WATER AVAILABILITY IN SOUTHERN PORTUGAL FOR DIFFERENT CLIMATE CHANGE SCENARIOS SUBJECTED TO BIAS CORRECTION

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Abstract:
Regional climate models provided precipitation and temperature time series for control (1961–1990) and scenario (2071–2100) periods. At southern Portugal, the climate models in the control period systematically present higher temperatures and lower precipitation than the observations. Therefore, the direct input of climate model data into hydrological models might result in more severe scenarios for future water availability. Three bias correction methods (Delta Change, Direct Forcing and Hybrid) are analysed and their performances in water availability impact studies are assessed. The Delta Change method assumes that the observed series variability is maintained in the scenario period and is corrected by the evolution predicted by the climate models. The Direct Forcing method maintains the scenario series variability, which is corrected by the bias found in the control period, and the Hybrid method maintains the control model series variability, which is corrected by the bias found in the control period and by the evolution predicted by the climate models. To assess the climate impacts in the water resources expected for the scenario period, a physically based spatially distributed hydrological model, SHETRAN, is used for runoff projections in a southern Portugal basin. The annual and seasonal runoff shows a runoff decrease in the scenario period, increasing the water shortage that is already experienced. The overall annual reduction varies between –80% and –35%. In general, the results show that the runoff reductions obtained with climate models corrected with the Delta Change method are highest but with a narrow range that varies between –80% and –52%.

Keywords: Bias correction; climate change models; hydrological modelling; southern Portugal

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Introduction

Climate change projections, which are based mainly on the outputs of Atmosphere-Ocean Global Circulation Models (GCM), are essential for different socio-economic sectors, such as agriculture, energy, public health and water resources. To estimate the impacts of climate change on river discharges, different scenarios of future temperature and precipitation series are used as inputs to hydrological models. The main limitation to the application of climate model projections in impact studies is the coarse spatial resolution of the GCMs, which clearly contrasts with the inputs needed in hydrological models. To fill this gap, a number of dynamical (Regional Climate Model − RCM) (Christensen *et al.*, 2007) and statistical (Wilby & Wigley, 1997; Zorita & von Storch, 1999) downscaling techniques have been developed.

RCMs are not suitable to be applied directly to hydrological studies because the simulated temperature and precipitation series for a control period differ systematically from the observed ones (Frei *et al.*, 2003, Blenkinsop & Fowler, 2007). Lopez-Moreno *et al.* (2007) used a set of six RCM and one GCM from the PRUDENCE project to analyse the uncertainty, direction and magnitude of precipitation and temperature series in the Pyrenees for the end of the 21st century. When assessing the ability of RCMs to reproduce the observed climate the results show that the mean difference between observed and simulated climates over the control period (1961–1990) are about 20% decrease in mean precipitation and a 1°C increase in mean temperature and these biases are subjected to a large spatial and seasonal variability.

Although it is recognised that climate models display systematic biases from observation, which are necessary transmitted to future scenarios, some authors prefer not to take into consideration the bias correction methods (Arnell *et al.*, 2003). Nevertheless, in most studies, bias correction is considered an important step, and various methods have been developed. The bias corrected climate scenarios are mostly constructed by applying monthly bias correction factors to temperature and precipitation series. The most common method is the Delta Change (Arnell & Reynard, 1996; Wood *et al.*, 1997; Arnell, 1998; Gellens & Roulin, 1998; Hay *et al.*, 2000; Middelkoop e*t al.*, 2001; Prudhomme *et al.*, 2003; Wilby & Harris, 2006; Merritt *et al.*, 2006; Graham *et al.*, 2007; Fowler & Kilsby, 2007 and Quintana *et al.*, 2010) that affect observations in control period by the climate model evolution factor to obtain future series. Another method largely used is the Direct Forcing (Graham *et al.*, 2007; Fowler *et al.*, 2007 and Thodsen,

2007) that affects the climate model scenario series by a bias correction factor that relates the monthly mean observations series with the monthly mean climate model control series. Bias correction of climate model series was also attempted by Lenderink *et al.* (2007) with a Hybrid method, achieved by applying Delta Change and Direct Forcing correction factors to the climate model control series. Other bias correction methods can be found in the literature, including non-linear methods as presented by Shabalova *et al.* (2003), Leander & Buishand (2007) and Piani *et al.* (2010) and quantile matching method according to Wood *et al.* (2004), Maurer & Hidalgo (2008) and Li *et al.* (2010).

The objective of this paper is to assess the water availability in the river Cobres basin with and without bias corrected climate simulations of future climate resulting from a combination of two global climate models and three regional climate models. With those results is possible to identify which bias correction method (Delta Change, Direct Forcing and Hybrid) seems more adequate considering the precipitation and temperature series pattern for the southern Portugal climate. The paper is organised as follows. First, climate model simulations for the control period (1961−1990) are presented and compared with the observed temperature and precipitation series. Secondly the three bias correction methods are analysed and explained. Then a southern Portugal basin is presented as a case study and the bias corrected climate model temperature and precipitation series are used as input for a physically base hydrological model. Finally, the precipitation and runoff results are discussed and the conclusions are presented.

Climate Data in Southern Portugal

Projected climate change model series are obtained from the outputs of daily total precipitation and daily average temperature of three RCMs developed by different institutions collaborating in the PRUDENCE project (Christensen *et al.*, 2002). Integrations using the GCM HadAM3H boundary conditions are available for all RCMs; integrations using the GCM ECHAM4 boundary conditions are available only for the RCAO and HIRHAM models and their acronyms are presented in **Table 1**. The greenhouse gas emission scenario considered is A2 (Nakicenovic *et al.*, 2000). The spatial resolution of these RCMs is close to 50 km. RCM integrations are available for two 30-year time slices, namely 1961−1990 (control period) and 2071−2100 (scenario period). The southern Portugal udometric and meteorological stations and the PRUDENCE climate models grid are located in **Fig. 1**.

Table 1. Acronyms of the Regional Climate Models and Global Climate Models combinations for the A2 emissions scenario

| RCM	AOGCM	Acronym
HIRHAM(Danish Meteorological Institute)	HadAM3H A2	dmi_hc
	ECHAM4/OPYC A2	dmi_ec
RCAO(Swedish Meteorological and	HadAM3H A2	smhi_hc
Hydrological Institute)	ECHAM4/OPYC A2	smhi_ec
HadRM3P(Hadley Centre)	HadAM3P A2	hc

The 35 udometric stations with daily precipitation records used in this paper are selected according to Mourato *et al.* (2010). Average daily temperature records are obtained from 22 meteorological stations. In each climate model cell, the observed series are weighted according to Thiessen polygons.

Relative difference in mean annual precipitation $((P_{RCM\ control}/P_{obs}) - 1)$ and absolute differences in annual mean temperature $(T_{RCM\ control} - T_{obs})$ between the climate models data and observations over southern Portugal in the control period, 1961−1990, are highly variable within the study area. Considering all climate models, the mean annual precipitation relative deviations vary between −12% (in the interior) and -84% (near the coast) and temperature absolute differences vary between +0.3ºC (near the southern coast) and +3.3ºC (interior north).

The bias is not uniform within the models throughout the year.

Table 2 summarises the annual and seasonal temperature differences and the precipitation relative deviations between the simulation series and observations for the control period, at southern Portugal. Seasons are defined as follows: winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November).

The model hc show the lower temperature differences except for summer, when all models agree with higher temperature differences. The lower temperature differences are observed in winter. The five climate scenarios considered, with the exception of summer, different RCMs forced by the same GCM displayed similar mean temperatures, so the GCM can be considered determinant. For precipitation, except for summer different regional models show good agreement. The precipitation series seem to be more influenced by the RCMs than by the GCMs.
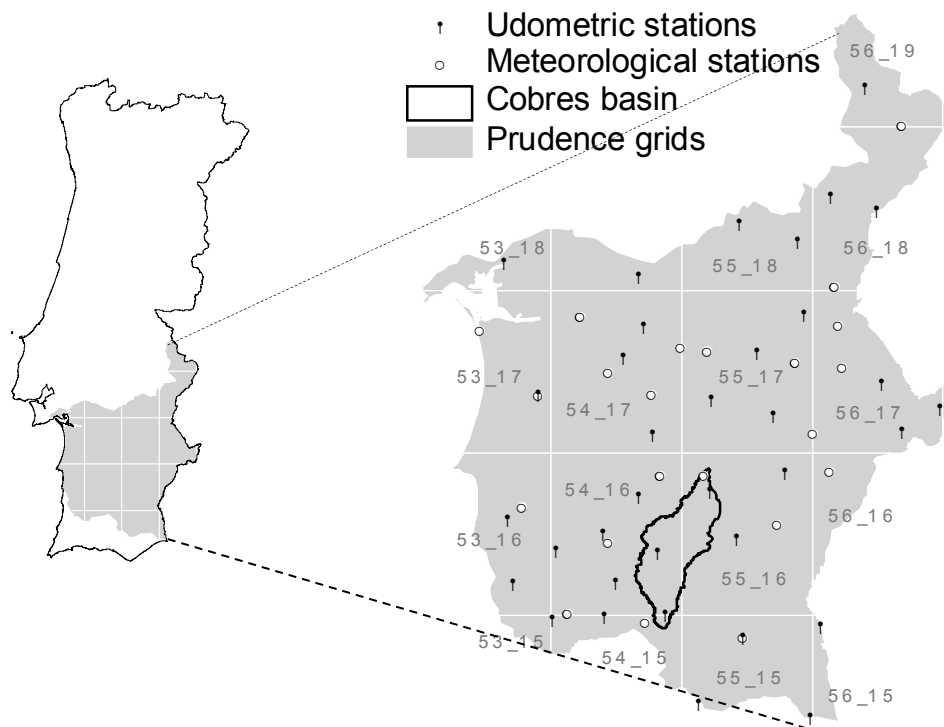
Fig. 1 Location of udometric and meteorological stations in the southern Portugal study area. PRUDENCE climate models grids and Cobres river basin boundaries. The grey area presents the three largest river basins in southern Portugal.

Table 2. Annual and seasonal relative deviation of total precipitation (%) and differences in temperature (ºC) between climate models simulations and observations (1961−1990) for the five climate models in southern Portugal

		dmi_ec	dmi_hc	hc	smhi_hc	smhi_ec
		Climate Model$_{control}$ − Observation				
Temperature (ºC)	Annual	2.3	2.0	1.3	1.9	2.4
	Autumn	1.8	2.1	0.9	1.7	1.3
	Winter	2.1	1.8	0.3	1.7	2.1
	Spring	2.4	1.6	1.4	1.8	3.0
	Summer	2.9	2.6	2.7	2.4	3.1
		(Climate Model$_{control}$ − Observation) / Observation				
Precipitation (%)	Annual	−41	−31	−55	−43	−68
	Autumn	−44	−35	−50	−41	−70
	Winter	−42	−37	−60	−43	−62
	Spring	−37	−20	−58	−42	−71
	Summer	−38	−25	−20	−67	−91

The range given by the climate models relative to the observation can be expressed by (Max − Min)$_{model}$/(Max − Min)$_{observation}$, and the series dispersion by (P$_{75}$ − P$_{25}$) where P$_{25}$ is the quartile 25 and P$_{75}$ is the quartile 75. The range of climate model temperature series is lower than the range of the annual and spring observed series. In winter and summer, the climate models present a higher range than the observed temperature series. The dispersion of annual, autumn and spring temperature series is lower than the dispersion of the observed series for the dmi_ec and dmi_hc climate models and higher for the other climate models. In winter and summer, the dispersion of all the climate models temperature series is higher. The range of precipitation series of the climate models is slightly lower than the range of the observed series except for model dmi_hc in spring. The dispersion of climate models precipitation is lower than the observed, except in spring, for climate models dmi_ec and hc.

It is possible to conclude that climate models for the control period present different mean values, range and distribution than the observations justifying the need for bias correction. This behaviour is different for temperature or precipitation and is also seasonal and climate model dependent.

Bias Correction Methods

Three simple bias correction methods, already applied in water resource impact studies will be considered in this research. These methods are (i) Delta Change (da); (ii) Direct Forcing (df) and (iii) Hybrid (hy).

The Delta Change method assumes that the observed series variability is maintained in the scenario period and is only corrected by the evolution predicted by the climate models (**Eqs 1** and **2** for precipitation and temperature, respectively).

$$P_{scenario} = P_{obs} \times \bar{P}_{RCMscenario} / \bar{P}_{RCMcontrol} \quad (1)$$

$$T_{scenario} = T_{obs} + (\bar{T}_{RCMscenario} - \bar{T}_{RCMcontrol}) \quad (2)$$

where P$_{scenario}$ is the scenario corrected daily precipitation (mm); P$_{obs}$ is the observed daily precipitation (mm); $\bar{P}_{RCMscenario}$ is the monthly precipitation (mm) in scenario model; $\bar{P}_{RCMcontrol}$ is the monthly precipitation (mm) in control model; T$_{scenario}$ is the scenario corrected daily temperature (ºC); T$_{obs}$ is the observed daily temperature (ºC); $\bar{T}_{RCMscenario}$ is the monthly mean temperature (ºC) in scenario model; and $\bar{T}_{RCMcontrol}$ is the monthly mean temperature (ºC) in control model.

The Direct Forcing method assumes that the future scenario variability is only corrected by the bias found in the control period between the climate model and observations (**Eqs 3** and **4** for precipitation and temperature, respectively).

$$P_{scenario} = P_{RCMscenario} \times \bar{P}_{obs} / \bar{P}_{RCMcontrol} \quad (3)$$

$$T_{scenario} = T_{RCMscenario} + (\bar{T}_{obs} - \bar{T}_{RCMcontrol}) \quad (4)$$

where, along with the previous notations: P$_{RCMscenario}$ is the daily precipitation (mm) in scenario model; $\bar{P}_{obs}$ is the monthly precipitation (mm) in observations; T$_{RCMscenario}$ is the daily temperature (ºC) in scenario model; and $\bar{T}_{obs}$ is the monthly temperature (ºC) in observations.

The Hybrid method assumes that the control series variability is maintained in the scenario period and is corrected by the bias found in the control period and by the evolution predicted by the climate models (**Eqs 5** and **6** for precipitation and temperature, respectively).

$$P_{scenario} = P_{RCMcontrol} \times (\bar{P}_{obs} / \bar{P}_{RCMcontrol}) \times (\bar{P}_{RCMscenario} / \bar{P}_{RCMcontrol}) \quad (5)$$

$$T_{scenario} = T_{RCMcontrol} + (\bar{T}_{obs} - \bar{T}_{RCMcontrol}) + (\bar{T}_{RCMscenario} - \bar{T}_{RCMcontrol}) \quad (6)$$

where, along with the previous notations: $P_{RCMcontrol}$ is the daily precipitation (mm) in control model; and $T_{RCMcontrol}$ is the daily temperature (ºC) in control model.

With the Delta Change method, the seasonal precipitation coefficient of variation is equal to the observed series and the temperature standard deviation remains the same in all models. The Direct Forcing and Hybrid bias correction methods end in corrected series with coefficients of variation different from the observed series and those differences are larger for precipitation than for temperature. With the Delta Change method, the number of non-precipitation days remains the same as the observations (in southern Portugal that can represent almost 80% of the year), which is not verified with the other methods.

Case Study

The Cobres river basin, a Guadiana sub-basin, at the Monte da Ponte section, covers 702 km^2 of predominantly sandy loam soils, and arable land use. The climate regime is representative of the climate conditions throughout southern Portugal. Runoff measurements are taken from the hydrometric station located at Monte da Ponte. Taking into account the SNIRH (www.snirh.pt) udometric stations network distribution and the corresponding area of Thiessen polygons, the udometric stations of Almodôvar, Castro Verde and Trindade are selected. The temperature observations are from the Mértola meteorological station from the Portuguese Institute of Meteorology. The information comprised the daily total precipitation and mean temperature for the control period (1961−1990).

The runoff series are obtained with the three-dimensional, physically-based, spatially distributed, coupled surface/subsurface, finite-difference hydrological model SHETRAN (Ewen *et al.,* 2000).This model is selected because it has already been used in other climate change impact studies (Bathurst *et al.,* 1996 and 2005). The precipitation series are introduced directly into the model, their spatial distribution is assessed by Thiessen polygons, and the temperature series are used to calculate the reference evapotranspiration, which is included in the model. The model calibration is conducted against daily flow measurements at Monte da Ponte hydrometric station during the period 1/10/1980 to 31/9/1984. Validation is performed for the period 1/10/1984 to 31/9/1987. The calibration and validation periods presented both dry and wet periods. The SHETRAN model parameters are estimated using a multi-objective criterion based on a daily time step. The observed and simulated daily flows are compared using the correlation coefficient (R), the percentage of volume deviation (Vd) and the Nash

Sutcliffe coefficient (NS). The Vd was of −2% during the calibration run and −1% in the validation run. The daily calibration and validation results were respectively: (i) R = 0.87 and NS = 0.76; (ii) R = 0.84 and NS = 0.71. The calibration and validation processes can be considered good.

The hydrological simulation framework consisted of 26 model runs: (i) one simulation based on temperature and precipitation observations for the period 1961−1990 ("*Reference*" simulation); (ii) five simulations with control period climate model series without bias correction (c); (iii) five simulations with scenario period climate model series without bias correction (s); (iv) fifteen simulations of the scenario period (2071−2100) with input of temperature and precipitation series with bias correction.

Results

The projected temperature and precipitation series differ according to the climate model and the bias correction method considered. **Figure 2** shows as an example the observed precipitation annual cycle (Castro Verde), the observed temperature annual cycle (Mértola) and the climate model dmi_ec annual cycle in both control and scenario periods. The climate model overestimates the temperature for all months, and, with the exception of July and August, it underestimates precipitation. For precipitation the climate model for the control period is nearest of the climate model for the scenario period than to the observations.

The number of days without precipitation in HIRHAM climate models for control and scenario period is respectively 43% and 46% lower than the observations. Climate models hc and smhi_hc precipitation series present a number of non rainy days lower than the observations respectively of 18% and 14% for the control period and 14% and 5% for the scenario period. The climate model smhi_ec shows a number of non rainy days 2% lower in the control period but 7% higher in the scenario period.

For the scenario period with delta change method bias correction the climate model precipitation series CV remains the same of the observations. The largest CV differences between the observation and the models with Hybrid and Direct Forcing bias correction are detected in summer and the differences between the bias correction methods are smaller for winter.

The results for the totals seasonal runoff are presented in **Fig. 3**. The results of the hydrological model simulations with climate models series without bias correction for the control period are extremely severe, with runoff reductions lower than the projected with bias corrected series.

(a)

(b)
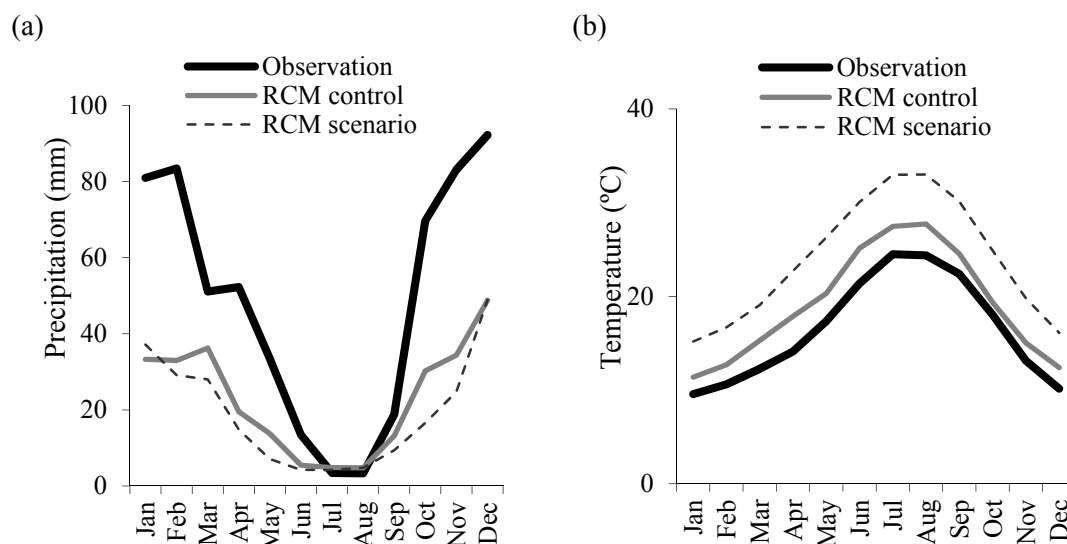
Fig. 2 Precipitation and temperature annual cycles for the observations and for the control and scenario simulations from the regional model HIRHAM forced by the ECHAM4 global climate model; a) Castro Verde udometric station and b) Mértola meteorological station.

All scenarios point to runoff decrease. For annual conditions, the simulations with the lowest and highest runoff reductions are, respectively, dmi_ec_df (−35%) and hc_da (−80%). In autumn, the hc_df simulations show the lowest (−61%) runoff reduction, while the highest runoff reduction is projected by smhi_ec_da (−96%). For winter, the lowest and highest runoff reductions are respectively for dmi_ec_df (−21%) and hc_da (−77%) climate projections. In spring the lowest runoff reduction is found in the smhi_hc_df (−40%) simulation and the highest in smhi_ec_df and smhi_ec_hy (−99%) simulations. The lowest and highest summer runoff reductions are associated with dmi_ec_df (−45%) and smhi_hc_df and smhi_hc_hy (−91%) respectively. There is no obvious pattern in the climate variability that is reflected in the runoff variability.

Cunha *et al.* (2002), who used climate projections of two GCMs for southern Portugal, obtained the following runoff range reductions: (i) annual, between −40% and −75%; (ii) winter, between −20% and −60%; iii) spring, between −40% and −80% and (iv) autumn, between −50% and −80%. The same authors considered climate data from a RCM and projected a runoff increase in winter between +40% to +100%, a mixed behaviour in spring and a runoff reduction between −80% and −100% in autumn. Kilsby *et al.* (2007), used the RCM HadRM3H bias corrected with change factors driven from the Direct Forcing method to produce simulation of future climates for the entire basin of Guadiana river (70 000 km^2),

obtaining reductions in surface flow, on a monthly basis, that vary between −10% for August and September and −30% for May and November, which are different from the ones presented in these research due to the use of a conceptual hydrological model with coarse spatial resolutions.

The range of runoff reduction for the models corrected with the change factors driven from the Delta Change method is: annual: −80% (85.5 mm) to −52% (55.5 mm); autumn: −96% (13.7 mm) to −81% (11.5 mm); winter: −77% (56.3 mm) to −37% (26.9 mm); spring: −99% (19.4 mm) to −81% (15.9 mm); summer: −89% (0.3 mm) to −45% (0.1 mm). The large range of runoff reduction obtained with the Direct Forcing method is due to the fact that the climate model series to the end of the XXI century, show a wider range of results, and the Hybrid method presents an intermediate behaviour because the climate model series are derived from the climate model in the control period (with lower amplitude).

In general, the results show that the simulations with scenarios driven with the Direct Forcing correction factors resulted in smaller runoff reductions than with the Delta Change method. The Hybrid method shows a mixed behaviour. For all bias correction methods, the runoff decrease is climate model dependent. The largest runoff reductions are expected to occur in summer; although, they are not significant in terms of water resources in southern Portugal. In winter, the projected runoff reduction is small, although winter is the season with more divergent model projections.
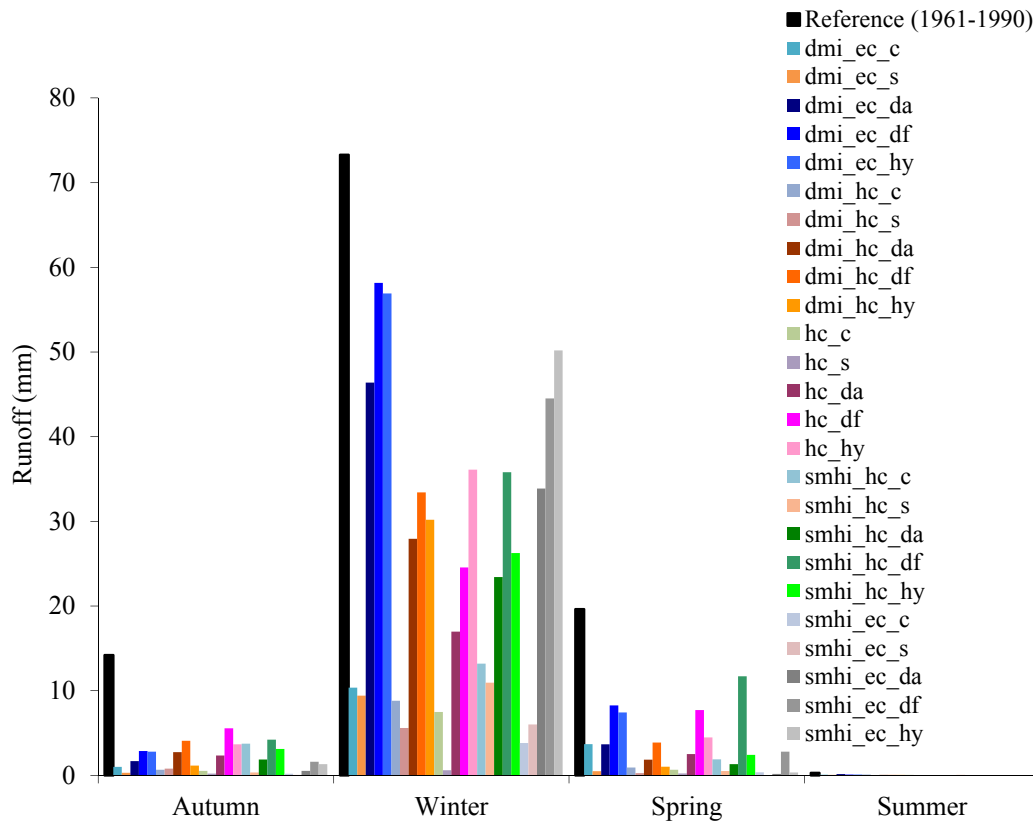
Fig. 3 Totals seasonal runoff at Monte da Ponte section for the 26 simulations: "Reference" simulation (with the observed precipitation and temperature series);simulations for the control and scenario period with climate model precipitation and temperature series without bias correction and; simulation for the scenario period with climate model precipitation and temperature series subject to three bias correction methods.

It is in spring and autumn that the largest runoff reductions are projected by all models, mainly by the model smhi_ec, which is also the model with the largest precipitation reduction in those seasons.

Climate models corrected with different bias correction methods lead not only to distinct mean runoff values but also to different distributions. The runoff range, for the simulations with bias corrected scenario series, is smaller than for the "Reference" simulation with observation series except for the climate models driven from the Direct Forcing and Hybrid correction factors in winter, and for the climate models driven by the Direct Forcing correction factors in spring. The runoff dispersion is greater in the scenario simulations than it is in the "Reference" simulation, except for summer conditions. Simulation with climate series driven by Delta Change correction factors lead to lower runoff dispersion.

These results underscore that different bias correction methods are season dependent and even with different underlying assumptions overall these variations are not directly transported to the runoff series due to the nonlinear precipitation-runoff relationship. As an analysis of all results an ensemble of the monthly runoff is presented in **Fig. 4**.
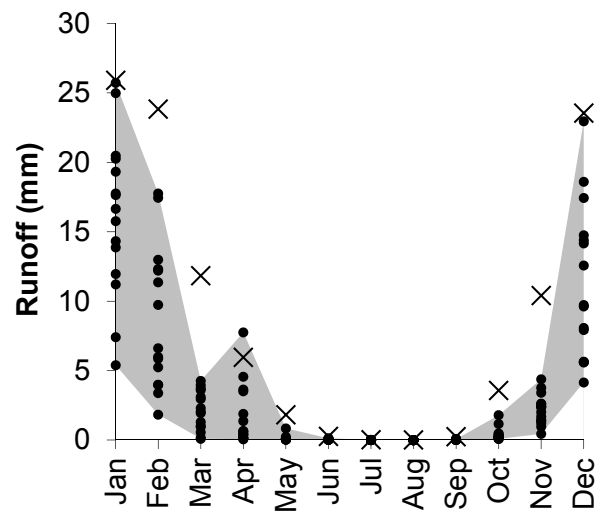
Fig. 4 Range of the monthly runoff ensemble for the scenario period (dots) in comparison with the "Reference" simulation (crosses) at Monte da Ponte section.

It clearly shows a generalised projected runoff reduction relative to the "Reference" simulation. The severe reduction in March may be a consequence of the severe decline in precipitation already observed in this particular month and referred by Mourato *et al.* (2010). The largest range of results occurs in winter, the season is characterised by a higher runoff values.

Conclusions

Over southern Portugal, all climate models for the control period systematically give lower values for precipitation and seem to be more influenced by the RCMs than by the GCMs and give higher values for temperature, and different RCMs forced by the same GCM display similar mean values.

In an attempt to improve confidence in future climate impacts on water resources, the 5 models are bias corrected with three different methods, resulting in an ensemble of 15 simulations. The bias correction methods are (i) Delta Change, (ii) Direct Forcing and (iii) Hybrid.

The availability of water resources for the period 2071−2100 at the Cobres river basin located in Southern Portugal is severely compromised with all projections showing runoff reduction. In general, the results show that small runoff reductions are obtained with climate models corrected with the change factors driven from the Direct Forcing or Hybrid methods, and the climate model scenarios corrected by the Delta Change method result in the highest reductions because the total amount of rain is concentrated in only a few days. Different climate models and bias correction method combinations lead not only to distinct mean values of runoff but also to different temporal variability during the scenario period.

No conclusions can be drawn about the uncertainty of the results because the simulations are not independent, but the results give a range of runoff projections with different distributions. Given the results of the 15 simulations and considering that all the bias corrected scenarios are likely to occur, a severe March an November runoff reduction is projected, and the largest spread of results occurs in winter, which is the season with highest runoff, and in which regional models driven by HadAM3H present the narrowest range of results.

This study clearly indicates that it is important to use several climate scenarios and different bias correction methods to produce robust conclusions in impact studies. Considering the bias correction methods different underlying assumptions combined with the regional precipitation pattern some bias correction methods can be considered more adequate than others. The runoff reduction trends projected by the results can be considered more certain if several scenarios are considered, although these trends show a large range.

At the present time, during spring and autumn, this region does not deal with water severe scarcity; therefore the projected runoff reductions should be considered in future water management strategies.

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