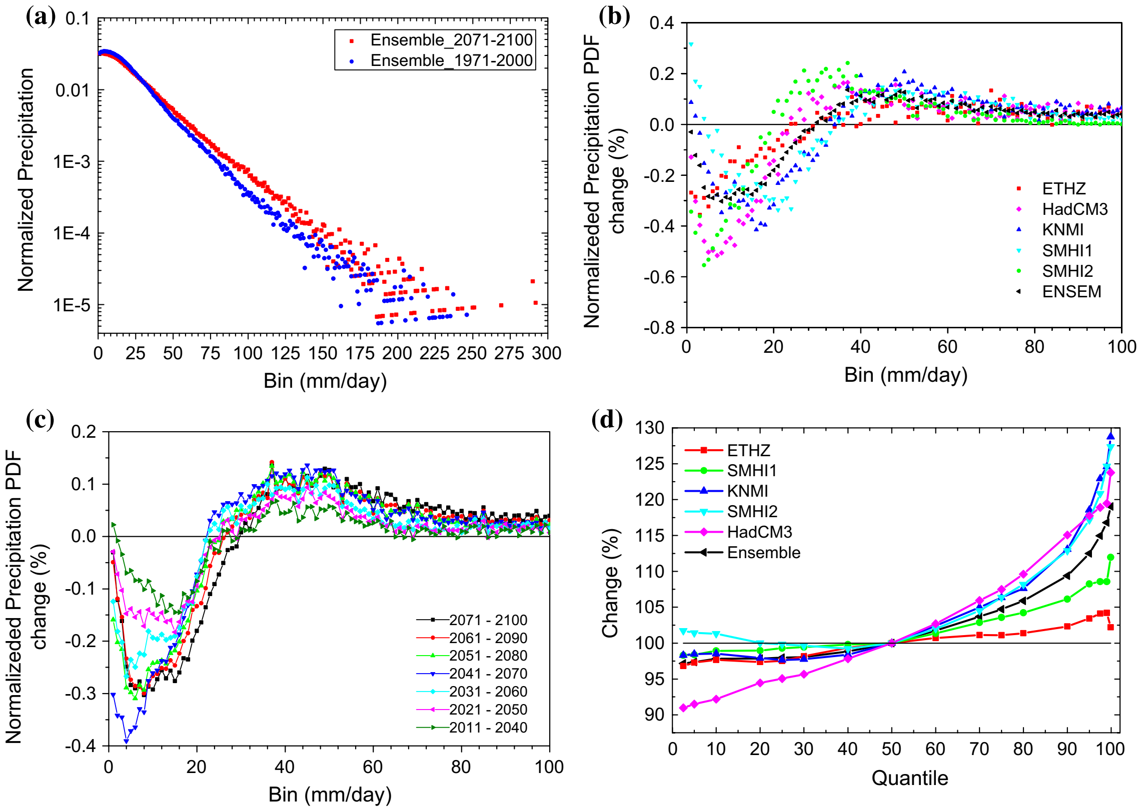

Fig. 8 **a** Ensemble PDF for present and future climate **b** Normalized precipitation PDF change (2071–2100 minus 1971–2000) for the five selected RCMs and the ensemble **c** Normalized precipitation PDF change of the ensemble, comparing climatological overlapping 30 year periods (XXI century) each 10 years apart and the present control climate and **d** changes of precipitation percentiles after adjusting for scale

a small decrease in the ensemble, whereas in the remaining basins the spread and the change are less relevant.

4 Conclusions

The impact of climate change on the hydrological cycle is a crucial issue in the Mediterranean region, and especially in Iberia. Many assessment studies focused in Europe (e.g. Christensen and Christensen 2007; Boberg et al. 2010) and in the Iberia as whole (e.g. Jerez et al. 2012, 2013) disregard the differences in the precipitation between Spain and Portugal, although Soares et al. (2012b) showed that there are significant differences between the description of Spanish and Portuguese precipitation by RCMs. The Portuguese mainland is one of the European regions with larger spatial precipitation gradients, from the northwestern region, directly affected by the passage of Atlantic storms, to the drier southern areas. A small shift in the storm trajectories can have a major impact on the mean and daily precipitation distributions over Portugal. The European scale studies focusing on Iberia indicate that RCMs have difficulties in representing the Iberian precipitation and suggest contradictory results concerning the changes of its PDFs (Boberg et al. 2010).

Standard point error statistics and PDF matching scores (S, S90), following Boberg et al. (2010), were computed to assess the quality of the control runs and to build an ensemble. The control runs of ENSEMBLES RCMs reveal an overall reasonable representation of the mean precipitation properties and of the normalized precipitation PDFs when compared with a high quality observational gridded dataset. The control RCM results have a significant spread, and show both an overestimation of the mean precipitation and of the contribution of heavier rainfall to the total precipitation. Aiming to build a higher quality ensemble, the two best preforming RCMs in each of the four chosen "scores", comprehending bias, MAPE, S and S90 skill scores, were selected for the ensemble. This allowed the selection of 5 RCMs (ETHZ, HADC3, KNMI, SMH1 and SMH2) that equally weighted composed the average ensemble, giving as much importance to the mean precipitation as to the PDFs. The ensemble mean and these five RCMs were used to characterize the precipitation changes over Portugal in response to the A1B scenario of emissions.

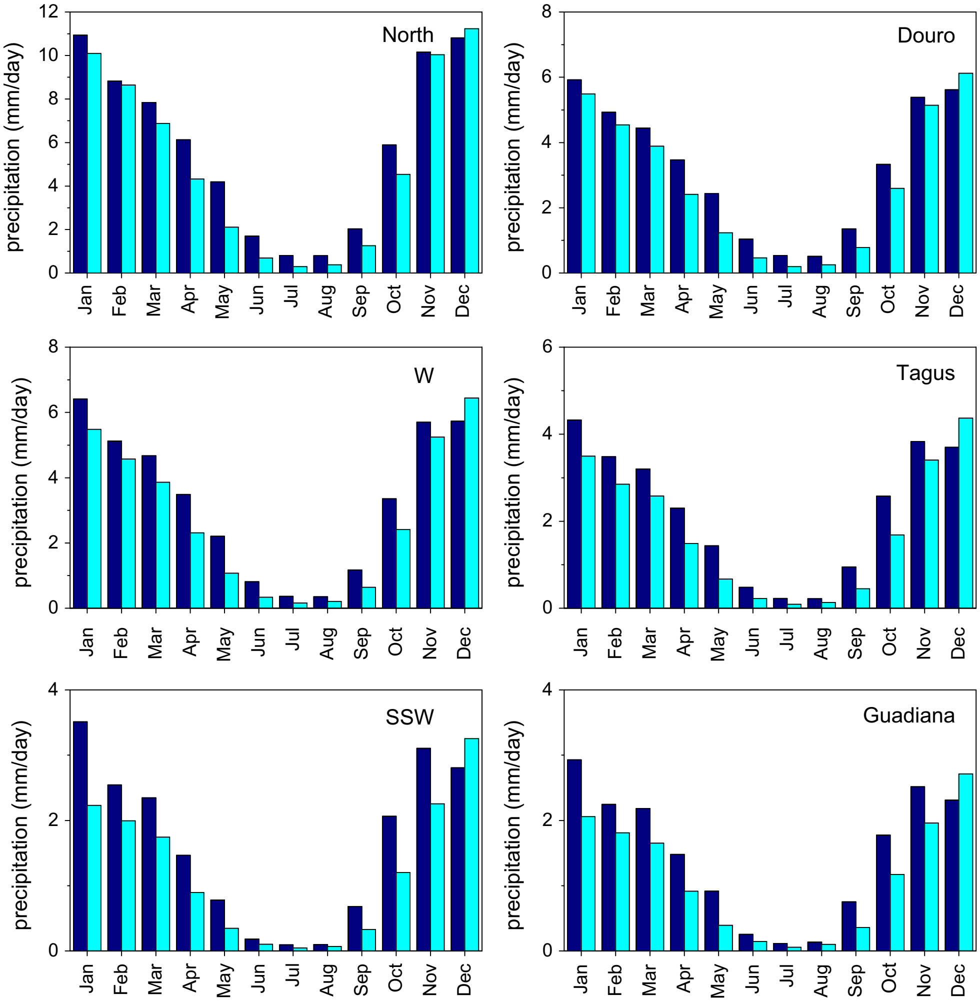

Fig. 9 Present (*blue*) and future (*cyan*) monthly mean precipitation for the six basins

For the A1B scenario, the individual RCMs and the ensemble synthetic model show an important decrease in yearly precipitation over Portugal, between 15 %, in the north, and over 30 % in the South. The precipitation decrease has a sharp seasonal dependency; values above 50 % occur in some places in summer, while precipitation diminishes above 20 and 30 %, respectively, in Autumn and Spring, across most of the Portuguese territory. In winter only a slight decrease can be seen. For Spain, Argüeso et al. (2012) showed similar rainfall reductions for annual mean precipitation, ranging from 20 to 40 %, which in summer spans between 30 and 70 %.

Concerning the precipitation PDFs, a consistent decrease of the contribution of light to moderate/high precipitation to the total precipitation was found, i.e. from precipitation bins spanning from 2 mm to 30 mm/day (90th percentile) for the ensemble synthetic model. This is in clear disagreement with the findings of Boberg et al. (2010) for Iberia, where an unchanging PDF was described. In the contrary, the contribution of higher precipitation bins to the total precipitation experiences an increase. Furthermore, the rising of the extreme precipitation quantiles (95th, 99th and 99.9th percentiles) is substantial, reaching values between 110 and 120 % when compared with present climate.

At the basin scale, a reduction in mean precipitation is accompanied by significant increases in precipitation extremes. All basins are expected to experience a precipitation reduction in all the months, with the exception of December. This month always presents a small increase of the basin precipitation values. Several summer and more importantly intermediate season months reveal, at the basin scale, rainfall reductions above 40 %. Moreover, in all basins, an amplification of heavy precipitation is noticeable, but such growth increases from North to South, i.e. from wetter to drier basins. The ensemble synthetic model points out for increases in the extreme precipitation

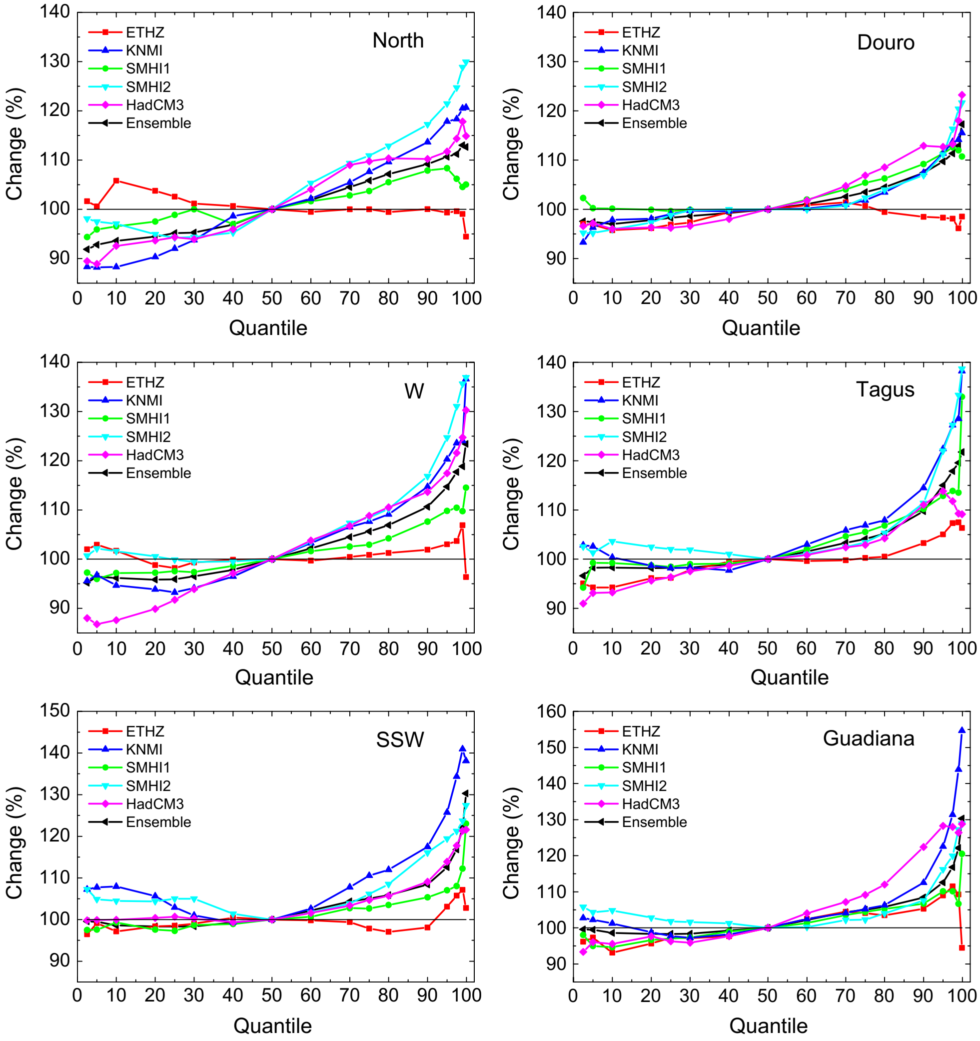

Fig. 10 As Fig. 8d for the six basins

percentiles ranging from 10 to 20 % in northern basins to 20–30 % in the southern basins.

All these results stress that future climate might be characterized by less precipitation, which is more clustered into extreme events, accentuating the vulnerability of Portuguese water cycle to global warming. These changes may have dramatic impacts on a very wide spectrum and vital sectors of Portuguese economy, like, agriculture, forestry, water supply and energy production.

Finally, it should be emphasized the significance of the results achieved for Portugal, that can constitute a general framework for comparison and basis for the assessment of the new generation of RCM simulations in the context of CMIP5 and of the new IPCC5 report. Actually, a new set of high resolution RCMs results are becoming available from the Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al. 2009).

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