CHANGES IN METEO-HYDROLOGICAL EXTREMES IN SPAIN AT DIFFERENT LEVELS OF GLOBAL WARMING

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ABSTRACT

This work assesses changes in the extremes of precipitation and streamflow in Spain assuming global warming scenarios of 1.5, 2, and 3 degrees Celsius from pre-industrial levels. We consider an ensemble of seven regional climate model simulations spanning the period 1970-2099 to evaluate precipitation changes and to drive a distributed hydrological model and thus to derive streamflow statistics under present and future climates. The climate simulations were performed under the umbrella of the EURO-CORDEX project, thus covering Europe with a spatial resolution of 0.11 degree both in latitude and longitude, the finest so far in this type of climatological multimodel and multi-scenario experiments. Preliminary results suggest that constraining global warming well below 2°C, as sought in the Paris Agreement, reduces the probability of increasing drought related indices.

Key words: extremes, drought, precipitation, streamflow, regional projections, Spain.

1. INTRODUCTION

The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), signed in December 2015, aims "to hold the increase in the global average temperature to below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5°C...". Following the Paris Agreement of December 2015 of the United Nations Framework Convention on Climate Change, scientists are urged to quantify socioeconomic impacts for different warming thresholds. For instance, recent research efforts have significantly boosted our knowledge on the risks at 1.5 and 2°C of warming, focusing relevant climate change impacts as for instance on economy (Burke et al., 2018), agriculture (Schleussner et al., 2016), power generation (Tobin et al., 2018) and ecosystems (Guiot and Cramer, 2016).

Previous works consistently indicate that flood risk is expected to increase in the future in most world regions, with largest increase in Asia, America and Europe (Alfieri et al., 2017). Donnelly et al. (2017) show that for most of Europe, the impacts of climate change on mean, low and high runoff and mean snowpack in Europe increase with increased warming level, however they do not provide an assessment of change in drought and extremes. Dosio and Fischer (2018) analyse projections of indices of mean and extreme climate in Europe and indicate that the change in precipitation due to 0.5°C warming is mostly non-significant at the grid point level. King and Karoly (2017) analyse changes in the highest 1 day precipitation and indicate that there is a signal that the heaviest rainfall events would likely become more intense at 2 °C warming compared to 1.5 °C. This result are confirmed also by Kjellström et al. (2018), that indicate that changes in precipitation, which are less robust than the ones in temperature, include decreases in the south of Europe. This precipitation decreases play an important role in the projected increase in future drought conditions in southern Europe. Global drought assessments coincide to indicate the Mediterranean region as a hotspot for future drought increases (Lehner et al., 2017; Naumann et al., 2018; Park et al., 2018). However, a detailed local-scale study analysing both precipitation and runoff changes, considering both the upper tail extremes and the drought conditions, remain to be done.

The Iberian Peninsula located on the southwest edge of Europe is a relevant region for such an analysis for two main reasons. First, precipitation and runoff play a major role on natural hazards and water resources (Garrote et al., 2007; Llasat, 2009), thus leading to one of the most vulnerable countries to water scarcity, droughts and floods in Europe (Kristensen, 2010). Secondly, its complex orography and particular location - at the transition area between extra-tropical and subtropical influence (Giorgi and Lionello, 2008) - determines a great variety of climates with both Atlantic and Mediterranean influences. Thus, precipitation and runoff are characterized by a complex spatial pattern (Serrano et al., 1999; Estrela et al., 2012), with a strong seasonal cycle and large interannual (Trigo and Palutikof, 2001) and spatial variability (Rodriguez-Puebla et al., 1998; Romero et al., 1998; Martin-Vide, 2004; Rodrigo and Trigo, 2007; Quintana-Seguí et al., 2016, 2017). Due to this strong variability, this region represents a challenge area for downscaling studies (see e.g. Turco et al., 2011). Taking these comments into account, the aim of this paper is to explore the changes in precipitation and runoff metrics in an ensemble of state-of-the-art regional climate projections (RCM) in the Mediterranean Europe at 1.5, 2 and 3◦C of mean global warming.

2. DATA AND METHODS

2.1. Precipitation and runoff data

Daily historical simulations from 1976 to 2005 and climate projections assuming the RCP8.5 scenario from 2006 to 2100 are calculated using an ensemble of seven regional climate simulations. The simulations were performed under the umbrella of the EURO-CORDEX project, covering Europe with a spatial resolution of 0.11 degrees both in latitude and longitude, the finest so far in this type of climatological multi-model and multi-scenario experiments (Jacob et al., 2014). Overall, the seven climate scenarios are combinations of three different general circulation models (GCM) which were then downscaled with four RCMs, as shown in Table 1. These are the RCMs that had the necessary variables at the moment of the design of this study and were chosen giving priority to models with driving GCMs with high ranking in the performance evaluation of CMIP5 models carried out by Perez et al. (2014).

Hydrological simulations are performed with the Lisflood model, a distributed semi-physically based rainfall–runoff model combined with a routing module for river channels (van der Knijff et al., 2010). For this work, Lisflood was run on the European domain at 5 km spatial resolution and daily time step using gridded meteorological variables extracted from the climate scenarios (see Alfieri et al., 2015 for more details). Lisflood is the operational model adopted by the European Flood Awareness System (Thielen et al., 2009) and it has been extensively validated in a number of case studies and operational systems at spatial scales ranging from small flash-flood prone catchments to large river basins (see e.g. Alfieri et al., 2012, 2015).

Institute	GCM	RCM
KNMI	EC-EARTH	RACMO22E
SMHI	HadGEM2-ES	RCA4
SMHI	EC-EARTH	RCA4
MPI-CSC	MPI-ESM-LR	REMO2009
CLMcom	MPI-ESM-LR	CCLM4-8-17
SMHI	MPI-ESM-LR	RCA4
CLMcom	EC-EARTH	CCLM4-8-17

Table 1: EURO-CORDEX climate models used in this study.

2.2. Precipitation and runoff indices

We analyse the regional climate change signals considering several indices for different future periods selecting the temporal windows where the global mean temperature increase is 1.5, 2 or 3°C. These change are expressed as the ratio (expressed as percentage of change) of the mean values for the corresponding future RCM simulations and the control ones in the baseline (1976-2005) period. The method to identify time windows follows the guidelines of the HELIX project (Betts et al., 2018): the time windows are centred on the years when the 20-year running mean of global average temperature exceeds 1.5, 2 and 3°C.

For precipitation, we calculate three indicators. First we calculate the total precipitation (hereinafter PRCPTOT). In addition, we estimate the changes in 20-year return values of annual maximum daily precipitation rates. In order to perform this analysis, a Generalized Extreme Value (GEV) distribution is fitted to the past and future 30-year samples of annual precipitation extremes using the method of L-moments similarly to the analysis performed for the IPCC (2012). This analysis has been performed with the extRemes package in R (https://www.jstatsoft.org/article/view/v072i08). Finally we calculate the standardized precipitation index (SPI; McKee et al., 1993) as meteorological drought indicator. SPI transforms accumulated precipitation values over a specific period (usually from 1 to 12 months) into a standard Gaussian distribution with zero mean and unit variance, with positive and negative values indicating wet and dry conditions, respectively. Specifically, for each RCM, the parameters that are required to calculate the SPI are determined relative to the distribution of the reference period 1976-2005 at each grid point. The fitted parameters are then used to calculate the historical and future SPI series. We calculate the annual SPI series (i.e. the SPI calculated in December relative to the period from January to December) with the SPEI package in R (Vicente-Serrano et al. 2010).

The analysis of runoff changes focuses on a similar set of three variables: the annual average streamflow, the 20-year return values of annual maximum daily runoff rates (calculated similarly as for the case of the values of precipitation return period) and the annual standardized runoff index (SRI), as hydrological drought indicator.

A resampling method is used to assess the statistical significance of the differences in the 20-year return values extremes at each grid point (similarly to Turco et al., 2015). To test the results against the null hypothesis of no change, for each time series we create 500 surrogate time series by randomly shuffling (without repetition) the past and future series, thus generating an ensemble of records where the possible temporal changes have been shuffled out. This provides 500 surrogate values of the differences between the two periods, which are used to estimate the confidence intervals for no change at each grid point.

3. RESULTS

Figure 1 shows the regional climate change signal for three precipitation indicators: the total precipitation, the 20-year return values of annual maximum daily precipitation and the SPI. A robust decrease in total precipitation changes appears mostly in the south of the region of study for the highest level of global warming considered. The decrease is also significant on the main mountain ranges, which are the main water towers of the Iberian Peninsula, the area were most water resources are generated. This is in line also with a decrease in the SPI indices, meaning that there is an increase in meteorological drought conditions. Instead, the extremes in maximum precipitation rates do not show changes that are statistically different from the past variability.

Figure 2 shows similar variables as Figure 1 but considering the runoff data. Also in this case, while the extreme do not show a clear pattern of change, the decrease in mean annual flow (water resources) and the increase in drought are apparent at the higher level of warming for Mediterranean and Southern Spain.

4. CONCLUSIONS

Our results suggest the urgency to develop and apply adaptation and mitigation strategies, also considering that, already at present, many areas in Spain suffer from problems related to climate change (Quiroga et al., 2011; Turco and Llasat, 2011).

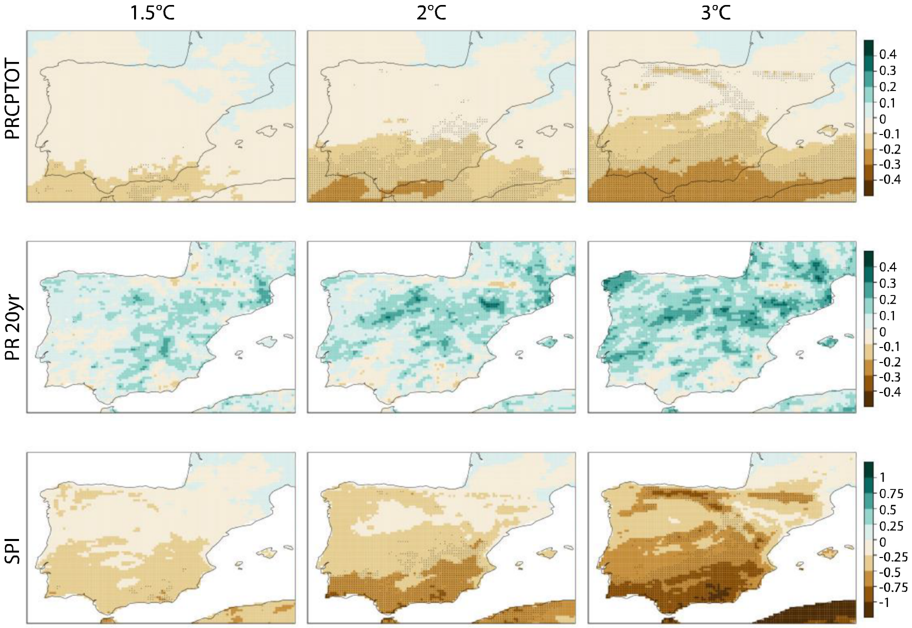

Figure 1. Ensemble mean of the changes (in %) of total precipitation (PRCPTOT) for 1.5, 2 and 3°C global warming (first line), of the change (in %) in 20-yr return values of annual extremes of daily precipitation (PR 20 yr, second line) and of the changes (in standard units) of the standardized precipitation index (SPI; third line). Dots indicate areas where at least 50% of the simulations show a statistically significant change and more than 66% agree on the direction of the change. Coloured areas (without dots) indicate that changes are small compared to natural variations, and white regions (if any) indicate that no agreement between the simulations is found (similar to Tebaldi et al. 2011).

Indeed, if future temperature increases are limited to 2°C, the impacts on water resources will be mostly limited to the southern Iberia, but if the increase reaches 3°C, the decrease in precipitation and the increase in drought will affect the majority of the region and in particular the main mountain ranges, which are the main water towers of Spain. This will probably exacerbate water scarcity, which is already a problem in the area, as the decreased water availability and increased drought will have to satisfy an increased demand, as the higher mean annual temperature will increase evapotranspiration in irrigated areas.

Specifically, our results indicate that by limiting the global warming below 2ºC, the situation in the Peninsula would not change substantially from the present conditions, with only a significant decrease in southern Andalusia. However, as the global mean temperature increases, the decrease in annual precipitation and the increase in drought conditions extend northward, affecting the Andalusia Community and Eastern Iberia, regions that already suffer from a deficit of water resources compared to the irrigation demand. This situation can aggravate the existing conflict between those regions for inter-basin water transfers, since the basins that currently have less water demand, compared to the water resources available, could be affected by the decrease in freshwater and the increase in demand due to climate change. Particularly serious could be this effect on the Segura basin, which is currently fed by the Tajo-Segura transfer, since above 2ºC the loss would also affect the headwaters of the Tagus River.

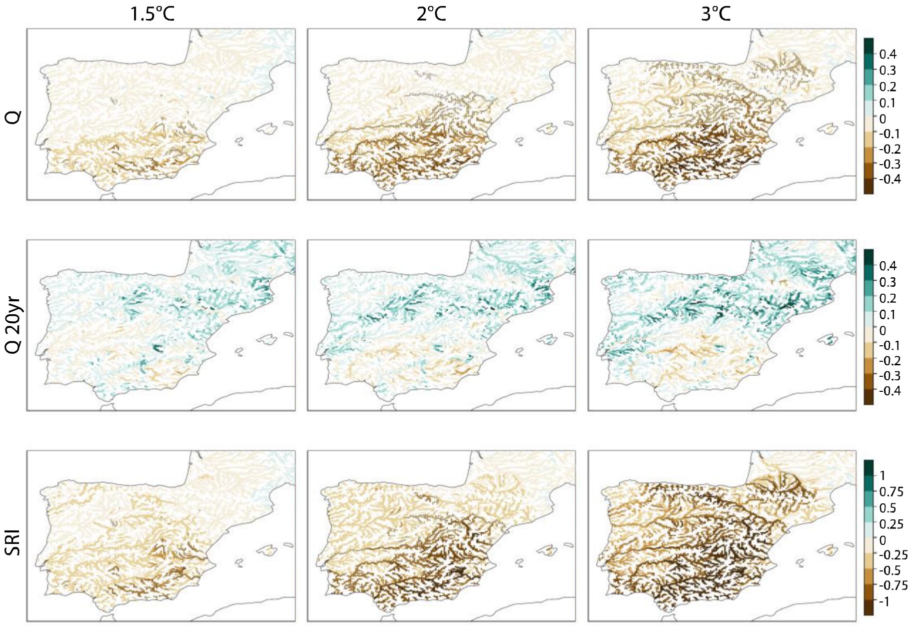

Figure 2. Ensemble mean of the changes (in %) of annual mean runoff (Q) for 1.5, 2 and 3°C global warming (first line), of the change (in %) in 20-yr return values of annual extremes of daily runoff (Q 20 yr, second line) and of the changes (in standard units) of the standardized runoff index (SRI; third line). Dots indicate areas where at least 50% of the simulations show a statistically significant change and more than 66% agree on the direction of the change. Coloured areas (without dots) indicate that changes are small compared to natural variations, and white regions (if any) indicate that no agreement between the simulations is found (similar to Tebaldi et al. 2011).

A different situation could occur in the basins of the North of the Peninsula. In general, the Cantabrian basins do not suffer from problems regarding the amount of water available. However, the scenarios show a worsening of the conditions that may be involved in the development of adaptation measures not currently foreseen. In the particular case of the Pyrenees, known as the Iberian Water Towers, since more than 70% of the Ebro River water is generated in these mountains, a significant decrease in precipitation is detected at and above the 2ºC warming level. These changes may produce irreversible damage to mountain ecosystems, increased risk of fires in wooded and mountainous areas of difficult access, losses in winter tourism, decrease in hydroelectric energy resources and decrease in water availability in the face of agricultural, industrial and urban water demand, thus aggravating the conflict over the uses of water.

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REFERENCES

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., Roo, A., Salamon, P., ... & Feyen, L. (2017). Global projections of river flood risk in a warmer world. Earth's Future, 5(2), 171-182. doi: https://doi.org/10.1002/2016EF000485

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, *19*(5), 2247. doi: https://doi.org/10.5194/hess-19-2247-2015

Alfieri, L., Thielen, J., & Pappenberger, F. (2012). Ensemble hydro-meteorological simulation for flash flood early detection in southern Switzerland. Journal of hydrology, 424, 143-153. doi: https://doi.org/10.1016/j.jhydrol.2011.12.038

Betts, R. A., Alfieri, L., Bradshaw, C., Caesar, J., Feyen, L., Friedlingstein, P., ... & Papadimitriou, L. (2018). Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5° C and 2° C global warming with a higher-resolution global climate model. Phil. Trans. R. Soc. A, 376(2119), 20160452. doi: https://doi.org/10.1098/rsta.2016.0452

Burke, M., Davis, W. M., & Diffenbaugh, N. S. (2018). Large potential reduction in economic damages under UN mitigation targets. Nature, 557(7706), 549.

Donnelly, C., Greuell, W., Andersson, J., Gerten, D., Pisacane, G., Roudier, P., & Ludwig, F. (2017). Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. Climatic Change, 143(1-2), 13-26. doi: https://doi.org/10.1007/s10584-017-1971-7

Dosio, A., & Fischer, E. M. (2018). Will half a degree make a difference? Robust projections of indices of mean and extreme climate in Europe under 1.5 C, 2 C, and 3 C global warming. Geophysical Research Letters, 45(2), 935-944. doi: https://doi.org/10.1002/2017GL076222

Estrela, T., Pérez-Martin, M.A., and Vargas, E., (2012). Impacts of climate change on water resources in Spain. Hydrological Sciences Journal, 57 (6), 1154–1167. doi: https://doi.org/10.1080/02626667.2012.702213

Garrote, L., F. Martin-Carrasco, F. Flores-Montoya, and A. Iglesias (2007). Linking drought indicators to policy actions in the Tagus basin drought management plan, Water Resour. Manage., 21(5), 873–882. doi: https://doi.org/10.1007/s11269-006-9086-3.

Giorgi, F., and Lionello, P. (2008). Climate change projections for the Med- iterranean region, Global Planet. Change, 63(2–3), 90–104. doi: https://doi.org/10.1016/ j.gloplacha.2007.09.005

Guiot, J., & Cramer, W. (2016). Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. Science, 354(6311), 465-468. doi: https://doi.org/10.1126/science.aah5015

IPCC. (2012). Changes in Impacts of Climate Extremes: Human Systems and Ecosystems. En C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, … P. M. Midgley (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (pp. 231-290). Cambridge, Reino Unido, y Nueva York, EEUU: Cambridge University Press.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., ... & Georgopoulou, E. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional environmental change*, *14*(2), 563-578. doi: https://doi.org/10.1007/s10113-013-0499-2

King, A. D., & Karoly, D. J. (2017). Climate extremes in Europe at 1.5 and 2 degrees of global warming. Environmental Research Letters, 12(11), 114031. doi: https://doi.org/10.1088/1748-9326/aa8e2c

Kjellström, E., Nikulin, G., Strandberg, G., Christensen, O. B., Jacob, D., Keuler, K., ... & Sørland, S. L. (2018). European climate change at global mean temperature increases of 1.5 and 2° C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models. Earth System Dynamics, 9(2), 459. doi: https://doi.org/10.5194/esd-9-459-2018

Kristensen, P. (2010), Water Resources: Quantity and Flows, Publications Office of the European Union, State Environ. Rep. 1/2010, Eur. Environ. Agency, Copenhagen. [Available at http://www.eea.europa.eu/soer/europe/ water-resources-quantity-and-flows.]

Lehner, F., Coats, S., Stocker, T. F., Pendergrass, A. G., Sanderson, B. M., Raible, C. C., & Smerdon, J. E. (2017). Projected drought risk in 1.5 C and 2 C warmer climates. Geophysical Research Letters, 44(14), 7419-7428. doi: https://doi.org/10.1002/2017GL074117

Llasat, M. C. (2009). High magnitude storms and floods, in The Physical Geography of the Mediterranean, edited by J. Woodward, ppl 513–540, Oxford Univ. Press, Cambridge, U. K.

Martin-Vide, J. (2004), Spatial distribution of a daily precipitation concen- tration index in peninsular Spain, Int. J. Climatol., 24(8), 959–971.doi: https://doi.org/10.1002/joc.1030.

McKee, T. B., Doeskin, N. J., Kleist, J. (1993). The Relationship of Drought Frequency and Duration to Time Scales. 8th Conf. on Applied Climatology. Am. Meteorol. Soc., 179–184.

Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R. A., Carrao, H., ... & Feyen, L. (2018). Global changes in drought conditions under different levels of warming. Geophysical Research Letters, 45(7), 3285-3296. doi: https://doi.org/10.1002/2017GL076521

Park, C. E., Jeong, S. J., Joshi, M., Osborn, T. J., Ho, C. H., Piao, S., ... & Kim, B. M. (2018). Keeping global warming within 1.5° C constrains emergence of aridification. Nature Climate Change, 1. doi: https://doi.org/10.1038/s41558-017-0034-4

Perez, J., Menendez, M., Mendez, F. J., and Losada, I. J. (2014). Evaluat- ing the performance of CMIP3 and CMIP5 global climate mod- els over the north-east Atlantic region, Clim. Dynam., 43, 2663– 2680. doi: https://doi.org/10.1007/s00382-014-2078-8

Quintana-Seguí, P., Peral, M. C., Turco, M., Llasat, M.-C., and Martin, E. (2016). Meteorological Analysis Systems in North-East Spain: Validation of SAFRAN and SPAN, J. Environ. Inform., 27, 116– 130. doi: https://doi.org/10.3808/jei.201600335.

Quintana-Seguí, P., Turco, M., Herrera, S., & Miguez-Macho, G. (2017). Validation of a new SAFRAN-based gridded precipitation product for Spain and comparisons to Spain02 and ERA-Interim. Hydrology and Earth System Sciences, 21(4), 2187. doi: https://doi.org/10.5194/hess-21-2187-2017

Quiroga Gomez, S., Garrote de Marcos, L., Iglesias Picazo, A., Fernández-Haddad, Z., Schlickenrieder, J., Lama Pedrosa, B. D., ... & Sánchez-Arcilla, A. (2010). The economic value of drought information for water management under climate change: a case study in the Ebro basin. Natural Hazards and Earth System Sciences, 11(3), 643-657.

Rodrigo, F. S. and Trigo, R. M. (2007). Trends in daily rainfall in the Ibe- rian Peninsula from 1951 to 2002, Int. J. Climatol., 27(4), 513–529. doi: https://doi.org/10.1002/joc.1409

Rodriguez-Puebla, C., Encinas, A., Nieto, S., and Garmendia, J. (1998). Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula, Int. J. Climatol., 18(3), 299–316.

Romero, R., Guijarro, J., Ramis, C. andAlonso, S. (1998). A 30-year (1964– 1993) daily rainfall data base for the Spanish Mediterranean regions: First exploratory study. Int. J. Climatol., 18(5), 541–560.

Schleussner, C.-F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W., and Schaeffer, M. (2016). Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C, Earth Syst. Dynam., 7, 327-351 doi: https://doi.org/10.5194/esd-7-327-2016

Serrano, A., Garcia, J., Mateos, V., Cancillo, M., and Garrido, J. (1999). Monthly modes of variation of precipitation over the Iberian peninsula. J. Clim., 12(9), 2894–2919.

Tebaldi, C., Arblaster, J. M., & Knutti, R. (2011). Mapping model agreement on future climate projections. Geophysical Research Letters, 38(23). doi: https://doi.org/10.1029/2011GL049863

Thielen, J., Bartholmes, J., Ramos, M.-H., and de Roo, A. (2009). The Eu- ropean Flood Alert System – Part 1: Concept and development, Hydrol. Earth Syst. Sci., 13, 125–140. doi: https://doi.org/10.5194/hess-13-125- 2009

Tobin, I., Greuell, W., Jerez, S., Ludwig, F., Vautard, R., van Vliet, M. T. H., & Bréon, F. M. (2018). Vulnerabilities and resilience of European power generation to 1.5° C, 2° C and 3° C warming. Environmental Research Letters, 13(4), 044024.

Trigo, R., and Palutikof, J. (2001). Precipitation scenarios over Iberia: A comparison between direct GCM output and different downscaling techniques. J. Clim., 14(23), 4422–4446.

Turco, M., & Llasat Botija, M. C. (2011). Trends in indices of daily precipitation extremes in Catalonia (NE Spain), 1951-2003. Natural Hazards and Earth System Sciences, 2011, Vol. 11, p. 3213-3226. doi: https://doi.org/10.5194/nhess-11-3213-2011

Turco, M., Palazzi, E., Hardenberg, J., & Provenzale, A. (2015). Observed climate change hotspots. Geophysical Research Letters, 42(9), 3521-3528. doi: https://doi.org/10.1002/2015GL063891

Turco, M., Quintana-Seguí, P., Llasat, M. C., Herrera, S., & Gutiérrez, J. M. (2011). Testing MOS precipitation downscaling for ENSEMBLES regional climate models over Spain. Journal of Geophysical Research: Atmospheres, 116(D18). doi: https://doi.org/10.1029/2011JD016166

Van der Knijff, J. M., Younis, J., and de Roo, A. P. J. (2010). LISFLOOD: A GIS-based distributed model for river basin scale water balance and flood simulation. Int. J. Geogr. Inf. Sci., 24, 189–212. doi: https://doi.org/10.1080/13658810802549154

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. Journal of climate, 23(7), 1696-1718. doi: https://doi.org/10.1175/2009JCLI2909.1