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THEMATIC ISSUE

Potential future impact of climate change on recharge in the Sierra de las Nieves (southern Spain) high-relief karst aquifer using regional climate models and statistical corrections

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Abstract

The Sierra de las Nieves high-relief karst aquifer, which is located in the natural park and UNESCO biosphere reserve of the same name, is an area of great interest due to its geological, geomorphological (both at the surface and underground), hydrogeological, and ecological value. The aquifer is not influenced by pumping and is considered to be a natural laboratory for karst research because of how well developed the main karst characteristics are at both the surface (karst depressions and karst springs) and underground (with a large network of caves). The hydrological cycle is sustained by relatively high precipitation (annual mean precipitation of approximately 1000 mm) and moderate temperatures (annual mean temperature of approximately 16 °C). However, these climate parameters are susceptible to significant disruption because of ongoing anthropogenic-driven climate change induced by increased CO_2 in the atmosphere. This paper offers an analysis and discussion of the impact that these potential future changes, estimated from the temperature and precipitation projections from regional climate models, may have on this karst aquifer, particularly on its recharge. The projections have been corrected using several techniques based on two hypotheses, bias correction and delta change approaches. We have focus on the future assessment for the horizon 2071–2100 under the most pessimistic emission scenario (RCP 8.5) contemplated within the last published IPCC report (IPCC, Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2014). It is expected that there will be, on average, a 27% reduction in precipitation and a 19% increase in temperature. This is a dangerous combination that will dramatically decrease recharge and will require new local adaptation measures, in addition to global mitigation measures, to prevent the area's resources, biodiversity, and geodiversity from being drastically diminished.

Keywords Future climate scenarios · Regional climate models · Delta change · Bias correction · Aquifer recharge

Introduction

Analyses of the impact of climate change on the hydrology of a region must use information about potential future climate scenarios, including precipitation and temperature time series generated by climate models (Shrestha et al. 2017; Reshmidevi et al. 2018). Regional climate models (RCMs) nested to general circulation models (GCMs) are employed to simulate potential future emission scenarios, with an increase in CO_2 emissions being the most likely scenario given the current trend (Egorova et al. 2018). This increase of CO_2 in the atmosphere has a greenhouse effect that modifies the future climate in ways that can be quantitatively assessed by climatic models. Of all the climatic variables produced by climatic models, we are interested in future precipitation and temperature time series, as they have

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the greatest effect on aquifer recharge (Toure et al. 2016). While GCMs provide climate change scenarios with a spatial resolution of hundreds of kilometers, this resolution has been increased to tens of kilometers using nested RCMs. For example, the EURO-CORDEX high-resolution climate change projections (Jacob et al. 2014) have a horizontal resolution of around 12.5 km, which is considered satisfactory for the hydrologic lumped model used in this study. In general, the statistics from the precipitation and temperature time series provided by climate models for the baseline period (or control series) will differ from the statistics of the observed time series (or historical time series) for the same baseline period. Because of this, the time series provided by the RCMs must be corrected (Lenderink et al. 2007; van Pelt et al. 2012). There are different correction techniques of differing degrees of complexity: first-order moment correction, first- and second-order moment corrections, regression techniques, quantile mapping, etc., (Christensen et al. 2008; Collados-Lara et al. 2018). These techniques can be applied using two different conceptual frameworks, bias correction and delta change (Räisänen and Räty 2013; Räty et al. 2014), depending on the combination of the observed climate time series and the climate time series provided by the models (simulated time series). In this study, both approaches, bias correction and delta change, have been applied to generate future precipitation and temperature time series for the lumped area of the Sierra de las Nieves karst aquifer. The time series were generated using nine RCMs nested to different GCMs. The aim of this work is to analyze the sensitivity of the time series generated according to the climate models and conceptual approaches applied, and to quantify the potential changes in precipitation and temperature. These potential climate change scenarios will be employed to assess the future recharge of the Sierra de las Nieves karst aquifer.

Methodology

In climate change impact studies, future precipitation and temperature time series can be generated by using historical observations and information from climate models (control time series and simulated time series) (Haerter et al. 2011). The way in which the two kinds of information are merged is defined by the conceptual model and the statistical correction employed (Figs. 1 and 2). The bias correction technique adjusts the model time series for the control time period by imposing a minimization of differences with the observed time series. The transformation function obtained is then applied to the future time series provided by the model. The hypothesis that underpins this methodology is that the differences between observed and modeled time series for the control period will apply in the future (Watanabe et al. 2012). On the other hand, delta change techniques assume that the relative changes between the simulation for the control period and the future are correctly approximated; thus, to generate the future time series, those changes are imposed on the observed time series (Räisänen and Räty 2013; Räty et al. 2014).

The two correction approaches have been applied using the first- and second-order moment corrections for the temperature time series and quantile mapping with empirical quantiles for the precipitation time series. For the proposed method to produce a first assessment of the future annual recharge with a simple conceptual approach, we intended to generate monthly future climate series (to take into account the seasonality of the climate and the potential impacts) with an accurate correction of the mean and the standard deviation of the series. These series will be aggregated to a yearly scale to generate the inputs

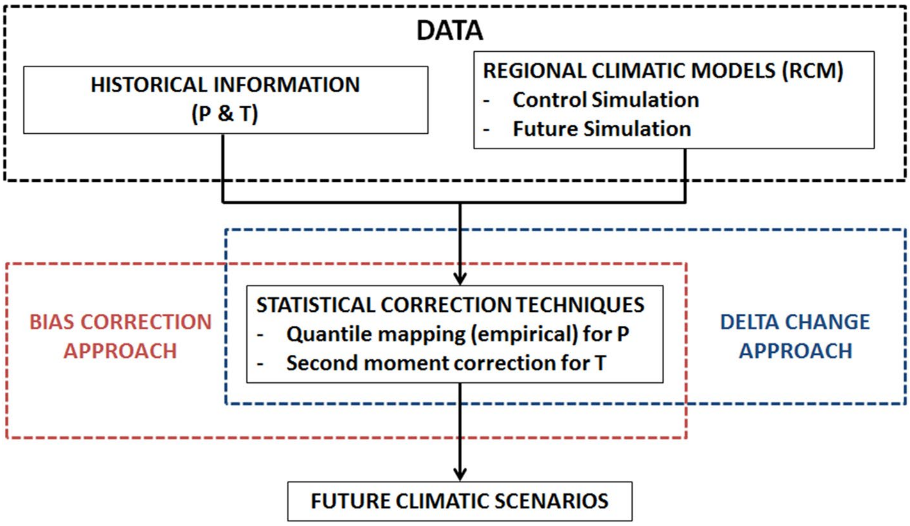


Fig. 1 Flowchart of the methodology used to generate potential future climate scenarios. The baseline data are historical time series of the target variables and the control and future simulations from RCMs. Different correction techniques can be used to generate future series. This study employed quantile mapping for precipitation and second-moment correction for temperature. All techniques can be used with two approaches: bias correction and delta change

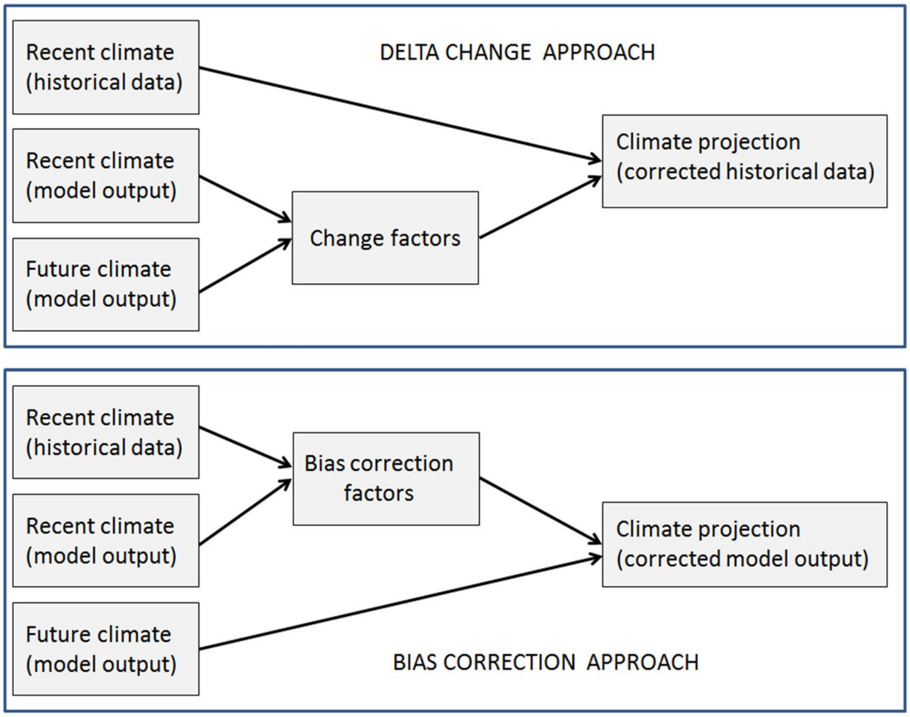


Fig. 2 Two different approaches to climate projection. The two approaches differ in the time series used to create the transformation function: control and future series from the model (delta change approach) and historical and control series (bias correction approach). The figure is based on Räisänen and Räty (2013)

to simulate future yearly recharge. A second-moment approach was selected for the assessment of monthly temperature series, because it is a simple approach (see formulation in Pulido-Velazquez et al. 2011) that can be easily applied providing accurate corrections for the cited statistics (Escriva-Bou et al. 2017; Pulido-Velazquez et al. 2018a, b). We did not select this approach for the precipitation series due to it might produce some negative future monthly values (Pulido-Velázquez et al. 2015), which would not have physical meaning. For this reason, we decided to apply a more complex approach, a quantile mapping technique, to the precipitation series which produces accurate results for the selected statistics (Collados-Lara et al. 2018), avoiding the cited negative values' issue. The different correction techniques differ in the way in which the future time series are corrected by a statistical transformation function $h(\cdot)$, such that the distribution of the modeled variable (e.g., precipitation, P_{m}) is equal to the distribution of the observed variable, P_{o}:

$$P_{\mathrm{o}} = h\left(P_{\mathrm{m}}\right). \tag{1}$$

And for temperature

$$T_{\mathrm{o}} = h'\left(T_{\mathrm{m}}\right), \tag{2}$$

where the transformation for temperature, $h'(\cdot)$, will generally differ from the one for precipitation.

The second-order moment correction technique maintains the changes in mean and standard deviation for the time series which define the transformation of the projection. In this study, the transformation function proposed in Pulido-Velazquez et al. (2011) is applied, such that:

$$T_{\mathrm{mc}} = a + bT_{\mathrm{m}}, \tag{3}$$

where the empirical constants a and b in Eq. (3) are obtained, so that the mean and standard deviation of the target distribution for a month m (January, February, etc.,) remain constant and T_{mc} is the corrected temperature of the modeled or future temperature in month m.

In quantile mapping techniques, the transformation function is defined by the cumulative distribution functions of the time series. In this study, the empirical quantile mapping technique proposed by Gudmundsson et al. (2012) is used:

$$P_{\mathrm{mc}} = F_{\mathrm{o}}^{-1}\left(F_{\mathrm{m}}\left(P_{\mathrm{m}}\right)\right), \tag{4}$$

where $F_{\mathrm{m}}(\cdot)$ is the cumulative distribution function of the modeled variable (precipitation or temperature) in a month m, while $F_{\mathrm{o}}^{-1}(\cdot)$ is the inverse of the cumulative distribution function of the target distribution. The empirical quantile method uses the empirical cumulative distribution function to solve Eq. (4) where linear interpolation is used between the empirical quantiles, and P_{mc} is the corrected precipitation of month m for the modeled or future precipitation.

These approaches provide a set of precipitation and temperature time series that represent potential future climate scenarios. To quantify the changes in recharge, R, the duality of recharge in the karst aquifer considered as a case study (Pardo-Igúzquiza et al. 2012) has been taken into account.

Recharge in most karst aquifers can be divided into concentrated and diffuse recharge. Concentrated recharge enters the aquifer along preferential flow paths related to underground karst conduits connected to potholes, sinkholes, and the epikarst at the surface. Variation in this part of the recharge is due solely to precipitation and thus any modifications to it simply equal the modification in precipitation (Fig. 3):

$$\Delta CR = \Delta P. \tag{5}$$

On the other hand, diffuse recharge must go through a soil–epikarst layer and represents a balance between precipitation and actual evapotranspiration which can be written as:

$$R = C(P - \mathrm{AET}), \tag{6}$$

where P is precipitation, AET is actual evapotranspiration, and C is a coefficient of infiltration that is considered to be constant during the historic and future periods. AET has been calculated at yearly scale by the empirical method proposed by Turc (1954):

$$\mathrm{AET} = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}}. \tag{7}$$

Here, the factor L is expressed as:

$$L = 300 + 25T + 0.05T^3, \tag{8}$$

where T is the mean annual temperature.

Historical annual recharge is provided by:

$$R_h = C_h\left(P_h - \mathrm{AET}_h\right), \tag{9}$$

where Eq. (9) is equal to Eq. (6) but with the subscript h denoting historical.

Future recharge is provided by:

$$R_f = C_f\left(P_f - \mathrm{AET}_f\right), \tag{10}$$

where Eq. (10) is equal to Eq. (6) but with the subscript f denoting final or projected values.

The variation in diffuse recharge (ΔDR) is provided by:

$$\Delta \mathrm{DR} = \frac{R_f - R_h}{R_h}. \tag{11}$$

Thus, taking into account the previous equations, one has:

$$\Delta \mathrm{DR} = \frac{C_f\left(P_f - \mathrm{AET}_f\right) - C_h\left(P_h - \mathrm{AET}_h\right)}{C_h\left(P_h - \mathrm{AET}_h\right)}. \tag{12}$$

Taking into account the hypothesis that the recharge coefficient C does not vary over time, so $C_f = C_h$, finally:

$$\Delta \mathrm{DR} = \frac{\left(P_f - \mathrm{AET}_f\right)}{\left(P_h - \mathrm{AET}_h\right)} - 1. \tag{13}$$

The final variation in recharge is a weighted average (Fig. 3) between the percentage of concentrated and diffuse recharge that takes place at the particular aquifer, as will be seen in the case study section:

$$\Delta R = \alpha \Delta \mathrm{DR} + (1 - \alpha)\Delta \mathrm{CR}, \tag{14}$$

where ΔR is the variation in recharge, α is the ratio of diffuse recharge, ΔDR is the variation in diffuse recharge, $(1 - \alpha)$ is

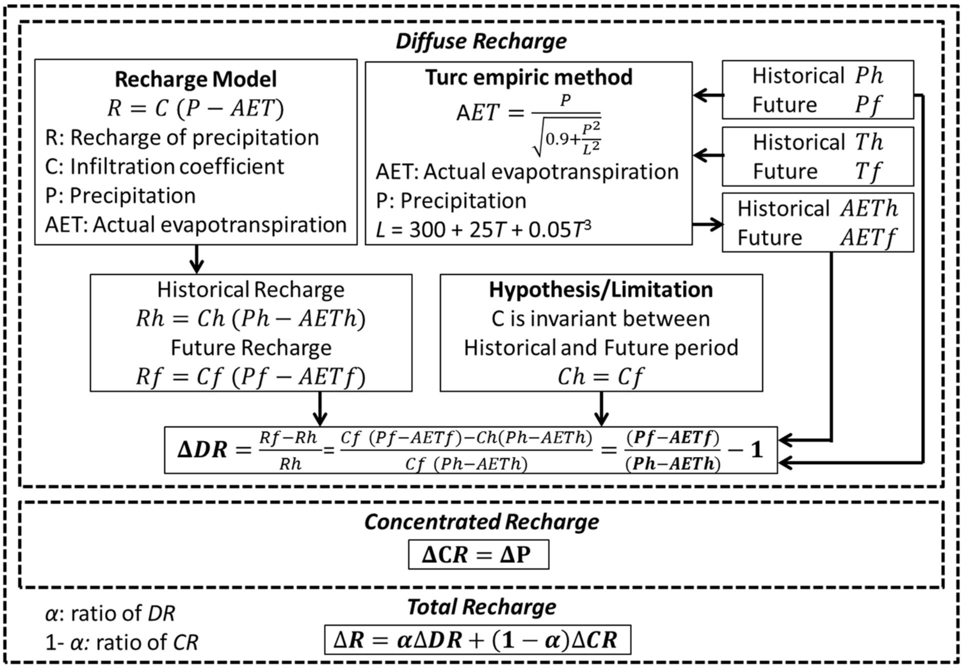


Fig. 3 Flowchart for assessing future changes in aquifer recharge. The calculation of diffuse recharge uses a simple model that involves precipitation and temperature. In this expression, we assume that the infiltration coefficient will remain invariant over time. The change in concentrated recharge is the same as the change in precipitation

the ratio of concentrated recharge, and ΔCR is the variation in concentrated recharge.

Case study

The study area (Fig. 4) is a karst aquifer with a surface area of 110 km^2 and located in the province of Málaga in southern Spain. It is a characteristic example of a Mediterranean high-relief karst aquifer and is completely contained within the Sierra de las Nieves Natural Park (Liñán-Baena 2005). The aquifer is made up of a sequence of carbonate rocks (dolostones, limestones, and carbonate breccias) folded in an overturned NW vergent syncline. The aquifer is divided into two blocks by an important tectonic feature: the Turquillas fault. The eastern part of the aquifer has been tectonically uplifted, around 500 m, compared to the western part. The aquifer contains significant water resources, and the three main karst springs are the sources of three important regional rivers: the Río Grande, Río Verde, and Río Genal. The area is also very rich in biodiversity and geodiversity, both on the surface and underground. The aquifer is also located inside the Sierra de las Nieves UNESCO Biosphere Reserve. As in any typical karst aquifer, there is a typical duality in recharge with concentrated a diffuse recharge. A study of the spatio-temporal variation of recharge using a spatially distributed model is shown in Pardo-Igúzquiza et al. (2012). The identification, delineation, and mapping of sinkholes (closed karst depressions) have been done using an exhaustive and automatic procedure described in Pardo-Igúzquiza et al. (2013). The vulnerability of this karst massif has been shown in Pardo-Igúzquia et al. (2015), while a mapping of the epikarst by remote sensing, geophysics, and field work has been shown in Pardo-Igúzquiza et al. (2018a). Finally, a description of the hydrogeology and modeling of one three main groundwater basins has been illustrated in Pardo-Igúzquiza et al. (2018b). Given the spatial complexity and anisotropy of this karst system, only a lumped model will be used below for the evaluation of recharge where the general conclusions of the previous study have been taken into account.

With respect to the experimental data, the historical precipitation and temperature data have been taken from the project Spain02 v4 (Herrera et al. 2016) for the period 1971–2000. Periods of 30 years are frequently employed in climate change impact studies, although, logically, as long as possible series are desirable. The Spain02 project provides an estimation of precipitation and temperature obtained using the original data from the Agencia Estatal de Meteorología (State Meteorological Agency—AEMET). Figure 5a shows the monthly precipitation and temperature means for the period in question, calculated using the Spain02 data. Precipitation is relatively high (annual mean precipitation of approximately 1000 mm) and temperatures are moderate (annual mean temperature of approximately 16 °C), which maintains the hydrologic cycle in the karst aquifer system. The main water input to the aquifer is precipitation and, after flowing along the interior of the aquifer, output is concentrated through the karst springs. The estimates from Spain02 have a spatial resolution of 12.5 km and use the same grid as the EURO-CORDEX project (Jacob et al. 2014). The latter project uses different RCMs associated with different

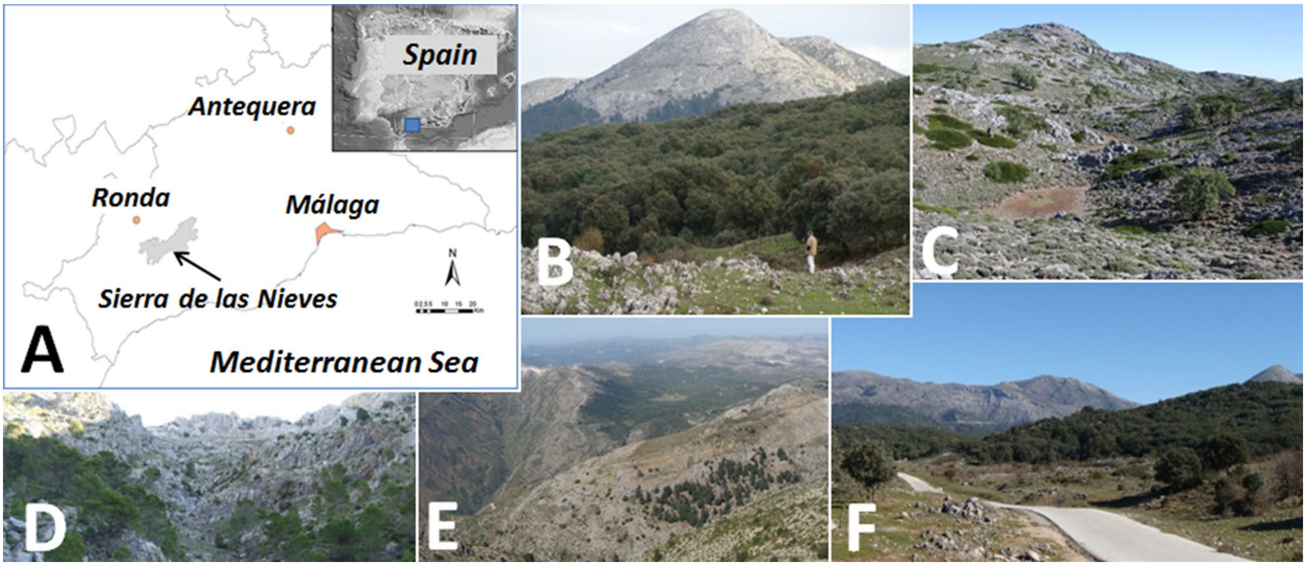
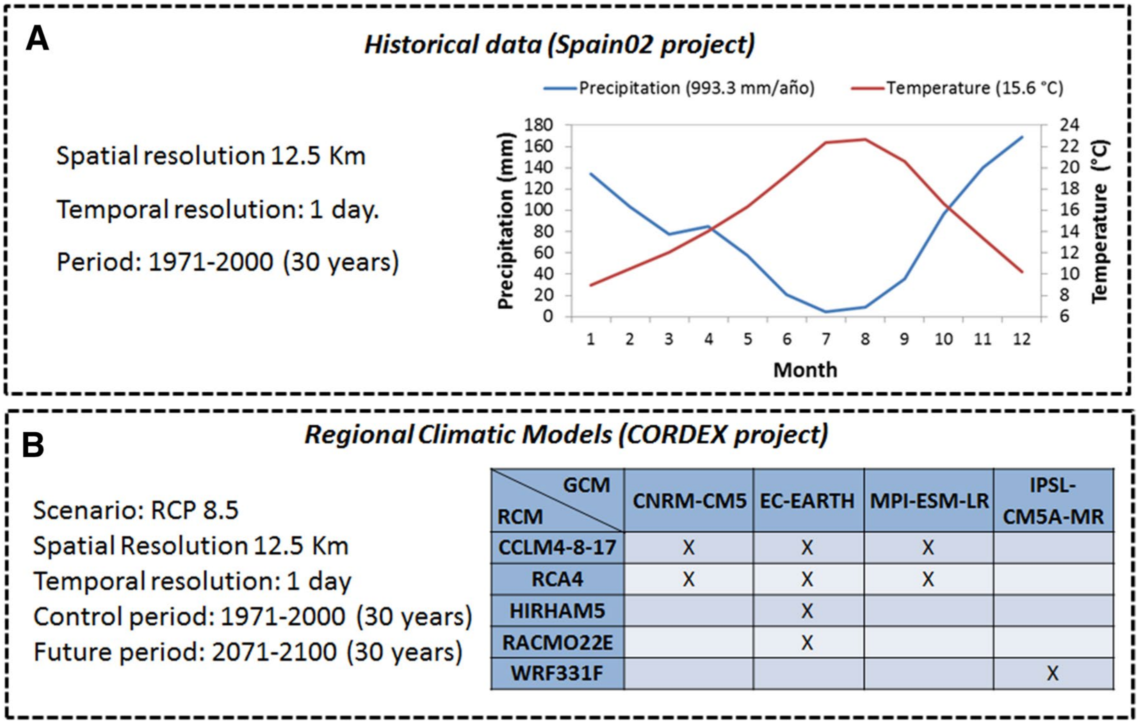


Fig. 4 **a** Geographical location of the Sierra de las Nieves karst aquifer in the province of Málaga in southern Spain. **b** Karst hill with regularized slope. **c** Dolines in the Torrecilla tectonic block. **d** The unsaturated zone of the Torrecilla block, which can reach more than 1000 m. **e** View (from the Torrecilla block) of the paleo-polje of the Nava block. **f** View (from the Nava block) of the Torrecilla block



Spatial resolution 12.5 Km

Temporal resolution: 1 day.

Period: 1971-2000 (30 years)

Scenario: RCP 8.5
Spatial Resolution 12.5 Km
Temporal resolution: 1 day
Control period: 1971-2000 (30 years)
Future period: 2071-2100 (30 years)

GCM RCM	CNRM-CM5	EC-EARTH	MPI-ESM-LR	IPSL-CM5A-MR
CCLM4-8-17	X	X	X	
RCA4	X	X	X	
HIRHAM5		X		
RACMO22E		X		
WRF331F				X

Fig. 5 **a** Mean precipitation and temperature for the historical period 1971–2000. Historical data from the Spain02 project have been used. **b** Regional and global climate models from the CORDEX project used in the study. The two projects have the same spatial and temporal resolutions

emission scenarios. This study considered Representative Concentration Pathways 8.5 (RCP8.5) (Riahi et al. 2011), for the future period 2071–2100. Compared to the total set of RCPs, RCP8.5 is the pathway with the highest greenhouse gas emissions, and thus the most pessimistic scenario. Figure 5b shows the regional and global climate models used in this study. The driving GCMs are: CNRM-CM5, EC-EARTH, MPI-ESM-LR, IPSL-CM5A-MR, and the RCMs are: CGLM4-8-17, HIRHAM5, RACMO22E, RCA4, and WRF331F, according to the combination shown in Fig. 5b.

The results show that, in many cases, the differences between the historical time series and the control time series (provided by the RCMs) can be important. Figure 6 shows these differences for our case study. The maximum, minimum, and mean relative differences for precipitation are 50.7%, 13.1%, and 26.5% for the mean and 38.4%, 0.11%, and 16.2% for the standard deviation. These same values for temperature are: 31.0%, 11.4%, and 20.9% for the mean and 72.7%, 58.1%, and 66.9% for the standard deviation. These differences mean that correction techniques must be applied to generate future climate scenarios. Figure 7 shows the relative difference between the future and control time series for the different RCMs. This information is used directly by the delta change approach for the perturbation of the historical time series to generate potential future scenarios. On the other hand, the bias correction approach uses the relative changes between the historic and control time series to provide corrected control time series for each regional climate model. All the corrected time series are similar (in mean and in standard deviation) to the observed time series, with maximum relative differences of 0.20% and 0.37% for mean and standard deviation of precipitation, and are essentially zero for temperature (Fig. 8). The same transformation function employed to correct the control simulation time series is applied to the future simulation time series to generate potential future scenarios.

The statistics for the future time series generated using the bias correction and delta change approaches are shown in Figs. 9 and 10, respectively. The time series are different depending on the RCM used, because each RCM predicts different future climate changes. The correction technique used also has an influence on these time series. With the first- and second-moment approach (used for temperature), the same mean values are obtained for the mean and standard deviation in both correction approaches (bias correction and delta change), but the monthly time series generated are different for the two approaches. However, the quantile mapping technique generates times series with different mean and standard deviations with the two correction approaches. Table 1 shows the relative changes in precipitation, temperature, and recharge forecasted for the period 2071–2100 as compared to the historical period 1971–2000. The mean

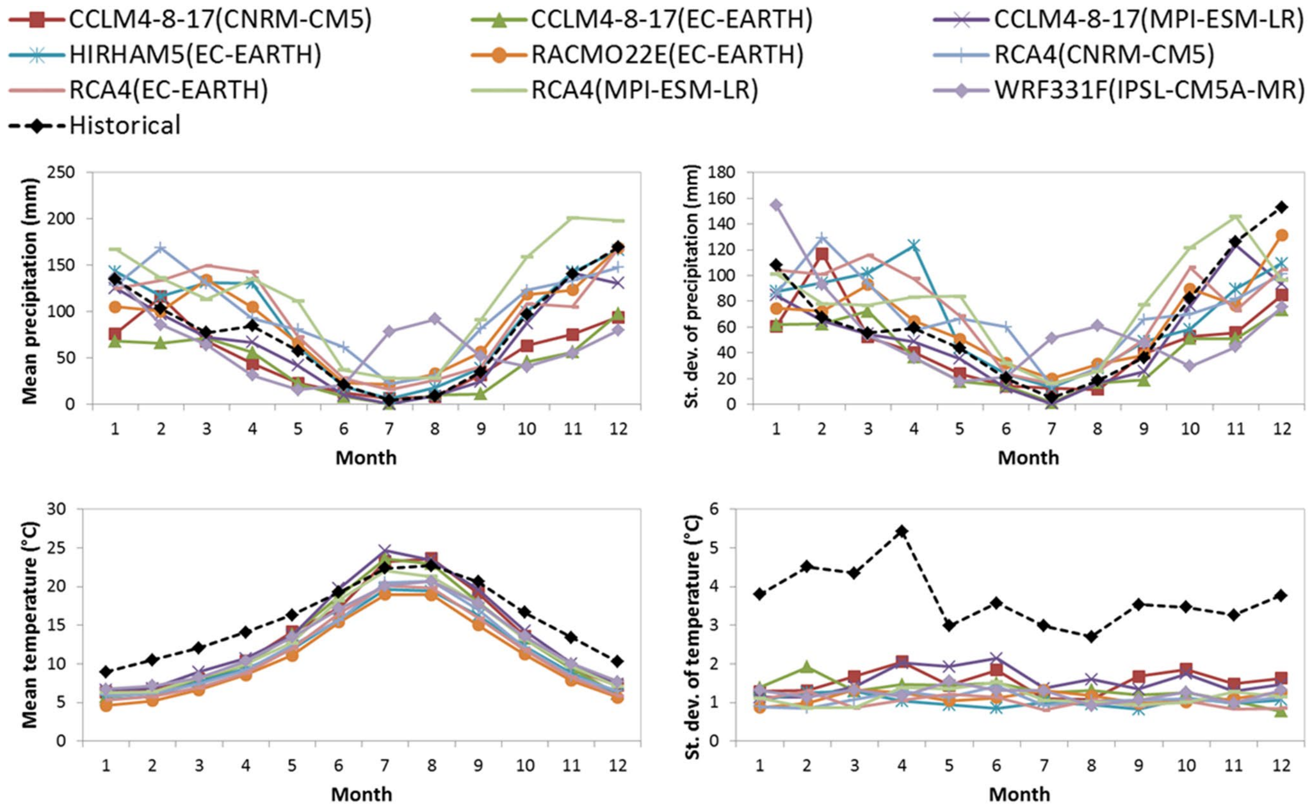


Fig. 6 Mean and standard deviation of the historical and control series for precipitation and temperature. The important differences between them imply that corrections are needed

reduction in precipitation is 27.2%, the mean increase in temperature is 19.4%, and the mean reduction in recharge is 53%. Table 1 has been created by taking into account the fact that in the Sierra de las Nieves karst aquifer, 30% of the recharge is concentrated and the remaining 70% is diffuse (Pardo-Igúzquiza et al. 2012). It has been assumed that this ratio will remain constant over time.

Discussion

It is widely recognized that there is a large degree of uncertainty in any climate change study. First of all, there is great uncertainty regarding the greenhouse gas emission scenario; however, it is worth considering the worst-case scenario, RCP8.5, as a warning of the consequences in the absence of climate change policies. Assuming that the trend of rising greenhouse gas emission continues, there are different climate models (both RCMs and GCMs) that can be used to make future climate projections. Every climate model includes its own model for the atmosphere, the ocean, the Earth's surface, and ice sheets as well, as different parameterizations of the physical processes that must be considered within each of these models. It is no surprise, then, that the different models provided different climate projections. This set of projections, taken together, may result in uncertainty. However, this issue has not been satisfactorily resolved, as there are many more climate models that could be considered, thereby increasing the set and, most likely, the uncertainty by resulting in a broader range of model responses. Although the outcome of each model could be weighted by its complexity, no model is definitive and research is carried out and improvements made to them periodically. Furthermore, the models' predictions for the historical control period are incorrect and they introduce a bias that must be taken into consideration and corrected, as has been done in this study. It has been found that the differences resulting from the different RCMs are much larger than those from the different approaches (bias correction and delta change) and correction techniques. This is logical, as the latter are tailored to reproduce the target statistics, while the different climate models are based on different assumptions and parameterizations.

With respect to recharge, other alternatives to evaluate recharge could be considered, like the procedure proposed in Pardo-Igúzquiza et al. (2012). However, the procedure used in this work is in line with the uncertainty introduced by the other methods. That is, the purpose is to have some numbers

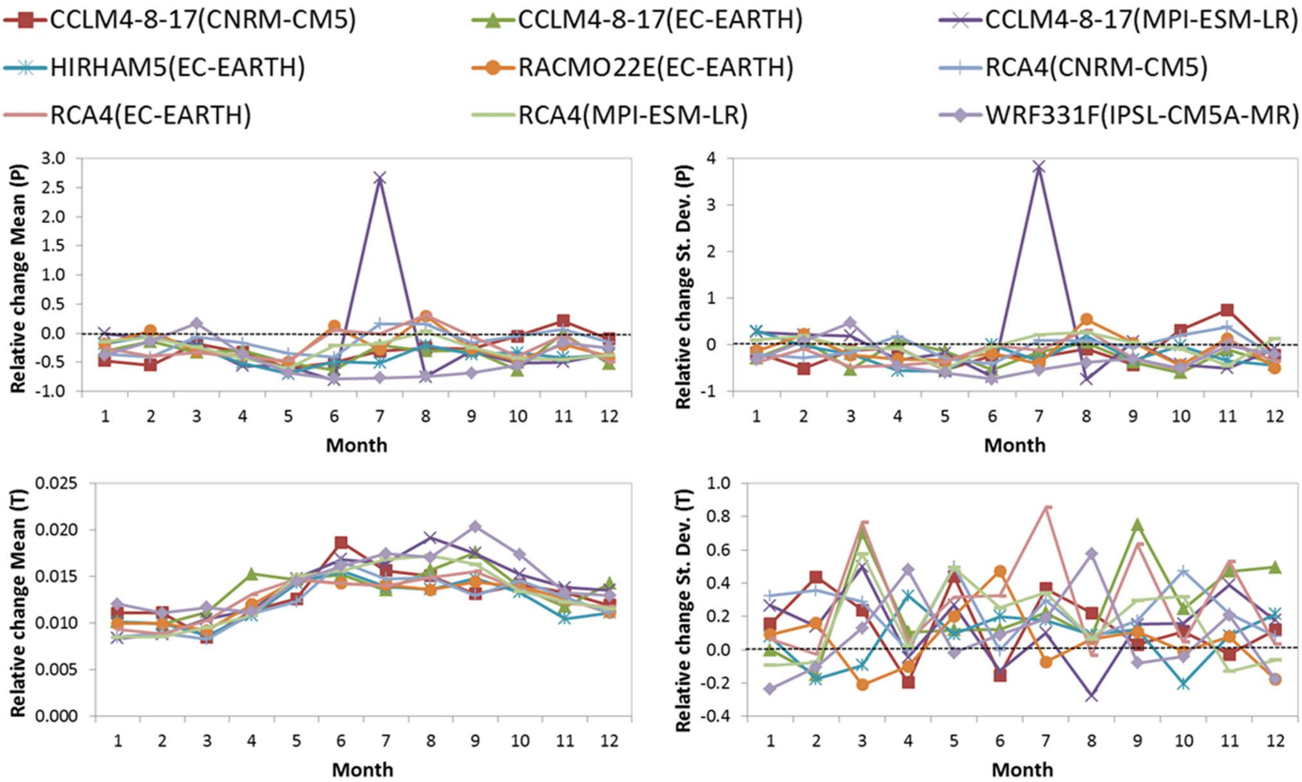


Fig. 7 Relative change in mean and standard deviation for the future precipitation and temperature series with respect to the control time series

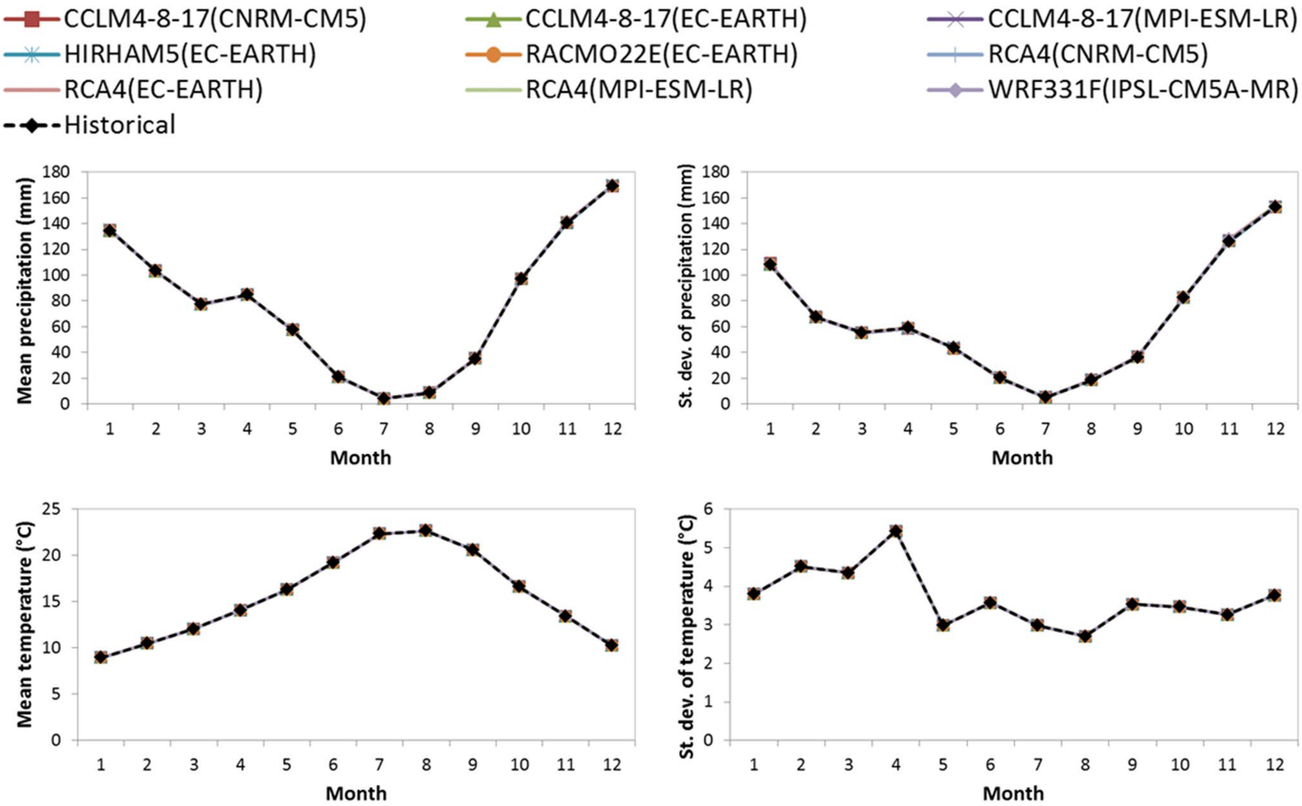


Fig. 8 Mean and standard deviation of the control precipitation and temperature time series for the period 1971–2000, after correction

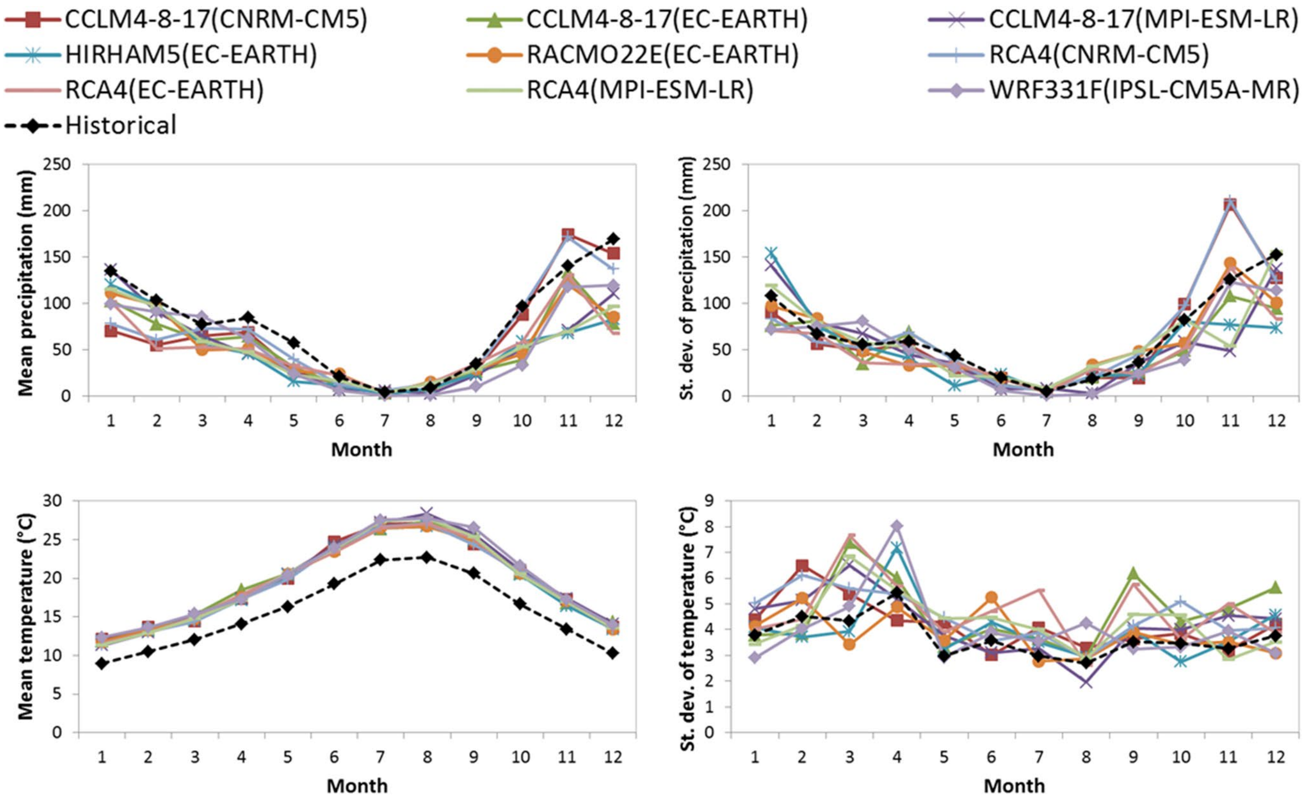


Fig. 9 Mean and standard deviation of the historical and generated future precipitation and temperature time series (bias correction approach) for the period 2071–2100

capable of characterizing potential future trends and that offer an idea of the dangerous situation that could unfold if no action is taken to stop climate change and if increases in greenhouse gas emissions are ignored.

It is very likely that the figures provided for the variation in recharge will be wrong, and there is a great degree of uncertainty attached to them. Nevertheless, they offer a scientifically based assessment of potential changes. Thus, the results should be taken as a warning that should be a call to action for park managers. This will involve preparing for the worst-case scenario, because if it comes to pass and nothing has been done, the consequences will be much worse than if action had been taken when the change in recharge was not as dramatic as that estimated in this study.

To our knowledge, this is one of the first assessments of climate change impact on aquifer recharge in Southern Spain. At scale of the whole Spain county (half a million o of square kilometers), a first assessment of future climate change impacts was performed by Pulido-Velazquez et al. (2018a, b), but it was focused on a short-term future horizon (2016–2045). For the Sierra de las Nieves area in that work, a mean reduction of 19% of the net recharge values was estimated in the period 2016–2045. If a linear trend of the mean recharge reduction was assumed, it would provide a reduction of the recharge for the 2071–2100 near to 45%, which is not far from the 53% estimated within this work. Other works, like Emilio Custodio et al. (2007), have suggested future reduction in recharge because of climate change in Doñana National Park (Southern Spain) but without any quantification on the amount of such reduction, while other works (Collados-Lara et al. 2018) suggest similar future reduction in rainfall and increase of temperature because of climate change in Sierra Nevada National Park (Southern Spain) but without evaluation of their effect on recharge.

Conclusions

A methodology for generating future climate change scenarios has been proposed in this study where different RCMs and different correction approaches and techniques have been used. For the area studied in this work, important changes in precipitation and temperature are expected for the period 2071–2100 for the future potential emission scenario RCP8.5, which could lead to important reductions in the aquifer's recharge. The mean value precipitation is expected to decrease and temperature increase with respect to the

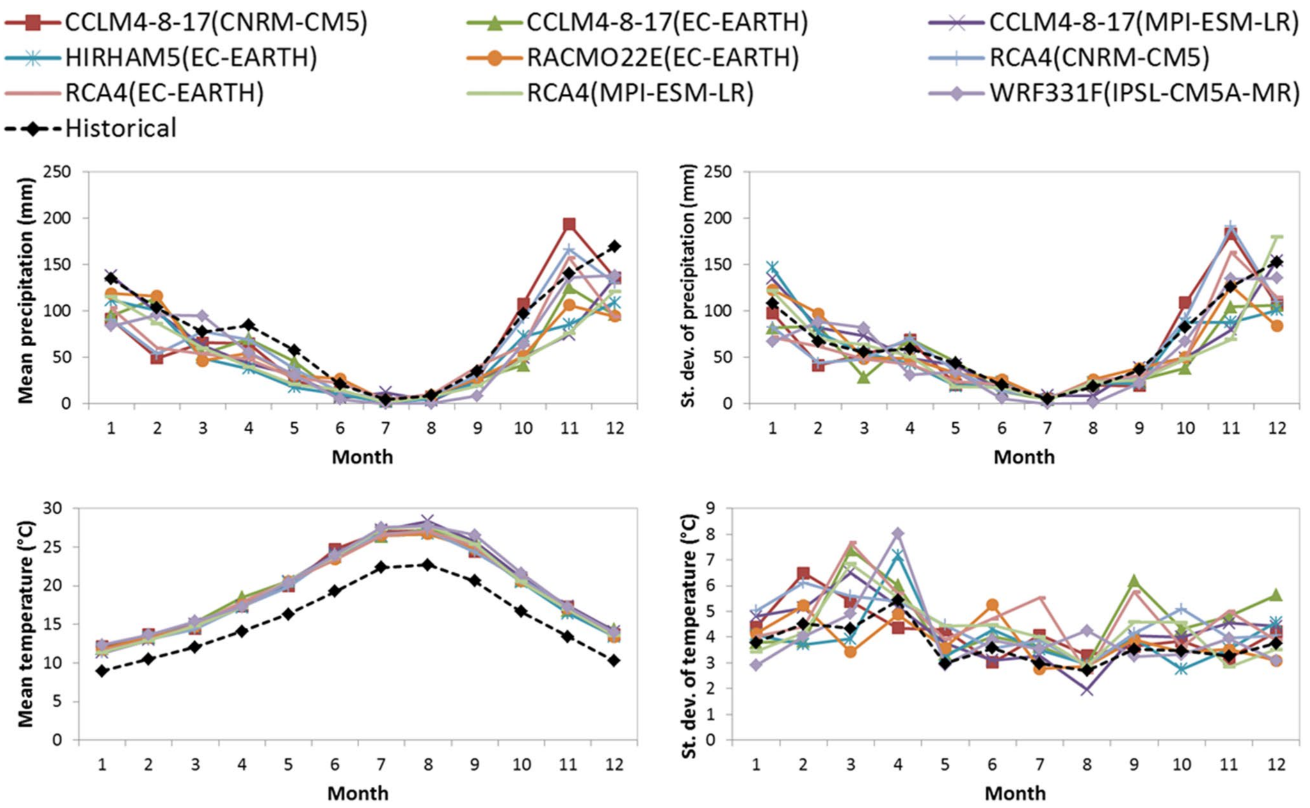


Fig. 10 Mean and standard deviation of the historical and the generated future precipitation and temperature time series (delta change approach) for the period 2071–2100

Table 1 Relative change (in percentage) of future precipitation (*P*) and temperature (*T*) for the bias correction and delta change approaches and the different RCMs employed

RCM (GCM)	Bias correction				Delta change			
	Δ*P* (%)	Δ*T* (%)	ΔDR (%)	Δ*R* (%)	Δ*P* (%)	Δ*T* (%)	ΔDR (%)	Δ*R* (%)
CCLM4-8-17(CNRM-CM5)	− 18.84	19.36	− 48.51	− 39.61	− 16.17	19.36	− 51.96	− 41.22
CCLM4-8-17(EC-EARTH)	− 31.74	19.52	− 70.89	− 59.15	− 26.33	19.52	− 66.18	− 54.23
CCLM4-8-17(MPI-ESM-LR)	− 31.88	19.60	− 69.28	− 58.06	− 26.93	19.60	− 62.28	− 51.68
HIRHAM5(EC-EARTH)	− 36.22	19.13	− 74.37	− 62.93	− 33.08	19.13	− 68.65	− 57.98
RACMO22E(EC-EARTH)	− 29.06	19.20	− 69.17	− 57.14	− 26.50	19.20	− 63.68	− 52.53
RCA4(CNRM-CM5)	− 15.18	19.12	− 42.04	− 33.98	− 17.09	19.12	− 53.06	− 42.27
RCA4(EC-EARTH)	− 33.24	19.26	− 72.49	− 60.72	− 26.54	19.26	− 65.39	− 53.74
RCA4(MPI-ESM-LR)	− 33.04	19.35	− 70.43	− 59.21	− 34.32	19.35	− 70.02	− 59.31
WRF331F(IPSL-CM5A-MR)	− 30.14	19.81	− 68.82	− 57.22	− 23.63	19.81	− 64.34	− 52.13

The relative change in diffuse recharge (DR) and total recharge (*R*) has also been calculated

historical period are 27.2% and 19.4%, respectively. These changes in precipitation and temperature would result in a mean decrease in recharge of 53%. This dramatic decrease in recharge will require new strategies for adapting to and mitigating climate change. The results should be taken by park managers as a warning sign, and the issue of climate change should be included on their agenda. The other objective of this work was to study the model's sensitivity to the correction approach and RCM used. With respect to relative change in mean annual temperature, there are no differences between the two approaches used. However, for precipitation, the differences range from 1.3 to 6.7%, which is also not that large. These values increase when sensitivity is measured with respect to the RCM used; in this case, the maximum differences are 0.68% for temperature and 21.0% and 18.2% for precipitation using the bias correction and delta change approaches, respectively. This implies that while the issue of time series correction has been solved, much more work is required by climatologists to improve their climate models.

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