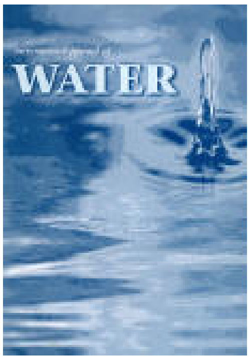

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Evaluation of the impact of climate change on water resources and droughts frequency and severity in a small-scale international catchment in the Iberian Peninsula

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Abstract: An evaluation of the potential effect of climate change on water resources and droughts has been performed in a small-scale international region in NW of the Iberian Peninsula. Twenty EURO-CORDEX climate projections were used for three future periods (2010–2040, 2040–2070 and 2070–2100) under RCP4.5 and RCP8.5. The bias of the climate projections was analysed and corrected using quantile mapping (QM) technique. A distributed model at a spatial resolution of 500 m was used for the hydrological simulation. The ensemble of projections simulated a reduction in runoff of –8.7% in RCP4.5 and –15.8% in RCP8.5 by the end of the century. High discrepancies between projections, due to the uncertainties of the process, cause differences within the river basin, but reductions in runoff are generalised all over the territory by 2100. The frequency and severity of droughts, estimated through a probabilistic approach, are likely to increase by the end of the century.

Keywords: climate change impact; hydrologic simulation; bias correction; water resources; droughts; international river basin management; drought frequency estimation; drought severity estimation.

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1 Introduction

The studies about the impact of climate change on water resources have become a very useful tool to estimate the changes in water availability in the future and therefore to take planning measures according to the estimations. However, at a regional scale there is still a high uncertainty on water availability under climate change scenarios, with many regions in the world with a high probability of suffering water scarcity in the future (Caretta et al., 2022).

General circulation models (GCMs) are a powerful tool to evaluate the evolution of global climate in the future. However, it is well known that GCM outputs are not suitable for direct use for the hydrological impact assessment due to their coarse resolution, which does not allow to simulate properly topography or some climatological processes affecting the runoff estimation at a river basin scale (Christensen et al., 2008; Hay et al., 2002; Minville et al., 2008), leading to unrealistic results of limited use (Piani et al., 2010a, 2010b).

Different techniques have been developed to downscale the GCMs' output using both statistical and dynamical downscaling (see Fowler et al., 2007 and Maraun et al., 2010 for reviews of their application to hydrological simulations). Statistical downscaling is based on statistical relationships between large-scale and local weather (Maraun et al., 2010), whereas dynamical downscaling is based on Regional Climate Models (RCMs) using GCM output as boundary conditions, simulating the climatic conditions in a specific region and therefore providing climate variables at a higher resolution than GCMs (Hay et al., 2002). RCMs have been widely used in the last years, since Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative was launched, aiming to provide a model evaluation and climate projection framework to connect GMCs and climate data users communities (Giorgi et al., 2009).

The European branch of CORDEX platform, EURO-CORDEX (Jacob et al., 2014), is the result of the collaboration of different European climate research institutions, which oversees the design and coordination of ensembles of RCM projections and provides regional climate projections at an unprecedented size and resolution (0.11º EUR-11 y 0.44º EUR-44) (Jacob et al., 2020). In the last years, the EURO-CORDEX climate projections have been widely used for research and other applications (Vautard et al., 2021), but there is still a need to increase the attention to their application to small-scale regions, especially those with a complex orography (Mascaro et al., 2018).

Despite the improvement of the performance in the last years of both GCMs and RCMs, they still present a bias with respect to observed climate. Failures in the conceptualisation of key physical processes, as well as the discretisation of the terrain into cells and the averaging of the variables in the cells, simplifying the natural heterogeneity of the natural system, have been pointed out as possible causes of the bias in these projections (Li et al., 2010; Teutschbein and Seibert, 2012). Some studies refer that RCMs tend to overestimate the frequency of precipitation (PRE) and the occurrence of light rainfall while underestimating heavy rainfall (Chen et al., 2013; Fowler et al., 2007; Piani et al., 2010a), as well as others highlight that the accuracy of RCMs depends on seasonality and the region of study (Maraun et al., 2010). These biases can have an important effect when simulating hydrological systems, e.g., snow melt affecting peak discharges or too much PRE forcing too much soil moisture and therefore more floods (Berg et al., 2012).

Different techniques have been proposed to tackle this bias, from linear scaling to more sophisticated techniques based on the comparison of the distribution of observed and simulated values. Many studies have carried out a review to compare these techniques (Berg et al., 2012; Chen et al., 2013; Themeβl et al., 2011; Teutschbein and Seibert, 2012), being the general conclusion that the best fit between simulated and observed data was reached by quantile mapping (QM) technique. This technique consists of correcting the distribution function of the simulated values to fit the distribution of the observed values by applying a transfer function, normally by fitting both simulated and observed series to theoretical functions. Within the QM concept, there are different techniques, depending on how the transformation function is applied.

The goal of this study is to apply these advanced techniques in the assessment of the water resources availability under climate change scenarios in a small-scale region in the Northwest Iberian Peninsula, shared between Spain and Portugal. The assessment was conducted using climate projections from EURO-CORDEX, after analysing their performance to simulate the regional climate. In this study, we first explore the observed bias in the projections, as well as the effect of the bias correction in the performance of the climate projections to describe the current climate. Second, we analyse the changes in the hydrological in the future, observing the effect of bias correction on these simulations, and the uncertainties associated to the whole process. Then, the simulated runoff for the future series is used to estimate the spatial distribution of the changes in annual river discharge, as well as the changes in the frequency and severity of droughts.

This paper is organised as follows. Section 1 serves as an introduction to the study. Section 2 explains the methodology, introducing the study area and the climate projections and the observational data utilised, as well as the hydrological model and the methodology used for the droughts analysis. Section 3 includes the results and discussion and finally, Section 4 deals with the summary and conclusions.

2 Methodology

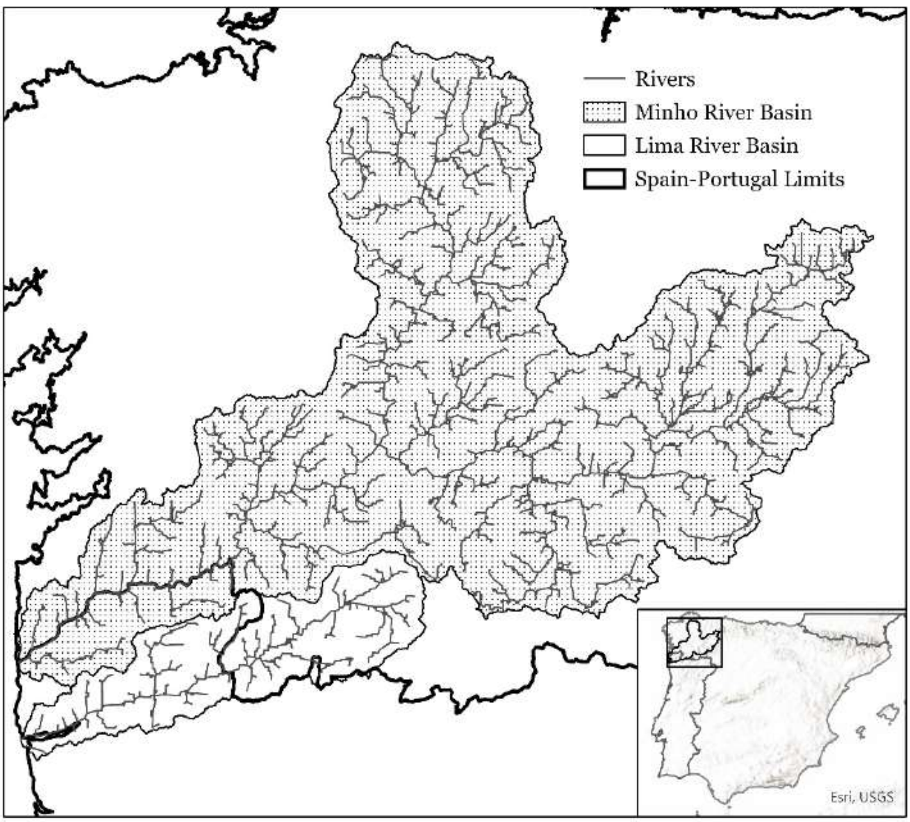
2.1 Study area

The study area is the Minho-Lima International River Basin, located in the northwest of the Iberian Peninsula (Figure 1). The total area of the river basin is 19,551 km^2, of which almost 90% corresponds to Spain and 10% to Portugal, whereas 87.3% corresponds to the Minho River Basin and 12.7% to the Lima River Basin. Orography is complex, presenting a difference in altitude from sea level to more than 2000 m in the mountain range in the eastern part of the river basin. Climate is oceanic in most part of the river basin except in the eastern part, where oceanic and continental Mediterranean climates are mixed. Considering the reference period between 1940/41 and 2011/12 used in the River Basin Management Plan (CHMS, 2015), the average annual PRE is around 1256 mm yr^{-1}, with a minimum of 800 mm yr^{-1} and a maximum of 1970 mm yr^{-1}. Average annual temperature is around 11ºC, with an average of 5ºC in winter and 17ºC in summer. Average available water resources in the river basin are around 769 mm yr^{-1} (14273 hm^3 yr^{-1}) for the same period, with a maximum of 1449 mm yr^{-1} (26910 hm^3 yr^{-1}) and a minimum of 329 mm yr^{-1} (6111 hm^3 yr^{-1}).

2.2 Climate simulations vs. observed data

Climate simulations were conducted using 20 different EURO-CORDEX climate projections, as result of ten different combinations of GCMs and RCMs (Table 1) under two climate change scenarios or Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCPs were defined for the Fifth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC) (Moss et al., 2010). All selected climate projections provide daily values of PRE, maximum (TMX) and minimum temperatures (TMN) with a spatial resolution of ~12.5 km (0.11º, CORDEX-11). In this study, daily values were aggregated monthly to work at the same time scale as the hydrological model.

Figure 1 Extent of the region of study, formed by the Minho and Lima International River Basin



To evaluate the ability of the climate projections to simulate climate in the region, the simulated values of PRE, TMX and TMN during the historical period were compared with ER19 dataset, used for the assessment of water resources in natural regime in Spain (CEDEX, 2020). ER19 dataset includes the monthly values of PRE, TMX and TMN for the 1940/41–2017/18 period covering the whole Iberian Peninsula with a spatial resolution of 500 m. These data were interpolated (CEDEX, 2020) using data from the Spanish Meteorological Agency (AEMET) and the Portuguese System of Water Resources Information (SNIRH). A 30-year-period was selected as the baseline period, considering hydrological years: 1970/1971-1999/2000. Please note that the hydrological year is considered to start in October (when soil moisture gets its minimum values after summertime) and ends in September. Moreover, the future period was divided in three 30-year-subperiods for the impact analysis: 2010/2011–2039/40, 2040/2041–2069/70 and 2070/71–2099/2100, hereafter referred as 2010–2040, 2040–2070 and 2070–2100, respectively, for simplification. Please note that MC and MS projections end in 2099, so a 29-year-period ending in 2098/99 was assumed in these cases for the 2070–2100 period.

Bias correction of climate projections was performed using QM technique based on empirical quantiles for PRE, TMX and TMN. The R package '*qmap*' (Gudmundsson, 2014) was used for this purpose. An interpolation process was necessary to use the climate projections data (~12.5 km) as an input into the hydrological model (500 m). Following the process described in Barranco (2011) and shown in Figure 2, monthly values of PRE, TMX and TMN were downscaled using monthly patterns for each variable. These patterns are represented by monthly average values of each variable considering a 30-year-period obtained from the Iberian Climatic Atlas (AEMET-IM, 2011).

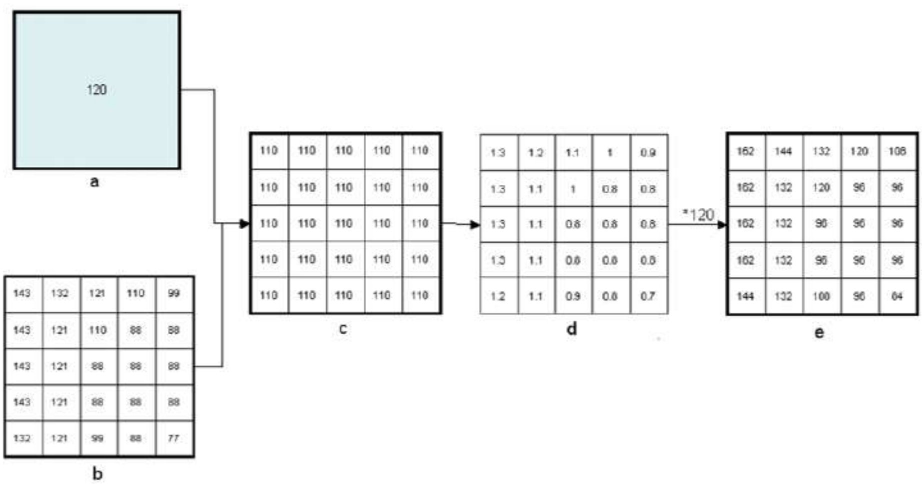
Table 1 List of the combinations of GCMs and RCMs used in the study, indicating the ID and the periods available in each simulation. In bold letters, the acronyms of the institution/organisation developer of the model in each case. CNRM: Centre National de Recherches Météorologiques (France); CERFACS: Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (France); ICHEC: Irish Centre for High-End Computing (Ireland); EC: Earth Consortium (Europe); IPSL: Institute Pierre Simon Laplace (France); MOHC: Met Office Hadley Centre (UK); MPI-M: Max Planck Institut für Meteorologie (Germany); CLMcom: Climate Limited-area Modelling-Community (international); SMHI: Sveriges meteorologiska och hydrologiska institut (Sweden); KNMI: Koninklijk Nederlands Meteorologisch Instituut (Netherlands); CSC: Climate Service Centre (Germany)

GCM	*RCM*	*ID*	*Historical period*	*Future period*
CNRM-CERFACS-CNRM-CM5	**CLMcom**-CCLM4-8-17	CC	1950–2005	2006–2100
CNRM-CERFACS-CNRM-CM5	**SMHI**-RCA4	CS	1970–2005	2006–2100
ICHEC-EC-EARTH	**KNMI**-RACMO22E	HK	1950–2005	2006–2100
IPSL-IPSL-CM5A-MR	**IPSL**-INERIS-WRF331F	II	1951–2005	2006–2100
IPSL-IPSL-CM5A-MR	**SMHI**-RCA4	IS	1970–2005	2006–2100
MOHC-HadGEM2-ES	**CLMcom**-CCLM4-8-17	MC	1950–2005	2006–2099
MOHC-HadGEM2-ES	**SMHI**-RCA4	MS	1970–2005	2006–2099
MPI-M-MPI-ESM-LR	**CLMcom**-CCLM4-8-17	PC	1950–2005	2006–2100
MPI-M-MPI-ESM-LR	**MPI-CSC**-REMO2009	PR	1950–2005	2006–2100
CNRM-CERFACS-CNRM-CM5	**CNRM**-ALADIN53	CA	1950–2005	2006–2100

2.3 Hydrological model

The hydrological model used for the study was the Integrated System for Precipitation-Runoff Modelling (SIMPA), a distributed model extensively used in Spain to evaluate water resources at a national level (Álvarez-Rodríguez et al., 2005; CEDEX, 2020; Estrela and Quintas, 1996; MIMAM, 2000; Ruiz-García, 1999) and to assess the impact of climate change on hydrological cycle (CEDEX, 2010, 2017). It simulates the soil water balance for each cell at a spatial resolution of 500m in a monthly basis. Input data are monthly PRE and potential evapotranspiration (PET), and it estimates snow production and melting, actual evapotranspiration (AET), soil moisture, infiltration and runoff.

Figure 2 Interpolation process based in the patterns factor method (precipitation values as an example): (a) value of an EURO-CORDEX grid cell (12 km resolution); (b) pattern values (500 m resolution) associated to the EURO-CORDEX grid cell; (c) average pattern value of the EURO-CORDEX cell considering all the pattern values associated to that cell; (d) conversion factor (relationship between b and c, which represents the spatial distribution of the variable in the ~12 km grid cell) and (e) final result applying conversion factors to the original EURO-CORDEX value (see online version for colours)



Source: Taken from Barranco (2011)

2.4 Drought analysis

To assess the impact of climate change on droughts frequency and severity, the changes in the return period of droughts events and the water deficit associated were analysed in all climate simulations for the baseline period and for each of the future periods. The methodology used was the one described in Salas et al. (2005), based itself on the application proposed by Yevjevich (1967) of the theory of runs to the occurrence of droughts events. This methodology has been previously used in other studies in Spain (CEDEX 2010, 2017).

To identify the return period of droughts events, synthetic series were created from the simulated runoff series, with a sufficient long period (6 million months) to statistically infer the frequency of occurrence of these events. These series were created with the same statistical features that the simulated runoff series for each period and each climate simulation through an ARIMA model using the functions available in the '*forecast*' R package (Hyndman and Khandakar, 2008). The multi-year droughts events were identified as those whose multi-year-average runoff was below the median runoff in each case (simulation, period and scenario). Then a duration (number of years) and a water deficit (difference between average annual runoff of the event and the median of the runoff series in each case) were associated to each event, obtaining two droughts-defining-variables that can be fitted to a probability density function. This function can be defined as the bivariate density distribution function ($f_{D,L}(d, l)$) of length L and accumulated deficit D, expressed as the product of the conditional distribution of D for a given L ($f_{D|L}(d)$) by the marginal distribution of L ($f_L(l)$) (equation (1)).

$$f_{D,L}(d,l) = f_{D|L}(d)\, f_L(l) \tag{1}$$

L is a discrete variable assumed to follow a geometric distribution, whereas D is a continuous variable assumed to follow a gamma distribution. Integrating the density function, we get the distribution function that allows to obtain the cumulative probability for a drought of any deficit ($D > Do$) and a given duration ($L = Lo$).

For each L category (1–5 years), there is a corresponding set of D values, thus a gamma distribution can be fitted for each category. The parameters of the gamma distribution are obtained by applying the maximum likelihood method to the series of each category.

Then, the return period in years (T) can be estimated. The difficulty lies in obtaining the annual probability of an n-year-drought. Salas et al. (2005) proposed to consider T as the mean of the interarrival times, measured as the time between the onset of each drought event. Considering that droughts events are independent, T can be calculated from equation (2) (see Salas et al., 2005 for rationale).

$$T = \frac{1}{p_1 p_0 P(D > D_0, L = L_o)} \tag{2}$$

where p_1 and p_0 are the probabilities of having a wet and dry year respectively.

Finally, the frequency-severity curves of droughts for all periods are represented individually for each L category (1–5 years), plotting the severity of the droughts (represented by the deficit considered as a % of the median of the simulated runoff series in each period) against the estimated frequency (T).

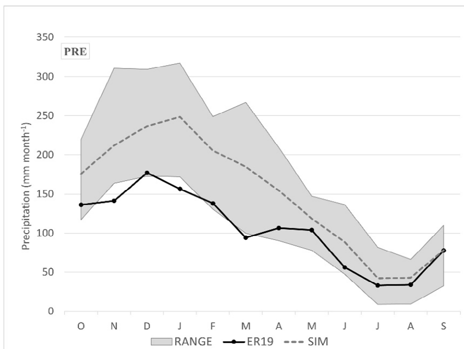
3 Results and discussion

3.1 Evaluation of GCM-RCMs performance. Effect of bias correction

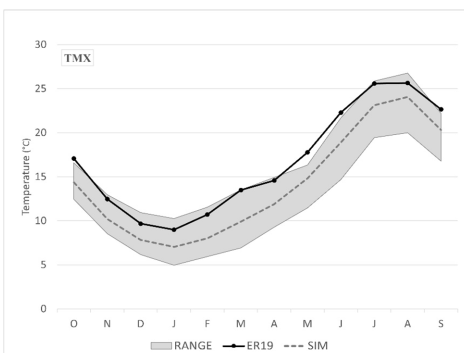
To assess the bias in the climate projections, monthly and annual simulated values were compared to the observed (ER19 dataset) during the baseline period, considering in both cases the averaged values for the whole river basin territory. The comparison of monthly values permits to analyse the ability of the projections to reproduce the seasonality in the region (Figure 3, simulated values represented by the mean and the range of the ensemble, for clarification in the representation). The analysis of the changes of annual values provides an overview of the ability to reproduce the climate. In this case, relative differences in the main statistics (mean, standard deviation and maximum and minimum values) between simulations and observed data were considered, before and after bias correction, separately for each model in order to be able to differentiate their performance. The results are discussed with the outcomes of some studies evaluating the EURO-CORDEX RCM ensemble.

Figure 3 Monthly values of precipitation (PRE), maximum temperature (TMX) and minimum temperature (TMN) of observed values (black solid line) and simulated (grey area: range of simulated values, grey dashed line: mean of the ensemble) during the baseline period (1970–2000). The values are averaged for the whole river basin territory

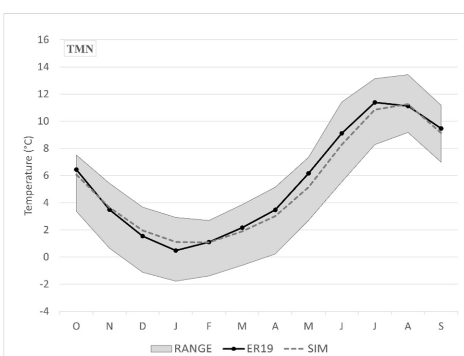
a)



b)



c)



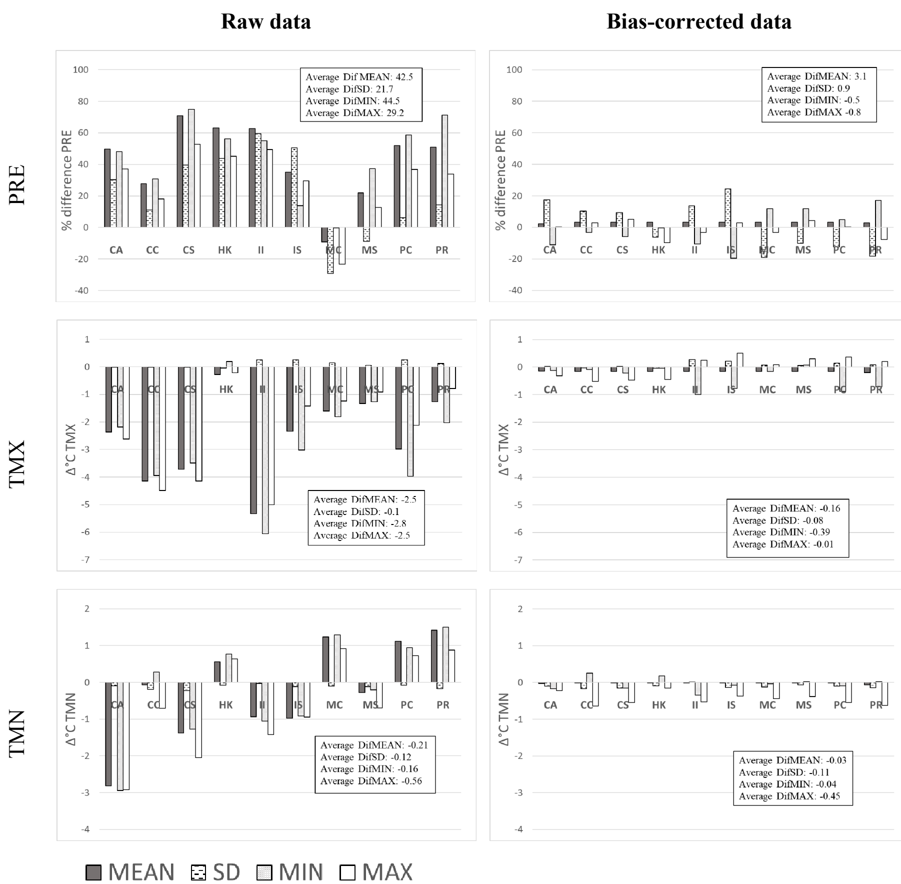
The climate simulations were able to reproduce reasonably well the seasonality in TMX and TMN, whereas PRE presented in general a more accused seasonality than the observed. Simulated values of monthly PRE were higher in winter and lower in summertime in all simulations, as it happens in observed data (Figure 3(a)). However, the magnitude of PRE was notably overestimated during the wetter period -from October to March-, with a high discrepancy between projections -almost 150 mm in some cases- during this period. When PRE decreases -from May to September- the simulations present a better performance, with an average for the ensemble similar to the observed and a narrower range of simulated values. Similar results were observed for this same region in CEDEX (2017). They are also similar to those obtained by Kotlarski et al. (2014) and Vautard et al. (2021), where different ensembles of EURO-CORDEX RCM projections were analysed at European-region scale, finding in both cases a general overestimation of PRE, indicating Vautard et al. (2021) that the positive bias was especially high in winter in some areas, including north of Iberian Peninsula. However, Mascaro et al. (2018), who evaluated the performance of simulated precipitation by EURO-CORDEX projections in a small-scale region (Sardinia island, ~24000 km^2), concluded that most models underestimated PRE in winter and autumn, whereas overestimation was obtained in summer. In their conclusions, they cite other studies with similarities and discrepancies in their outcomes (see point 3 of conclusions in Mascaro et al., 2018 for references), pointing out as a possible explanation the differences in the GCM-RCM selection and the setup of the climate experiments, the region of study and its extent, as well as the reference dataset used in each case (Mascaro et al., 2018).

In our study, the overestimation during the wetter period is translated into a positive bias of the total annual values, with some projections -CS, HK, II- simulating an annual mean value over + 60% respect the observed and only one -MC- registered a negative bias (–9%) (Figure 4). The average of the differences of the ensemble in the annual mean and the annual minimum was over +40%, whereas the annual maximum and the annual standard deviation were around +29% and +20% of the observed, respectively. The range of the discrepancies between projections (–9 to +71%) is similar to the one obtained for this region in CEDEX (2017) (–1 to +73%). The range reported by Kotlarski et al. (2014) for the Iberian Peninsula was narrower (from –20 to +40% for the Iberian Peninsula). Likewise, Herrera et al. (2020), who evaluated eight EURO-CORDEX RCMs for the Iberian Peninsula, obtained differences from –21% to +53%. The differences can be explained by the different reference datasets used in each case (see Herrera et al., 2020 for a comparison of different reference datasets), as well the different extent of the region considered in each case.

After bias correction the average difference was notably reduced for all the statistics, being around +3% difference in the mean, and less than ±1% in the rest. The difference in the mean remained quite similar in all the projections, but not in extreme values and standard deviation, where there were some differences between projections, especially in the standard deviation, ranging from –20% (MC) to +25 % (IS) difference. This would indicate that empirical QM performs better for the mean than for dispersion measures. This circumstance is inherent to many bias correction techniques, as was analysed by Teutschbein and Seibert (2012), who evaluated different bias correction techniques, and

Gundmundsson et al. (2012), who compared different QM techniques, concluding that the empirical QM was the technique which showed the best performance.

Figure 4 Relative difference of the simulated mean, standard deviation (SD), minimum (MIN) and maximum (MAX) values against the observed during the baseline period in the raw data (left) and in the bias-corrected data (right). Units: % for PRE; °C for temperatures. The values are averaged for the whole river basin territory



Regarding the bias of the temperatures, underestimation was observed every month in the simulated TMX, being the range of the ensemble quite homogeneous during all year (Figure 3(b)). Consequently, annual TMX was also underestimated by all the projections in the raw data except HK, which presented very close values to the observed (Figure 4). On the other hand, the II projection simulated an annual mean TMX of 5.3ºC below the observed. The average of the annual mean TMX considering all the projections was 2.5ºC below the observed, with a similar range of difference in the minimum and maximum values, whereas the simulated annual standard deviation took similar values to the observed in all cases. Bias correction produced a drastic reduction of differences in all statistics, being close to zero as average in all cases. The difference in the mean was quite homogeneous in all projections, whereas differences in standard deviation and extreme values presented a slightly higher range of values.

The TMN values were well simulated considering all simulations as an ensemble, with an average value quite similar to the observed during all year (Figure 3(c)). However, this average value is the result of the different behaviour of each projection, with some overestimating TMN and some underestimating it. In some cases, this difference can be relevant, as it is the simulation of temperatures below zero during wintertime of projection CA (not shown), a circumstance with severe implications in the water balance that does not occur in the observed data. This different behaviour can be observed as well in the annual values. CA projection predicted annual mean TMN around 3ºC less than observed, both in mean and extreme values (Figure 4). After bias correction, all the projections presented almost no differences in all statistics.

These results are concordant to those reported by Kotlarski et al. (2014), who estimated a bias up to –2ºC for most models and seasons, despite the differences observed between models. Vautard et al. (2021) found a substantial underestimation on TMX in some regions, including the Iberian Peninsula, whereas the bias in TMN was different in each case, so they concluded it was model dependant. Grouping the results by same GMC or RCM, they found that RCM had a stronger influence on this bias than the GCM.

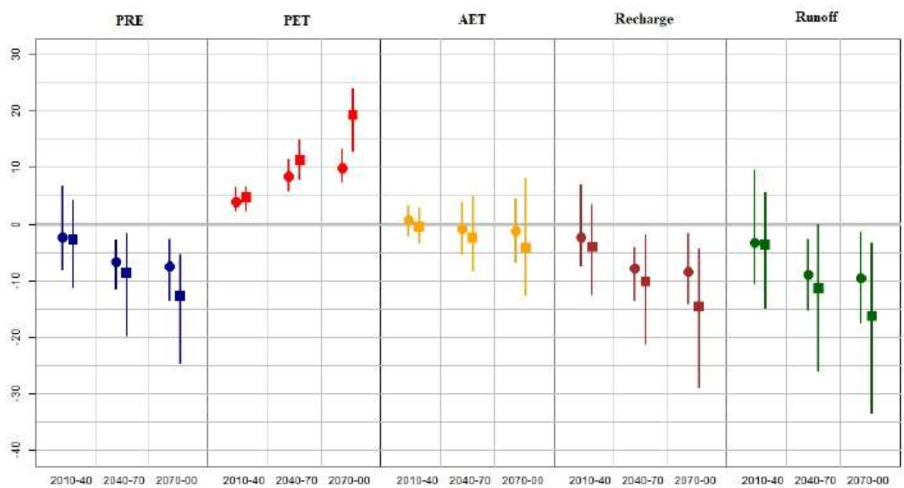
3.2 Change in hydrological variables. Effect of bias correction on hydrological simulation

The impact of climate change on the hydrological variables has been measured as the relative change in the variables during the future periods with respect to the 1970–2000 baseline period. Monthly and annual values of these changes, spatially averaged for the whole river basin, were analysed, as well as the spatial distribution of the annual runoff changes. In all cases, the changes were averaged for each future subperiod (2010–2040, 2040–2070 and 2070–2100).

Tables 2 and 3 include the changes in mean annual values of average temperature (TEM) and PRE, respectively, simulated by each climate projection for each period and scenario, as well as the mean change of the ensemble. In this case, only the results after bias correction are provided, as they are very similar before and after bias correction. Considering the mean of the ensemble, in 2010–2040 there would be slight changes in the input variables, with PRE slightly reduced with respect to the baseline period (–1.4% in both scenarios) and an increase of around +1ºC in TEM in both scenarios. In 2040–2070 the changes would become more notable, with important reductions in PRE in both scenarios (–7.2% in RCP4.5 and –9.6% in RCP8.5) and a noticeable increase in TEM (+1.7ºC in RCP4.5 and +2.3ºC in RCP8.5). By the end of the century, the reduction in PRE simulated by the ensemble in RCP4.5 remains similar to the previous period, but in RCP8.5 the reduction becomes more severe, with a reduction of –14.2%. The increase in TEM would also be more accused in RCP8.5, with an increase of 4.1ºC with respect to the baseline period, double than the increase predicted in RCP4.5.

Figure 5 Relative change (%) for each future period with respect to the baseline period (1970–2000) in precipitation (PRE), potential evapotranspiration (PET), actual evapotranspiration (AET), groundwater recharge and runoff in the raw-data simulation (left) and the bias-corrected simulation (right). Points: mean of the ensemble; lines: range of all the simulations; circles: RCP 4.5; squares: RCP 8.5. The values are averaged for the whole river basin territory (see online version for colours)

Raw data simulation



Bias-corrected simulation

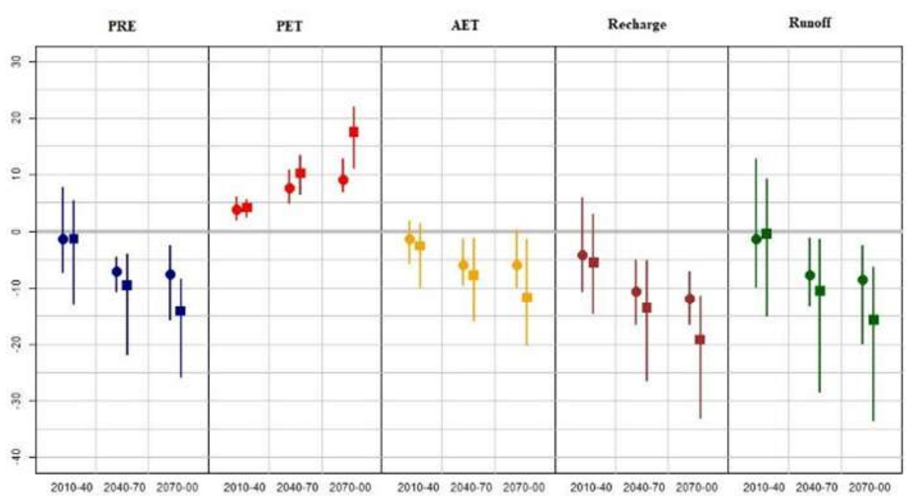


Figure 5 summarises the result of the hydrological simulation, showing the relative changes in the annual values of the main hydrological variables, averaged for the whole river basin, in each subperiod using both raw and bias-corrected data under RCP4.5 and RCP8.5 scenarios. The progressive reduction over the century simulated in PRE in both scenarios translates to the rest of the variables that depend on the amount of water available, like AET, groundwater recharge and total runoff. The decrease in the mean annual change in these variables gets more pronounced with time, being the reduction in the RCP8.5 scenario generally more severe than in RCP4.5. PET is the only variable that increases over time, due to the increase in the temperatures simulated by all projections. This increment does not translate to an increase in AET, because of the reduction of water availability due to having less PRE. The magnitudes of the means of the changes simulated by the ensemble in PRE, AET and runoff are similar for both raw and bias-corrected data simulations (Figure 5). However, the differences in the changes of AET and soil moisture are notable if considering raw or bias-corrected simulations. Table 4 shows the magnitudes of the changes in mean annual values of runoff (only bias-corrected results, as they are very similar to raw simulations). In 2010–2040, the reduction would be small under both scenarios (–1.3% in RCP4.5 and –0.5 in RCP8.5), but in the next periods the reduction will be more severe (–7.8% for RCP4.5 and –10.6% for RCP8.5 in 2040–2070 and –8.7% for RCP4.5 and –15.8% for RCP8.5 in 2070–2100).

Table 2 Change (Δ°C) in TEM for every future period respect to baseline period (1970–2000) under RCP4.5 and RCP8.5 simulated by each projection and the mean of the ensemble. The values are bias corrected and averaged for the whole river basin territory

TEM (Δ°C)	*Period*	*CA*	*CC*	*CS*	*HK*	*II*	*IS*	*MC*	*MS*	*PC*	*PR*	*MEAN*
RCP 4.5	2010–2040	0.9	0.8	0.9	1.1	1.0	1.2	1.3	1.3	0.6	0.6	1.0
	2040–2070	1.5	1.4	1.4	1.8	1.4	1.8	2.5	2.4	1.2	1.2	1.7
	2070–2100	2.1	1.9	2.0	2.0	1.7	2.2	2.9	3.0	1.8	1.8	2.1
RCP 8.5	2010–2040	0.8	0.7	0.7	1.4	1.0	1.2	1.5	1.5	1.0	1.0	1.1
	2040–2070	2.3	2.0	2.2	2.4	1.8	2.5	3.1	3.1	2.1	2.0	2.3
	2070–2100	4.0	3.6	4.1	4.2	3.3	4.1	5.0	5.0	3.7	3.6	4.1

Table 3 Relative change (%) in PRE for every future period respect to baseline period under RCP4.5 and RCP8.5 simulated by each projection and the mean of the ensemble. The values are bias corrected and averaged for the whole river basin territory

PRE (Δ%)	*Period*	*CA*	*CC*	*CS*	*HK*	*II*	*IS*	*MC*	*MS*	*PC*	*PR*	*MEAN*
RCP 4.5	2010–2040	–2.5	–4.0	–2.8	–2.0	–7.3	–7.2	6.8	7.8	–0.9	–1.4	–1.4
	2040–2070	–8.3	–10.7	–8.2	–6.5	–4.6	–5.7	–10.6	–7.3	–4.6	–5.3	–7.2
	2070–2100	–2.5	–6.7	–6.5	–5.8	–6.9	–5.1	–8.7	–4.6	–15.7	–14.3	–7.7
RCP 8.5	2010–2040	2.4	–0.4	2.1	1.3	–4.4	–1.0	4.9	5.4	–13.0	–10.9	–1.4
	2040–2070	–6.3	–7.3	–9.5	–4.4	–5.5	–4.2	–21.7	–19.5	–11.0	–6.6	–9.6
	2070–2100	–8.4	–16.8	–12.7	–9.1	–10.5	–11.9	–25.8	–21.2	–15.1	–10.7	–14.2

The range of the magnitude of the changes simulated by the projections (Figure 5) shows large discrepancies between models. PET (derived from TMX and TMN) shows an increasing variability with time, whereas PRE presents a wide range of simulated values in all periods, which is translated to the rest of hydrological variables. Bias correction did not affect this variability, showing both simulations (raw and bias-corrected data) similar ranges, which indicates that bias correction did not modify the climate signal of the projections. In the case of PRE, the difference in the simulated change is quite large in all periods in both scenarios, ranging from 6% to 18% points of difference. In the case of PET, this range increases progressively with time, being 3–4 points of difference in 2010–2040 and 6–10 in 2070–2100 in the two scenarios. The range of variability of AET, similarly to PET, increases over time, although the range of values is noticeable larger due to the influence of PRE, ranging from 7 to 11 in 2010–2040 to 10–18 in 2070–2100 in the two scenarios. In this case, bias correction would have some influence, as some of the projections would estimate an increase in AET in all the periods in the raw simulation, whereas after bias correction they generally simulate decreases in AET. The variability of groundwater recharge and runoff is especially high in RCP8.5, where the range of values in 2040–2070 and 2070–2100 would be up to 21 (groundwater recharge) and 27 (runoff) percentage points of difference, which is derived from the complexity of simulating these processes.

Table 4 Relative change (%) in runoff for every future period respect to baseline period under RCP4.5 and RCP8.5 simulated by each projection and the mean of the ensemble. The values are bias corrected and averaged for the whole river basin territory

RUNOFF (Δ%)	*Period*	*CA*	*CC*	*CS*	*HK*	*II*	*IS*	*MC*	*MS*	*PC*	*PR*	*MEAN*
RCP 4.5	2010–2040	–5.4	–4.0	–4.1	–4.6	–9.9	–9.7	10.6	12.8	2.1	–0.8	–1.3
	2040–2070	–11.2	–12.1	–9.8	–9.9	–3.8	–4.6	–13.3	–10.0	–1.2	–2.4	–7.8
	2070–2100	–3.7	–6.7	–8.6	–9.6	–5.0	–2.5	–8.8	–4.0	–19.8	–17.8	–8.7
RCP 8.5	2010–2040	3.3	2.2	3.1	4.3	–5.0	0.4	7.3	9.2	–15.0	–14.4	–0.5
	2040–2070	–9.5	–6.3	–12.7	–4.6	–3.5	–1.3	–28.4	–27.7	–7.9	–3.8	–10.6
	2070–2100	–13.1	–17.6	–17.0	–7.3	–11.7	–10.4	–33.6	–29.2	–11.8	–6.3	–15.8

The changes in the hydrological variables for each period and scenario follow the same pattern, with small differences in the magnitude and the range of values than those reported in Barranco et al. (2014) for the whole Spanish territory, despite the differences in the setup of the experiment (different CGMs, statistical downscaling, different climate change scenarios). In that case, only changes in the variables based in simulated values for both the future and baseline period were provided, as bias correction was not performed. However, they did not find clear differences in the seasonality of the simulated runoff compared to the observed. This could be explained by the different biases of the GCMs simulations. In that case, precipitation was underestimated (–19.3% as average), therefore there is no excess of water simulated that could affect AET and soil moisture. This issue highlights the recommendation of Maurer and Pierce (2014), among other studies, of analysing the convenience of performing the bias correction in each case. In this regard, Teutschbein and Seibert (2012) analysed the effect of bias correction on the monthly mean streamflow in six small catchments, finding a general improvement of the QM bias-corrected simulations, even though the performance was unequal in some cases.

3.3 Uncertainties of the process

The variability of the results is the outcome of different sources of uncertainties accumulated during the whole process: the GCMs and RCMs simulations, the RCPs scenarios, the bias correction, the interpolation process, the hydrological model and parameterisation, and the variability of the natural system. Kay et al. (2009) analysed the sources of uncertainty in hydrological climate change impacts, concluding that GCMs structure was the most important, especially when some of the GCMs showed values extremely high. In that case, when the results of that GCM were removed, the other sources became more significant, but still uncertainties from future climate modelling were higher than those derived from hydrological modelling. Barranco et al. (2014) also pointed out GCMs as the source of uncertainty with most influence, as simulations derived from same GCM but different emissions scenario and downscaling method showed similar results. These conclusions are coherent with our results, where projections that simulate a different behaviour than the rest of the ensemble are normally derived from the same GCM, even after bias correction. For instance, MC and MS projections –both derived from MOHC-HadGEM2-ES- simulate an important increase in PRE and runoff for 2010–2040 in RCP4.5 (Table 2), whereas the rest of projections simulate reductions (except PC, which simulates a slight increase in runoff). Within these reductions, they are notably higher in the II and IS projections –both derived from IPSL-CM5A-MR-. In the RCP8.5, MC and MS projections also show important discrepancies with the rest of the ensemble, simulating strong reductions in PRE and runoff in 2040–2070 and 2070–2100, whilst the rest of projections present lower values of reduction. PC and PR projections -derived from MPI-ESM-LR, also present some discrepancies with the rest (stronger reduction of PRE and runoff by 2070–2100 in RCP4.5).

Regarding the EURO-CORDEX projections, Vautard et al. (2021) explored the influence of GCMs and RCMs (without bias correction) in the results by grouping the evaluation metrics by the projections of the same GCM or RCM. They found a high variability among European regions but concluded that in general RCMs do not improve significantly over GCMs in terms of mean biases on precipitation. One reason could be the bias that RCMs themselves introduce in the results, as Kotlarski et al. (2014) or Mascaro et al. (2018) describe. These biases lead to certain level of uncertainty that even after bias correction produce a high variability between models. Analysing the models as an ensemble and not individually permits to reduce this uncertainty (Teutschbein and Seibert, 2010).

Bias correction, whilst effective, also introduces some uncertainty in the process (Pastén-Zapata et al., 2020). Besides, QM has some limitations that must be considered when analysing the results. The main one is the assumption of stationary condition of the bias detected in the climate projections during the baseline period (Teutschbein and Seibert, 2012, 2013), which means to assume that the transfer function will be constant in the future, which may not hold (Li et al., 2010). In this regard, the choice of the training period is also a key question when applying QM (Lafon et al., 2013). To solve this issue, some authors validated the bias correction performing a cross-validation check, using different periods of the training period to check the consistency of the correction (Li et al., 2010, Themeβl et al., 2011), obtaining positive results, which indicates the robustness of the method. Another issue is the adjustment of the extreme values to those observed during the training period (Themeβl et al., 2011). Some studies point out that it modifies the extreme precipitations trends -not the mean- of the climate models (Maurer and Pierce, 2014; Cannon et al., 2015), which could be the cause of the amplification of the errors in the modelled runoff (Teng et al., 2015). In our study, though, it is not a matter of importance due to the monthly scale of the study, which reduces the influence of daily extreme values.

Hydrological modelling is another source of uncertainty, due to missing processes in the model structure or errors in the parameters' calibration (Clark et al., 2016). Although Mendoza et al. (2015) found that the hydrological model's choice led to substantial intermodel differences, they only analysed one GCM-RCM combination. Kay et al. (2009), however, compared different GCM-RCM combinations with different future emissions scenarios and hydrological models, concluding that the hydrological simulation was the least influential on the variability of the results. Minville et al. (2008) had already reached the same conclusion. In any case, to reduce the uncertainty due to hydrological modelling, Clark et al. (2016) suggests using multiple spatial configurations and multiple model parameter values. In our case, we consider this is unnecessary, as the SIMPA hydrological model has been calibrated and successfully implemented to assess water resources in Spain (CEDEX, 2020).

3.4 Spatial distribution of impacts on annual river discharge

Annual river discharge ($hm^3\ yr^{-1}$) was calculated for every cell of the hydrographic network as the volume of water flowing through the river cell during a year, considering all the runoff that is routed to every specific river cell. The river cells were considered as those with an average flow greater than $100\ l\ s^{-1}$ and with a catchment area greater than $10\ km^2$. To facilitate the identification of the potential impact of climate change on each area, the average of the relative annual change of the ensemble was represented for every future period in Figure 6 (only bias-corrected data shown), whereas Figure 7 shows the changes in annual river discharge in specific locations of the hydrographic network next to the main towns of the river basin (only bias-corrected data shown).

Figure 6 Mean change (%) in annual river discharge in the river basin simulated by the ensemble of projections for 2010–2040 (left), 2040–2070 (middle) and 2070–2100 (right) respect to 1970–2000 for both scenarios (RCP4.5 top; RCP8.5 bottom). Subdivisions show the exploitation systems in which the river basin is divided. The values are bias corrected (see online version for colours)

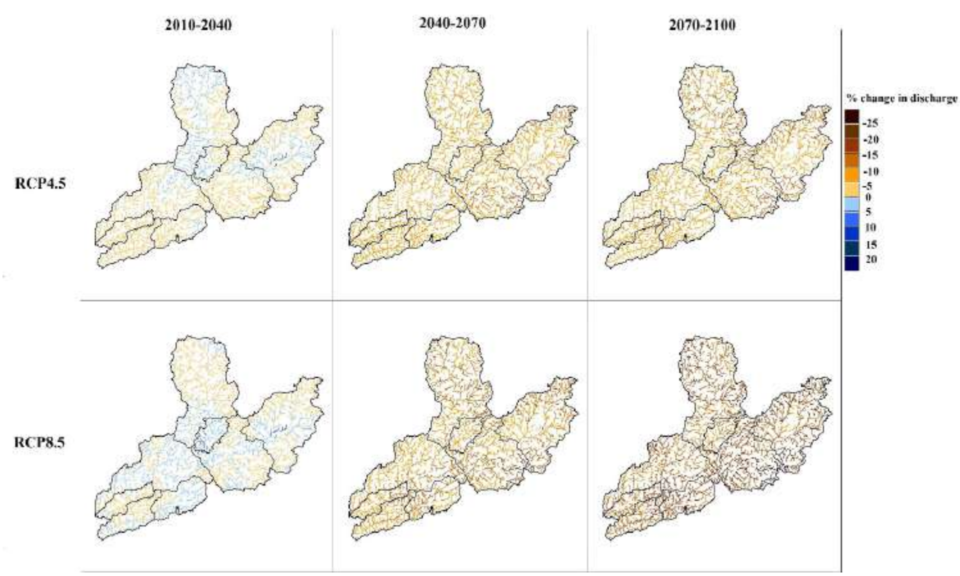
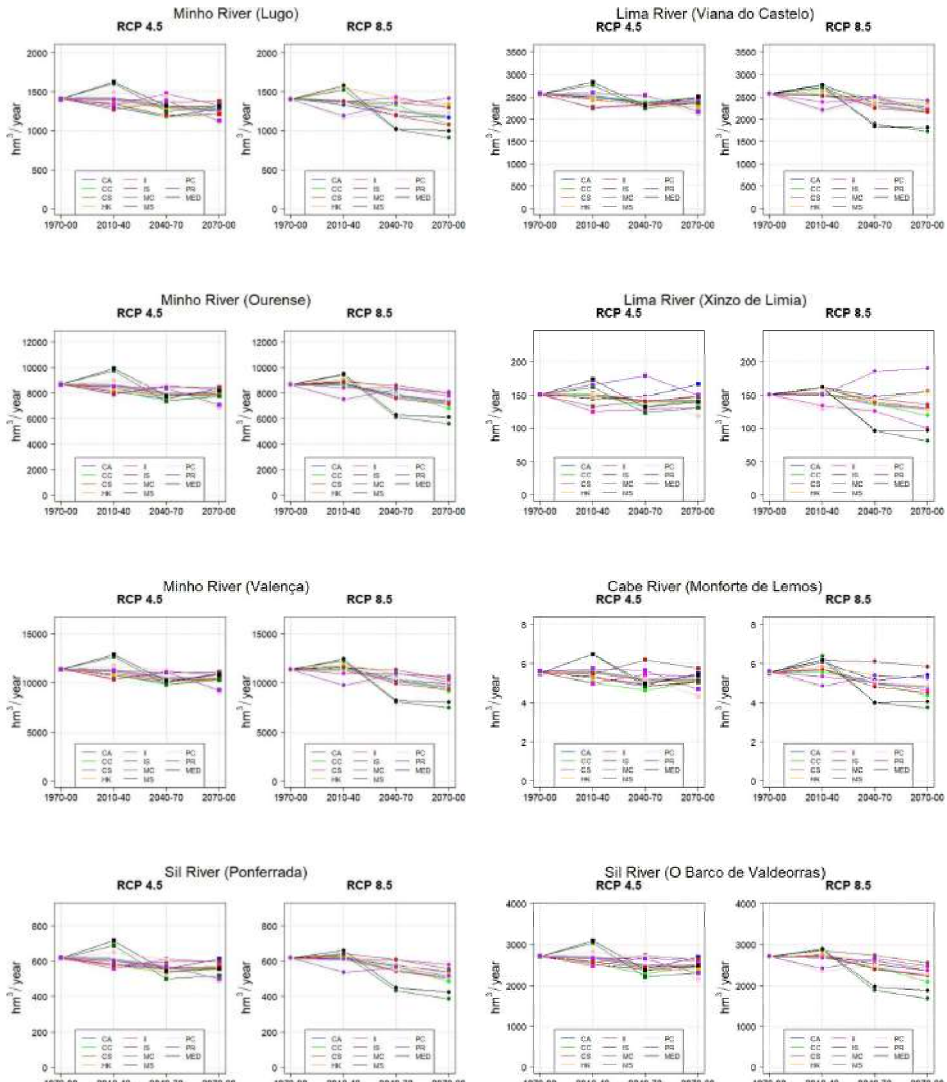


Figure 7 Evolution of water resources (hm^3 yr^{-1}) available at the main towns across the river basin simulated by each projection and the mean of the ensemble (MED) under RCP4.5 (graph on the left in each panel) and RCP8.5 (graph on the right). The values are bias corrected (see online version for colours)



In general, the ensemble of the projections simulates a progressive reduction with time of the annual river discharge all over the territory, being more accused by the end of the century in the RCP8.5 scenario. However, in 2010–2040 there are some areas where the ensemble simulates an increase in the streamflows up to +5%, being in RCP8.5 more extensive (most of the southern half of the river basin) than in RCP4.5 (central valleys of north and east). This is derived from the fact that there are some projections which indicate a strong increase in precipitation, translated into a strong increase in runoff. This is the case of the MC and MS projections, especially remarkable in RCP4.5, as they simulate a strong increase (up to +15%) in the annual river discharge all over the territory in both scenarios (not shown), affecting the mean of the ensemble and, therefore, the mean of the changes in annual river discharge in all locations (Figure 7).

For the following periods, in the RCP4.5 the reductions of annual river discharge are predicted all over the territory, mostly between –5 and –10%, with some mountainous areas with highest reductions in 2070–2100. Please note that in these areas the annual river discharge magnitude is small, so little changes in magnitude can lead to relative changes of certain magnitude. In RCP8.5 the reductions simulated by the ensembles are also generalised all over the hydrographic network. In this scenario, most of the river basin would register reductions between –15 and –25% by the end of the century. In this case, MC and MS projections simulate high reductions (over –25%) all over the territory (not shown), which increases the magnitude of the reduction of the ensemble. This generalised reductions in both scenarios and periods translate into an increasing reduction with time in annual river discharge in all locations (Figure 7). The variability of the magnitude predicted by the different projections remain high, especially for 2070–2100 in RCP8.5 scenario. It is remarkable that MC and MS projections simulate, as already commented above, much lower annual river discharge than the rest of projections for 2040–2070 and 2070–2100 periods.

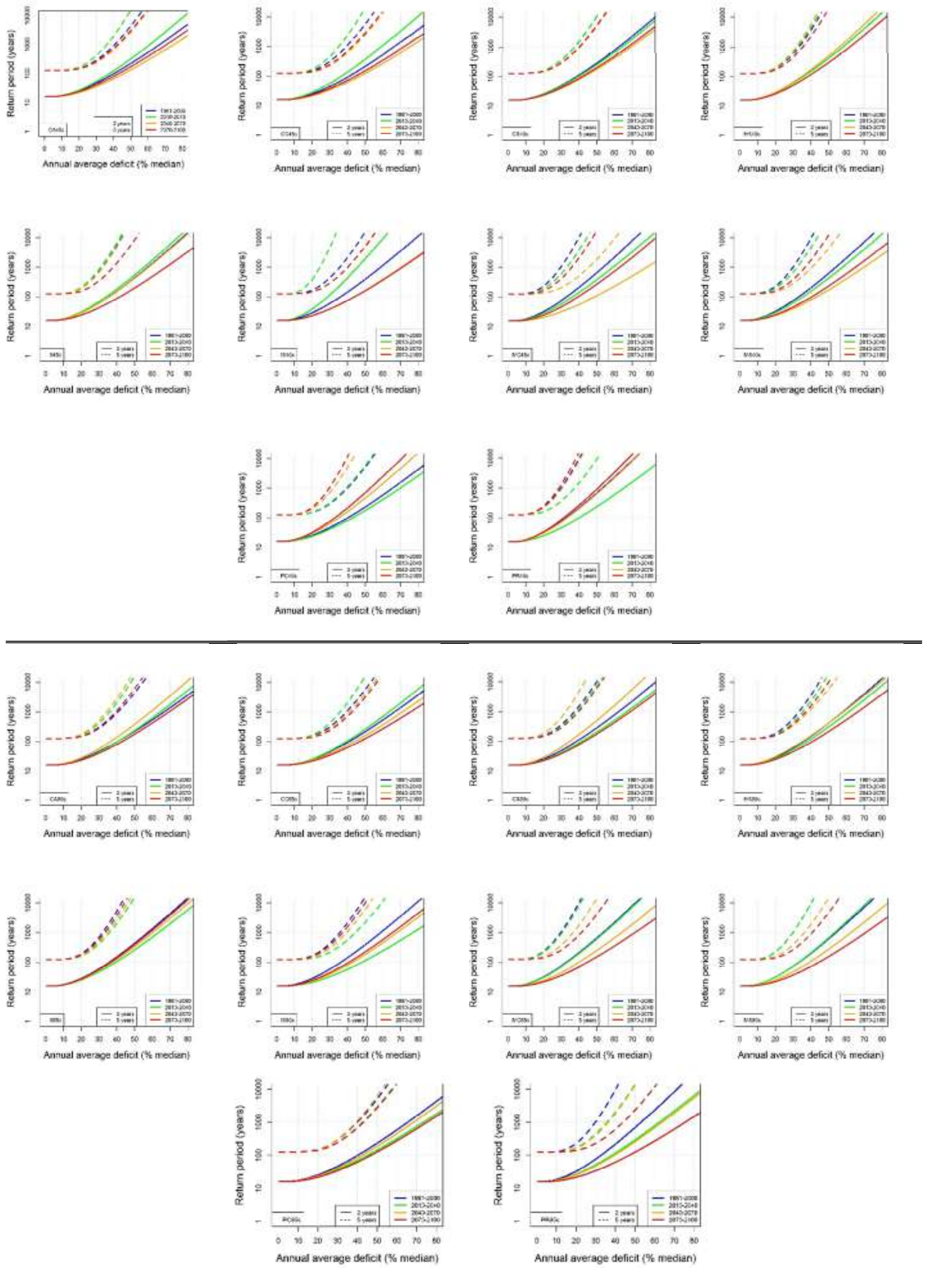
3.5 Impact on droughts frequency and severity

Figure 8 shows the graphs of severity of 2- and 5-year droughts for both scenarios. The mean cumulative deficit is shown in abscissae and the return period in years in ordinates. The impact of climate change on droughts is obtained by comparing the curves for each future period with the baseline period curve. It should be noted that, in this study, the droughts are defined with respect to the median of each period, which implies that the graphs indicate changes in the drought regime, with respect to its statistical distribution.

There is a great variability between models, but there are some general agreements in the simulations. Firstly, it is observed in both scenarios that short-term droughts would be more frequent than long-term droughts. The frequency of mild droughts (low mean annual deficit) is similar for all periods in all cases, with T slightly higher than 10 years for 2-years droughts and T around 100 years for 5-years droughts. As the severity increases (higher mean annual deficit), the differences between periods become more relevant, as well as the discrepancies between projections. Each climate projection predicts a different curve for each period, although in each case they estimate similar changes for the 2-year and 5-year droughts.

In the RCP 4.5 scenario, some projections show no large changes between periods in the T of both the 2-year and 5-year droughts (CS, HK), while others show significant differences (IS, MC). Most projections would indicate that the most severe 2-year droughts would be more frequent (lower T) in 2040–2070 or 2070–2100. In some cases, the 2040–2070 and 2070–2100 curves are very similar (CA, CC, CS, MS) while in others the projections indicate that deficit for a same T would be higher in 2040–2070 (MC) or in 2070–2100 (HK, II, IS). There are also projections that predict droughts more severe in 2010–2040 (PC, PR). The situation is very similar for the 5-year droughts, although the T values are higher in all cases.

Figure 8 Curves of return period (years) against annual average deficit (% of the median of runoff por each period) of the 2-years droughts (solid lines) and 5-years droughts (dashed lines) for the baseline period (blue lines) and the future periods (2010–2040: green line; 2040–2070: yellow line; 2070–2100: red lines) simulated by each projection (one for panel) under the RCP 4.5 (top) and RCP8.5 (bottom). The values are bias corrected and averaged for the whole river basin territory (see online version for colours)



In the RCP 8.5 scenario, most projections (CA, CC, CS, HK, MC, MS, PC, PR) indicate that 2-years droughts would be more severe during 2070–2100 for a given *T*. The remaining projections (II, IS) would indicate that the most severe droughts would occur in 2010–2040. For 5-year droughts, the forecasts would be similar, with six projections indicating an increase in the deficit associated to each *T* in 2070–2100 (CC, CS, MC, MS, PC, PR), one in 2040–2070 (HK) and two in 2010–2040 (II, IS). The remaining projection, CA, would be the only one indicating a higher frequency of droughts in baseline period, although the curve is very similar to the one for 2070–2100.

This variability in the results contrasts with the agreement between the models obtained in Spinoni et al. (2018), who investigated the droughts frequency and severity in the future at European level. All the 11 models used in the study agreed on simulate an increase in the frequency and severity of droughts in the future for RCP4.5 and RCP8.5 scenarios. The results are not easy to compare though due to the difference in the drought modelling approach. They used a combined indicator based on the standardised precipitation index (SPI), the standardised precipitation evapotranspiration index (SPEI) and the reconnaissance drought indicator (RDI). Ojeda et al. (2021) used a similar approach (just SPI and SPEI indicators) for the Iberian Peninsula. They only used two models, so we cannot get any conclusion about the variability between models, but they found that droughts severity may increase in the future. In any case, in our study, despite the differences between projections, the results would suggest similar conclusions than the mentioned studies, with a majority of projections that predict an increase in the frequency and severity in the future.

4 Summary and conclusions

The impact of climate change on water resources and droughts frequency and severity have been analysed for the Minho-Lima International River Basin, a small-scale region in NW Iberian Peninsula. First, the study analyses the ability of an ensemble of EURO-CORDEX climate projections to simulate current climate in the region, finding a generalised bias in the simulations. Most of the projections overestimate precipitations and underestimate maximum temperatures, whilst minimum temperatures bias is model dependent. After bias correction by quantile mapping, the performance of the climate projections improved the simulation of both annual and monthly values. The study also explored the effect of bias correction on the simulation of the hydrological cycle. The changes and the patterns predicted in the future in the hydrological variables were similar before and after bias correction, but the magnitudes were more realistic in the bias-corrected simulation. In any case, the need of bias correction performance should be analysed in each case, depending on observed bias in climate projections and the objective of the study.

The impact of climate change indicates a progressive reduction of precipitations, especially from 2040, which translates into a reduction in runoff. The mean of the change in runoff simulated by the ensemble at the end of the century with respect the baseline period is –8.7% for the RCP4.5 and –15.8% for the RCP8.5. The results showed a high variability between climate projections, result of the uncertainties derived in each step of the process, extensively described in the literature and briefly discussed in the study.

The main source of uncertainty appears to be the global and regional climate models, which highlights the necessity of using an ensemble instead of just few models. Other sources should not be ignored, as bias correction, which implies some assumptions that must be considered when analysing results.

Finally, based on the runoff series simulated, the spatial distribution of river discharge was analysed, as well as the droughts frequency and severity. The first, showed a higher variability in the near future, with some areas increasing their water resources, but from 2040 the reductions are generalised all over the territory, being more accused in the RCP8.5. Regarding the droughts, a probabilistic approach was used to estimate the return period associated to certain duration of droughts and their severity. Each projection gave a different forecast, but there was a general agreement in increasing the frequency of more severe droughts by the end of the century.

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