Robust inferences on climate change patterns of precipitation extremes in the Iberian Peninsula

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Abstract

This work presents a methodology to make robust inferences on climate change from an ensemble of model simulations. This methodology is used to assess climate change projections and associated uncertainties of Iberian daily-total precipitation from a reference past climate (1961 – 1990) to a near-future (2021 – 2050) and distant-future (2069 – 2098) climates. Precipitation changes are estimated for annual and seasonal total amounts, and for some extreme indices. Daily-total data was obtained from the multi-model ensemble of fifteen Regional Climate Model (RCM) simulations provided by the European project ENSEMBLES. These RCMs were driven by boundary conditions imposed by Global Climate Models that ran under historic conditions from 1961 to 2000, and under the A1B scenario, from 2001 to 2100, defined by the Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change. Non-parametric statistical methods are used for climate change detection: linear trends for the entire period (1961 – 2098) estimated by the Theil-Sen method and tested by the Mann-Kendall test, and climate-median differences between the two future climates and the past climate tested by the Mann-Whiteney test.

Inferences on the climate change signal are made after the non-parametric statistics of the multi-model ensemble median, while the associated uncertainties are quantified by the spread of these statistics across the ensemble. Robust climate change patterns are built using only the grid points where a significant climate change is found with low uncertainties. The results highlight the importance of taking into account the spread across an ensemble of climate simulations when

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making inferences on climate change from the ensemble-mean or ensemble-median.

Keywords: Extreme Precipitation Indices, Robust Climate Change Inferences, Regional Climate Models, Iberian Peninsula

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1. Introduction

Precipitation variability has an essential role in water management, which in turn controls agriculture, as well as other economic activities and ultimately social development and behaviour. It is now generally accepted that the increase of atmospheric greenhouse gas concentrations can increase the frequency of extreme precipitation events in many regions of the globe. Increased concentrations of greenhouse gases in the atmosphere increase downwelling infrared radiation, and this global heating at the surface not only acts to increase temperatures but also increases evaporation which enhances the atmospheric moisture content. Consequently all weather systems, which feed on the available moisture through storm-scale moisture convergence, are likely to produce correspondingly enhanced precipitation rates (Trenberth, 1999). Furthermore, the moistening of the atmosphere can result in progressively larger frequency increases at high precipitation intensities, which can even occur in regions where the mean value decreases. Consistent with the aforementioned conceptual considerations, the frequency of extreme precipitation events has increased over the sixty years over many areas of the globe, as a consequence of global warming (Alexander et al., 2006; Solomon et al., 2007). Furthermore, recent global warming experiments with Global Climate Models (GCMs) project for the twenty-first century an increase of precipitation extremes in many regions (Wehner, 2004). Future multi-model scenarios employed in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR) revealed significant negative trends in the annual mean precipitation over the Iberian Peninsula (Kharin et al., 2007). The same result was reported by the project Climate Change in Portugal Scenarios, Impacts and Adaptation Measures (SIAM, Santos et al. (2002)), when comparing projections for 2070-2099 with the a past climate (1961-1990), for Portugal.

GCMs have allowed for a better scientific understanding of anthropogenic global climate change and this led to commensurate developments of mitigation strategies. However, the horizontal resolution of GCMs is larger than the scale of most precipitating cloud systems. This is especially true for highly convective storms that often produce heavy precipitation. In view of the pressing need for regional projections, much effort has been expended in recent years on developing regional projections through diverse methodologies. A review of the different downscaling methods can be found in Wilby and Wigley (1997) and Giorgi et al. (2004), as well in the IPCC Third (Giorgi et al., 2001; Mearns et al., 2001) and Fourth (Christensen et al., 2007) ARs. Dynamical downscaling, which consists in nesting a RCM inside a GCM, is now considered to have better performances than statistical downscaling techniques (Murphy, 1999). RCMs represent an effective method of adding fine-scale detail to simulated patterns of climate variability and change as they resolve better the local land-surface properties such orography, coasts and vegetation, and the internal regional climate variability through their better resolution of atmospheric dynamics and processes (Jones et al., 1995).

The pioneer European project PRUDENCE (Christensen and Christensen, 2007) followed by ENSEMBLES (van der Linden and Mitchell, 2009) provided multi-model ensembles of RCM simulations for Europe which has been extensively analysed not only by the official modelling groups but also by the word scientific community. Given the spread among RCM simulations (Déqué et al., 2011), particularly high for precipitation, it is mandatory to take into account the uncertainties when making inferences on climate change, specially for precipitation extremes. This work presents a methodology to draw robust inferences on regional climate change from an ensemble of model simulations.

2. Data and Methods

2.1. ENSEMBLES' Multi-Model Ensemble

A daily-total precipitation dataset was built after the multi-model ensemble (MME) of Regional Climate Model (RCM) simulations performed by the Research Teams RT3/RT2B of the ENSEMBLES project (van der Linden and Mitchell, 2009). ENSEMBLES regional simulations were performed by thirteen RCMs driven by at least one of six GCMs. The GCMs ran under historic (1961 – 2000) forcing conditions and, for the period 2001 – 2050 (or 2001 – 2100), under the A1B (or A2) emission scenario defined in the Special Report on Emission Scenarios (SRES) of the IPCC. The GCM outputs were then used as boundary conditions to drive the RCMs in a European domain with a horizontal spatial resolution of approximately 25 km (and 50 km) and a temporal resolution of 6 hours.

In this work we use the RCM-GCM pairs whose scenario simulation ran under A1B conditions till the end of the twenty first century. The highest spatial resolution simulations are used. A total of fifteen GCM-driven simulations results from these requirements. Table 1 shows the RCM-GCM pair(s) used by each institution to perform the GCM-driven simulation(s). These simulations were carried out by the modelling group of the following nine European institutions: the Community Climate Change Consortium for Ireland (C4I); the Centre National de Recherches Météorologiques of MÉTÉO FRANCE (CNRM); the Danish Meteorological Institute (DMI); the Swiss Federal Institute of Technology in Zürich (ETHZ); the International Center for Theoretical Physics in Trieste, Italy (ICTP); the Royal Netherlands Meteorological Institute (KNMI); the UK Met Office of the Hadley Centre (METO-HC); the Max Planck Institute for Meteorology in Hamburg, Germany (MPI-M); and the Swedish Meteorological and Hydrological Institute (SMHI).

Some notes about Table 1 are worth mentioning. The RCA3 model used by SMHI and C4I must be considered different RCMs because C4I used a modified version of the original model developed by SMHI. METO-HC simulations form a "perturbed physics" ensemble (Murphy et al., 2004) generated by HadCM3 and HadRM3 models, and should be considered, for the present purposes, as simulations produced by three different RCMs, each one driven by a different GCM. Parameters controlling the sensitivity of the models to Greenhouse Gas (GHG) emissions were perturbed in three different ways for each RCM-GCM pair, leading to very different climate responses (Collins et al., 2006): the standard, low and high sensitivity simulations. Note finally that, with the exceptions of only two RCMs (DMI-HIRHAM5 and SMHI-RCA), each one driven by three GCMs, all other RCMs were driven by a single GCM.

Since not all simulations reach the end of 2099, all simulations were truncated at the end of the year 2098. Finally, the data covering the IP spatial domain was selected. The resulting dataset is a multi-model ensemble (MME) composed by fifteen GCM-driven RCM simulations (ensemble

Table 1: Simulations, produced by ENSEMBLES' modelling groups, analysed in this work.

Institution	RCM	GCM
C4I	RCA3 (Jones et al., 2004)	HadCM3-Q16 (Gordon et al., 2000)
CNRM	RM5.1 (Radu et al., 2008)	ARPEGE (Gibelin and Déqué, 2003)
DMI	HIRHAM5 (Christensen et al., 1996)	ARPEGE (Gibelin and Déqué, 2003) BCM (Furevik et al., 2004) ECHAM5-r3 (Roeckner et al., 2003)
ETHZ	CLM (Böhm et al., 2006)	HadCM3-Q0 (Gordon et al., 2000)
ICTP	REGCM3 (Giorgi and Mearns, 1999)	ECHAM5-r3 (Roeckner et al., 2003)
KNMI	RACMO2 (van Meijgaard et al., 2008)	ECHAM5-r3 (Roeckner et al., 2003)
METO-HC	HadRM3-Q0 (Collins et al., 2006) HadRM3-Q3 (Collins et al., 2006) HadRM3-Q16 (Collins et al., 2006)	HadCM3-Q0 (Gordon et al., 2000) HadCM3-Q3 (Gordon et al., 2000) HadCM3-Q16 (Gordon et al., 2000)
MPI-M	REMO (Jacob, 2001)	ECHAM5-r3 (Roeckner et al., 2003)
SMHI	RCA (Kjellström et al., 2005)	BCM (Furevik et al., 2004) ECHAM5-r3 (Roeckner et al., 2003) HadCM3-Q3 (Gordon et al., 2000)

members) of daily-total precipitation over Iberia from 1961 to 2098. We will refer to this ensemble as the ENSEMBLES MME.

2.2. ETCCDI Multi-Model Ensembles

Several indices have been defined and used to detect and quantify historical and future climate changes in daily precipitation extremes (Frich et al., 2002; Tebaldi et al., 2006; **?**; Frei et al., 2006). A collection of these precipitation indices was assembled and proposed by the CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) with the purpose of establishing a standard set of indices which allows a better comparison between different studies often based on different observed datasets or different models.

Table 2 presents the definitions of the ETCCDI precipitation indices chosen for this work. Although PRCTOT was included in the list by the ETCCDI team, and it is used in the calculations of some extreme indices, one should keep in mind that it is not an index of extreme precipitation.

For each member of the ENSEMBLES MME described in Section 2.1, annual and seasonal precipitation ETCCDI indices were computed yielding annual and seasonal MMEs for each ETC-

Table 2: ETCCDI precipitation indices used in the present work. The period T represents an entire year, or one of the four standard seasons. A wet day is defined as a day with total precipitation amount greater or equal than 1.0 mm.

Acronym	Definition
PRCTOT	Total amount of precipitation of the wet days in period T
CDD	Maximum number of Consecutive Dry Days in period T
Rx5day	Maximum of total amount of 5-consecutive wet days in period T
R95T	Percentage of PRCTOT due to days with daily-total amount greater or equal than the 95th percentile computed the with wet days of the reference climate (1961-1990)

CDI index (ETCCDI MME). Given the chosen indices defined in Table 2, we have four ETCCDI MMEs: PRCTOT MME, CDD MME, Rx5day MME, and RT95 MME. Each one of these MMEs has five versions: one computed from annual data, and four computed from seasonal data (winter, spring, summer, and autumn). Note also that each member of the ensembles is a time series with one value per year from 1961 to 2098.

From each ETCCDI MME, the MME Median (ETCCDI MMEM) was built by computing the median of the index, for each year, of all ensemble members. Note that ETCCDI indices are not computed directly from the ENSEMBLES' MME because the median of this ensemble cannot be determined since its members have different calendars for the A1B simulation.

The majority of the RCMs has a rotated grid of 0.22^o resolution with the north pole located at (39.25N, 162W). For the RCMs with different grids, the ETCCDI time-varying fields were interpolated to this grid.

2.3. Climate change detection methods

Climate change of ETCCDI indices is accessed by a non-parametric methodology. For each index, the following analyses were performed onto the corresponding ETCCDI MME (fifteen members) and also onto the ETCCDI MMEM:

- Linear trend analysis

Theil-Sen linear trend, from 1961 to 2098, tested by the Mann-Kendall test.

- Climate-median differences
  Differences between the climatologies, estimated by the time-median, of a near-future (2021 – 2050) and a distant-future (2069 – 2098) climates from the climatology of a reference climate (1961 – 1990), tested by the Mann-Whitney test.

These statistics (trend or climate-median differences) are commonly used as climate change estimators. For each statistic we obtain fifteen estimates from the ETCCDI MME and one from the ETCCDI MMEM. Climate change projection is evaluated by the later estimate, while the uncertainty of this projection is evaluated by the spread of the former estimates around the later. Here, we evaluate this spread using a modified version of the Median Absolute Deviation (MAD) statistic:

$$\text{MME SPREAD}(T) = \text{Median}\left(\left|\frac{T_{MMEk} - T_{MMEM}}{T_{MMEM}}\right|\right), k = 1, ..., 15 \quad (1)$$

where T is a statistic of an ETCCDI index, T_{MMEk} is its value estimated from the kth member of the ETCCDI MME, and T_{MMEM} is its value estimated from the ETCCDI MMEM. Shortly, MME SPREAD is the median of all relative absolute deviations of the MME estimates from the MMEM estimate.

3. Results

3.1. Climate change patterns

The climate change detection methods (Section 2.3) applied to each ETCCDI index of Table 2 yield spatial patterns of trends and climate-median differences of each index over the Iberian Peninsula. For each index, these patterns are shown in two distinct figures: (i) a figure where the patterns are built with grid points that have significant, at a 0.05 significant level, statistics; and (ii) another figure where the patterns are built with grid points that satisfy the condition in (i) and also that have a MME SPREAD(T) $\leq$ 50%. Therefore, this last figure presents robust patterns of climate change, since they are composed by grid points where most simulations agree in their climate change projection.

For PRCTOT the patterns with or without the MME SPREAD(T) $\leq 50\%$ restriction are indistinguishable, thus, only one figure is presented (Figure 1). Both the trend and the climate-median differences provide the same climate change projections: a decrease in annual precipitation over the entire Peninsula, specially on the north and northwest. The decrease of annual precipitation is due to the decrease in spring, summer and autumn. Note that no changes are projected for winter.

Significant climate changes of CDD estimated with the MMEM are presented in Figure 2, while significant robust changes (significant MMEM CDD changes where MME SPREAD(CDD) $\leq 50\%$) are shown in Figure 3. This is a good example of the importance of identifying the grid points where the change is not only statistically significant but also robust. Figure 2 shows that the annual number of consecutive dry days is projected to be higher in both future climates than it is in the reference climate. However, from Figure 3 we can see that CDD is projected to increase till 2050 but to decrease afterwards. The increase of annual CDD projected for the near-future climate is due to the decrease of CDD in summer, and, to a lesser extent, in spring.

Results for the amount of precipitation of the wettest episode of five consecutive wet days (Rx5day) are presented in Figure 4. Only one figure is presented since almost all grid points with significant changes have a MME SPREAD($Rx5day$) $\leq 50\%$. The annual Rx5day precipitation is projected to decrease near the Mediterranean shores. Some grid points have a positive trend, but they account for a negligible fraction of the Iberian area. The behaviour of the annual index is due to the winter season when 5-consecutive wet day episodes have higher precipitation amounts, besides being more frequent. An important feature is the Rx5day decrease projected to occur in spring and autumn for the major part of the Peninsula. This result is consistent with the projected decrease of total precipitation (PRCTOT) in these seasons (Figure 1). For the dry season (summer) a decrease of episodes is projected to occur in northern Iberia, which is the rainiest region.

Finally, the projected changes for the percentage of total precipitation occurred in days with precipitation above the $90th$ percentile of the reference climate (R95T) are presented in Figures 5 and 6. Except for summer, there is a noticeable disagreement between RCM projections, that is, the MME SPREAD($R95T$) is high. Note that while the annual and winter patterns of Figure 5 show an increase of R95T, no projected changes stand out from Figure 6. These results suggest that some RCMs project an increase while others project a decrease of this index. Taking into account the robust climate projections shown in Figure 6, the remarkable features are the decrease of R95T in northern Iberia in summer and in the south-southwest in autumn.

4. Summary and Conclusions

A methodology to make robust inferences on climate change from an ensemble of model simulations was presented. This methodology was used to assess climate change projections and associated uncertainties of daily-total precipitation simulated by fifteen RCM-GCM configurations.

Precipitation changes were estimated for annual and seasonal total amounts, and for the following extreme indices: maximum number of Consecutive Dry Days, maximum of total amount of 5-consecutive wet days, and percentage of total precipitation occurred in days with precipitation above the $90th$ percentile of a reference climate. Climate change projections of these indices was addressed by applying the following non-parametric methods to the ensemble-median: linear trends for 1961 – 2098 estimated by the Theil-Sen method and tested by the Mann-Kendall test, and climate-median deviations of the 2021 – 2050 and 2069 – 2098 periods from the 1961 – 1990 period. The same methods were applied to all members of the ensemble and a measure of the spread of the resulting statistics across the ensemble was quantified.

The spatial patterns of statistical significant, at 0.05 significance level, trends and climate-median differences of the indices were presented with and without the constraint of low spread of these statistics across the ensemble. The differences between these patterns are notorious for extreme indices, like CDD and R90T. This fact lead us to realize the importance of discarding regions with high projection uncertainties when making climate change inferences. Note, for example, that a significant increase of CDD is projected to occur till the end of the twenty-first century for all seasons except winter, but only the summer changes till 2050 are robust. For R90T, we would infer an increase in winter, when only the decreases in summer (autumn) in the north-northwestern (southwestern) Iberia are robust changes.

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References

Alexander, L. V., Zhang, X., T. C, P., Ceaser, J., et al., 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res. 111 (D5), D05109. URL `http://onlinelibrary.wiley.com/doi/10.1029/2005JD006290/abstract`

Böhm, U., Kücken, M., Ahrens, W., Block, A., Hauffe, D., Keuler, K., Rockel, B., Will, A., 2006. CLM - the climate version of LM: brief description and long-term applications. COSMO Newsletter 6, 225–235.

Christensen, J. H., Christensen, O. B., 2007. A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Climatic Change 81 (S1), 7–30, DOI: 10.1007/s10584-006-9210-7. URL `http://www.springerlink.com/index/10.1007/s10584-006-9210-7`

Christensen, J. H., Christensen, O. B., Lopez, P., van Meijgaard, E., Botzet, M., 1996. The HIRHAM4 regional atmospheric climate model. Scientific Report 96-04, DMI Copenhagen.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., Jones, R., Kolli, R. K., Kwon, W. K., Laprise, R., Rueda, V. M., Mearns, L., Menendez, C. G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., Arritt, R., Benestad, R., Beniston, M., Bromwich, D., Caya, D., Comiso, J., de Elia, R., Dethloff, K., 2007. Regional Climate Projections. In Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK. URL `http://epic.awi.de/4973/`

Collins, M., Booth, B., Harris, G., Murphy, J., Sexton, D., Webb, M., 2006. Towards quantifying uncertainty in transient climate change. Clim. Dyn. 27 (2), 127–147, DOI: 10.1007/s00382-006-0121-0.
URL http://dx.doi.org/10.1007/s00382-006-0121-0

Déqué, M., Somot, S., Sanchez-Gomez, E., Goodess, C. M., Jacob, D., Lenderink, G., Christensen, O. B., 2011. The spread amongst ENSEMBLES regional scenarios: regional climate models, driving general circulation models and interannual variability. Clim. Dyn. 38 (5-6), 951–964, DOI: 10.1007/s00382-011-1053-x.
URL http://www.springerlink.com/index/10.1007/s00382-011-1053-x

Frei, C., Schöll, R., Fukutome, S., Schimidi, S., Vidale, P. L., 2006. Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models. J. Geophys. Res-Atmos. 111, D06105, DOI: 10.1029/2005JD005965.
URL http://onlinelibrary.wiley.com/doi/10.1029/2005JD005965/abstract

Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Tank, A. M. G. K., Peterson, T., 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim. Res. 19, 193–212.

Furevik, T., Bentsen, M., Drange, H., Kindem, I. K. T., Kvamst, N. G., Sorteberg, A., 2004. Description and evaluation of the bergen climate model: ARPEGE coupled with MICOM. Clim. Dyn. 21 (1), 27–51, DOI: 10.1007/s00382-003-0317-5.
URL http://dx.doi.org/10.1007/s00382-003-0317-5

Gibelin, A. L., Déqué, M., 2003. Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim. Dyn. 20, 327–339, DOI: 10.1007/s00382-002-0277-1.
URL http://link.springer.com/article/10.1007/s00382-002-0277-1

Giorgi, F., Bi, X., Pal, J., 2004. Mean, interannual variability and trends in a regional climate change experiment over Europe. II: climate change scenarios (2071–2100). Clim. Dyn. 23 (7-8),

839–858, DOI: 10.1007/s00382-004-0467-0.
URL http://link.springer.com/article/10.1007/s00382-004-0467-0

Giorgi, F., Christensen, J., Hulme, M., von Storch, H., Whetton, P., Jones, R., Mearns, L., Fu, C., Arritt, R., Bates, B., Benestad, R., Boer, G., Buishand, A., Castro, M., Chen, D., Cramer, W., Crane, R., Crossly, J., Dehn, M., Dethloff, K., Dippner, J., Emori, S., Francisco, R., Fyfe, J., Gerstengarbe, F., Gutowski, W., Gyalistras, D., Hanssen-Bauer, I., Hantel, M., Hassell, D., Heimann, D., Jack, C., Jacobeit, J., Kato, H., Katz, R., Kauker, F., Knutson, T., Lal, M., Landsea, C., Laprise, R., Leung, L., Lynch, A., May, W., McGregor, J., Miller, N., Murphy, J., Ribalaygua, J., Rinke, A., Rummukainen, M., Semazzi, F., Walsh, K., Werner, P., Widmann, M., Wilby, R., Wild, M., Xue, Y., 2001. Regional Climate Information- Evaluation and Projections. In Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.
URL http://epic.awi.de/4973/

Giorgi, F., Mearns, L. O., 1999. Introduction to special section: Regional Climate Modeling Revisited. J. Geophys. Res-Atmos. 104(D6), 6335–6352, DOI: 10.1007/s00382-011-1053-x.
URL http://onlinelibrary.wiley.com/doi/10.1029/98JD02072/abstract

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., Wood, R. A., 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim. Dyn. 16 (2), 147–168, DOI: 10.1007/s003820050010.
URL http://dx.doi.org/10.1007/s003820050010

Jacob, D., 2001. A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. Meteorol. Atmos. Phys. 77 (1), 61–73, DOI: 10.1007/s007030170017.
URL http://dx.doi.org/10.1007/s007030170017

Jones, C. G., Willen, U., Ullesrtig, A., Hanssson, U., 2004. The Rossby Centre regional atmospheric

climate model part I: model climatology and performance for the present climate over Europe. Ambio 33 (4), 199–210, DOI: 10.1579/0044-7447-33.4.199.
URL http://www.bioone.org/doi/abs/10.1579/0044-7447-33.4.199

Jones, R. G., Murphy, J. M., Noguer, M., 1995. Simulation of climate change over europe using a nested regional-climate model. I: Assessment of control climate, including sensitivity to location of lateral boundaries. Q. J. R. Meteorol. Soc. 121 (526), 1413–1449.

Kharin, V. V., Zwiers, F. W., Zhang, X., Hegerl, G. C., 2007. Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations. J. Clim. 20 (8), 1419–1444, DOI: 10.1175/JCLI4066.1.
URL http://journals.ametsoc.org/doi/abs/10.1175/JCLI4066.1

Kjellström, E., Bärring, L., Gollvik, S., Hansson, U., Jones, C., Samuelsson, P., Rummukainen, M., Ullersig, A., Willen, U., Wyser, K., 2005. A 140-year simulation of European climate with the new version of the Rossby Centre regional atmospheric climate model (RCA3). Reports of meteorology and climatology, SMHI, SE-60176 Norrkoping, Sweden 108, 54 pp.

Mearns, L. O., Hulme, M., Carter, T. R., Leemans, R., Lal, M., Whetton, P., 2001. Climate Scenario Development. In Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.
URL http://epic.awi.de/4973/

Murphy, J., 1999. An Evaluation of Statistical and Dynamical Techniques for Downscaling Local Climate. J. Clim. 12 (8), 2256–2284.
URL http://dx.doi.org/10.1175/1520-0442(1999)012<2256:AEOSAD>2.0.CO;2

Murphy, J. M., Sexton, D. M. H., Barnett, D. N., Jones, G. S., Webb, M. J., Collins, M., Stainforth, D. A., 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature 430, 768–772, DOI: 10.1038/nature02771.
URL http://www.nature.com/nature/journal/v430/n7001/full/nature02771.html

Radu, R., Déqué, M., Somot, S., 2008. Spectral nudging in a spectral regional climate model. Tellus A 60A (5), 898–910, DOI: 10.1111/j.1600-0870.2008.00341.x.
URL http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0870.2008.00341.x/abstract

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Rhodin, E. M. A., Schlese, U., Schulzweida, U., Tompkins, A., 2003. The atmospheric general circulation model ECHAM5. Part I: model description. Max Planck Institute for Meteorology Rep. 349. Available from MPI for Meteorology, Bundesstr 53, 20146 Hamburg, Germany, 127 pp.
URL http://pubman.mpdl.mpg.de/pubman/faces/viewItemOverviewPage.jsp?itemId=escidoc:99526

Santos, F. D., Forbes, K., Moita, R., 2002. Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures - SIAM Project. Gradiva, Lisbon, Portugal.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H., 2007. Climate change 2007: the Physical Science Basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Vol. 4. Cambridge University Press, 714 pp.

Tebaldi, C., Hayhoe, K., Arblaster, J. M., Meehl, G. M., 2006. Going to extremes: and intercomparison of model-simulated historical and future changes in extreme events. Climatic Change 79 (3-4), 185–211, DOI: 10.1007/s10584-006-9051-4.
URL http://www.springerlink.com/index/10.1007/s10584-006-9051-4

Trenberth, E. K., 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. Climatic Change 42, 337–339.

van der Linden, P., Mitchell, J., 2009. ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre. FitzRoy Road, Exeter EX1 3PB, UK, 160 pp.

van Meijgaard, E., van Ulft, L. H., van de Berg, W. J., Bosveld, F. C., van den Hurk, B. J. J. M., Lenderink, G., Siebesma, A. P., 2008. The KNMI regional atmospheric climate model RACMO, version 2.1. Koninklijk Nederlands Meteorologisch Instituut, 43 pp.

Wehner, M. F., 2004. Predicted twenty-first-century changes in seasonal extreme precipitation events in the Parallel Climate Model. J. Clim 17 (21), 4281–4290, DOI: 10.1175/JCLI3197.1. URL http://dx.doi.org/10.1175/JCLI3197.1

Wilby, R. L., Wigley, T. M. L., 1997. Downscaling general circulation model output: a review of methods and limitations. Prog. Phys. Geog. 21 (4), 530–548, DOI: 10.1177/030913339702100403. URL http://ppg.sagepub.com/content/21/4/530

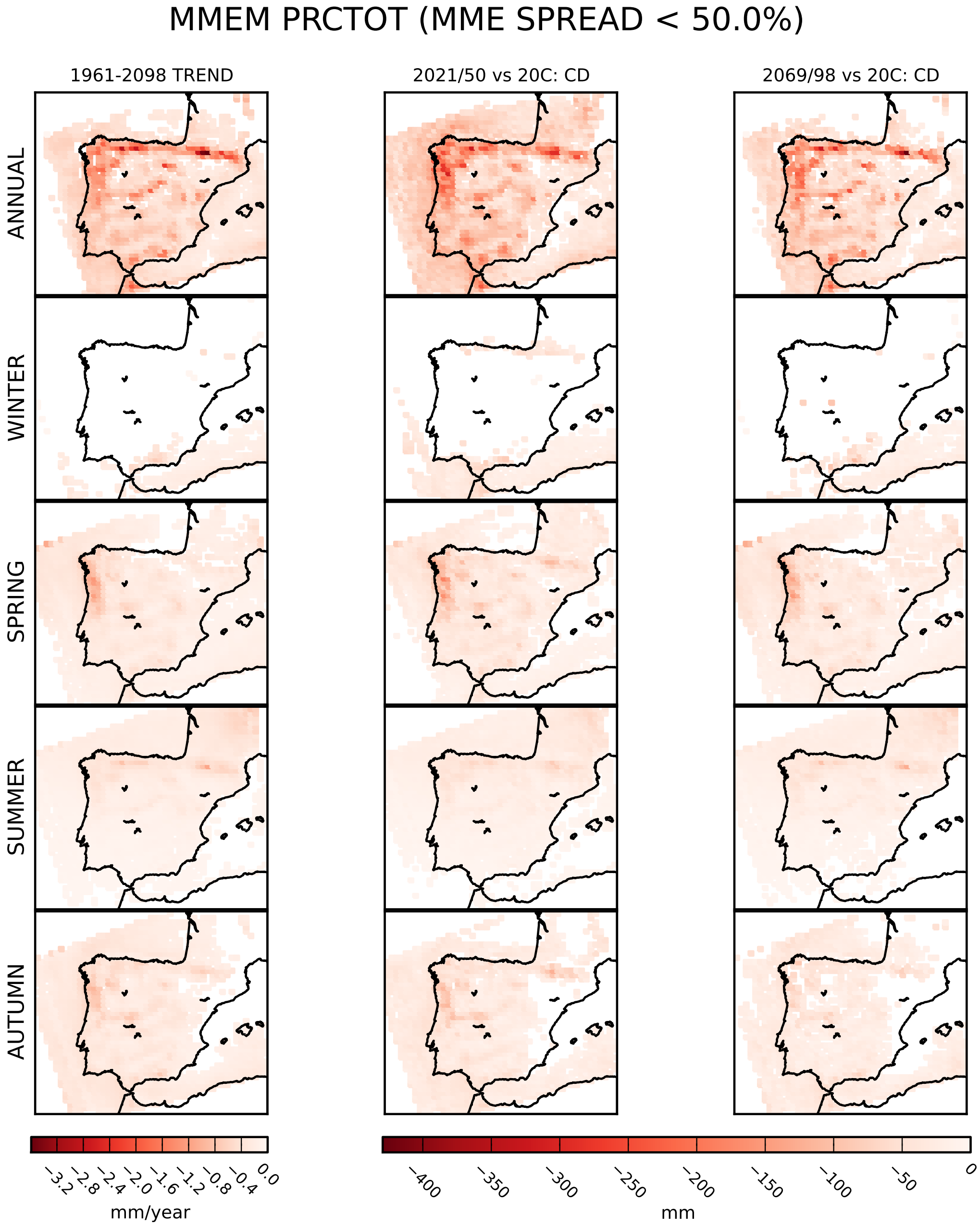

Figure 1: Annual and seasonal MMEM PRCTOT climate change statistics. Left column: Theil-Sen linear trend from 1961 to 2098; Middle column: climate-median difference (CD) between the near-future (2021-2050) climate and the reference (1961 − 1990) climate. Right column: as the middle column but for the distant-future (2069-2098) climate. Values significant at a 0.05 significance level, assuming the A1B scenario, according to the Mann-Kendall test for trends, and Mann-Whiteney test for climate-median differences. Significant values also have a MME SPREAD($PRCTOT$) $\leq 50\%$.

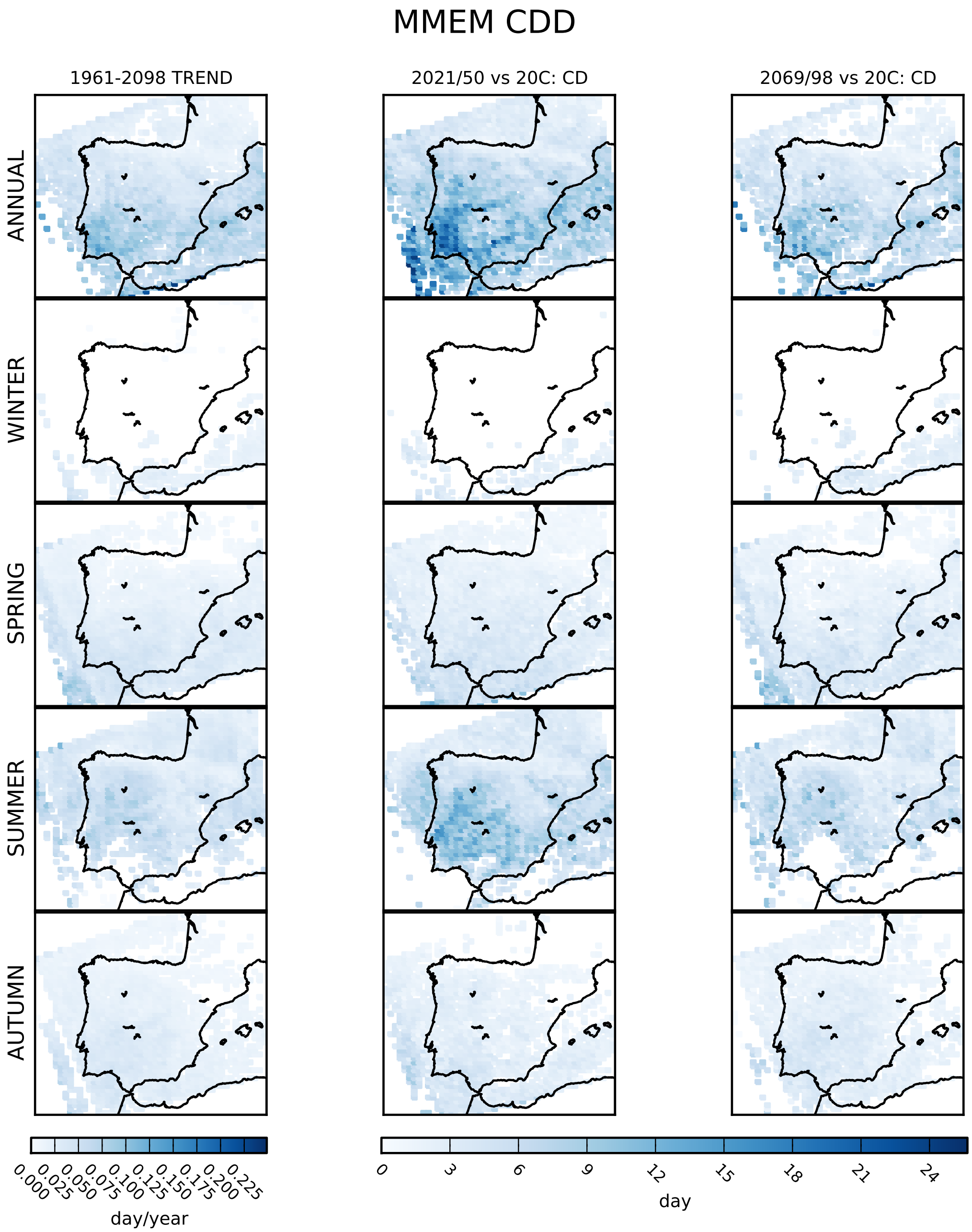

Figure 2: As Figure 1 but for CDD without the constraint of MME SPREAD(CDD) $\leq 50\%$.

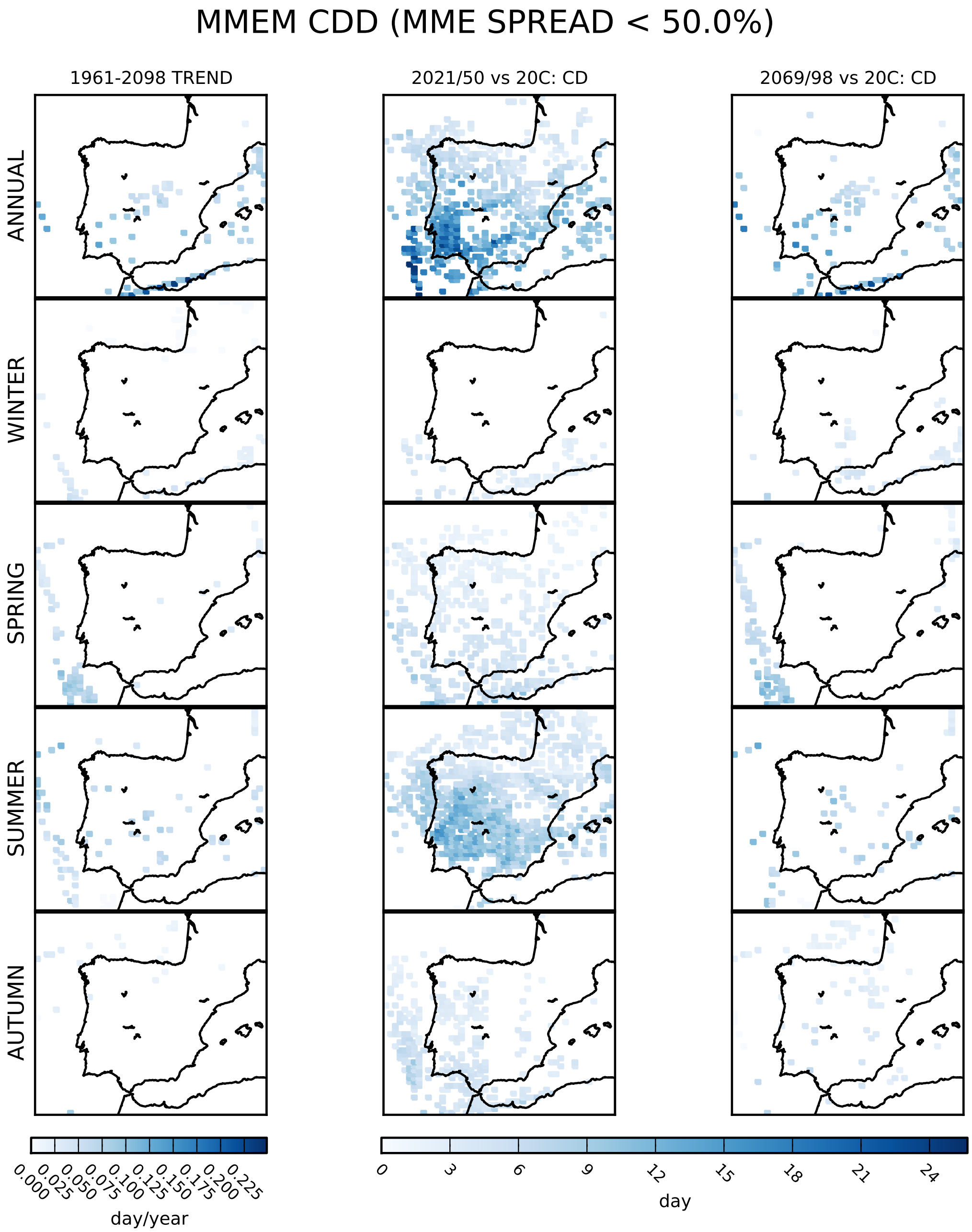

Figure 3: As Figure 1 but for CDD with MME SPREAD(CDD) $\leq$ 50%.

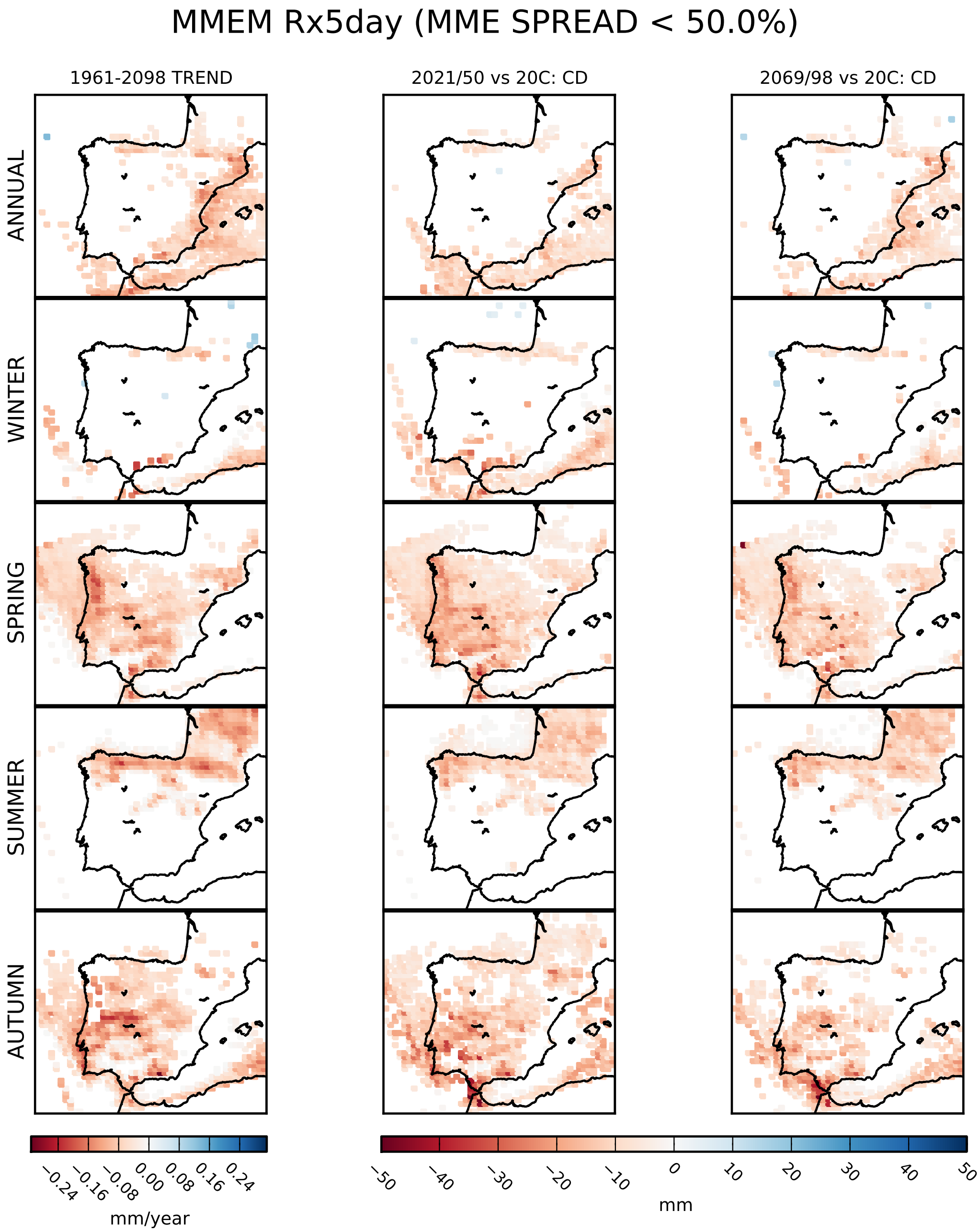

Figure 4: As Figure 1 but for Rx5day with MME SPREAD($Rx5day$) $\leq$ 50%.

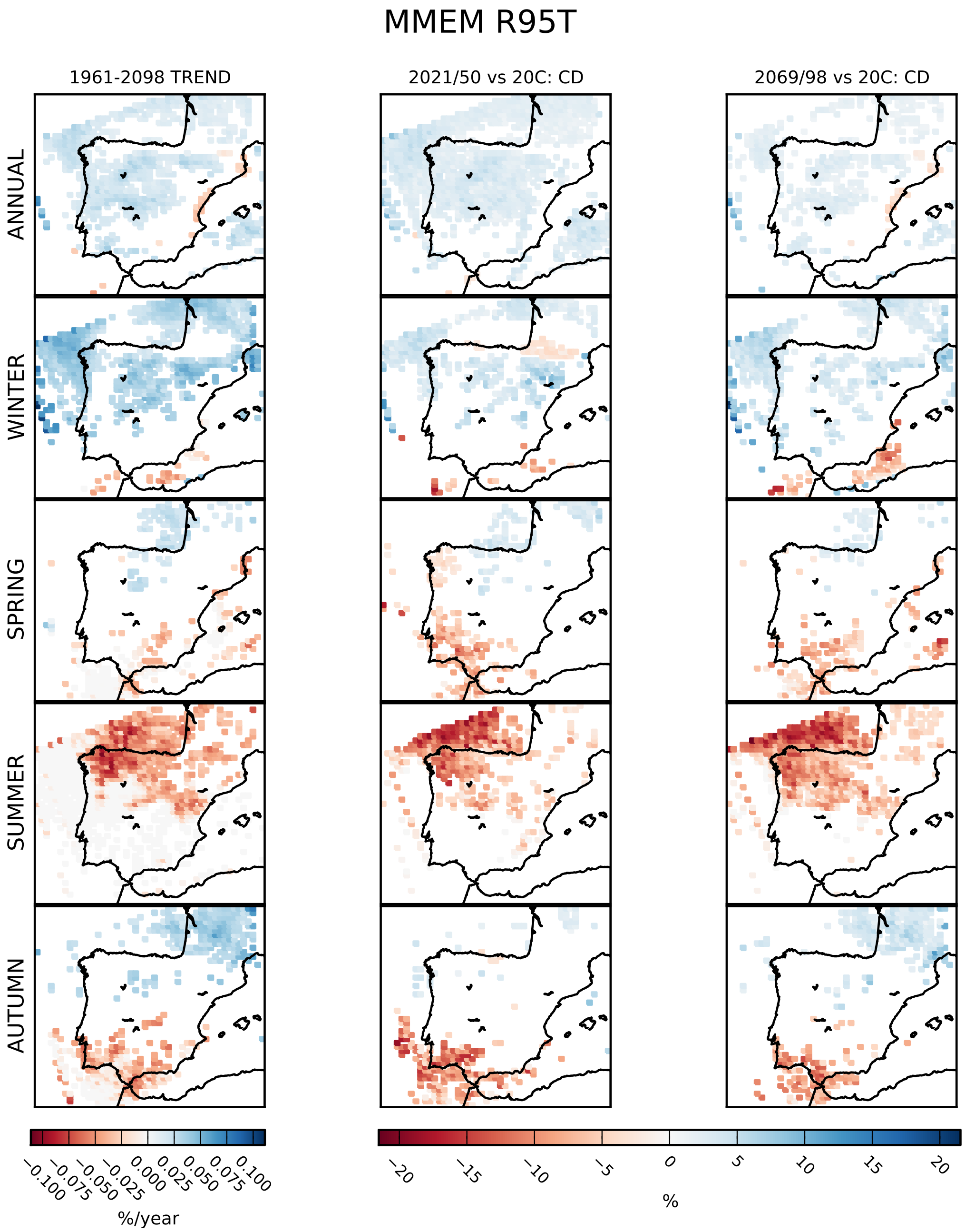

Figure 5: As Figure 1 but for R95T without the constraint of MME SPREAD($R95T$) $\leq 50\%$.

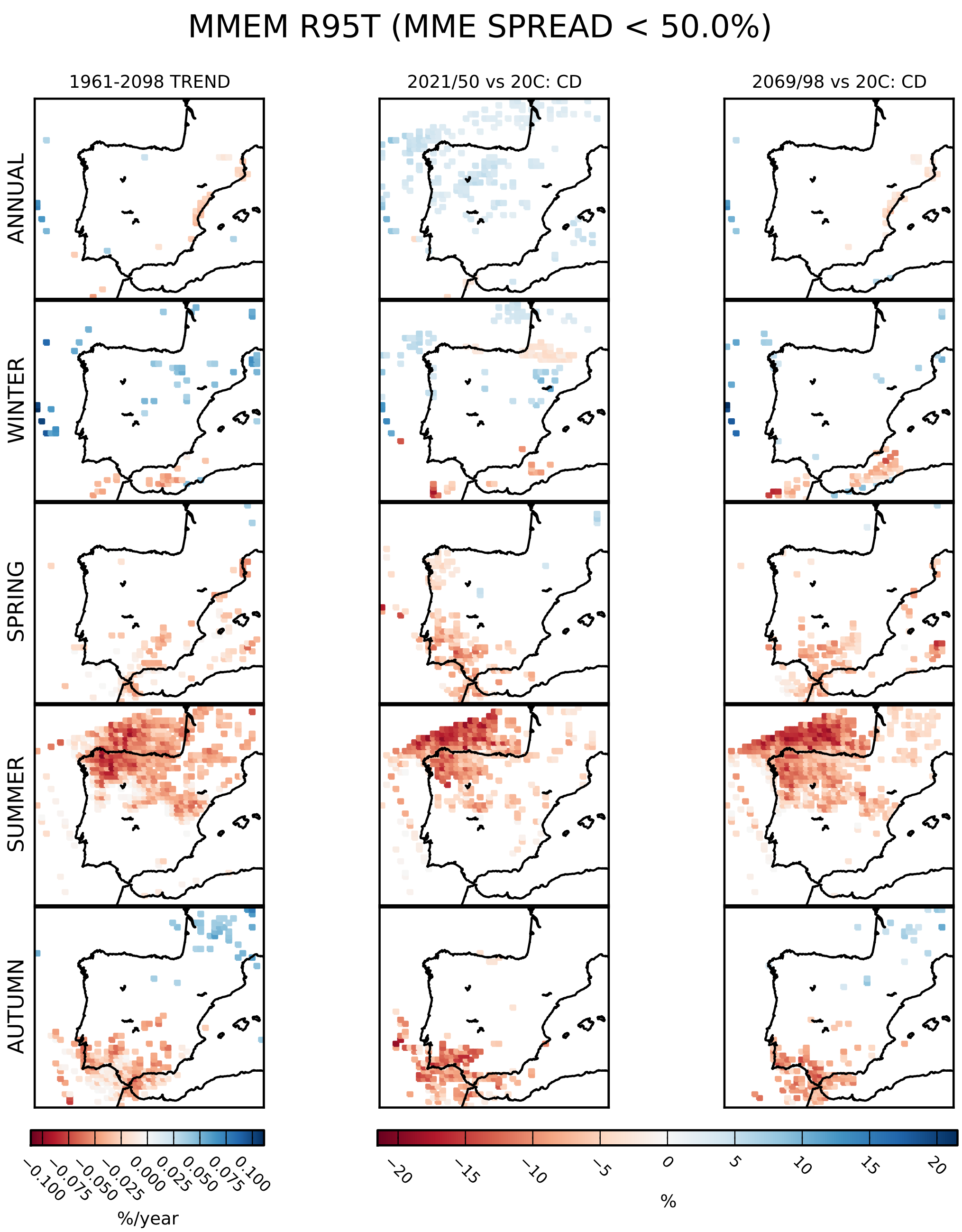

Figure 6: As Figure 1 but for R95T with MME SPREAD($R95T$) $\leq 50\%$.