Universidad Internacional Menéndez Pelayo

MASTER EN CAMBIO GLOBAL

UNIVERSIDAD INTERNACIONAL MENEDEZ PELAYO

Statistical Downscaling of Precipitation in Spain for the 21st Century Using a Multi-model Ensemble

Matías Frugone Alvarez

September 2011, Palma de Mallorca
España.

Universitat de les Illes Balears

CSIC

IMEDEA

Tesis de Máster

Statistical Downscaling of Precipitation in Spain for the 21st Century Using a Multi-model Ensemble

Matías Frugone Alvarez

Advisor: Dr. Romualdo Romero March

September 2011, Palma de Mallorca
España.

Contents

Pag.

0. Abstract.. 2

1. Introduction.. 3-5

2. Methods.. 6-9

    2.1. Study area and data.. 6
    2.2. Generation of annual and seasonal precipitation........... 6-8
    2.3. Data Analysis.. 8-9

3. Results and discussion.. 9-12

    3.1. Annual precipitation.. 9
    3.2 Seasonal precipitation.. 11

4. Summery and Conclusions.. 13-16

5. Acknowledgements.. 16

6. References.. 17-20

7. Figure Legends 21-23

8. Figures.. 24-33

Statistical Downscaling of Precipitation in Spain for the 21st Century Using a Multi-model Ensemble

Matias Frugone Alvarez[1*], Oscar Javier[2], Romu Romero[2***]**

[1]Laboratorio Internacional de Investigación del Cambio Global, LINCGlobal, [2]Grup de Meteorologia (Departament de Física), Universitst de les Illes Baleares, UIB

Received

*Corresponding author address: *Avda. Montañana, 1005. 50059 Zaragoza, Spain. E-mail: mfrugone@.csic.es, Telephone: (+34) 976 716034, Fax: (+34) 976 716019 . **Ctra. de Valldemossa, km. 7.5 07122 Palma de Mallorca, Spain., . E-mail: javier.osca@uib.es , Telephone: (+34) 971173233, Fax: (+34) 971173426. ***Ctra. de Valldemossa, km. 7.5 07122 Palma de Mallorca, SPAIN, . E-mail: Romu.Romero@uib.es, Telephone: (+34)-971173233 , Fax: (+34)-971173426

ABSTRACT: Variations in frequency and intensity of precipitation events due to Climate Change would be devastating to the socioeconomic development and ecosystems. Recent studies suggest changes in precipitation extreme events globally, but there are still many uncertainties about the effects at local and regional. Here we present an Empirical-Statistical Downscaling by the Method of Analogues for Spanish peninsula and the Baleares Islands using precipitations gridpoint of high resolution and the output of four GCM to project the ensemble mean rainfall patterns annual and seasonal for the twenty-first century. In this study, we identify important variations in the average composition of annual and seasonal precipitation. The method predicts changes of until ±6% in annual extreme precipitation events during the first 40 years in great part of the eastern and central Spain and an increase in extreme drought events of Asturias, Cantabria, Euskadi, Andalusia and the Balearic Islands during practically all century. However, the major percentage changes are found in the seasons with variation of until ±15% regarding at present climate. These changes are very important in the climate context of Spain, which certainly can not be studied only from the perspective of the annual precipitation. In this work we use only four GCMs for estimating changes in precipitation where ensemble mean error is less than the introduced by a single model. At present, understanding the inherent variability in the climate projections of precipitation are fundamental to improve the estimates for the multiple scenarios of the Global Change and estimate the effects of anthropogenic emissions of greenhouse gases on the Earth System.

KEYWORDS: Statistical Downscaling, Climate Change, Analog Model, General Circulation Models, Atmospheric Patterns, Rain Patterns

1. Introduction

The real magnitude of the human activity impacts on the Earth System is not yet completely known [*Reto Knutti and Hegerl*, 2008; *Loarie et al.*, 2009; *Matthias et al.*, 2011]. Nowadays, the planet is experimenting a fast increase of the greenhouse gases emission (GHG), unprecedented in the human history, forecasted by the Intergovernmental Panel on Climate Change (IPCC) to 900-1100 p.p.m for the end of this century, figures never seen in over 35 million years [*Breecker et al.*, 2010; *Pagani et al.*, 2005]. In any case, the global demanding of goods and services has increased gradually because of a raise in the hyper-exponential population growth rate and a change in the consumption habits, specially in countries with emerging economies, which generates even more speculations and risks of a change of no return [*Solomon et al.*, 2009; *Weitzman*, 2009]. All this leads us to an uncertain future regarding the Global Change, where all the efforts made by the scientific community are focused on evaluating forecasts, reducing uncertainties and regionalize impacts, everything is attached to a generation of better models and new emission scenario, the most important tools to estimate the effects and define the adaptation process [*Moss et al.*, 2010; *Randall et al.*, 2007].

The precipitation changes in a local and regional scale are part of the principal uncertainties by the anthropogenic modifications of the flows among the different biogeochemistry reservoirs [*Schiermeier*, 2010]. Recent evidences of a growth of extreme precipitation events in the last 50 years in the north Hemisphere, indicate that concentration of the greenhouse gases in the atmosphere, not only affects the global precipitation average, but also the frequency of the events towards the upper tail of the distribution, which would have a greater impact in a regional and local scale [*Min et al.*, 2011; *Palmer and Raisanen*, 2002; *R. P. Allan et al.*, 2010].

Unlike other atmospheric variables like temperature, precipitation is highly conditioned to physiografic characteristics [Sotillo et al., 2003], which makes the GCMs resolution (of 100 to 300km horizontal and 20 to 30 levels vertical) may not be very suitable to model precipitation scale or good enough to satisfy the requests made by different users working with this kind of information, like for example in biodiversity studies [*Araújo et al.*, 2011]. Considerable international and also national efforts have been made to get standardized methods of regionalization of atmospheric variables from the different models available. Investigation programs, like the ENSAMBLE Project in a European level (http://www.ensembles-eu.org) or the ESTCENA Project (http://www.meteo.unican.es/en/projects/esTcena) in a Spanish level, have been able to incorporate several approximations of Dynamic and Statistical Downscaling to develop a projection by ensembles system based on “state-of-the-art” global climate models (GCMs) and models of regional high resolution over Europe.

The Dynamic Downscaling technique (that refers to the differential equations development and numerical solution) runs a high resolution Regional Climate Model (RCM) of area limited high-resolution, forced with variables of a GCM as boundary condition. This method generates very good results, even when the different RCM are not independent from its boundary condition and may present bias [*Amengual et al.*, 2007; *Frei et al.*, 2006]. The Empirical-Statistical Downscaling (ESD) is based on the idea that the regional climate is conditioned by the climatic variables on a large scale (predictors) through its strong influence on the local and regional statistic variables (predictands). So the exit of the GCM simulation on a high scale introduce on statistic models to estimate the climatic characteristic of a region. This technique is subdivided in different statistic subtechniques: linear, no linear and weather generators, the choice of one or another depend of the select variability and the objectives of this study. Both techniques ESD and RCM are two independent and complementary ways to deal with the problem of regionalize the variability obtain by the GCM.

On the frame of ESD philosophy, in this work we used an Analog Method (Lorenz, 1969), who is a generalization of the Nearest Neighbored method to associate the Atmospheric Circulation pattern provide by the GCMs and reanalysis ERA-40 with pattern or distribution of rain obtained from high resolution database Spain02 (20 km.). The final result will be project the changes of precipitation all around Spain peninsula and Baleares islands for a stage emission A1B by the end of 21st century. This technique shows be very efficient to predict precipitation variability above Peninsula and Mediterraneo. [Dehn 1999; Sumner et al. 2003]. By the way, ESD have a series of limitation product of strong assumptions: (a) the statistic relation between predictors and predictands keeps the constant time; (b) predictors modulate in an efficient way the climatic change signal and (c) GCMs provide a good description of the predictor [Benestad, 2010]. We used the available database of ESTCENA project to generate the ensemble mean from different statistically standardized GCMs to project the composites of precipitation a seasonal and annual level.

The structure of this work is: One section with used dates and methods, follow by the results, an argument and a final conclusion. This work is settled on the precipitation variability in respect to 1980-1999 all around Spain except Canarias.

2. Methods

2.1. Study area and data

This work is part of the ESTCENA project, which provided all the statistically homogenized data of the different General Circulation Models (GCMs) and the remarks that made the series of daily precipitation in Spain in the 21st Century. These results were obtained by the training of the method described in the following section from the atmospheric fields of the ERA-40 reanalysis and the observations of the precipitation of high resolution Spain02 of 0,2º (20km aprox). The observation net of precipitation (Figure 1) was built from a database of 2756 interpolated stations in two faces using a binary and ordinary Kriging to generate a 1445 regular grid of observations over all the Spaniard Peninsula and the Balearic Islands [Herrera et al., 2010b].

2.2 Generation of annual and seasonal precipitation.

The method was modified from *Sumner et al., 2003* and consists in a period of training (from 1961 to 1999) where the Atmospheric Patterns (APs) of the reanalysis ERA-40 and the Rain Patterns (RPs) obtained from the Spain02 precipitation grid to generate a probability table AP-RP are standardized and classified.

The standardization of variables is made to base the patterns classification, not much on the magnitude of the geopotential fields used, but on the sort of atmospherical circulation. We use a PCA (Principal Components Analysis) to classify the APs in order to increase the technological efficiency (even when is not indispensable to the method) and a cluster analysis to group them in the euclidean space with the k-means algorithm, based on the atmospheric flow indicated by the geopotential height at 500 and 925 hPa. We have to classify every GCM according to the APs collection found for the training period, for the whether in the present and the future. The days with precipitation 0mm (predictably in a high pressure situation over the zone) are also considered to be a part of the clusters generated. The number of groups to generate was determined by the test pseudo-F [*Caliński and Harabasz*, 1974].

The APs (f_i) frequencies of the future period are compensated with a correction rate [*Sumner et al.*, 2003], calculated as:

$c_i = AP_{fi}^{ERA40} / AP_{fi}^{CGM's}$;

Such as $F_i = f_i \; c_i$;

Where F_i represents the compensated frequency, c_i is the rate of compensation AP_{fi}^{ERA40} and $AP_{fi}^{CGM's}$ are the absolute frequencies of the ERA-40 and the GCMs Atmospheric Patterns for the same present or training period respectively.

Analogously we use the Spain02 database to classify the RPs and correlate them with the APs frequencies to create the AP-RP probabilities table. This table is used to generate forecasts with future compensated APs frequencies derived from the GCMs atmospherical fields. After we obtained the AP-RP occurrence probabilities we proceed to show the RPs so the A1B scenery of emission, multiplying the probabilities origin AP-RP by the AP absolute frequency vector in the forecast time. This way, we obtain the average map of a period by getting the average of the different RP's composites, where every composite is the average of the rain cluster days, and the average is determined by the appearance probability of every RP calculated earlier from its absolute frequencies. The previous method applied in all the future period will allow to cast the annual rain and also select the precipitation frequencies for each season to get the average maps of the RPs composites to those seasons.

2.3. Data Analysis

To analyze the results we select a first period of 20 years, between 1980 and 1999, considered as analogous of the “present weather” and a series of five periods between 2000-2019; 2020-2039; 2040-2059; 2060-2079 and 2080-2099, considered as “future weather” to get the ensemble mean, the standard deviation and percentage changes regarding the present weather for the different average maps of annual and seasonal precipitation of the GCMs. In which every one is calculated as:

$m(z_{kj}) = E[z_{kj}]$;

$s(z_{kj}) = \mathrm{Std}[z_{kj}]$;

$PC_{kj}= 100 * [\ [(z_{kj})_p - (z_{kj})_f]\ /\ (z_{kj})_p\ ]$;

$m(PC_{kj})= E[PC(z_{kj})]$;

Where z_{kj} is a *regionalized variable* that represents the annual or seasonal precipitation for the period obtained with a model j in the geographic point k. The ensemble mean $m(z_{kj})$ is only the expected value of z_{kj} and $s(z_{kj})$ it’s standard deviation. The term $PC(z_{kj})$ and $m(PC_{kj})$ is the Change Percentage and it’s respective ensemble mean, where the subscript p and f indicate the present and future period, respectively.

The spatial distribution of the obtained values is represented by a Box-Plot and the percentage changes were analyzed with the Empirical Cumulative Distribution Function (CDF) in order to build a distribution of the frequencies accumulated according to the free distribution of each set of data. To validate the method, we compared the annual and seasonal precipitation predicted by the method for the period 1980-1999 with the one “observed” on the net of high resolution Spain02 precipitation.

Every data and analysis were obtained by using the MATLAB platform with the Toolbox Meteolab developed by the Santander Meteorology Group (University of Cantabria) and the Meteorology Group of the Balearic Islands University.

3. Results and discussion

3.1. Annual precipitation

The GCMs used to project the precipitation for the century 21^{st} are shown in Table 1. Every GCM is the result of a homogenization process and a statistical standardization made by the ESTCENA project to compare the output of the different models [Brands et al., 2011]. We only used 4 models from all the GCMs because they are the only available that show all the necessary atmospheric fields to make it consistent with the reanalysis.

Figure 2, shows the distribution of the annual precipitation values mean predicted by Spain02, compensated, uncompensated and the different GCMs on a net of 1445 points during the validation period (1980-1999). In general, the models values show a great variability regarding the average with many extreme and outliers values that can be classified in two groups according to the resemblance of their forecasts. One group made with the HADGEM and HADGEM2 models, that predict a lower level of distribution for the estimated annual precipitation values, this is not strange because the models are not independent. And a second group made with the

BCM2 and MPH5 models, that predict a higher level of precipitation values. For Spain, HADGEM2 and MPH5 are the models with the best performance since they present a low frequency of mistake. However this can not be generalized to other regions because not even the models with the best performance can solve all the climatic system compounds in an explicit way in a low scale [*Knutti*, 2008; *Tebaldi and Knutti*, 2007]. On the other hand, the obtained values with the non compensated models present some standard deviation higher than the compensated models. The effect to compensate, based in the reconciliation of the GCMs, with the reanalysis in present climate, supposes indeed a reduction of the disagreement between models along the future climate.

Figure 3 and Figure 4 shows the spatial distribution of the annual precipitation from the ensemble and its deviations for the different periods, these values are not significantly different to the precipitation values calculated to the present climate. Otherwise, the distribution of the typical diversions of annual precipitation obtained for Spain with compensated method show smaller values than the predicted by non compensated models, specially at the east of Spain, Galicia and areas of high mountains, where the diversions can reach the 50 mm, this means that the composites of the RPs to every model are different from each other in this points. This diversions should decrease when adding to the ensemble the precipitation estimated by the additional models not considered in this study.

Figure 5b compares annual precipitation percentage changes from different periods to 1980-1999. The *Empirical cumulative distribution function* (CDF) for the first percentage change accumulated (blue line), shows a great increase of the positives percentage values, even though the highest value does not exceed the 6%, they predict more rainy years with respect to the present climate. However, at the end of the century this situation reversed in favor of the accumulated negative percentage changes up to a 30% with respect to the other future periods. This means dryer years than in the present, while the positive percentage changes decrease gradually on 2020-2039 to become a level of percentage changes “0”.

Figure 5a shows the maps of percentage changes for the GCMs compensated, where the most affected zones since the first forth decades of the 21st century experiment an increase to 4% to 6% in relation to the present, specially in Extremadura, great part of Andalucía, Castilla la mancha and the Madrid Community.

The areas that experiment the most negatives percentages (~- 4%) are the Valencian Community and in a minor way Cantabria, Euskadi and Navarra. In the middle of the 21st century the percentage changes tend to 0, although they keep the negative value near to –4% in Cantabria, Euskadi and Navarra. We expect that during the last decades of the 21st century, the percentage changes increase mostly in west Andalucía, Asturias, Cantabria, Euskadi, Navarra and Baleares with negative values near to –5% in Galicia, Castile and Leon, Aragón, south zone of Extremadura y Castilla la Mancha and Valenciana community we expect percentage changes of 5%.

3.2. Seasonal precipitation

The values predicted for some of the year seasons are higher in magnitude than the predicted for the annual precipitation, mostly in the CDFs, these differences are because in Spain the seasonal precipitation present a remarked regime, characterized by months of the year very rainy and a long periods with none or very little precipitation. The CDFs for the four seasons of the year show on Figure 6b and 6c where the higher negative percentage changes occur during summer and spring seasons with values that reach -15 %. For the spring seasons, a big number of droughts are predicted less though than the ones forecasted for the summer seasons. Otherwise, on figure 6c we observe a more rainy tendency at the end of the century, with percentage changes up to 10%, mostly in the accumulated frequencies of higher changes to 5%, which indicates more extreme rains compared to the present. On the other hand, the forecasts for the autumn seasons on the first 40 years of the 21st Century foresee an increase in rains, similar to the percentage changes forecasted for winters at the end of the century, to later change the drought tendency to a -9%.

In a regional level, the most affected zones by negative changes of precipitation during spring seasons at the end of the century are Andalucía, Murcia and Baleares, with variations between a 5 or 6% (Fig. 8). In summer, the higher negative precipitation changes are observed in Galicia and Menorca with lower variations of –12% and positive precipitation changes in the centre of Spain with variations of 5% (Fig. 9). In winter the higher negative changes are in Asturias, Cantabria and Euskadi and the higher positive percentage variation are forecasted in a great part of the east of the peninsula like Murcia and the Valencian Community (Fig.7). For the autumn seasons not many variations are expected at the end of the century, only during the first 40 years where precipitation changes follow a similar pattern to estimated changes in winter with positive percentage variations of 10% in Galicia and the east of Castile and Leon (Fig. 10).

4. Summary and conclusions

In this work we associate the Atmospheric Circulation Patterns got from the different GCMs to the typical Spanish Rain Patterns to obtain a regionalization of the precipitation in a A1B emission's scenery. The consequences of the Climate Change on the precipitation allow the forecast of two conflicting effects in a regional level. In one hand, the method indicates an increase of the annual precipitation in the next 40 years in a great part of the east and central Spain, this tendency decreases towards the end of century, only the east of Castile and León, south of Extremadura and a few areas of the Valencian Community and Aragón remain the same. And in the other hand the method points towards a decrease of the annual precipitation mostly in Asturias, Cantabria and Euskadi that remain the same during the 21st Century. Specially in the last decades, where the drought periods are intensified at the same time as the precipitation are progressively reducing in other areas of Spain, such as the west of Andalusia and the Balearic Island. For the annual seasons, more abrupt changes are forecasted to the end of the Century in the winter precipitation, increasing considerably in regions like Galicia the entire occidental border of Spain. Is also forecasted more intense summer droughts, mostly in Galicia west of Balearic Islands. Further more, is remarkable that the method shows an increase of the extreme events of precipitation during the summer seasons in the center of the Penynsula, and a general decrease in the rain frequencies during autumns and springs.

In Spain, the climate variability and predictability of the precipitation on regional scale is crucial to show the economic social energetic and environmental development under a scenery of Global Change. Is also one of the variables where the models differ more in their predictions in a global or regional level, this is because it is not spread in a homogeneous way over the territory and depend mostly on climatic and orographic characteristics of every area. The method's possibility to predict the varieties of the annual and seasonal precipitation on regional scale associated to changes in the atmospherical circulation in the low troposphere is thanks to the Spain02 high resolution precipitation database. This makes possible the reduction of our estimation rates to obtain a consistent forecast according to the different GCMs. However, we are now only considering four GCMs, which clearly limits our conclusions, since the "ensemble mean" like the diffusion in models or uncertainty vary according to the number of inputs we use. Therefore, is necessary to add all the GCMs available in the future to improve the estimate and delimit the associated error. Besides, it would be interesting to incorporate stochastic variations when generating the rain patterns (e.g. Weather Generators) which give us the possibility to associate the precipitation to other determined atmospheric variables such as temperature, humidity or wind speed, this will improve our prediction verisimilitude and uncertainty for sure.

Finally, since the Weather Generators can also be used to obtain daily rain maps, they would make a powerful tool to attend to the different areas, and to the specialists evaluating the impact of the climate change, associated to temporary high frequency phenomenon. In this work we associate the Atmospheric Circulation Patterns got from the different GCMs to the typical Spanish Rain Patterns to obtain a regionalization of the precipitation in a A1B emission's scenery. The consequences of the Climate Change on the precipitation allow the forecast of two conflicting effects in a regional level. In one hand, the method indicates an increase of the annual precipitation in the next 40 years in a great part of the east and central Spain, this tendency decreases towards the end of century, only the east of Castile and León, south of Extremadura and a few areas of the Valencian Community and Aragón remain the same. And in the other hand the method points towards a decrease of the annual precipitation mostly in Asturias, Cantabria and Euskadi that remain the same during the 21^{st} Century. Specially in the last decades, where the drought periods are intensified at the same time as the precipitation are progressively reducing in other areas of Spain, such as the west of Andalusia and the Balearic Island. For the annual seasons, more abrupt changes are forecasted to the end of the Century in the winter precipitation, increasing considerably in regions like Galicia the entire occidental border of Spain. Is also forecasted more intense summer droughts, mostly in Galicia west of Balearic Islands. Further more, is remarkable that the method shows an increase of the extreme events of precipitation during the summer seasons in the center of the Penynsula, and a general decrease in the rain frequencies during autumns and springs.

In Spain, the climate variability and predictability of the precipitation on regional scale is crucial to show the economic social energetic and environmental development under a scenery of Global Change. Is also one of the variables where the models differ more in their predictions in a global or regional level, this is because it is not spread in a homogeneous way over the territory and depend mostly on climatic and orographic characteristics of every area. The method’s possibility to predict the varieties of the annual and seasonal precipitation on regional scale associated to changes in the atmospherical circulation in the low troposphere is thanks to the Spain02 high resolution precipitation database. This makes possible the reduction of our estimation rates to obtain a consistent forecast according to the different GCMs. However, we are now only considering four GCMs, which clearly limits our conclusions, since the “ensemble mean” like the diffusion in models or uncertainty vary according to the number of inputs we use. Therefore, is necessary to add all the GCMs available in the future to improve the estimate and delimit the associated error. Besides, it would be interesting to incorporate stochastic variations when generating the rain patterns (e.g. Weather Generators) which give us the possibility to associate the precipitation to other determined atmospheric variables such as temperature, humidity or wind speed, this will improve our prediction verisimilitude and uncertainty for sure.

Finally, since the Weather Generators can also be used to obtain daily rain maps, they would make a powerful tool to attend to the different areas, and to the specialists evaluating the impact of the climate change, associated to temporary high frequency phenomenon.

Acknowledgements

We acknowledge the CGL2008-01271/CLI (MEDICANES) Spanish project, which is partially supported with FEDER funds; and the ESTCENA project (Exp. 200800050084078), an strategic action from Plan Nacional de I+D+i 2008-2011 funded by Spanish Ministry of Medio Ambiente y Medio Rural y Marino. This study is part of research program sponsored by the CSIC-PUC International Laboratory for Global Change (LINC-Global).

REFERENCES

Amengual, A., R. Romero, V. Homar, C. Ramis, and S. Alonso (2007), Impact of the lateral boundary conditions resolution on dynamical downscaling of precipitation in mediterranean spain, *Climate Dynamics*, *29*(5), 487-499.

Araújo, M. B., D. Alagador, M. Cabeza, D. Nogués-Bravo, and W. Thuiller (2011), Climate change threatens European conservation areas, *Ecology Letters*, *14*(5), 484-492.

Benestad, R. (2010), Downscaling precipitation extremes, *Theoretical and Applied Climatology*, *100*(1), 1-21.

Brands, S., S. Herrera, D. San-Martín, and J. Gutiérrez (2011), Validation of the ENSEMBLES global climate models over southwestern Europe using probability density functions, from a downscaling perspective, *Climate Research*, *48*(2-3), 145-161.

Breecker, D. O., Z. D. Sharp, and L. D. McFadden (2010), Atmospheric CO2 concentrations during ancient greenhouse climates were similar to those predicted for A.D. 2100, *Proceedings of the National Academy of Sciences*, *107*(2), 576-580.

Caliński, T., and J. Harabasz (1974), A dendrite method for cluster analysis, *Communications in Statistics*, *3*(1), 1-27.

Dehn, M. (1999), Application of an analog downscaling technique to the assessment of future landslide activity--a case study in the Italian Alps, *Climate Research*, *13*(2), 103-113.

Frei, C., R. Schöll, S. Fukutome, J. Schmidli, and P. L. Vidale (2006), Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models, *J. Geophys. Res.*, *111*, D06105, 1-22.

Herrera, S., L. Fita, J. Fernández, and J. M. Gutiérrez (2010a), Evaluation of the mean and extreme precipitation regimes from the ENSEMBLES regional climate multimodel simulations over Spain, *J. Geophys. Res.*, *115*(D21), D21117, 1-13.

Herrera, S., J. M. Gutiérrez, R. Ancell, M. R. Pons, M. D. Frías, and J. Fernández (2010b), Development and analysis of a 50-year high-resolution daily gridded precipitation dataset over Spain (Spain02), *International Journal of Climatology*, 1-19.

Knutti, R. (2008), A review of uncertainties in global temperature projections over the twenty-first century, *J. Clim.*, *21*, 2651-2663.

Knutti, R., and G. C. Hegerl (2008), The equilibrium sensitivity of the Earth's temperature to radiation changes, *Nature Geosci*, *1*(11), 735-743.

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly (2009), The velocity of climate change, *Nature*, *462*(7276), 1052-1055.

Matthias, G., W.Schmidt, A. Lorenz, H. Held, and E. Kriegler (2011), Climate targets under uncertainty: challenges and remedies, *Climatic Change*, *104*, 783–791.

Min, S.-K., X. Zhang, F. W. Zwiers, and G. C. Hegerl (2011), Human contribution to more-intense precipitation extremes, *Nature*, *470*, 378-381.

Moss, R. H., et al. (2010), The next generation of scenarios for climate change research and assessment, *Nature*, *463*(7282), 747-756.

Pagani, M., J. C. Zachos, K. H. Freeman, B. Tipple, and S. Bohaty (2005), Marked Decline in Atmospheric Carbon Dioxide Concentrations During the Paleogene, *Science*, *309*(5734), 600-603.

Palmer, T. N., and J. Raisanen (2002), Quantifying the risk of extreme seasonal precipitation events in a changing climate, *Nature*, *415*(6871), 512-514.

R. P. Allan, B. J Soden, V. OJohn, W. Ingram, and a. P. Good (2010), Current changes in tropical precipitation, *Environmental Research Letters, 5*, 1-7.

Randall, D. A., et al. (2007), Cilmate Models and Their Evaluation. 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 [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. edited, pp. 589-662, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Romero, R., G. Sumner, C. Ramis, and A. Genoves (1999a), A Classification Of The Atmospheric Circulation Patterns Producing Significant Daily Rainfall In The Spanish Mediterranean Area, Wiley, Chichester, *Int. J. Climatol*., 19, 765–785.

Romero, R., C. Ramis, A. Guijarro J, and G. Sumner (1999b), Daily rainfall affinity areas in Mediterranean Spain, *International Journal of Climatology, 19*(5), 557-578.

Schiermeier, Q. (2010), The real holes in climate science, *Nature, 463*, 284-287.

Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein (2009), Irreversible climate change due to carbon dioxide emissions, *PNAS, vol. 106*(6), 1705-1709.

Sotillo, M. G., C. Ramis, R. Romero, S. Alonso, and V. Homar (2003), Role of orography in the spatial distribution of precipitation over the Spanish Mediterranean zone, *Climate Research, 23*(3), 247-261.

Sumner, G. N., R. Romero, V. Homar, C. Ramis, S. Alonso, and E. Zorita (2003), An estimate of the effects of climate change on the rainfall of Mediterranean Spain by the late twenty first century, *Climate Dynamics, 20*(7), 789-805.

Tebaldi, C., and R. Knutti (2007), The use of the multi-model ensemble in probabilistic climate projections, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1857), 2053-2075.

Weitzman, M. (2009), On modeling and interpreting the economics of catastrophic climate change, *Rev. Econ. Stat*, 1, 1-19.

Figure Legends

Table 1. Overview of the GCMs used in this study for the scenario A1B and list of variables available for the geopotential heights. The 12 models corresponds to the IPCC-AR4 model versions , whereas BCCR-BCM2, CNCM-CM3, METO-HCHadGEM, MPI-ECHAM5 and METO-HCHadGEM2 correspond to the new versions available developed within the ENSEMBLES project (*S. Brands et. al*, 2010 modified.).

Figure 1. Study area, basin names and number of grid points are as follows: 1, Catalana (57 grid points); 2, North (178 grid points); 3, Duero (225 grid points); 4, Tajo (150 grid points); 5, Guadiana (159 grid points); 6, Guadalquivir (163 grid points); 7, South (59 grid points); 8, Segura (56 grid points); 9, Levante (127 grid points); 10, Ebro (234 grid points); 11, Baleares (37 grid points). (*S. Brands et. al*, 2010 modified.)

Figure 2. Box Plot of Ensemble Mean precipitation in all 1445 gridpoints during the validation period (1980–1999) for observed data, calibrated, uncalibrated and the four GCMs developed by the ENSEMBLES project.

Figure 3. Spatial distribution of the ensemble means of annual precipitation for CGMs. Periods compensated (a) and uncompensated (d): 1980-1999; 2000–2019; 2020–2039; 2040–2059; 2060–2070; 2080-2099.

Figure 4. Spatial distribution of the Standard Deviation of annual precipitation for CGMs. Periods compensated (a) and uncompensated (d): 1980-1999; 2000–2019; 2020–2039; 2040–2059; 2060–2070; 2080-2099.

Figure 5. Percentage changes of the annual precipitation. (a) Spatial distribution and (b) Empirical Cumulative Distribution Function (CDF) of the data compensated. Periods: 1980/99-2000/19 (blue line); 1980/99-2020/39 (light blue line); 1980/99-2040/59 (green line); 1980/99-2060/70 (yellow line); 1980/99-2080/99 (red line).

Figure 6. Empirical cumulative distribution function (CDF) for the percentage changes in seasonal rainfall; (a) winter, (b) spring, (c) summer, (d) autumn. Periods: 1980/99-2000/19 (blue line); 1980/99-2020/39 (light blue line); 1980/99-2040/59 (green line); 1980/99-2060/70 (yellow line); 1980/99-2080/99 (red line).

Figure 7. Winter precipitation for Spain. (a) Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999.

Figure 8. Spring precipitation for Spain. (a) Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999.

Figure 9. Sumner precipitation for Spain. (a) Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999.

Figure 10. Autumn precipitation for Spain: (a) Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999

1

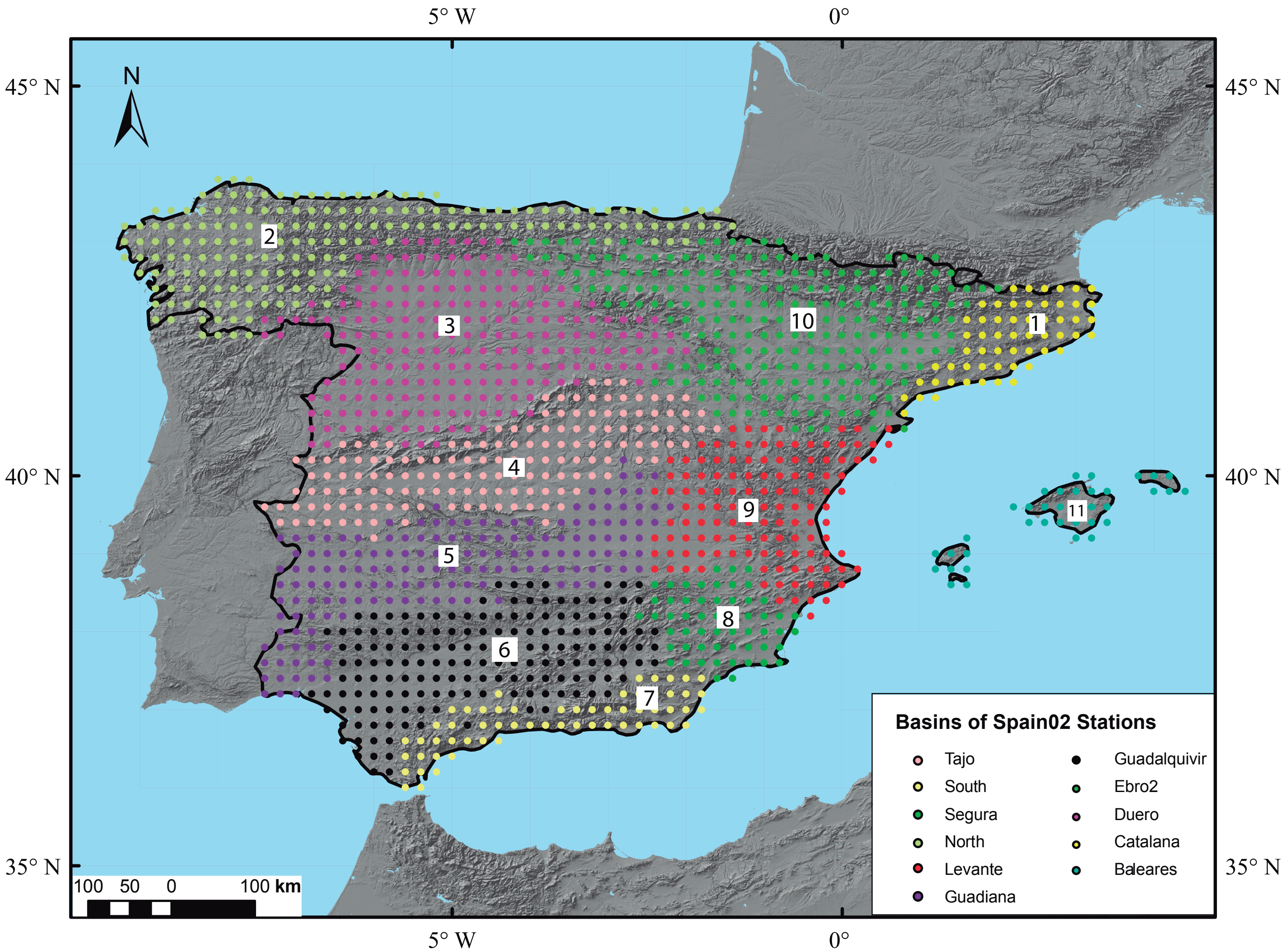


Figure. 1. Study area, basin names and number of grid points are as follows: 1, Catalana (57 grid points); 2, North (178 grid points); 3, Duero (225 grid points); 4, Tajo (150 grid points); 5, Guadiana (159 grid points); 6, Guadalquivir (163 grid points); 7, South (59 grid points); 8, Segura (56 grid points); 9, Levante (127 grid points); 10, Ebro (234 grid points); 11, Baleares (37 grid points). (S. Brands et. al, 2010 modified.)

GCM	Name Acronym	Institution	Information	Z850	Z700	Z500	Z950
BCCR-BCM2*	BCM2	Bjerknes Institute of Climate Res.	Drange 2006	x	x	x	x
CNCM-CM3*	CNCM3	Centre National de Recher. Mét.	Royer 2006	x	x	x	x
ECHO-G	EGMAM	Freie Universität Berlin	Niehörster 2008		x	x	
IPSL-CM4	IPCM4	Institute Pierre Simon Laplace	Dufresne 2007		x	x	
METO-HCHadGEM*	HADGEM	Hadley Centre	Johns 2008		x	x	
MPI-ECHAM5*	MPEH5	Max Planck Institut	Roeckner 2007		x	x	
CNCM-CM33	CNCM33	Centre National de Recher. Mét.	Royer 2008		x	x	
ECHO-G2	EGMAM2	Freie Universität Berlin	Huebener 2008		x	x	
IPSL-CM4v2	IPCM4V2	Institute Pierre Simon Laplace	Dufresne 2009		x	x	
METO-HCHadCM3C	HADCM3C	Hadley Centre	Johns 2009a	x	x	x	
METO-HCHadGEM2*	HADGEM2	Hadley Centre	Johns 2009b	x	x	x	
MPI-ECHAM5C	MPEH5C	Max Planck Institut	Roeckner 2008		x	x	x

(*):Versions statistically standardizer by the ESTCENA project.

Table 1. Overview of the GCMs used in this study for the scenario A1B and list of variables available for the geopotential heights. The 12 models corresponds to the IPCC-AR4 model versions, whereas BCCR-BCM2, CNCM-CM3, METO-HCHadGEM, MPI-ECHAM5 and METO-HCHadGEM2 correspond to the new versions available developed within the ENSEMBLES project (S. Brands et. al, 2010 modified.).

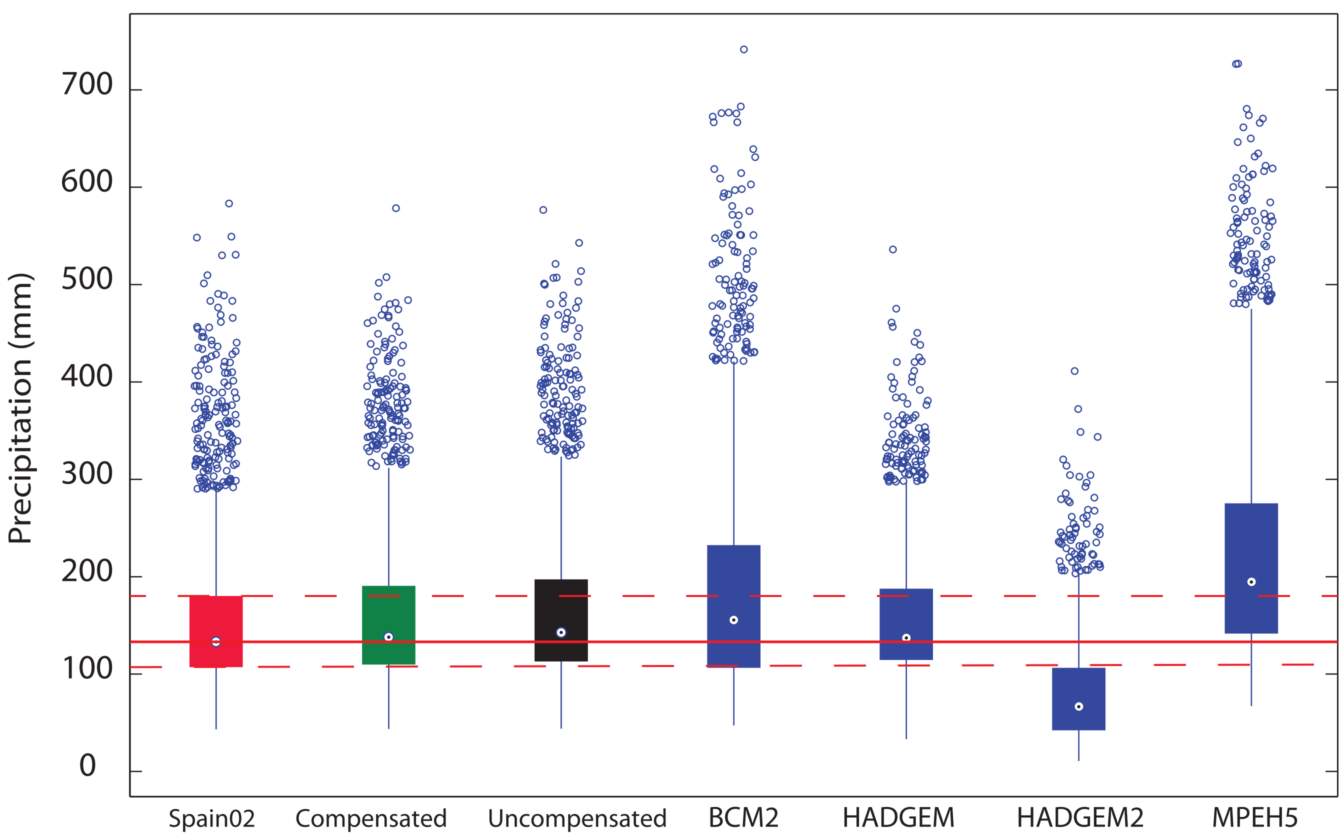


Figure. 2 Box Plot of Ensemble Mean precipitation in all 1445 gridpoints during the validation period (1980–1999) for Observed data, Compensated, Uncompensated and the four GCMs developed by the ENSEMBLES project.

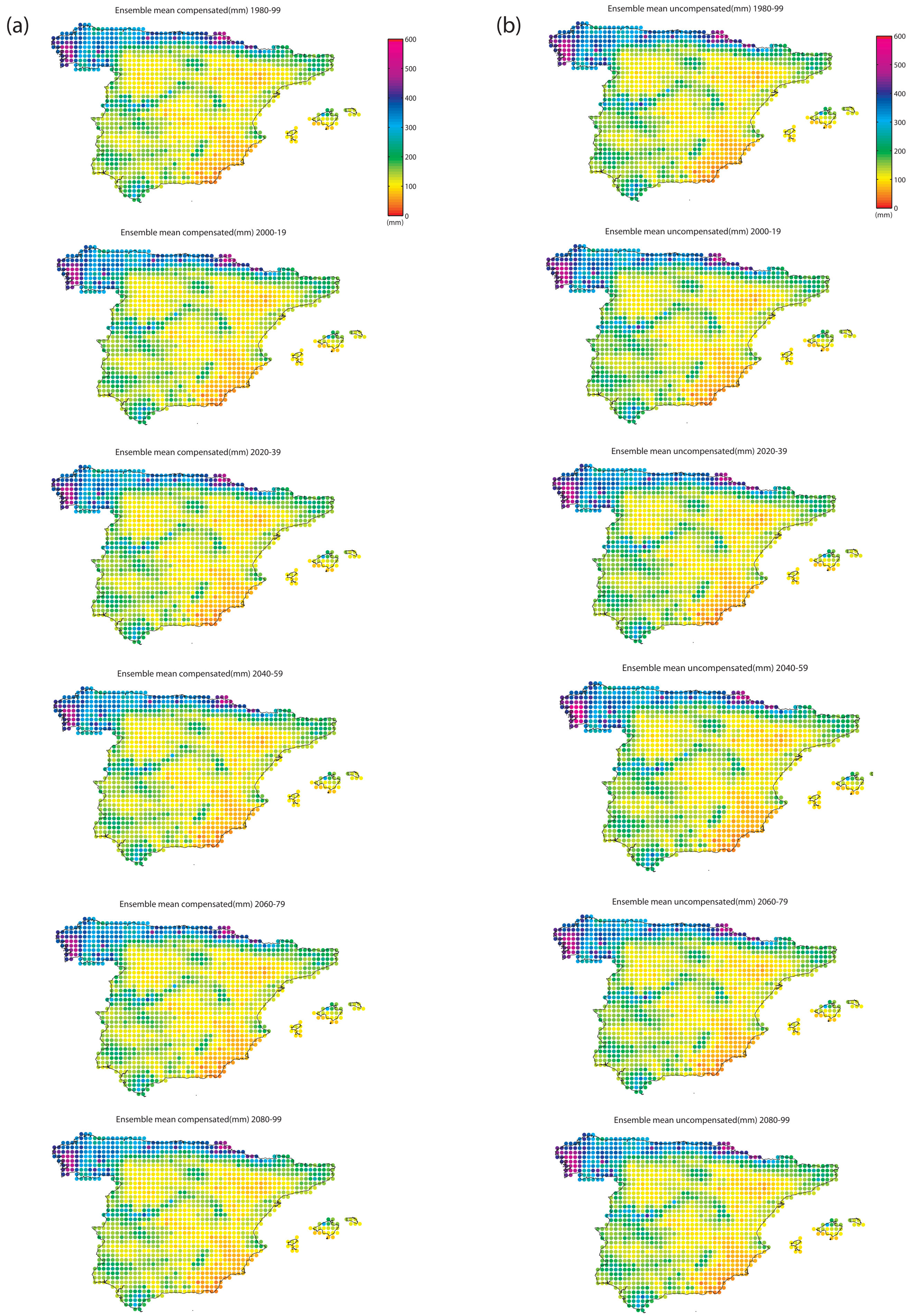


Figure. 3. Spatial distribution of the ensemble means of annual precipitation for CGMs. Periods Compensated (a) and Uncompensated (d): 1980-1999; 2000–2019; 2020–2039; 2040–2059; 2060–2070; 2080-2099.

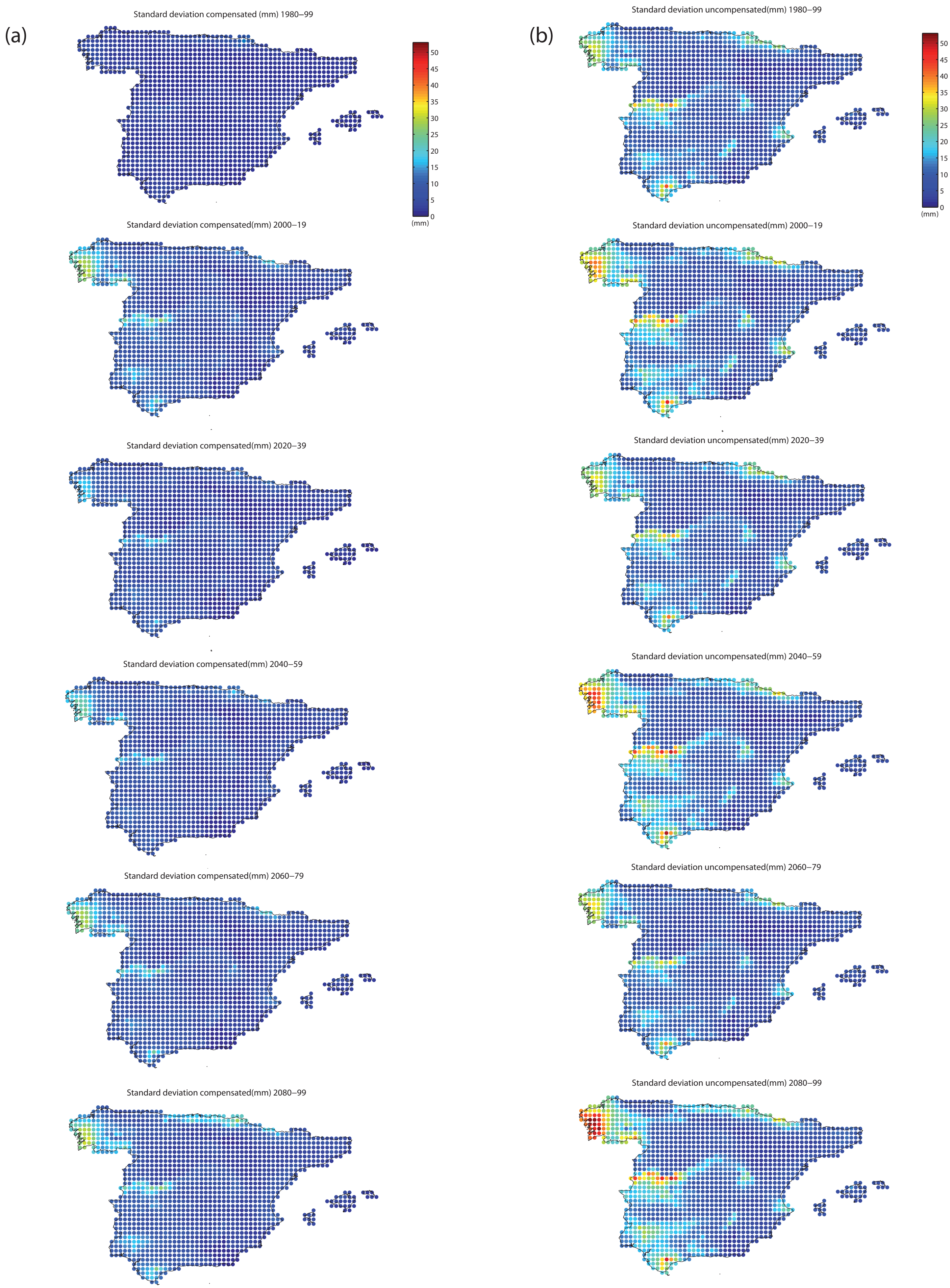


Figure. 4. Spatial distribution of the Standard Deviation of annual precipitation for CGMs. Periods Compensated (a) and Uncompensated (d): 1980-1999; 2000–2019; 2020–2039; 2040–2059; 2060–2070; 2080-2099.

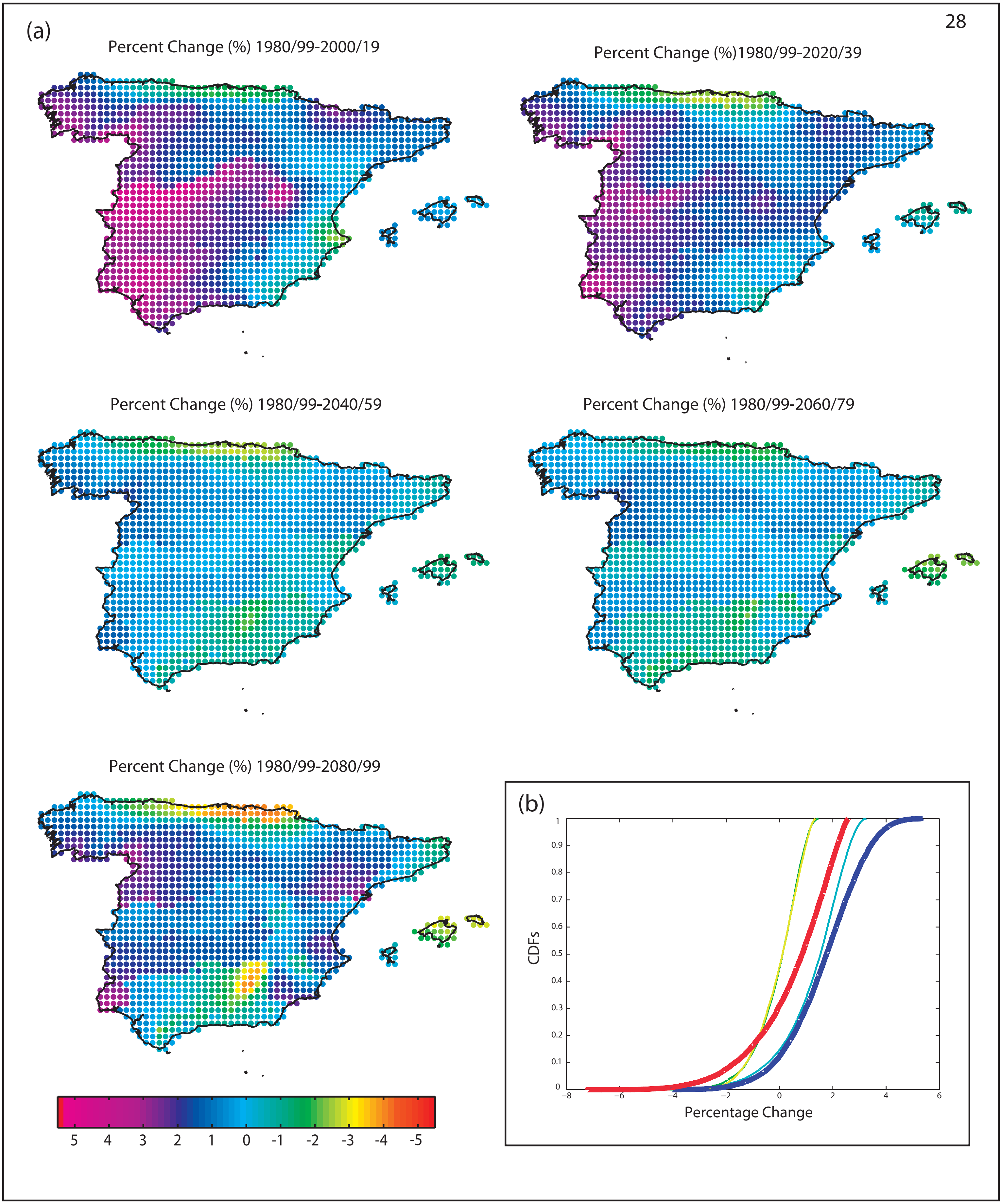


Figure. 5. Percentage changes of the annual precipitation. (a) Spatial distribution and (b) Empirical Cumulative Distribution Function (CDF) of the data Compensated. Periods: 1980/99-2000/19 (blue line); 1980/99-2020/39 (light blue line); 1980/99-2040/59 (green line); 1980/99-2060/70 (yellow line); 1980/99-2080/99 (red line).

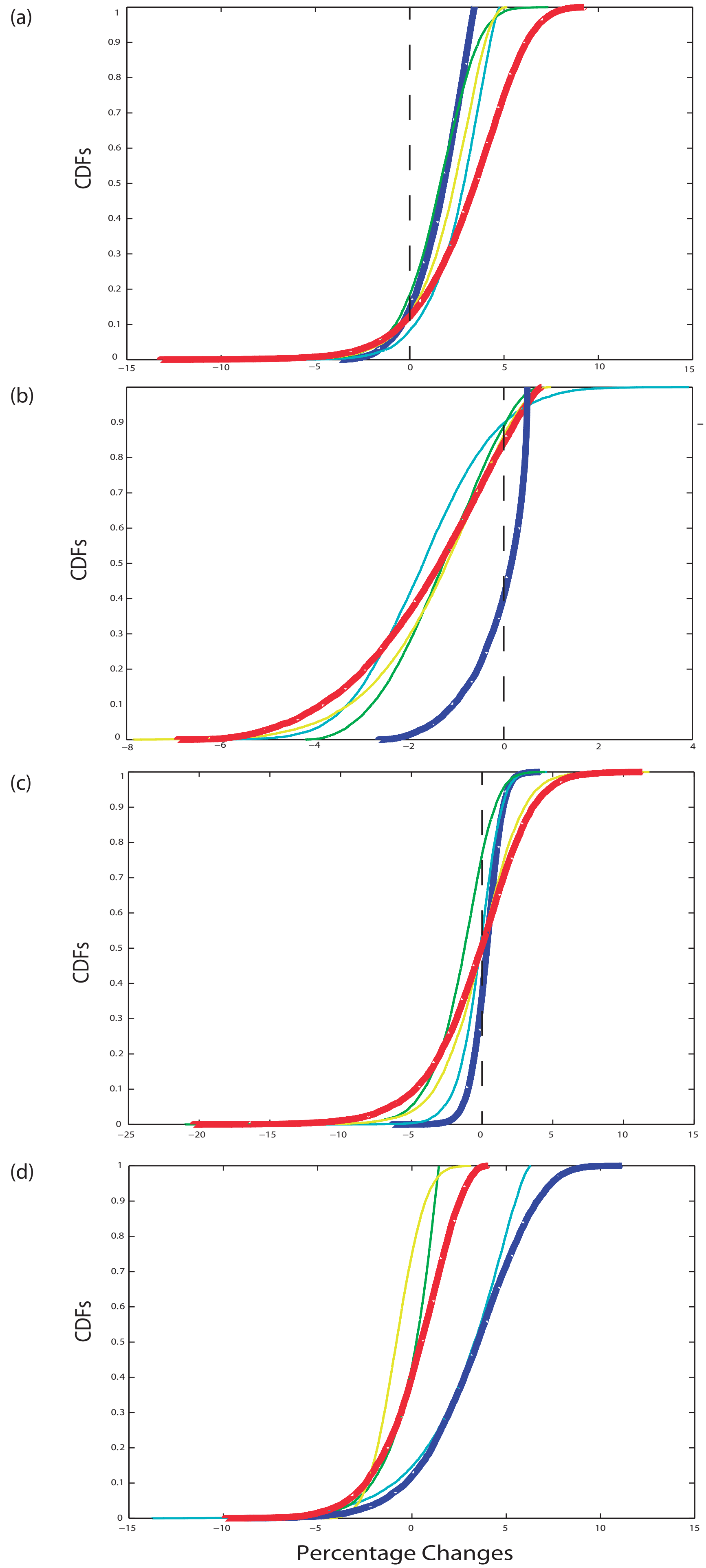


Figure. 6. Empirical cumulative distribution function (CDF) for the percentage changes in seasonal rainfall; (a) winter, (b) spring, (c) summer, (d) autumn. Periods: 1980/99-2000/19 (blue line); 1980/99-2020/39 (light blue line); 1980/99-2040/59 (green line); 1980/99-2060/70 (yellow line); 1980/99-2080/99 (red line).

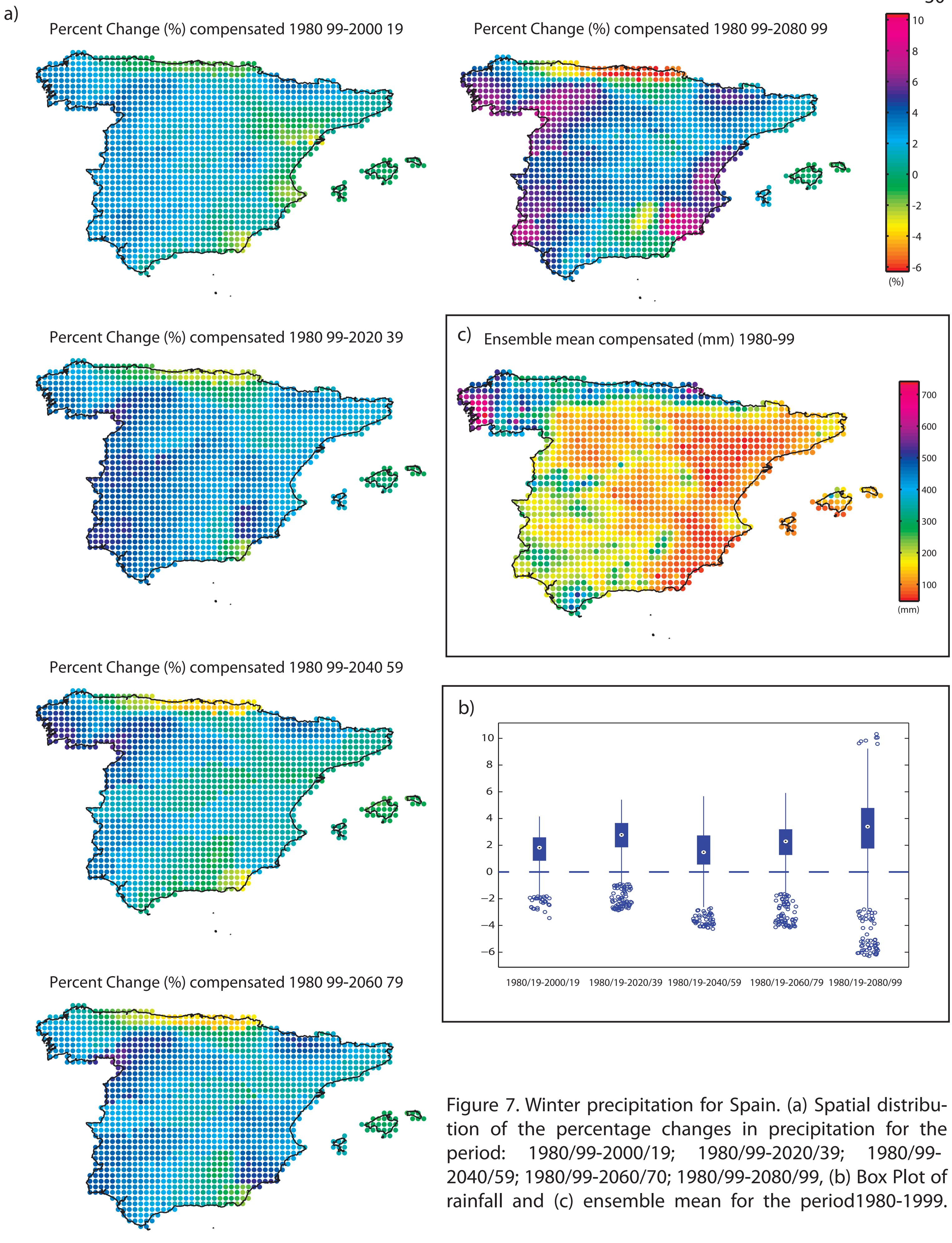
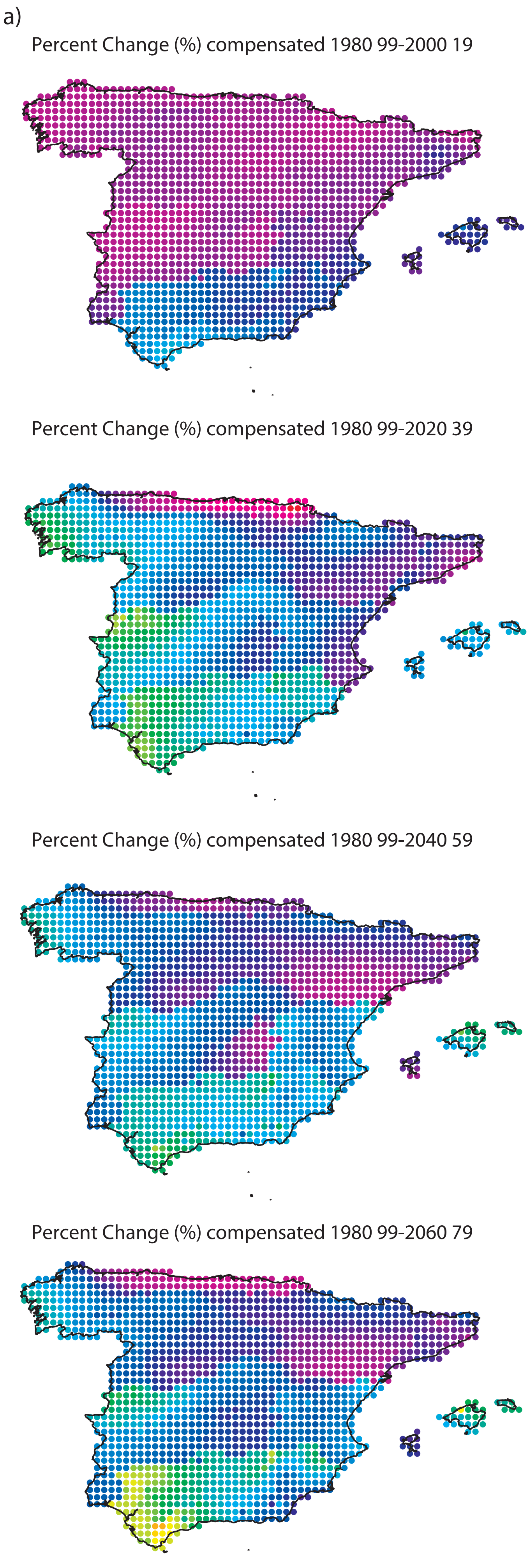
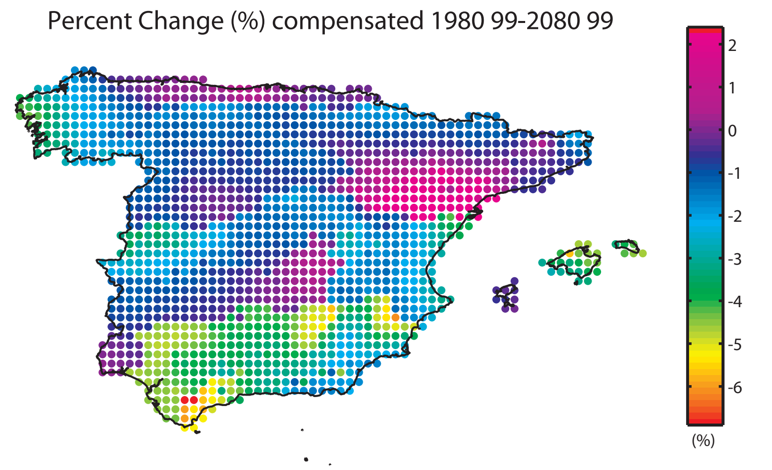
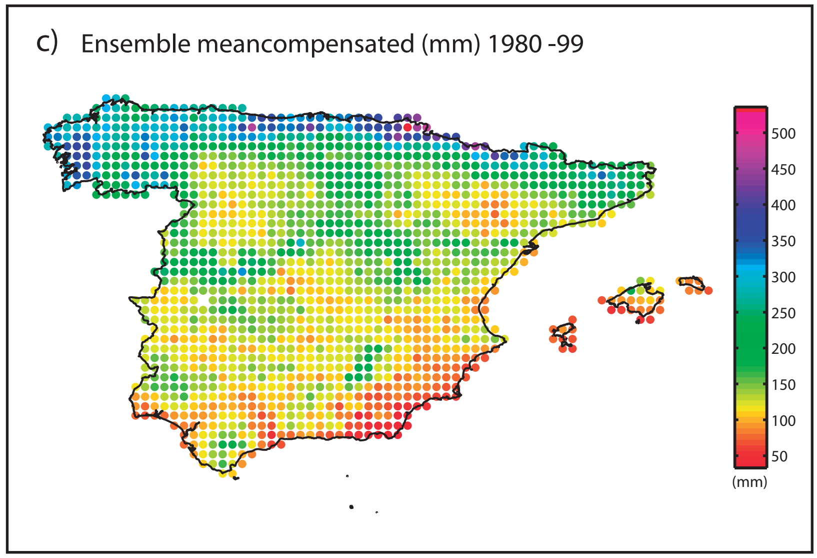


Figure 7. Winter precipitation for Spain. (a) Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999.







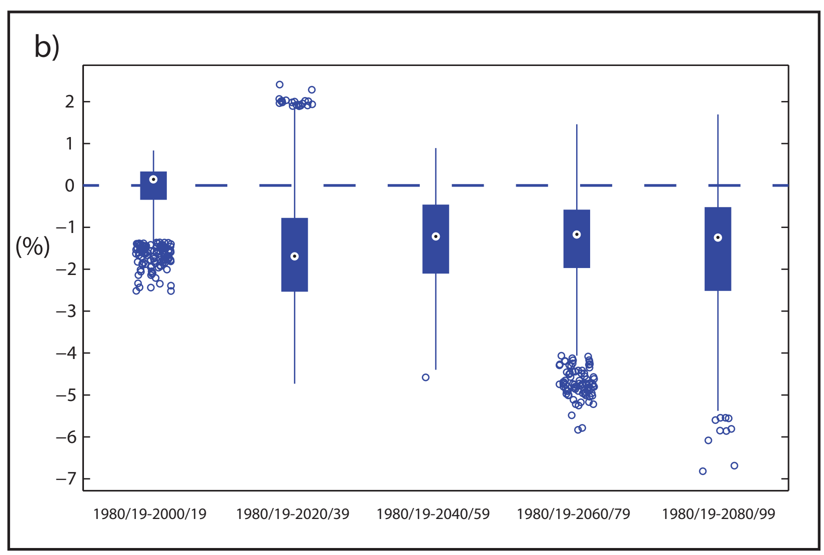


Figure 8. Spring precipitation for Spain. (a) Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999.

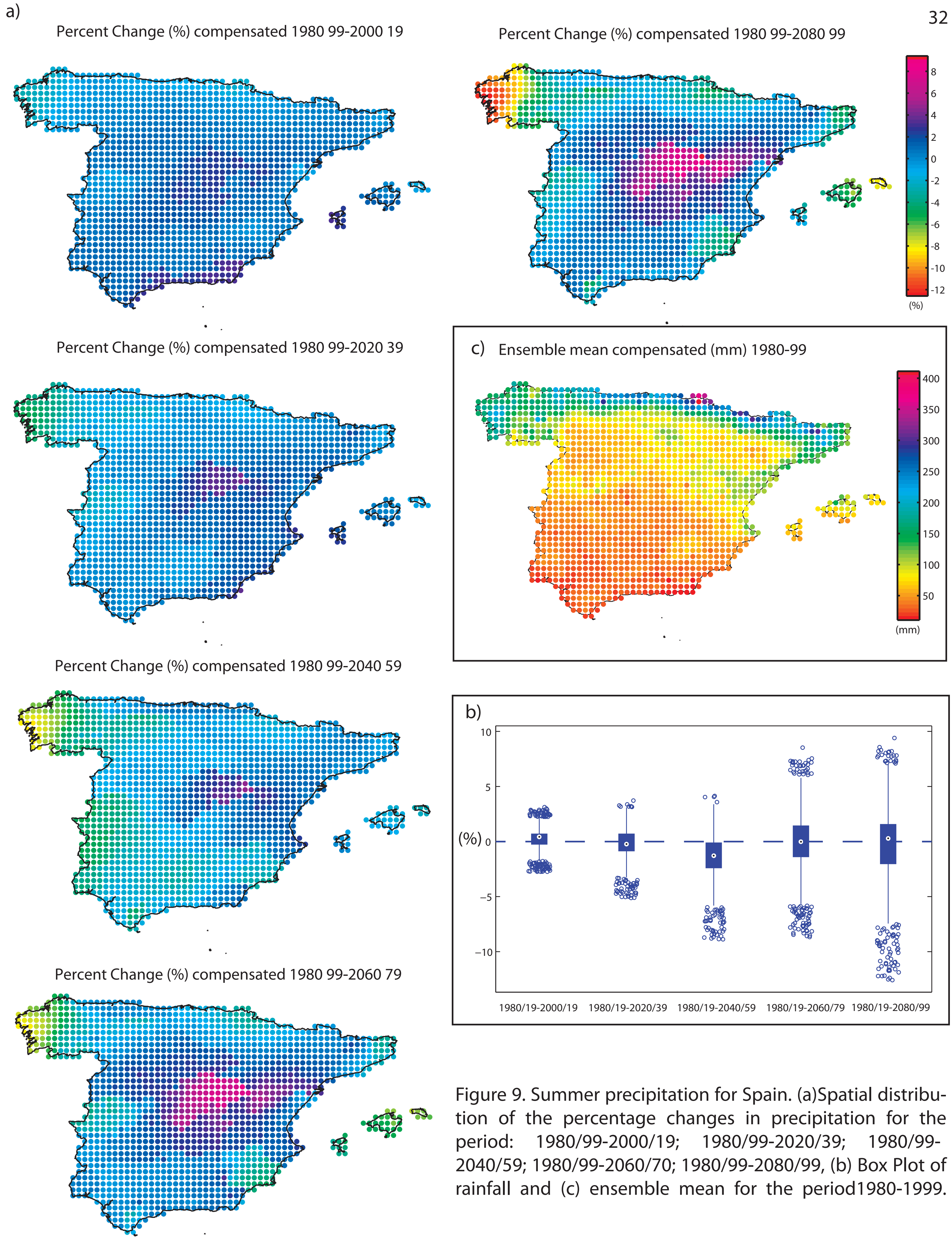
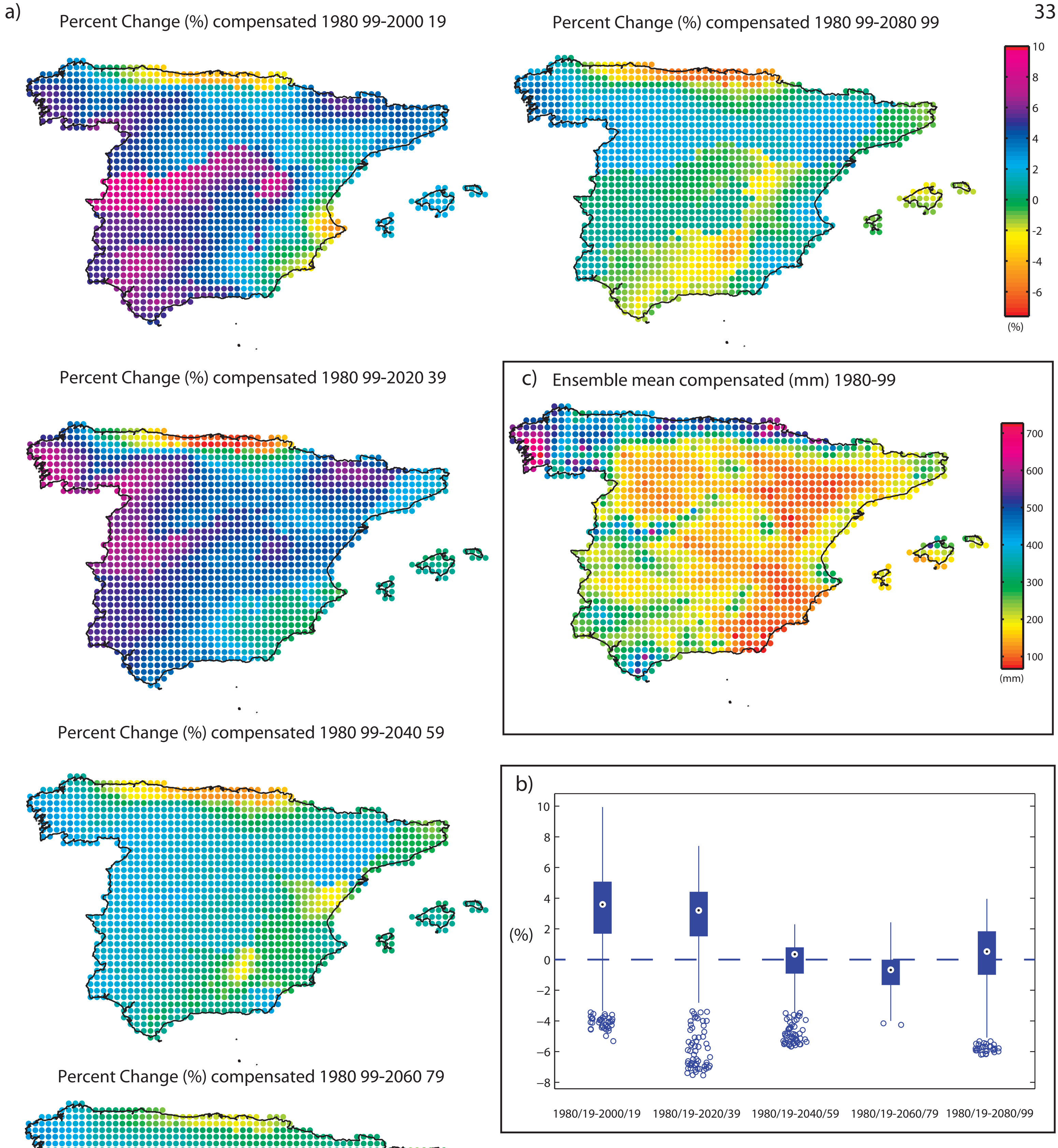


Figure 9. Summer precipitation for Spain. (a)Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999.



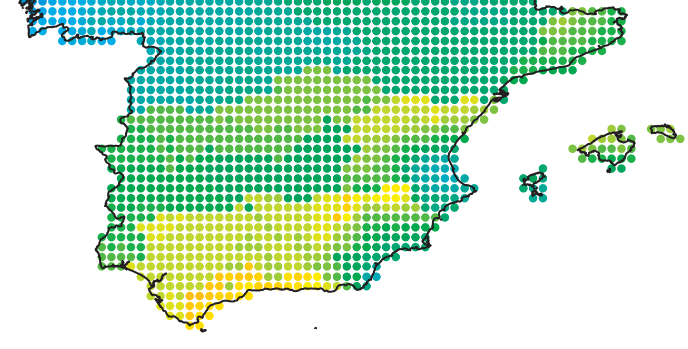


Figure 10. Autumn precipitation for Spain: (a) Spatial distribution of the percentage changes in precipitation for the period: 1980/99-2000/19; 1980/99-2020/39; 1980/99-2040/59; 1980/99-2060/70; 1980/99-2080/99, (b) Box Plot of rainfall and (c) ensemble mean for the period1980-1999.