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Quantifying hydrological responses of small Mediterranean catchments under climate change projections

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HIGHLIGHTS

- We model climate change impacts on the hydrology of two Mediterranean catchments.
- We quantify changes in hydrologic indicators and associated uncertainty.
- Climatic change induces alteration of Mediterranean catchment flow regimes.
- Impacts of climatic change depend on catchment characteristics and seasonality.

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ABSTRACT

Catchment flow regimes alteration is likely to be a prominent consequence of climate change projections in the Mediterranean. Here we explore the potential effects of climatic change on the flow regime of the Thau and the Chiba catchments which are located in Southern France and Northeastern Tunisia, respectively. The Soil and Water Assessment Tool (SWAT) hydrological model is forced with projections from an ensemble of 4 climate model (CM) to assess changes and uncertainty in relevant hydrological indicators related to water balance, magnitude, frequency and timing of the flow between a reference (1971–2000) and future (2041–2071) periods. Results indicate that both catchments are likely to experience a decrease in precipitation and increase in temperature in the future. Consequently, runoff and soil water content are projected to decrease whereas potential evapotranspiration is likely to increase in both catchments. Yet uncertain, the projected magnitudes of these changes are higher in the wet period than in the dry period. Analyses of extreme flow show similar trend in both catchments, projecting a decrease in both high flow and low flow magnitudes for various time durations. Further, significant increase in low flow frequency as a proxy for hydrological droughts is projected for both catchments but with higher uncertainty in the wet period than in the dry period. Although no changes in the average timing of maximum and minimum flow events for different flow durations are projected, substantial uncertainty remains in the hydrological projections. While the results in both catchments show consistent trend of change for most of the hydrologic indicators, the overall degree of alteration on the flow regime of the Chiba catchment is projected to be higher than that of the Thau catchment. The projected magnitudes of alteration as well as their associated uncertainty vary depending on the catchment characteristics and flow seasonality.

1. Introduction

Projected changes in climate and their potential impacts on catchment response are of concern for sustainable management of water resources (Ludwig et al., 2011; Luo et al., 2013). Climatic change will be most keenly expressed through decrease of availability and access to water resources especially in already water-stressed regions such as the Mediterranean (Ludwig et al., 2011). It is widely admitted that the Mediterranean will be one of the prominent 'hot-spots' for climatic change and variability (IPCC, 2007; Giorgi and Lionello, 2008; López-Moreno et al., 2011; Schneider et al., 2013). The combined decrease in precipitation and increase in temperature as projected by Global Circulation Models (GCMs) is likely to increase soil evaporation, increase the atmospheric CO_2 concentrations, and thereby change plant transpiration and growth (e.g. Butcher et al., 2014), reduce soil moisture (e.g. Senatore et al., 2011), and decrease rivers discharge magnitudes

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(e.g. Lespinas et al., 2014) with additional threats to fresh water in the Mediterranean region (García-Ruiz et al., 2011; Candela et al., 2012; Schneider et al., 2013). While these projections can provide useful information for developing and supporting climatic change impacts adaptation and mitigation plans at regional level, they are not quantitatively and qualitatively sufficient for supporting practical water resources management at the catchment scale. Projected trends and magnitudes of change based on regional projections can significantly differ at the catchment scale (Pielke et al., 2002; Koutsouris et al., 2010). Indeed, as moving from regional to catchment scale the heterogeneity and natural variability in both climatic and hydrological processes increase making the assessment of hydrological impacts of climatic change more complex and uncertain. For instance, some hydrological processes (e.g. low flows) can be more controlled by the properties of the soil, geology, climatic conditions, and aquifer characteristics rather by hydrologic and climatic patterns at regional level. In addition, climate model (CM) developed at global or regional level remains uncertain to provide reliable climatic data at the catchment level (Lespinas et al., 2014). Therefore, the need to better understand the potential impacts of climatic change on catchment hydrology is apparent since little knowledge still exists as responses vary from one region to another (Oni et al., 2014). However, only a few studies addressed these issues particularly in the Mediterranean despite the abundance of small catchments in this region (Senatore et al., 2011; Lespinas et al., 2014). For example, in southern Italy Senatore et al. (2011) used projections of three regional climate models (RCMs) with resolution below 20 km in conjunction with the Intermediate Space Time Resolution Hydrological Model (In-STRHyM) for assessing the hydrological impacts (e.g. runoff, groundwater storage, etc.) of climatic change in a relatively small catchment (1000 km^2). The authors pointed out the need for assessing the impacts of climatic change at the catchment scale by stating that their study provided results with no precedent detailed temporal (daily) and spatial (1 km) resolution in southern Italy. In southern France, Lespinas et al. (2014) assessed the impacts of climatic change on the discharge of medium to small-sized coastal river basins (4957–730 km^2) using an ensemble of RCMs with a resolution between 25 and 50 km and the GR2M hydrological model. In North Africa, the study by Tramblay et al. (2013) is the first evaluation for hydrological impacts of high-resolution (50 and 12 km) RCM (ALADIN-Climate) simulations in a 1800 km^2 catchment located in North Morocco. In Tunisia, the studies by Abouabdillah et al. (2010) and Sellami et al. (2015) are among the few attempts that tackled the effects of climatic change on the hydrology of small catchments.

Most of the climatic change impact studies available so far have focused on analysis of hydrological changes and sporadically on estimate of the associated uncertainty. One of the main reasons could be the numerous uncertainty sources related to climate and hydrological model structure, parameter, input data, initial conditions, and emission scenario (Teng et al., 2011; Lespinas et al., 2014). Indeed, the assessment of these uncertainties is difficult due to their complex interaction and propagation throughout the modeling chain (Ludwig et al., 2011; Oni et al., 2014; Refsgaard et al., 2014). Several studies (Arnell, 2011; Teng et al., 2011; Kwon et al., 2012) acknowledged that CM projections are the main source of uncertainty in climatic change impacts assessment. Others (Bastola et al., 2008; Velázquez et al., 2013; Sellami et al., 2015) demonstrated that hydrological model uncertainty, mainly parametric uncertainty, is far to be neglected in climatic change impact studies. These studies among others (e.g. Tebaldi and Knutti, 2007; Refsgaard et al., 2014; Huang et al., 2015) suggested the use of a multi-model ensemble approach to better characterize the uncertainty and provide efficient long-term ensemble mean projection. The combination of several independent models provides higher reliability and consistent prediction than a single model as reported in many studies (Giorgi and Mearns, 2002; Knutti, 2010; Koutroulis et al., 2013). However, using multiple climate models as forcing to the hydrologic model is still not very common in climatic change impacts studies in particular in the Mediterranean. The CLIMB project (Climate-Induced Changes on the Hydrology of Mediterranean Basins), funded by the 7th Framework Program of the European Union, is a research project that aims at reducing this gap by using multiple hydro-climate models to understand the impacts of climatic change on the hydrology of several Mediterranean catchments and quantify their associated uncertainty (Ludwig et al., 2010). For this purpose, CLIMB relies on a multi-model ensemble approach in which downscaled and bias corrected outputs from four GCMs_RCMs combinations are used as forcing to different hydrological models.

Wide panoply of hydrological models used for assessing climatic change impacts exists in the literature over a wide range of scales and environmental conditions across the globe. The selection of the hydrological model is based on the objectives of the study and its capability to cope with the spatial heterogeneity of the catchment features, thus allowing spatially distributed representations of the physical processes and simulations. The computational cost is also an important factor that should be taken into consideration in particular when long-term impacts of climate change are to be assessed. For instance, Ludwig et al. (2009) used three hydrological models namely the distributed hydrological model PROMET, the semi-distributed model Hydrotel and the lumped model HSAMI for investigating changes in a Bavarian catchment response due to climate change forcing. Others (Musau et al., 2015; Zhang et al., 2015) used process-based semi-distributed models such as the Soil and Water Assessment Tool (Neitsh et al., 2005) to assess hydrological impacts of climatic change using different climate models underpinned with different greenhouse gas emissions scenarios. But most of the studies confirmed that the choice of the hydrological model affects the climate change impacts results and thus it must be carefully evaluated (e.g. Ludwig et al., 2009; Velázquez et al., 2013).

When it comes to assess the impacts of climatic change on catchment responses, the difficulty lies in the identification of hydrologically meaningful metrics that should be able to cover all the facets of the flow regime and compatible with the modeling scale. Ideally, these hydrological indicators should support operational catchment river management (Richter et al., 1996; DeGasperi et al., 2009). Although a broad range of hydrologic indicators exists in the literature (Richter et al., 1996, 1998; Olden and Poff, 2003; Gao et al., 2012), catchment scale assessment of hydrological consequences of climatic change that combines flow characteristics related to water balance (e.g., potential evapotranspiration, soil water content, runoff, etc.), flow magnitude, and extreme flows (e.g. low flows.) frequency, timing and duration, is still lacking in particular in the Mediterranean region.

Numerous authors (e.g. Morris et al., 2012; Laizé et al., 2013) reported the need to examine a range of different indicators describing magnitude, frequency, duration and timing of the flow, but such appraisals have not been applied so far in Mediterranean catchments. Therefore, this study aims at providing a quantitative assessment of the potential impacts of climatic change on local hydrological responses in the Mediterranean taking the Thau (southern France) and the Chiba (northeastern Tunisia) catchments as typical Mediterranean study sites. Specifically, the hydrological Soil and Water Assessment Tool (SWAT) is forced by outputs of an ensemble of multi-climate models to assess changes in catchment flow regimes between a reference (1971–2000) and future (2041–2070) climate change scenarios. Average changes and uncertainty in relevant hydrological indicators related to catchment water balance, flow magnitudes, extremes, duration and timing are subsequently analyzed and quantified.

2. Material and methods

2.1. Study cases description

Two small catchments, the Thau and Chiba catchment, located on either side of the Mediterranean basin were selected (Fig. 1). The Thau catchment is located on the French Mediterranean coast (Languedoc-Rousillon region) and drains an area of approximately 280 km^2. Average