

Research Article

A Statistical Tool to Generate Potential Future Climate Scenarios for Hydrology Applications

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Global warming associated with greenhouse emissions will modify the availability of water resources in the future. Methodologies and tools to assess the impacts of climate change are useful for policy making. In this work, a new tool to generate potential future climate scenarios in a water resources system from historical and regional climate models' information has been developed. The GROUNDNS tool allows generation of the future series of precipitation, temperature (minimum, mean, and maximum), and potential evapotranspiration. It is a valuable tool for assessing the impacts of climate change in hydrological applications since these variables play a significant role in the water cycle, and it can be applicable to any case study. The tool uses different approaches and statistical correction techniques to generate individual local projections and ensembles of them. The non-equiflexible ensembles are created by combining the individual projections whose control or corrected control simulation has a better fit to the historical series in terms of basic and droughts statistics. In this work, the tool is presented, and the methodology implemented is described. It is also applied to a case study to illustrate how the tool works. The tool was previously tested in different typologies of water resources systems that cover different spatial scales (river basin, aquifer, mountain range, and country), obtaining satisfactory results. The local future scenarios can be propagated through appropriate hydrological models to study the impacts on other variables (e.g., aquifer recharge, chloride concentration in coastal aquifers, streamflow, snow cover area, and snow depth). The tool is also useful in quantifying the uncertainties of the future scenarios by combining them with stochastic weather generators.

1. Introduction

Adaptation to climate change (CC) is one of the greatest challenges that humans will face in the coming decades [1, 2]. This is related to greenhouse gas emissions, mainly anthropogenic carbon dioxide emissions [3]. CC is accepted by the scientific community and most of the society [4]. In the last decades, unprecedented changes (increment in temperature (T) of the atmosphere and oceans, changes in the spatiotemporal variability of precipitation (P) (including more extreme events), reduction of ice, snow, and groundwater levels, and rises in sea level) have been observed [2, 5]. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [3]

includes four future trajectories of anthropogenic carbon dioxide emissions for the twenty-first century, called representative concentration pathways (RCPs). From these trajectories, different climate institutes and organizations develop regional climate models (RCMs) whose data are coordinated and collected by the World Climate Research Program (WCRP) through the CORDEX project [6].

Despite the multiple uncertainties related to RCMs, they provide valuable information that could be used for further evaluation and policy making [7, 8]. Water systems, which are essential for life, are and will be one of the most affected by CC. In general, CC will modify the spatiotemporal variability of climatic variables. Among them, P and T are the main variables that govern the hydrological cycle [9, 10].

Decision makers should have enough information about how these systems will change in the future to design appropriate adaptation strategies. For this reason, local scenarios of CC have to be generated from the climatic model simulations to analyse impacts on water resources (WR) systems.

Potential local future scenarios of P and T can be used to propagate impacts of CC on other hydrological variables in different WR systems, such as river basin [11, 12], aquifer [13, 14], and mountain range [15, 16]. RCMs include control and future simulations of P and T among other climatic variables. However, the RCM simulations cannot be used directly due to the high amount of uncertainties [17, 18]. The statistics of the control series can differ a lot from the statistics provided by historical or observed time series for the considered baseline period. Therefore, the time series provided by the RCMs must be corrected [19, 20] before using them for other applications, generating local series for the specific WR system.

Different statistical correction techniques can be used, such as correction of first- and second-order moments or regression approaches. They have different degrees of complexity and can have different accuracy. These correction techniques can be applied under two conceptual approaches: bias correction and delta change [21, 22]. RCMs and/or correction techniques can be evaluated comparing the control or corrected control simulation series with the historical information. Equifeasible and non-equifeasible (defined by giving more weight to the more reliable projections) ensembles of individual predictions can be employed to obtain more robust predictions [23]. The generation of potential local scenarios, through the correction of the RCMs simulations, involves several nontrivial tasks (selection of the RCMs, RCPs, and reference and future periods and/or level of global warming and application of the correction approaches and techniques) which should be addressed before the propagation of the impacts to hydrological variables. Therefore, tools and methodologies that automate the process are valuable for hydrological applications. Some tools are available to generate local future climate scenarios. Most of them are focused on the bias correction approach using different correction techniques mainly based on the statistical distribution of data (e.g., qmap [24] and CMhyd [25]). However, as far as we know, the application of different correction techniques under the delta change approach requires generating scenarios for specific future horizons and/or level of global warming that have not been included in a tool. On the other hand, these tools do not include the option of creating non-equifeasible ensembles of projections with different weights depending on the reliability of RCMs and correction techniques attending to some basic and/or drought statistics. In this work, these possibilities are incorporated.

We present a new tool to generate potential future CC scenarios for hydrology applications. The GROUND_S (GeneRation of pO_tential fU_ture CC sceNarios for hydrology applicationS) tool generates distributed future monthly series of P , T (maximum, minimum, and mean) and potential evapotranspiration (ETP) using as inputs

historical series and RCM simulations. This tool integrates some methodological aspects studied in previous works [12, 26] (generation of individual projections and creation of ensembles of them) and new potentialities (identification of the period of the RCM to be used for a specific local warming and generation of ETP projections) into an intuitive command-line interface applicable to any case study. The main advantages of the tool are (1) its applicability to any case study and series of data (RCMs, RCPs, simulation periods, etc.), (2) it only requires historical data and RCM simulations to generate the potential future scenarios, (3) it allows using different approaches and statistical correction techniques, and (4) it generates individual local projections and ensembles, including equifeasible and non-equifeasible approaches considering the approximation to historical basic and drought statistics.

The GROUND_S tool allows different possibilities of generating future scenarios and can be used for different purposes depending on the interest of the users:

- Specific level of local warming vs. a specific future period: users can be interested in studying the availability of WR under different RCMs or know how the system will change according to a defined warming.
- Individual projections or ensembles of projections: based on multicriteria analyses [8], they allow to select the individual projections that provide the best approximation to some selected basic statistics (first, second, and/or third moment) or drought statistics (frequency, intensity, magnitude, and duration), which are assessed by applying the Run Theory to the Standard Precipitation Index (SPI) series for the studied variable. They also allow to define ensembles scenarios by combining the selected individual projections. The first option is indicated to quantify uncertainty by using several RCMs and the second to obtain more robust prediction of mean values.
- Different variables according to the preferences of the user: P , maximum, mean, and minimum T and ETP.

These future scenarios are also useful to assess impacts of CC on the availability of WR in a system by propagating the climate inputs to other variables with appropriate hydrological models.

2. Description of the Tool: Data, Methods, and Example Results

Figure 1 shows a flow chart of the methodology implemented in the tool GROUND_S to generate potential climate scenarios to assess impacts on WR systems. The tool, which includes four subroutines, was written entirely in Fortran 90 and can be executed under a command-line interface. The description of the inputs, parameters, subroutines, and outputs of the tool are shown in Figure 2.

The target is to use historical long enough monthly series of P and T (maximum, minimum, and mean) to generate future potential local climatic scenarios of them. It also includes a subroutine to calculate ETP. Note that monthly

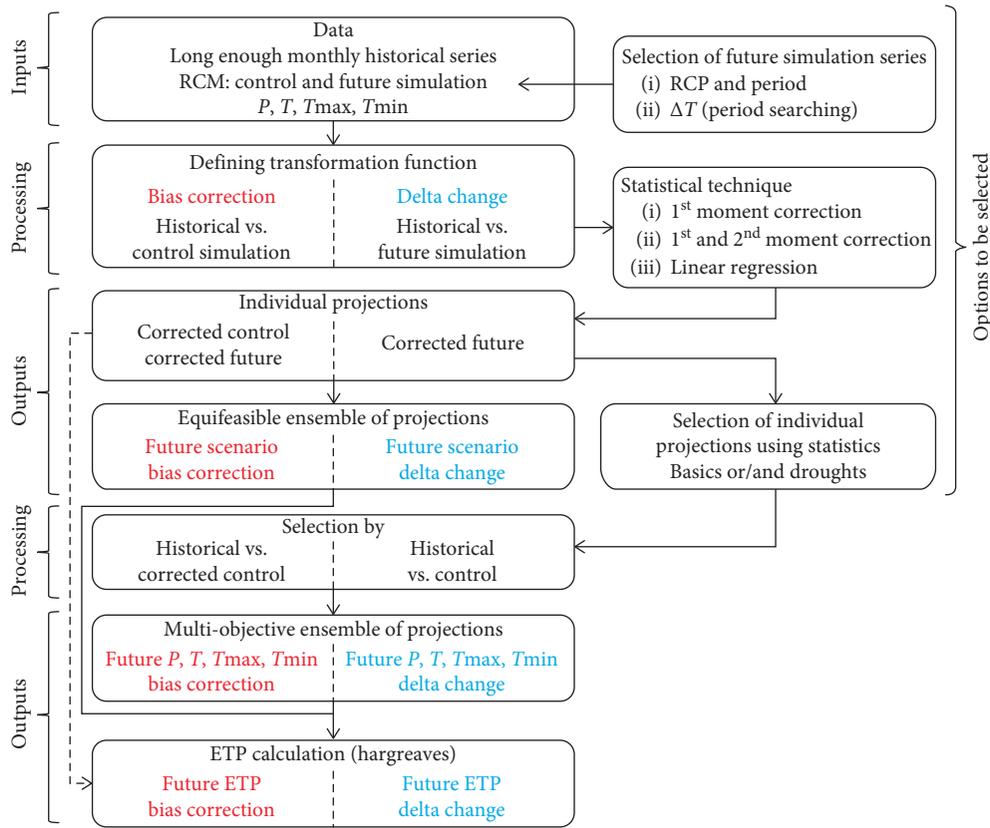


FIGURE 1: Flow chart of the assessment performed with the tool.

series should be complete (without gaps) and the quality of the data should be assessed by the user to ensure that they are representative of the climatology of the study area. It can be applied to point series that correspond to gauges measurements (in which gaps have to be previously completed) or to distributed fields, previously estimated on a grid with an appropriate method. Note that, in any case, those series have to cover the adopted historical reference period. The individual local series are generated using the subroutine *inpro.exe* that requires as inputs the monthly series of the climatic variables and the parameters L , N , and M which represent the length of the series (number of months), the numbers of points or stations considered in the case study, and the code (from 1 to the number of RCMs considered) that represents the RCM to be used, respectively. The historical series should be long enough in order to fulfil the assumption of stationarity of their statistics. If the series are not long enough, they might include drought or wet periods that modify the statistics of the series, making them not representative of the baseline period. A period of at least 30 years is recommended [12, 27]. With respect to the selection of the future projections, the tool allows two possibilities: (1) to fix a future horizon (specific period of time) or (2) to use an increment in mean T (e.g., local warming of 1°C) with respect to the value for the adopted historical reference period. The second procedure can be done by using the subroutine *search.exe*. It requires as input data the future simulation series of T for each RCM considered for the whole period available, the adopted longitude (e.g., 30 years) for the

reference period, and the mean increment of T . This subroutine identifies a future period with a longitude equal to the historical (e.g., 30 years) in which the fixed local warming with respect to the historical is reached. The subroutine calculates a moving average considering an aggregation window equal to the considered length of the future simulation series and compares these values with the simulation series for the reference period. These increments of T represent different levels of local warming. The T and P series for the identified period will be used to perform the statistical correction of the series to generate the local scenarios that fulfil the adopted warming criteria.

In this work, we have applied it to a case study, used as an example to illustrate how the tool generates future series of climatic variables. The historical series employed correspond to a point (located in the province of Granada, south Spain) (longitude: -4.0877 , latitude: 37.3789 , and elevation: 1016 m a.s.l.) of the grid used by the Spain02 v04 project [28]. This project includes P and T interpolated for continental Spain. The CC information was obtained from RCMs from the CORDEX project [6]. We selected two RCMs (CCLM4-8-17 nested to the CNRM-CM5 and WRF331F nested to IPSL-CM5A-MR) and the most pessimist scenario (RCP8.5). Both project use the same grid for Spain (spatial resolution of 12.5 km).

Using the subroutine *search.exe*, we calculated a 30-year moving average that allows us to identify when a specific warming is reached. Figure 3 shows the increment of temperature with respect to the reference period

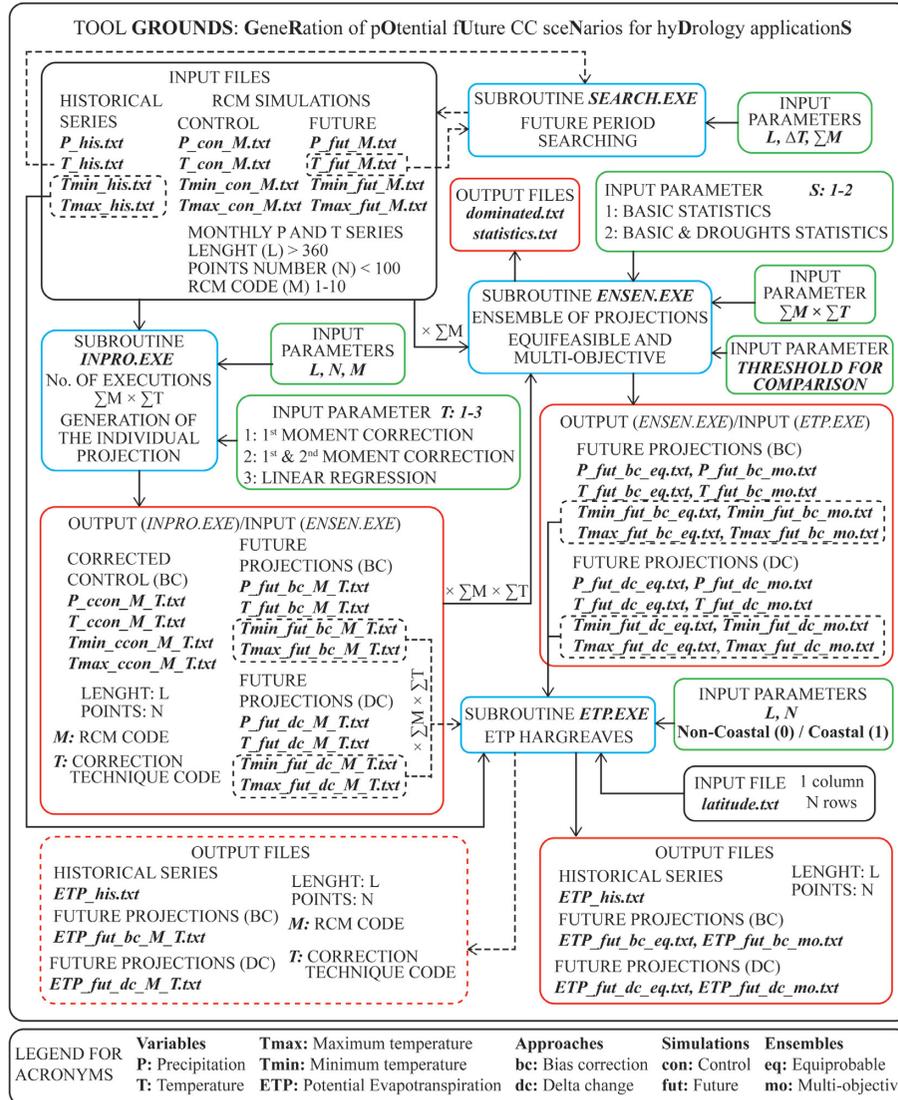


FIGURE 2: Flow chart of the GROUNDS tool subroutines.

(1971–2000) for the two RCMs considered and different future periods.

In this study, we selected the same future period for the generation of scenarios (2071–2100). Note that if a specific local warming is selected, different periods (periods in which the constraint is fulfilled) should be considered for each RCM. For example, in our case, a local warming of 4°C is reached for 2071–2100 in the case of CCLM4-8-17 nested to CNRM-CM5 and for 2064–2093 in the case of WRF331F nested to IPSL-CM5A-MR (see Figure 3).

The subroutine *inpro.exe* uses two conceptual approaches (bias correction and delta change) and three correction techniques, defined by a transformation function, to generate future potential scenarios (see Figure 1). The bias correction approach defines a transformation function to modify the control simulation series to another one whose statistics are more similar to the historical ones. The same function is applied to the future simulation series assuming that the bias between the historical data and the RCM simulations will be maintained invariant in the future

[29, 30]. On the other hand, the delta change approach assumes that the RCMs provide good approximation of the relative changes between future and control simulations, and those changes are applied to the historical series to generate future projections [22, 31]. Note that delta change approach does not correct the RCM simulations; it only modifies the historical series to obtain the future series. From the point of view of the tool, the main difference between bias correction and delta change is that the first generates corrected control series for each combination of correction technique and RCM. The tool allows using three different correction techniques: first moment correction (code 1), first and second moment correction (code 2), and linear regression (code 3) (see Figure 2). These techniques, unlike quantile mapping techniques, do not assume a specific statistical distribution of data. The different correction techniques are applied at monthly scale. In the first moment correction, the transformation function is performed considering only the mean values, while the first and second moment correction technique considers mean and standard deviation. The

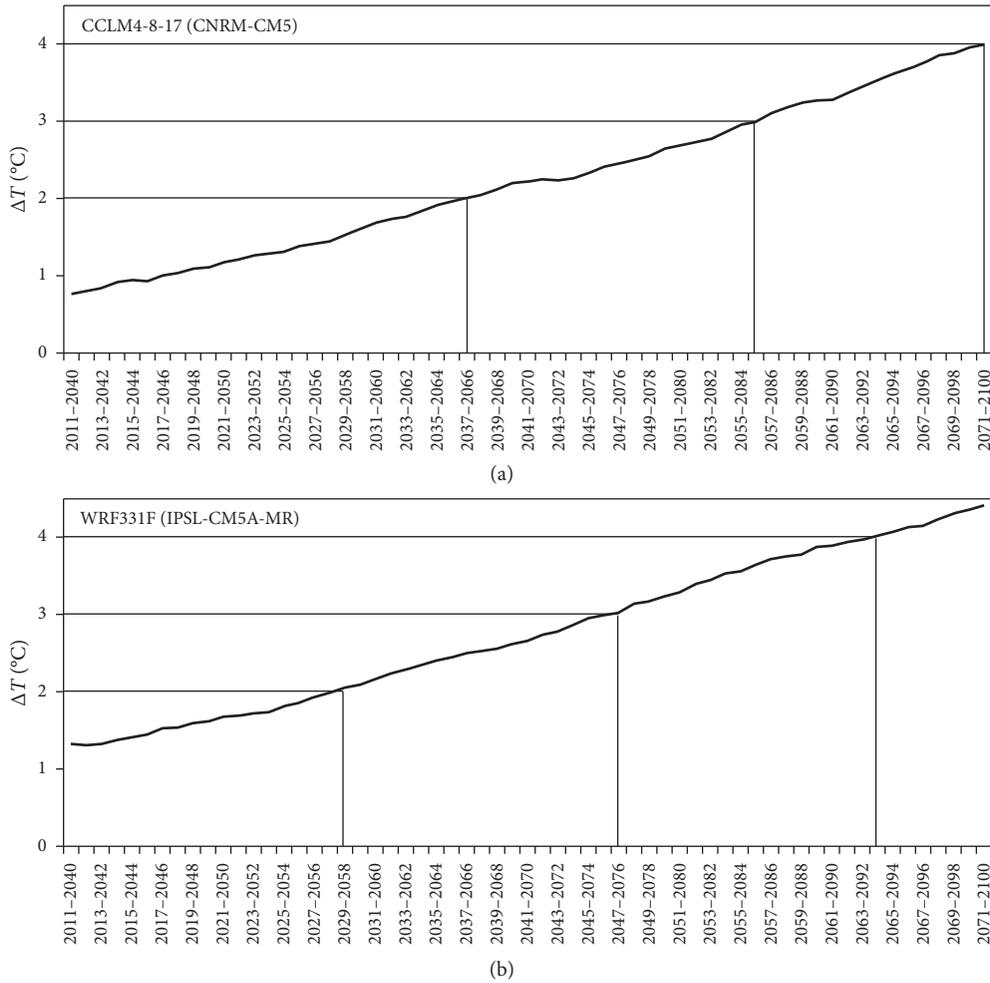


FIGURE 3: Local warming reached with respect to the reference period (1971–2000) for the (a) RCM CCLM4-8-17 nested to GCM CNRM-CM5 and (b) RCM WRF331F nested to GCM IPSL-CM5A-MR.

transformation function in the linear regression is elaborated through fitting a regression model between historical data and control simulation in the case of the bias correction approach and between the control simulation and future simulation in the case of the delta change approach. Note that the tool employs the best linear fit and provides the correlation coefficient (R^2) of it. The user should decide if its accuracy is enough. For the case study presented in this work, R^2 is above 0.85 for RCM CCLM4-8-17 nested to CNRM-CM5 and 0.67 for WRF331F nested to IPSL-CM5A-MR in the case of P . In the case of T , these values are 0.70 and 0.75, respectively. Figure 4 shows the historical data and the individual projections obtained for P and T for the considered case study. The average monthly results for the mean year have been represented in Figure 5.

The generated scenarios can be used as individual local projections or create ensembles of them that could produce more robust climate scenarios than those based on a single projection [23]. The subroutine *ensen.exe* allows to generate four ensembles of individual projections. Two of them are defined by combining, as equiflexible members, all the individual projections generated by applying delta change or

bias correction approaches (see Figure 2). Two other options are defined by combining only the noneliminated projections in the multiobjective analysis for the two approaches (delta change and bias correction). The tool allows performance of the multiobjective analyses by considering only basic statistics (mean, standard deviation, and asymmetry coefficient) or including also drought statistics (duration, magnitude, and intensity). The drought statistics are calculated by applying the Run Theory to the corresponding SPI monthly series [12, 32]. The drought statistics series are calculated considering different thresholds of SPI values (it covers the whole range of negative values of SPI obtained) to define drought periods. In the calculation of the SPI, the probability of occurrence of P in the RCM simulations was obtained by using the parameters calibrated from the historical series to perform an appropriate comparison [12]. In this analysis, an RCM or a combination of RCM and correction technique is eliminated (dominated solution in multiobjective terminology), if another projection has a better fit to the historical data for all the statistics. The index employed to measure the goodness of fit is the mean of the quadratic difference between simulations and historical

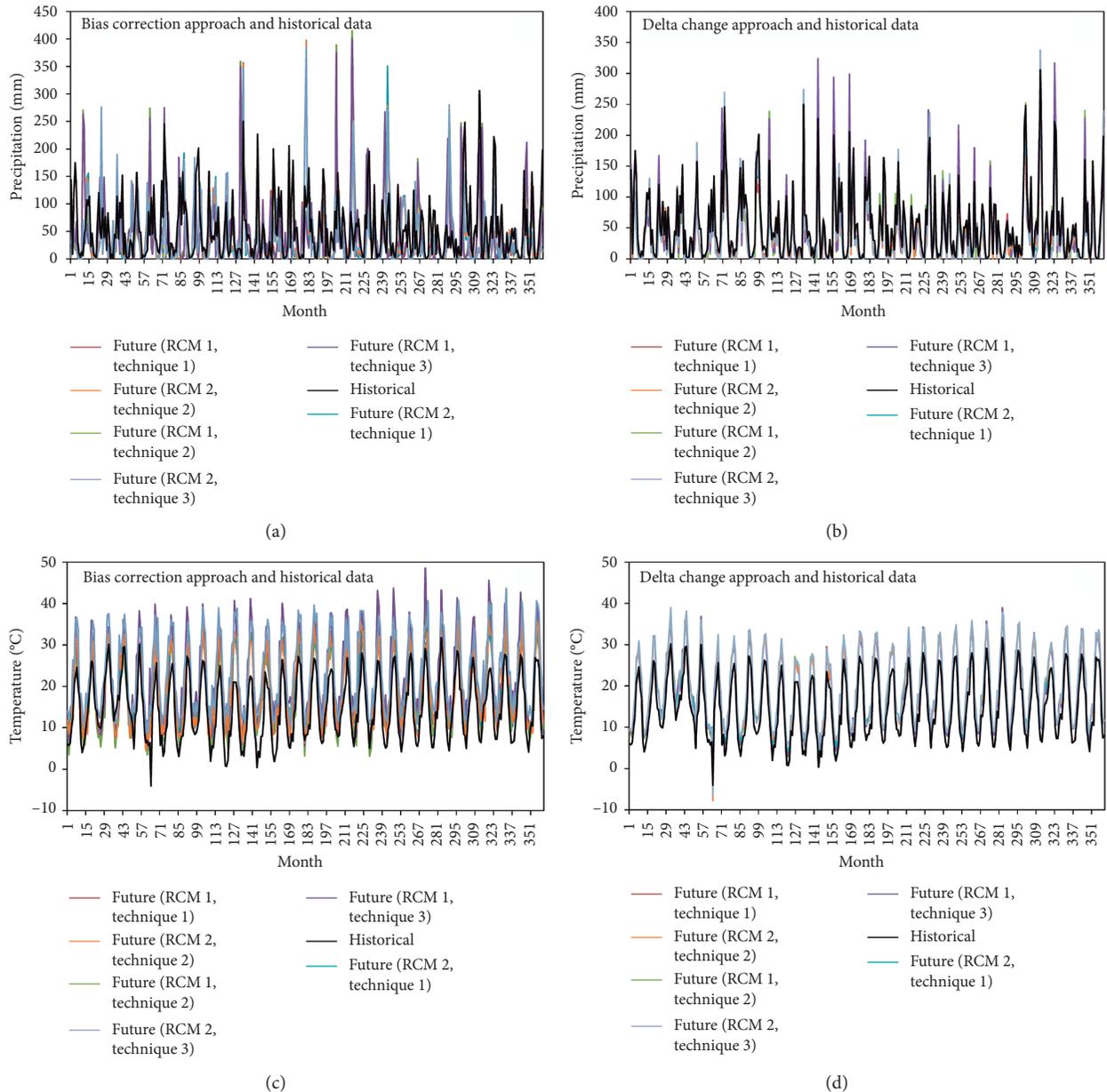


FIGURE 4: Historical data and individual projections of P using the (a) bias correction approach and (b) delta change approach and of T using the (c) bias correction approach and (d) delta change approach generated by using the GROUNDSTOOL tool.

series divided by the square of the mean historical value for each statistic. This index is applied to each considered statistic. The tool also includes a threshold (it can be modified by the user) that allows us to define when an approach is considered significantly better than others with respect to a specific statistic. This threshold, measured in percentage of relative difference, allows us to assume that certain differences in some statistics are not significant. For the considered example, this threshold has been considered 3%. The subroutine *ensen.exe* also generates the files *dominated.txt* and *statistics.txt*. The first indicates the combinations of RCMs and techniques (in the case of bias correction approach) and RCMs (in the case of delta change approach) that are dominated solutions. These solutions are

eliminated to obtain the non-inefficient ensembles. The second file includes the values of the indices used for the multiobjective analysis. For the case study, the combination of the second RCM (WRF331F nested to IPSL-CM5A-MR) and the first correction technique (first moment correction) was identified as dominated solution. The mean values of P and T obtained with the ensembles and their standard deviations for the case study are represented in Figure 6. In the case of delta change, the efficient and the multiobjective ensembles are equivalent because there is no dominated solution attending to the two RCMs considered. For the case study, an important reduction in P (mean of the four ensembles of 23.7%) and increase in T (mean of the four ensembles of 32.6%) are obtained. With respect to the

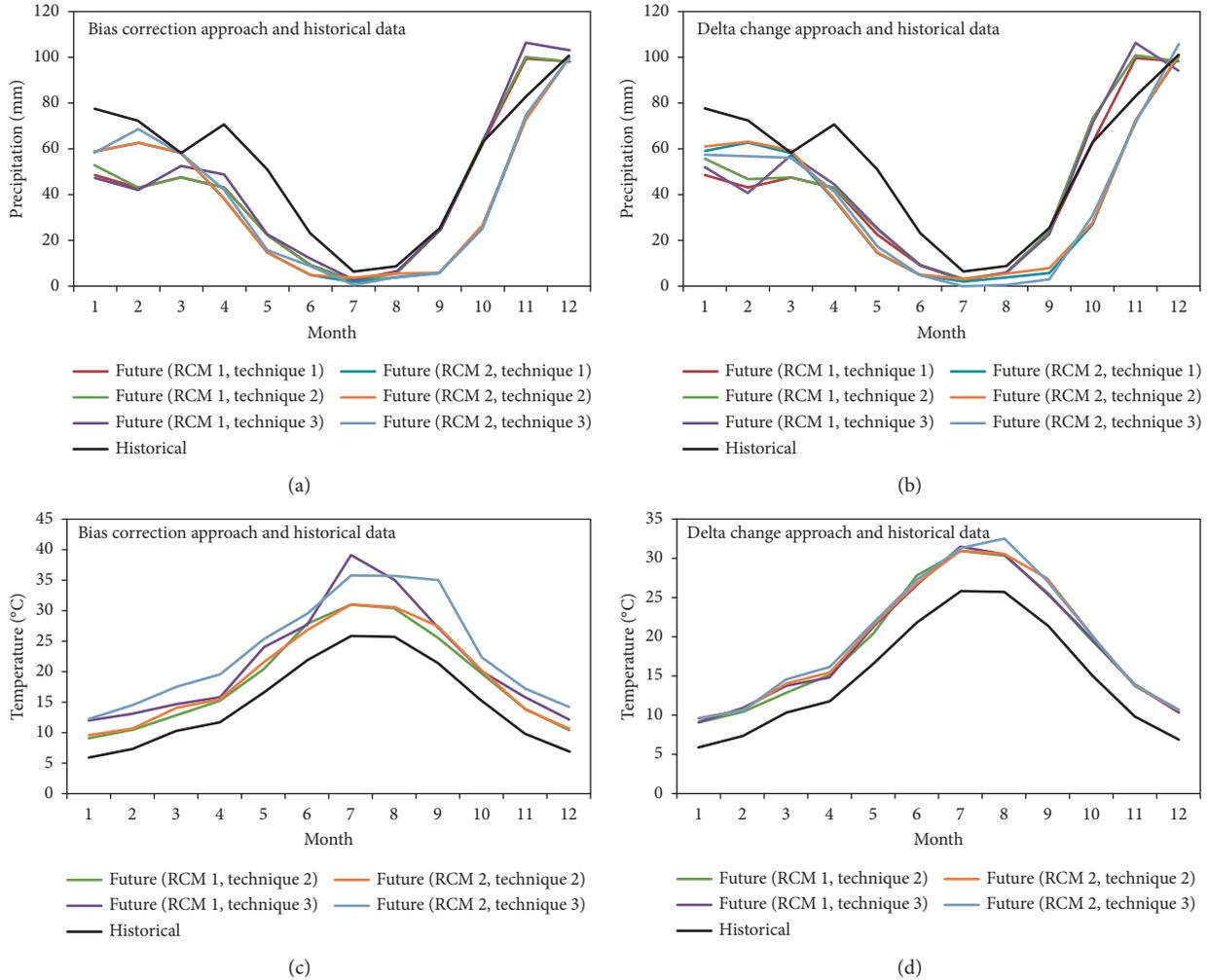


FIGURE 5: Mean year at monthly scale for the historical data and individual projections of P using the (a) bias correction approach and (b) delta change approach and of T using the (c) bias correction approach and (d) delta change approach generated by using the GROUNDS tool.

standard deviation, in the case of P , the ensembles show a lower value with the exception of the autumn where some ensembles predict an increment of the variability. In the case of the temperature, the bias correction approaches predict a lower variability and the delta change approaches a higher variability.

Finally, the tool also allows calculating historical and future ETP series by means of the subroutine *ETP.exe*. This subroutine employs the Hargreaves method [33, 34] and requires as inputs the historical and the future ensembles (or individual projections) of maximum and minimum T and the latitude of each location or station considered. The tool employs the modified method proposed by Samani [35]. This method uses tabulated values (depending on the latitude) to calculate solar radiation. It is also needed to indicate if the study area is located in a coastal or noncoastal zone to determine an empirical coefficient, which should be different for interior regions and for coastal regions [36]. The mean historical and future ETP for the case study have been represented in Figure 7. The mean increment of the four future ensembles of ETP with respect to the historical data is 31.8%.

3. Utility and Discussion

The GROUNDS tool allows correcting the future climatic simulations using the observed series to reduce the uncertainties of the RCMs. The tool requires complete monthly series (without gaps) and an adequate assessment of the quality in order to ensure that they represent the climatology of the case study. These corrected projections are plausible scenarios that intend to be representative of a period or a mean increment of T (local or global warming). The IPCC in some of its latest reports opts for using a mean increment of global warming to better reach users and decision makers (e.g., [37]). Some research works included this approach too [38, 39]. Multiple future series could be generated for the same climatic conditions. The stochastic weather generators (SWG) provide multiple synthetic time series of weather data for a location or multiple locations based on the statistical characteristics of the observed climate at these locations [40, 41]. A large amount of works employed SWG to assess the impact of CC [42, 43]. The tool presented in this work could be combined with a SWG to generate multiple

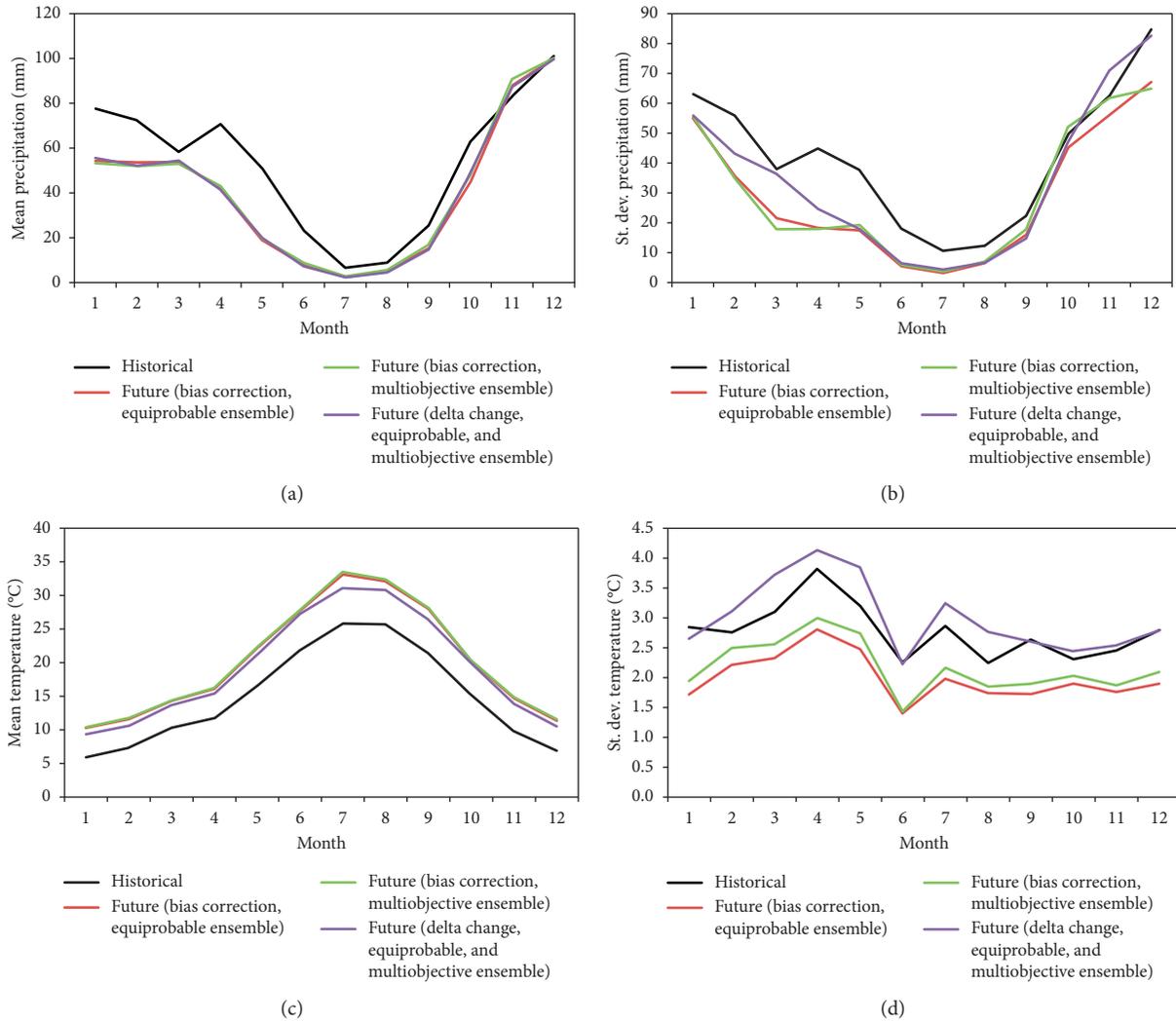


FIGURE 6: Mean year at monthly scale for the historical data and future ensembles of (a), (b) P and its standard deviation and (c), (d) T and its standard deviation generated by using the GROUNDS tool for the case study. Note that for the example considered in the case of the delta change approach, the multiobjective ensembles are equivalent to the equifeasible ensembles because there is not any dominated solution.

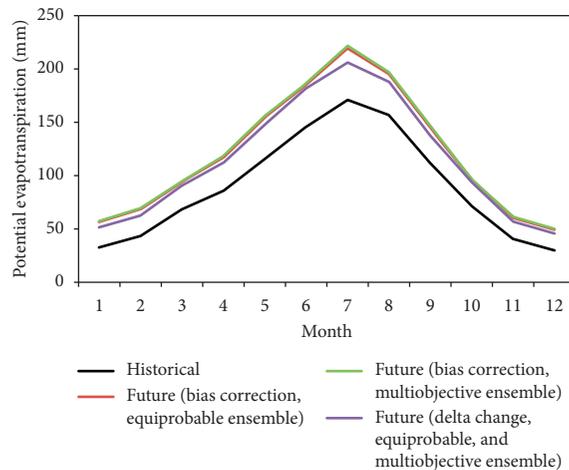


FIGURE 7: Mean year at monthly scale for the historical and future ensembles of ETP generated by using the GROUNDS tool for the case study. Note that for the example considered in the case of the delta change approach, the multiobjective ensembles are equivalent to the equifeasible ensembles because there is not any dominated solution.

series of potential future local scenarios of CC which could feed hydrological models quantifying the uncertainty of the projections through a Monte Carlo analysis [44, 45].

As pointed in the Introduction section, one of the main advantages of the GROUNDNS tool is its applicability to different cases studies. In recent years, two subroutines of the tool (*inpro.exe* and *ensen.exe*) have been employed to generate potential scenarios for assessing CC impacts in different typologies of WR systems. It has been tested in cases covering different spatial scales: country [26], basin [12], aquifer [14, 46, 47], and mountain range [16, 48]. Furthermore, the local scenarios of CC generated by using the GROUNDNS tool have been propagated to different variables in different case studies: recharge [16, 26], ground subsidence [47], and snow cover area [48]. The tool has been proven to be effective for hydrological applications and could contribute to the analyses to support decision-making processes by experts or public participation [49, 50].

All the cited applications correspond to case studies located in Spain, where important reduction in P and increment in T are expected due to CC. The tool also allows quantifying the change in variability of the climatic variables at seasonal and monthly scale. This variability in general will be higher due to CC [51, 52]. For the case showed in this study, the tool predicts a higher variability of P in autumn. In the case of T , the delta change ensembles show higher variability than the historical data (see Figure 6).

We have developed a general tool that uses several correction techniques (first moment correction, first and second moment correction, and linear regression). It does not include correction techniques based on the cumulative distribution function, which have been employed by other authors with good results [53, 54]. However, the differences between these techniques and more simple techniques, as first and second moment corrections, are not significant for the hydrological applications where we have tested them [12]. On the other hand, the tool employs and generates monthly series. This could be an inconvenience for some hydrological applications that use daily data [55–57]. The possibility of generating daily data was tested, but if the second moment correction is applied, it might generate negative values of P . If these values are moved to zero, the statistics of the series can suffer modifications and the information from RCMs can be altered [31]. However, the monthly series can be transformed to daily series using the daily pattern of distribution of the monthly historical values to distribute the generated future monthly values [48].

On the other hand, the local future scenarios can be propagated through appropriate hydrological models to study the impacts on other variables (e.g., aquifer recharge or discharge [26], chloride concentration in coastal aquifers [46], streamflow, snow cover area, and snow depth [48]). They can be even propagated with other models to assess nonhydrological physical variables (e.g., subsidence [47]).

4. Conclusions

In this work, the new tool GROUNDNS, which generates potential future local scenarios of CC, has been presented.

The tool is applicable to any case study and requires historical and RCM simulation information to generate individual local projections. The generated future scenarios can be used as individual local projections or create ensembles of them that could produce more robust climate scenarios taking into account basic and droughts statistics. The tool also allows determination of the future simulation period from a specific increment in mean T (local warming scenario) and propagation the impacts on T to ETP.

For the case study (located in south Spain) used to illustrate the functionalities of the tool, an important reduction in P (in mean 23.7%) and an increment in T and ETP (in mean 32.6% and 31.8%, respectively) have been obtained.

Two subroutines of the tool have proven to be effective for different scales of application and spatiotemporal resolutions in previous works (see the previous section). The tool can be also combined with appropriate hydrological models to propagate impacts of CC to other hydrological variables or SWG to assess the uncertainty of the generated future scenarios in these models.

Data Availability

The historical data and the RCM simulations used to support the findings of this study come from previously reported studies and datasets, which have been cited. The software developed in this study may be available for research purposes upon request from the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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