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Impacts of climate change on precipitation and discharge extremes through the use of statistical downscaling approaches in a Mediterranean basin

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HIGHLIGHTS

- Statistical analysis in a basin in Sardinia shows high uncertainty of climate projections of precipitation extremes.
- Soil properties and topography control the basin response to extreme storms.
- Statistical downscaling of precipitation is useful to improve accuracy of physically-based hydrologic simulations.

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ABSTRACT

Mediterranean region is characterized by high precipitation variability often enhanced by orography, with strong seasonality and large inter-annual fluctuations, and by high heterogeneity of terrain and land surface properties. As a consequence, catchments in this area are often prone to the occurrence of hydrometeorological extremes, including storms, floods and flash-floods. A number of climate studies focused in the Mediterranean region predict that extreme events will occur with higher intensity and frequency, thus requiring further analyses to assess their effect at the land surface, particularly in small- and medium-sized watersheds. In this study, climate and hydrologic simulations produced within the Climate Induced Changes on the Hydrology of Mediterranean Basins (CLIMB) EU FP7 research project were used to analyze how precipitation extremes propagate into discharge extremes in the Rio Mannu basin (472.5 km^2), located in Sardinia, Italy. The basin hydrologic response to climate forcings in a reference (1971–2000) and a future (2041–2070) period was simulated through the combined use of a set of global and regional climate models, statistical downscaling techniques, and a process based distributed hydrologic model. We analyzed and compared the distribution of annual maxima extracted from hourly and daily precipitation and peak discharge time series, simulated by the hydrologic model under climate forcing. For this aim, yearly maxima were fit by the Generalized Extreme Value (GEV) distribution using a regional approach. Next, we discussed commonality and contrasting behaviors of precipitation and discharge maxima distributions to better understand how hydrological transformations impact propagation of extremes. Finally, we show how rainfall statistical downscaling algorithms produce more reliable forcings for hydrological models than coarse climate model outputs.

1. Introduction

Potential changes in future climate are expected to affect the intensity of the hydrologic cycle, with consequences on the availability of water resources and the occurrence and severity of meteorological and hydrologic extremes, including droughts, storms, and floods (IPCC, Intergovernmental Panel on Climate Change, 2007; Navarra and Tubiana, 2013). The quantification of the impact of climate change on the hydrologic cycle is, in most cases, carried out through the combined use of climate and hydrologic models. Currently, the majority of these studies have focused on the impact on water resources and drought, evaluated over monthly or annual time scales (e.g., Senatore et al., 2011; Sulis et al., 2012; Tramblay et al., 2013; López-Moreno et al., 2014; Piras et al., 2014; Smiatek et al., 2014). Only a few studies have

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evaluated the impact on future occurrence of hydrometeorological extreme events (see e.g. Kharin and Zwiers, 2005; Benestad and Haugen, 2007; Raff et al., 2009; Gilroy and McCuen, 2012; Vezzoli and Mercogliano, 2013; Camici et al., 2014).

Extremes in the Earth Sciences are often investigated by characterizing the statistical distribution of the yearly maxima of the variable of interest. This approach is commonly adopted also in statistical hydrology to quantify rainfall and flood extremes (Greis and Wood, 1981; Rossi et al., 1984; Martins and Stedinger, 2000; Koutsoyiannis, 2004a, 2004b; Reis et al., 2005; Di Baldassarre et al., 2006; Vezzoli, 2012). See also the review by Katz et al. (2002). Since the distribution of rainfall and flood extremes is usually skewed and displays heavy right tails (due to the occurrence of rare and very high extremes), which are difficult and problematic to characterize with single site yearly maxima time series, regional approaches have been proposed to reduce the uncertainty in distribution parameter estimation (Hosking and Wallis, 1997). Among the different probability distributions that have been applied to characterize yearly maxima of hydrologic observations, the Generalized Extreme Value (GEV) distribution deserves a special consideration. Indeed, under certain conditions, dividing a time series in large enough time blocks, if there exists a limiting distribution of the set of maxima extracted by each block, such a distribution belongs to the GEV family (Fisher and Tippet, 1928; Gnedenko, 1943; Gumbel, 1958). A block length of one year is usually assumed as a trade off in order to have a reasonable number of (annual) maxima overcoming at the same time possible seasonal drifts. In the study of the extremes in the context of climate change, the GEV has been applied, among the others, by Kharin and Zwiers (2005) to characterize trends of temperature and precipitation extremes, by Gilroy and McCuen (2012) to represent the annual maximum 24-h precipitation events from a general circulation model, and by Vezzoli and Mercogliano (2013) to evaluate the effects of land cover and climate change on peak flood probability.

Besides the well-known problems related to statistical inference on small samples, one of the major difficulties for the quantification of the impacts of climate change on extremes is the coarseness of climate model outputs (~25 km if considering high resolution simulations of regional climate models, RCMs) and hydrologic simulations in relatively small basins (order of 1000 km^2 and less). To overcome this limitation, downscaling (or disaggregation) models can be used to increase the resolution of coarse precipitation outputs of climate models (Wilby and Wigley, 1997; Harpham and Wilby, 2005; Raff et al., 2009; Quintana Segui et al., 2010, 2011; Bardossy and Pegram, 2011; Camici et al., 2014). A class of downscaling techniques is able to reproduce the scale-invariance and multifractal properties of precipitation in space and time (Deidda et al., 1999, 2004; Deidda, 1999, 2000; Badas et al., 2006) and is, then, particularly suitable to create high-resolution forcings (a few km, sub-daily) for process-based hydrologic models. Recently, Piras et al. (2014) used a multifractal downscaling model to increase the resolution of RCM outputs and create hourly forcings for a process-based hydrologic model applied in a small Mediterranean basin. While the utility of this type of downscaling models seems intuitive, to our knowledge, a study that explicitly compares simulations with and without the use of this tool has never been conducted.

The Mediterranean region is characterized by large climate variability with alternation of dry and wet periods, which affect availability of water resources (Hoerling et al., 2012), and occurrence of high intensity storms that often lead to floods and flash floods (Delrieu et al., 2005; Borga et al., 2007; Silvestro et al., 2012). Future climate projections predict that the Mediterranean area will be, globally, a hot spot with high sensitivity to future climate changes (e.g., Giorgi, 2006; Giorgi and Lionello, 2008). Based on these main motivations, the Climate Induced changes on the hydrology of Mediterranean Basins (CLIMB) project was funded by the 7th Framework Program of the European Union to (i) quantify the impact of climate change on the hydrologic response of Mediterranean catchments, (ii) evaluate the associated uncertainties, and (iii) identify measures to mitigate the risk (Ludwig et al., 2010).

One of the seven study sites of the CLIMB project is the Rio Mannu basin (472.5 km^2) located in Sardinia (Italy). In this watershed, numerical simulations based on different climate and hydrologic models, statistical analyses and field campaigns were used or carried out to support a set of climate impact studies (Cassiani et al., 2011; Deidda et al., 2013; Mascaro et al., 2013a; Piras et al., 2014; Ursino et al., 2014). In one of these studies, Mascaro et al. (2013a) calibrated and validated in the Rio Mannu basin a fully-distributed and physically-based hydrologic model, known as TIN- based Real Time Integrated Basin Simulator (tRIBS), utilizing a combination of ground observations and two downscaling (or disaggregation) tools. In a subsequent work, outputs of four climate models (Deidda et al., 2013) were bias corrected and downscaled and, then, used as high-resolution forcings for the tRIBS model that simulated the basin hydrologic response in reference (1971–2000) and future (2041–2070) periods (Piras et al., 2014). Consistent with other climate change studies in Mediterranean basins (e.g., Senatore et al., 2011), results of Piras et al. (2014) indicated: a future reduction in mean annual precipitation (ensemble average of −12.70%) and a raise in temperature (+2.18 °C); a significant decrease of mean annual runoff (−32.55%); and a general reduction of soil water content and actual evapotranspiration and a drop in the groundwater table, with spatial variations related to terrain and soil properties.

In this work, we pursue two main objectives. First, we investigate the impact of climate change on precipitation and discharge extremes, by quantifying variations from the historical to a possible future climate using the fine-resolution disaggregated outputs of four climate models and the spatially-distributed hydrologic simulations in the Rio Mannu basin. For this aim, we fitted the GEV probability distribution to the series of annual maximum daily and hourly precipitation and annual maximum peak discharge using a regional approach. After estimating the GEV parameters, we explore the uncertainty among the climate models and compare the parameters of the statistical distributions of extreme precipitation and discharge.

The second goal of this work is to demonstrate the value of statistical downscaling tools to increase the spatiotemporal resolution of precipitation outputs of climate models, thus creating high-resolution forcings required to apply process-based hydrologic models in small- and medium-sized basins. For this purpose, we compare two sets of hydrologic simulations: one conducted with fine-resolution disaggregated precipitation forcings (Fine simulation) and the other with precipitation outputs at the original resolution of the climate models (Coarse simulation). We first focus on the capacity to represent extreme events, both in terms of high intensity storms and floods. Next, we consider the main components of the water balance simulated by the two settings. The differences between outputs of Coarse and Fine simulations are explored by analyzing how the use of forcings with different spatiotemporal resolutions impacts the type of physical processes simulated by the hydrologic model.

2. Study area

The study site is the Rio Mannu di San Sperate basin, a medium-sized watershed of 472.5 km^2 located in an agricultural area of southern Sardinia, Italy (Fig. 1). The basin is characterized by gentle topography, with elevation ranging from 66 to 963 m a.s.l. and slope from 7% in the western plain to 34% in the rugged eastern mountains (basin average of 17%). The mean annual precipitation is 680 mm, for the greatest part concentrated from September to May. The discharge at the outlet is ~1 m^3/s during most of the year, with flood events usually occurring in autumn and winter as a result of large frontal systems (Chessa et al., 1999; Mascaro et al., 2013b). The climate of the region is Mediterranean with strong seasonality and significant interannual variability that leads to an alternation of wet and dry multiyear periods, including prolonged droughts. As a result, the Rio Mannu basin is characterized by a complex hydrologic response, where runoff can be potentially generated according to all main physical mechanisms (Beven, 2002). The soil