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Regional downscaling of Mediterranean droughts under past and future climatic conditions

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ABSTRACT

The complexity of the Mediterranean climate with its high precipitation variability and its unequal seasonal distribution with a wet season from approximately October to April and a dry season in summer set general conditions for a high vulnerability of the Mediterranean area to droughts. In the last few decades the risk of drought episodes appears to be enhanced in the Mediterranean area due to temperature increases combined with precipitation decreases. This general change towards warmer and dryer conditions is expected to continue in the future. In the present study droughts are represented by the Standardized Precipitation Index (SPI), at 114 stations located across the Mediterranean area. The SPI is a normalized measure of drought severity relative to a specific location, obtained from rainfall totals aggregated over different time periods. This allows a comparison of different locations and the delineation of homogeneous regions with similar SPI variability. 13 regions have been identified. A downscaling approach using circulation types based on geopotential heights and relative humidity as predictors has been set up to downscale the SPI time series in the different regions. The downscaling approach has been validated using running 21 years validation periods, in order to assess the skill of the method during different climatic conditions and to detect possible non-stationarities in the predictors-predictand relationships. Results show that the downscaling method provided satisfactory results, except for the most arid regions. Future projections, provided from a three member ensemble of the MPI-ESM-LR model under scenario RCP 8.5, indicate an increase in the drought severity and occurrence for the whole Mediterranean region for the period 2070–2100.

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1. Introduction

Drought is a natural part of climate variability and occurs on a variety of different spatial and temporal scales. Due to its significant impact on natural and human systems it is of great concern that droughts are expected to experience large changes under human-induced climate change. In particular, droughts are affecting the Mediterranean region due to the strong interannual variability of precipitation, which is one of the most important characteristic of the Mediterranean climate (Lionello, 2012). These droughts periods are already threatening the water resources in countries across the Mediterranean basin, in particular those located in its southernmost shores. Indeed, a trend towards drier conditions and increased drought occurrence after the 1970s has been observed for most western and central Mediterranean regions (Alpert et al., 2002; Sousa et al., 2011; Hoerling et al., 2012; Tramblay et al., 2013; Vicente-Serrano et al., 2014; Spinoni et al., 2015). In addition, future climate projections (Sanchez et al., 2004; Giorgi and Lionello, 2008; Hertig and Jacobeit, 2008a, 2008b; Garcia-Ruiz et al., 2011; Sheffield and Wood, 2008; Hertig et al., 2012; Dubrovsky et al., 2014) indicate a possible decrease in precipitation together with a temperature increase; consequently the future droughts may be more severe. Therefore, there is a need to better quantify this threat to water resources with methods tailored for the specific Mediterranean climatic conditions.

The droughts periods can be defined as a water deficit by comparison to a long-term average condition (Hayes et al., 2011), by opposition to aridity that is a more permanent feature of climate (Mishra and Singh, 2010). Different formulations exist, and they can be classified as meteorological or hydrological droughts, depending on the variables used to compute them (Mishra and Singh, 2010). The most common approach to quantify droughts in a meteorological sense (i.e. based on precipitation only) is the Standardized Precipitation Index (SPI) proposed by McKee et al. (1993). Further, it has been recently recommended by the WMO to use this index to analyze droughts in various climatic regions (Hayes et al., 2011). Other metrics exist to quantify droughts, such as the Self-Calibrating Palmer Drought Severity Index (Wells et al., 2004) or the Standardized precipitation evapotranspiration index recently proposed by Vicente-Serrano et al. (2010). However

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both indices rely on precipitation and evapotranspiration, which is very complex to estimate over long time periods and at the regional scale (Kingston et al., 2009), adding additional uncertainties in the assessment of the climate change impacts (Sheffield and Wood, 2008; Trenberth et al., 2014). This is the reason why several studies preferred the well-known SPI index to perform climate change impact studies on droughts, such as Blenkinsop and Fowler (2007), Heinrich and Gobiet (2012), Russo et al. (2013), and Beck et al. (2015).

A few studies up to now have attempted to produce projections of future droughts for the Mediterranean basin. The recent work of Dubrovsky et al. (2014) focused on the whole Mediterranean domain with the Palmer Drought Severity Index (PDSI), using weather generators driven by a set of 16 GCMs from the CMIP3 experiment under the emission scenario A2. Their results indicate a trend towards reduced precipitation amounts and longer drought spells all across the Mediterranean at the time horizon 2070–2099. In addition, Heinrich and Gobiet (2012) performed a study over Europe, yet encompassing the northern part of the Mediterranean basin, using bias-corrected RCMs (using the E-OBS database) from the ENSEMBLES project with both SPI and PDSI droughts indices. They found under the A1B scenario for 2021–2050 an increase in mean dry event frequency for the southernmost regions of Europe. Similarly, Russo et al. (2013) used bias-corrected outputs from five RCMs from ENSEMBLES and introduced a non-stationary SPI index, based on a non-stationary Gamma distribution with a time-varying scale parameter. Their results show that more robust change signals are obtained using the non-stationary SPI index. The projected changes suggest an increased frequency of dry winters and summers in south Europe for the period 2069–2098 under the emission scenario A1B.

To produce drought scenarios for the Mediterranean region, there is a need to validate the downscaling methods before applying them to make future projections. Beside the uncertainty of climate model projections and the role of natural climate variability, the skill of the downscaling methods must be assessed to estimate their potential uncertainties (Maraun et al., 2015). Indeed, due to the presence of trends reported in several areas of the Mediterranean and the complex climate affected by the interactions between large scale circulation, mid-latitude and sub-tropical processes (Mariotti and Dell'Aquila, 2012), there is a need to adopt a framework able to cope with non-stationarity of climate (Verdon-Kidd and Kiem, 2010; Hertig and Jacobeit, 2014; Hertig et al., 2015). Hertig and Jacobeit (2013) proposed a method to validate downscaling methods in a non-stationary context, based on multiple cross-validations of different periods using a stratified sampling. With is approach, it is possible to capture the inter-annual variations in the downscaling efficiency, that could be related to changes in the weather regime dynamics or long-term oscillations such as the NAO.

The objective of this paper is to analyze droughts in a changing climate for the Mediterranean region, using statistical downscaling methods. A set of 125 stations located across the Mediterranean area with a long period of record of daily precipitation data is considered for this purpose. First, a regionalization based on SPI values at the different stations is provided in order to identify regions with a similar behavior in terms of drought occurrence. Second, a downscaling approach is proposed, taking into account the possible trends in precipitation data, using a non-stationary SPI index (Russo et al., 2013), but also the non-stationarity in the statistical transfer functions between the large-scale predictors and regional droughts. The proposed methodology is evaluated during historical climate conditions prior to make future projections on droughts occurrence and intensity.

2. Datasets

2.1. Observed precipitation

Daily precipitation data for 125 stations in the Mediterranean area are considered. They have been collected from the GLOWA Jordan River Project (Global Change and the Hydrological Cycle, Kunstmann et al., 2006), from the EMULATE project (European and North Atlantic daily to MULtidecadal climATE variability, Moberg et al., 2006), from the European Climate Assessment and Dataset (Klein Tank et al., 2002) and from the daily database for North Africa of Tramblay et al. (2013). Fig. 1 shows the record length of the stations available in this study. 114 station time series share the period between 1970 and 2000 and subsequent analyses will concentrate on these stations. All stations have been subjected to homogeneity tests in previous studies and they do not include >5% missing data during the extended winter season, from October to April. The season from October to April was chosen to define a common analysis period across the whole Mediterranean area, leaving out the months with very little to virtually no rainfall amounts in some Mediterranean regions.

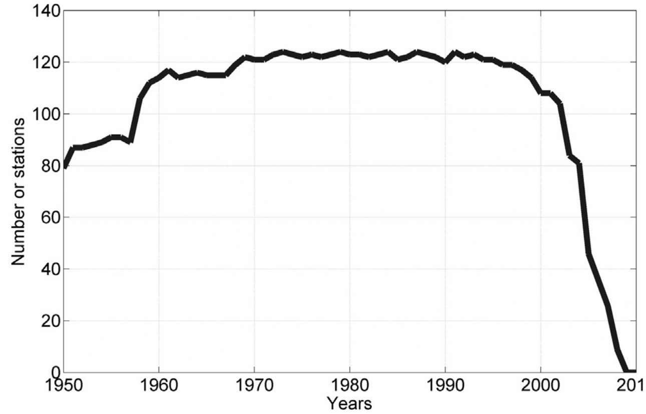

Fig. 1. Number of stations available in this study with <5% mission data for each year.

2.2. Reanalysis and GCM data

The predictor variables for the observational time period were retrieved from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis project (Kalnay et al., 1996; Kistler et al., 2001). Geopotential heights, specific humidity, relative humidity as well as the zonal and meridional wind components from the 700 hPa and 850 hPa levels were selected.

Model data were taken from a three-member MPI-ESM-LR ensemble (Max Planck Institute Earth System Model running on low resolution grid). Historical and RCP8.5 scenario (Van Vuuren et al., 2011) runs performed for the Coupled Model Intercomparison Project round 5 (CMIP5) were downloaded from the CMIP5 archive (http://pcmdi9.llnl.gov/esgf-web-fe/). We used the period 1950–2005 of the historical runs and the period 2006–2100 of the scenario runs. The horizontal resolution of the model output data (1.875°) was fitted to that of the reanalysis data (NCEP reanalysis 2.5° × 2.5°) using ordinary kriging.

3. Methodology

3.1. Standardized Precipitation Index (SPI)

The computation of the SPI from monthly precipitation amounts usually relies on a Gamma distribution (for the European area see for instance Lloyd-Hughes and Saunders, 2002). Since no studies have been performed with the observed precipitation data set used in this study, there is a need to evaluate the suitability of the Gamma distribution. Indeed, as noted by Mishra and Singh (2010), simulating precipitation using a probability distribution might cause errors if the probability distribution is not chosen correctly.

To that end, different distributions commonly used to model precipitation are compared, including the Gamma, Exponential and Log-Normal distributions. To identify the best fit among stations, the

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