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LETTER

Severe climate-induced water shortage and extremes in Crete

A letter

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Abstract Climate change is expected to have a significant impact on the hydrologic cycle, creating changes in freshwater resources. The Intergovernmental Panel on Climate Change (IPCC) predicts that, as a result, floods and prolonged droughts will take place at increasingly frequent periods. The Mediterranean has been described as one of the main climate change "hot-spots", with recent simulations showing a collective picture of substantial drying and warming. This effect appears more pronounced during warm periods, when the seasonal decrease of precipitation can exceed control climatology by 25–30%. Despite the decreasing annual rainfall trend, an increase in the amount and intensity of wintertime rainfall is evident. However, the scientific question on the quantitative impact of these signals to small scale coastal watersheds and Mediterranean islands has not been answered. The state-of-the-art Ensembles dataset was employed to assess the impact of the changing climate on the water availability of the island of Crete at basin scale. Here, the Ensembles precipitation and temperature data is used as input for a rainfall–runoff model previous calibrated for the whole island with the principle of regionalization. Data analysis for the period

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1970–2100 reveals an overall decreasing precipitation trend which, combined with a temperature rise, leads to substantial reduction of water availability. Quantitative results of hydrological change provide the data required to improve knowledge and adaptation policy to water shortages.

1 Introduction

Global Change will seriously affect hydrological processes and alter the supply of ecosystem services that are vital for human well-being (Schroter et al. 2005; Maxwell and Kollet 2008; IPCC 2007). Climate model Ensembles predicts a 10–30% decrease of runoff in southern Europe by the year 2050 with considerable potential regional-scale consequences for economies and ecosystems (Milly et al. 2005). Among all European regions, the Mediterranean appears most vulnerable to global change, with multiple potential impacts related primarily to increased temperatures and reduced precipitation (Schroter et al. 2005; Giorgi and Lionello 2007; Somot et al. 2006, 2008). The influence of climate variables is crucial for a proper understanding of water availability in any given territory. Scientific communities from the fields of water resources and climate strive to analyze, quantify and predict the components of the current and future global water cycles as well as the status of water resources. The authors, coming from the water resources and climate scientific communities, collaborate to study the climate change effects on hydrological processes at the river catchment scale for the island of Crete. Changes in precipitation and temperature that are predicted by global climate models for Special Report on Emissions Scenarios (SRES) cannot be used to assess impacts on small catchment scale without previously applying a downscaling methodology. For this purpose, statistical and dynamic downscaling are often compared (e.g. Murphy 1999; Spak et al. 2007; Landman et al. 2009), with the latter offering a more comprehensive and consistent approach (Rummukainen 2010) as well as robust spatial coverage at ungauged locations.

2 Methodology

We use results of the Ensembles project focusing on the island of Crete. Simulations from 10 RCMs (Jacob et al. 2007, 2008; Roeckner et al. 2004; Van der Linden and Mitchell 2009) were run over the European continent at a horizontal resolution of about 25 km (Fig. 1). The RCMs' lateral boundary conditions were provided by 8 GCMs for the period 1951–2100 (Table 1). Previous multi-model experiment results (e.g. Christensen and Christensen 2007; Déqué et al. 2005, 2007; Van der Linden and Mitchell 2009), suggest the independence of RCM output, even when using the same GCM lateral boundary conditions. All simulations were forced using observed GHG green house gas and aerosol concentrations until 2000 and SRES A1B concentrations scenario until 2100. As shown by Sanchez-Gomez et al. (2009), the Ensembles RCMs simulate well the long-term trends and the inter-annual variability of the frequency of occurrence of weather regimes, over Europe-Atlantic during the period 1961–2000.

The RCMs are chosen based on their spatial and temporal extent as well as their ability to simulate the present climate. RCM-specific weights are calculated in order to construct the optimal ensemble output for precipitation at a monthly time

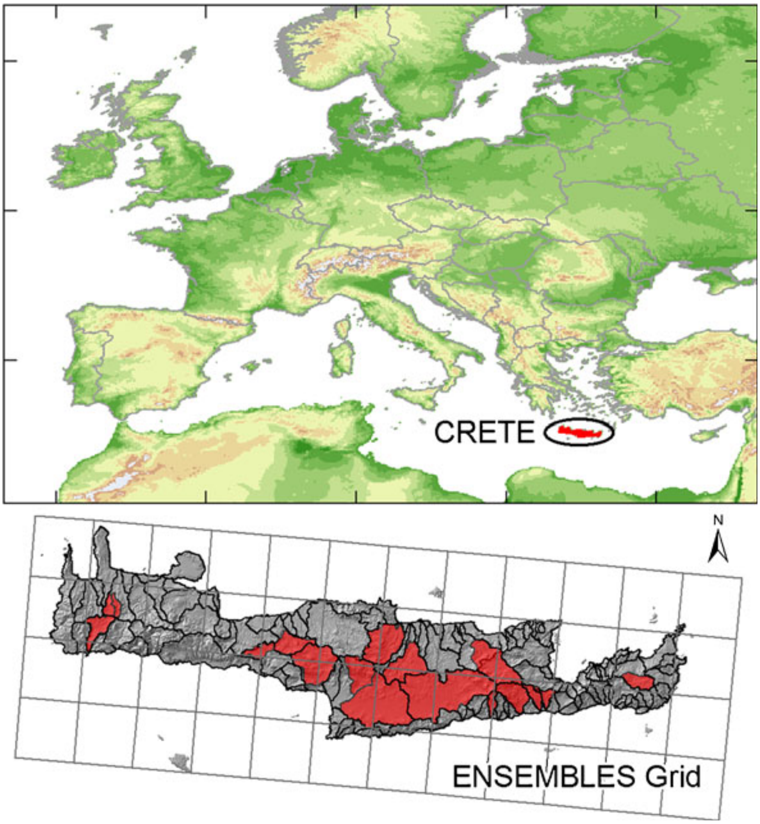

Fig. 1 Location of Crete Island, delineated watersheds and the mesh of the ENSEMBLES regional climate models. *Red areas* represent gauged watersheds at the outlets

step and at watershed level. The weights are calculated according to the probability density distributions and the annual cycle of monthly climate variables as described in Christensen et al. (2010). Additional information for Ensemble RCMs weighting is presented in Electronic Supplementary Material. The output is then bias corrected against data obtained from 53 rainfall and 15 temperature stations for the period

Table 1 List of ensembles regional climate models (RCMs)

No.	Institute	RCM	Driving GCM	References
1	ETH	CLM	HadCM	Jaeger et al. (2008)
2	ICTP	RegCM	ECHAM5-r3	Giorgi and Mearns (1999)
3	KNMI	RACMO2	ECHAM5-r3	van Meijgaard et al. (2008)
4	METOHC	HadRM3Q0	HadCM3Q0	Collins et al. (2010)
5	METOHC	HadRM3Q3	HadCM3Q3	Collins et al. (2010)
6	METOHC	HadRM3Q16	HadCM3Q16	Collins et al. (2010)
7	C4I	RCA3	HadCM3Q16	Kjellström et al. (2005)
8	MPI	REMO	ECHAM5-r3	Jacob (2001)
9	SMHI	RCA	BCM	Kjellström et al. (2005)
10	DMI	HIRHAM	ARPEGE	Christensen et al. (2006)

Table 2 Estimated mean daily percentage p_i

Month	J	F	M	A	M	J	J	A	S	O	N	D
p_i	0.126	0.179	0.247	0.305	0.341	0.355	0.354	0.320	0.255	0.151	0.130	0.104

1970–2000 and interpolated at basin scale. Here we follow a two-step bias correction procedure that adjusts rainfall to approximate the observed long-term frequency and intensity distribution (Ines and Hansen 2006; Law and Kelton 1982; Wood et al. 2002). The correction involves truncating the RCM rainfall distribution and then mapping it onto a gamma distribution fitted to the observed intensity distribution. For the island of Crete, over the period 1973–2000, the weighted Ensembles results underestimate local observed precipitation by 28%, while models perform better for temperature with only a slight overestimation of 0.6%.

The SAC-SMA continuous rainfall–runoff model is used to generate streamflow from rainfall and evapotranspiration (ET_0) measurements, following Tsanis and Apostolaki (2009). For simulations of future periods, where ET_0 data is not available, the Blaney–Cridlle (Allen and Pruitt 1986) equation was applied to calculate ET^{BC} using monthly Ensembles air temperature estimations T as input. The mean daily percentage of annual daytime p_i (Table 2) given by $p_i = ET_{0i}^{BC}/(0.46 \cdot T_i + 8)N_i$, where $i \in (1, 12)$ and N the days in month i, is estimated for the study area and then used to generate future ET_0^{BC}. The rainfall–runoff model was then calibrated and validated for 15 gauged basins (Fig. 1), with a genetic algorithm scheme (Wang and Yen 1999) using the Nash–Sutcliffe model accuracy statistic as the objective function. The calibration input is derived from the interpolation of 53 rainfall, 15 temperature and 20 pan evaporation stations at basin scale values for the period 1970–2000. In order to address uncertainty issues and generalize the model for the whole island, multiple parameter sets (Pareto solution) for each watershed are produced (Gupta et al. 1998). Finally, model parameters are regionalized for the 110 basins that cover the whole island, based on watershed characteristics (morphology, long term meteorology and geology) by using a multi-linear regression, in order to provide the water balance for the island and its basins.

3 Results

The RCM output analysis is based on four 30-year time slices and represents the spatial average of the grid cells that cover Crete in the Ensembles domain. The first period (observed) 1970–2000 was used for weighting, bias correction and interpretation for the three future (2010–2040, 2040–2070 and 2070–2100) periods. According to the Ensembles results of 10 RCMs, monthly precipitation over Crete (Fig. 1) follows a negative trend of about 26 mm per decade (Fig. 2) and average monthly temperature shows a positive trend of 0.5°C per decade. Here we consider that the period 1970–2000 is indicative of the current conditions. Analysis reveals that, in comparison to the control climatology, future projections show a decrease of rainfall averages (Figs. 2 and 3). During the upcoming 2010–2040 period, we expect $12(\pm 25)\%$ less mean precipitation and $1.9(\pm 0.8)^{\circ}$C higher average temperatures over the island of Crete. Respectively, during the next two time periods of 2040–2070 and 2070–2100, the average precipitation will decrease by $20(\pm 46)\%$ and $29(\pm 41)\%$, respectively, while average temperature will increase by $3.8(\pm 0.6)^{\circ}$C and

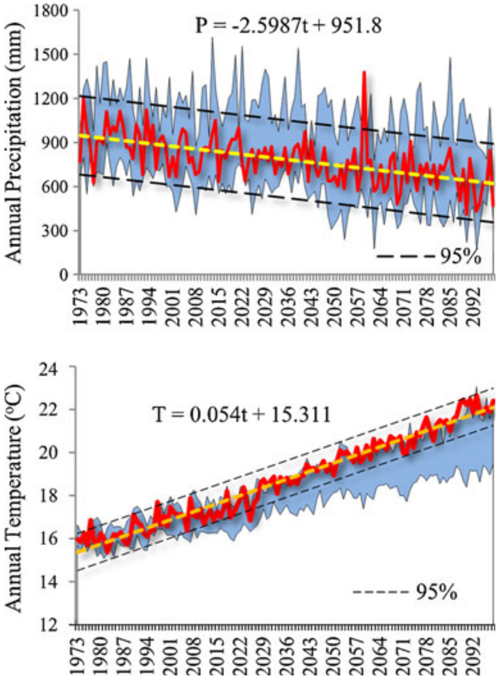

Fig. 2 *Red lines* represent the ensemble of average annual precipitation and temperature of all RCMs for Crete. *Orange dashed lines* represent annual ensemble precipitation and temperature trends. The *blue area* represents the amplitude of the annual precipitation and temperature (min and max) of all the RCMs

5.4(±0.8)°C. All bounds are estimated at a 95% confidence interval. Comparing the control climatology with future time slices, the most important observations can be summarized as: (a) 2010–2040: increase in the maximum and minimum monthly precipitation and maximum daily precipitation, (b) 2040–2070: a significant decrease of spring and winter precipitation could lead to drier hydrological years, (c) 2070–2100: maximum monthly precipitation will increase and the seasonal precipitation of winter and spring will further decrease.

These signals are present in most projections from Ensembles RCMs and may be due to local feedbacks or to changes in circulation patterns and modes of natural variability (Giorgi 2006; Lionello et al. 2006). The probability distribution function (PDF) of the monthly precipitation has a longer tail for the future climate periods when compared to the past climate. Similar trends were projected for Central Europe where, even as summers become drier, there is higher probability for an increase in severe summer precipitation (Christensen and Christensen 2003). The Ensembles projections also indicate a change in the seasonality of monthly precipitation (Fig. 3). Furthermore, there is evidence of an increase in maximum daily precipitation during autumn. Mildly wet days are expected to be fewer by 15% while high precipitation events occurrence could increase up to 35%.

The average precipitation for a normal year in the island of Crete is approximately 934 mm or 7,697 Mm^3 (Tsanis and Naoum 2003). Following the standardization with the respective basin areas, the annual water balance breaks down to 68–76% evapotranspiration, 14–17% infiltration and 10–15% runoff. The average annual water availability for the island of Crete (total surface runoff and infiltration to groundwater) of the period 1970–2000 was 1,908 Mm^3 (3,407 m^3 capita$^-$1 year^{-1}),

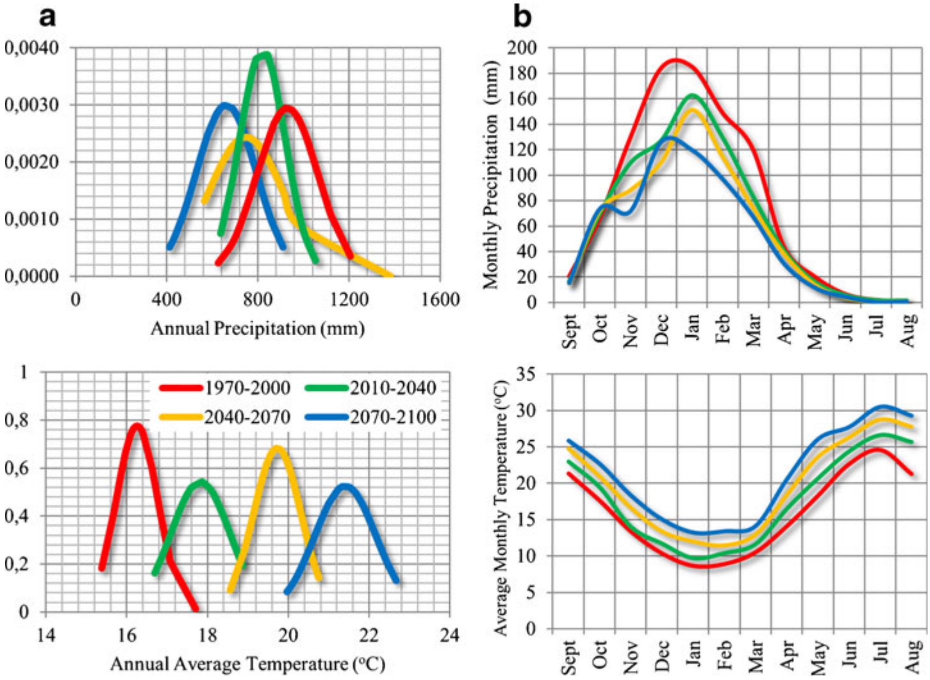

Fig. 3 Normal PDFs representing the weighted bias-adjusted results of all Ensembles members per time slice for **a** annual precipitation and temperature (*left panels*) and **b** seasonality shift of monthly precipitation and temperature (*right panels*)

while only 19.5% (372 Mm^3 or 664 m^3 capita^{-1} year^{-1}) are exploited covering the 70% of the total existing demand (536 Mm^3 or 956 m^3 capita^{-1} year^{-1}). These numbers classify Crete as a water district under high water stress in the index of water scarcity classification (Heap et al. 1998). Obviously, the limiting factor is not precipitation but the fact that most of runoff ends untapped to the sea. Also, a large part of the infiltration takes place over karstic formations and resurfaces through springs (e.g. Fleury et al. 2007; Siart et al. 2009; Maramathas and Boudouvis 2006), having the same fate as runoff. The above, combined with the non-uniform precipitation distribution in the island (a reduction of almost 300 mm from the west to the east part of the island and a strong orographic effect), make water supply in the island a scarce and unevenly distributed commodity.

Hydrological modeling of Ensembles output projects a decreasing trend for both infiltration and runoff for the period 1970 to 2100 (Fig. 4). For this period, there is a decreased rate in infiltration by 5.8 mm and in surface runoff by 5.4 mm per decade. Figure 5 shows the joint (bivariate) PDF for changes in temperature and water availability for three future time slices. The distribution of a variable within a bin of the other is normal and therefore producing a bivariate normal distribution for two related, normally distributed variables (Wilks 2006). The changes in availability distributions (runoff + infiltration) with higher probabilities are negative. During the upcoming 2010–2040 period, the projected temperature increase of around 2.4°C could probably (80%) cause a decrease of the available water within a range of 0%

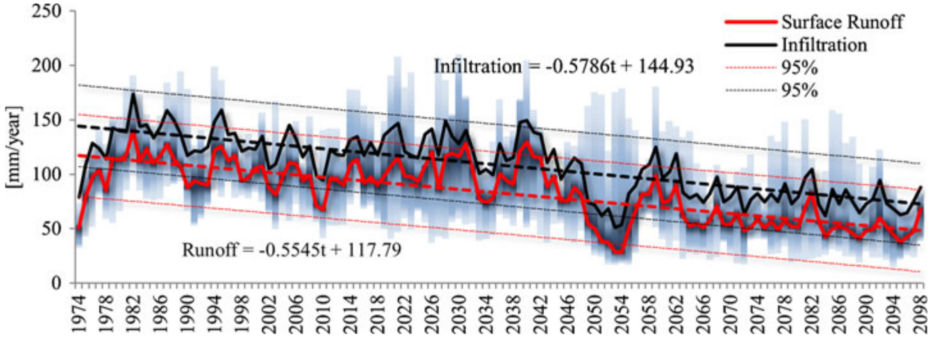

Fig. 4 *Red and black lines* (*upper panel*) represent the ensemble of average annual surface runoff and infiltration, respectively. *Dashed bold lines* represent the corresponding trends with dashed lines representing the 95% confidence interval. *Blue gradually filled bars* indicate the combined amplitude of ensemble RCMs and hydrological modeling

to 50%. For the 2040–2070 period a temperature increase of about 3.5°C will possibly (by 80%) alter water availability by −45%. By 2100 there is an 80% probability that a projected 5.4°C temperature increase will decrease the water availability by

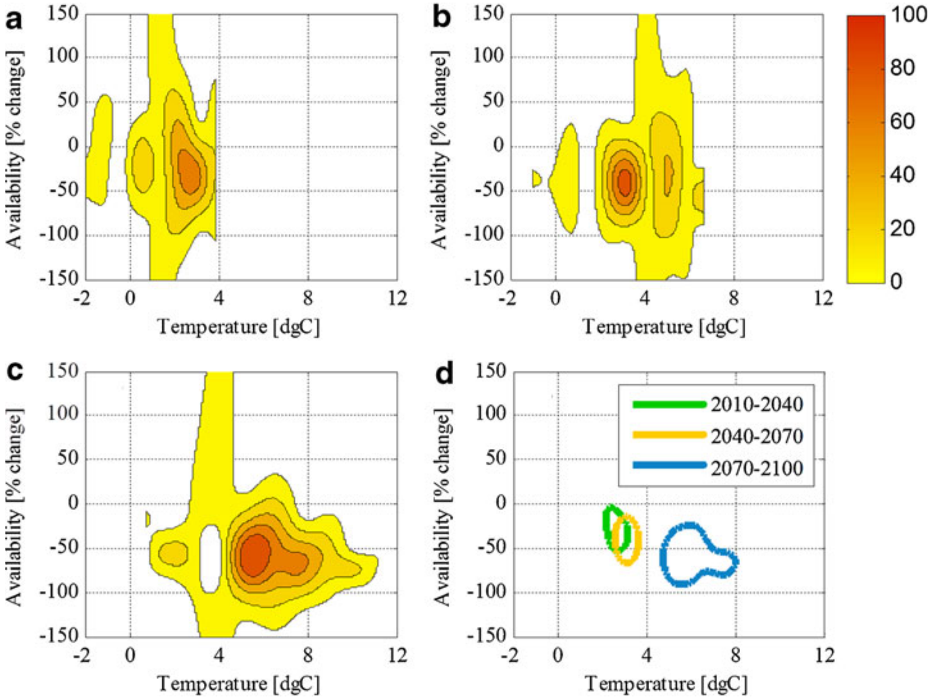

Fig. 5 Bivariate PDFs for temperature and water availability (runoff + infiltration) change (%) response for **a** 2010–2040 minus 1970–2000, **b** 2040–2070 minus 1970–2000 and **c** 2070–2100 minus 1970–2000) for Crete. Contours indicating densities are plotted for 20, 40, 60, 80 and 100 of $10^{-2}{}^{\circ}\mathrm{C}^{-1}\mathrm{dg}\%^{-1}$ per month; **d** summarizes the change in availability through the three time slices for 60 of $10^{-2}{}^{\circ}\mathrm{C}^{-1}\mathrm{dg}\%^{-1}$ per month

almost 50% while the probability that it will remain unchanged is less than 5%. Figure 5d summarizes these results for the 60% probability, showing the clear trend of decreasing availability as temperature increases.

The above results are in agreement with previous findings based on the SPI drought index (McKee et al. 1993). Ensembles' projections for 2010–2100 indicate a gradual decrease of precipitation and therefore an extended period of mild droughts. This phenomenon will negatively affect the status of the ecosystems and human environments and may lead to intense water scarcity problems. Concerning long period droughts, more than half of the total area of Crete is about to experience dry conditions during 28%, 69% and 97% of 2010–2040, 2040–2070 and 2070–2100 periods respectively, while extremely dry conditions will cover 52% of the Crete area during the 21st century (Koutroulis et al. 2010b).

4 Conclusions and discussion

During the last decade, the island of Crete has faced an increased number of floods (Koutroulis et al. 2010a) and droughts (Koutroulis et al. 2010b), while during the summer of 2008 there was severe water shortage in Mediterranean countries and drastic measures were undertaken to rectify this situation. In July 2008, the reservoirs in the islands of Greece were at the lowest level and the amount of water that had to be delivered via tankers was 10% larger than in 2007 at a cost of 11 million Euros. Agriculture and tourism are the two industries most vulnerable to water scarcity. From Majorca to Cyprus, Mediterranean islands and mainland will also face an increased probability of extreme drought. The fraction of the visitor induced water consumption varies significantly (13% for Corsica, 5% for Cyprus, 2.4% for Crete) but in every case the fraction of the tourism sector to the GDP is substantial. While agricultural products cover mostly local consumption, a blow in the tourism industry could have a much wider impact affecting more than 90 million tourists (Koundouri 2008).

The analysis of climate models data indicates that today's extreme events will intensify, i.e., precipitation on average is likely to be less frequent but more intense and droughts are likely to become more frequent and severe in some regions. Shorter rainy periods could seriously affect the water resources by significant reduction of water availability with wide ranging consequences for local societies and ecosystems. As shown herein, the quantitative impact of these changes on water availability can be substantial at watershed level, especially in a Mediterranean island like Crete. The Floods Directive and the policy on droughts, included in the EU Water Framework Directive (WFD), (CEC 2007, 2008, 2009), provide a specific framework of objectives, principals, definitions and measures to adopt, for assessing the impact of climate change on water resources. This framework enables decision-makers to develop and constantly review flood risk and drought management plans. In view of the new basin scale results presented here, these plans should be updated including the procedure on data analysis and output interpretation. Extended basin scale results are presented in Electronic Supplementary Material. The basin scale approach can enhance the water availability awareness for the purpose of providing more robust integrated water management insights, under the implementation of the WFD. Given the global hazard posed by extreme climatic events, the above findings can be employed to carefully assess the climatic impact on water at basin scale. The current situation of the world economy and the often reduced national investment programmes call for low cost, short and long term water management strategies in order to tackle the climate induced changes in water availability and extremes and achieve the sustainability of precious water resources.

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