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European drought climatologies and trends based on a multi-indicator approach

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ABSTRACT

Drought is one of the most important weather-induced phenomena which may have severe impacts on different areas such as agriculture, economy, energy production, and society. From a meteorological point of view, drought can be induced and/or reinforced by lack of precipitation, hot temperatures and enhanced evapotranspiration. Starting from a multi-indicator approach, we present European-wide meteorological drought climatologies and trends for the period 1950–2012. As input data, we used precipitation and temperature data from the E-OBS (spatial resolution: 0.25° × 0.25°) gridded dataset of the European Climate Assessment and Dataset (ECA&D). Precipitation, temperature, and the derived potential evapotranspiration (PET) have been used to compute three drought indicators: the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), and the Reconnaissance Drought Index (RDI). SPI, SPEI, and RDI, calculated for 12-month accumulation period, have been rationally merged into a combined indicator and this quantity has been used to obtain drought frequency, duration, and severity for the entire Europe. We identified the following drought hotspots: Scandinavia, Eastern Europe, and Russia in 1951–1970, no particular hotspot in 1971–1990, the Mediterranean region and the Baltic Republics in 1991–2010. A linear trend analysis shows that drought variables increased in the period 1950–2012 in South-Western Europe, in particular in the Mediterranean and Carpathian regions, with precipitation decrease and PET increase as drivers. Drought variables show a decrease in Scandinavia, Belarus, Ukraine and Russia: precipitation increase is the main driver. In Central Europe and the Balkans, drought variables show a moderate increase, for the significant PET increase outbalances a not significant precipitation increase.

1. Introduction

Drought is a natural phenomenon occurring in all climates. Due to its often long duration and large spatial extent, it results in considerable social, environmental, and economic costs (Vogt and Somma, 2000) as prolonged droughts can foster land degradation in arid and semi-arid areas with far-reaching and sometimes irreversible damage to ecosystems (Winslow et al., 2011). However, drought is a temporary condition that should not be mistaken for permanent water scarcity (Van Loon and Van Lanen, 2013) or desertification as such (Vogt et al., 2011; Spinoni et al., 2014b).

Though droughts have been frequently studied in the past (for a review, see Mishra and Singh, 2011), a unique definition of drought is missing due to its complex nature and manifold impacts (Wilhite and Glantz, 1985; Smakhtin and Schipper, 2008). Following Mishra and Singh (2010), droughts can be classified as meteorological, agricultural, hydrological, ground-water, and socio-economic. In this study we refer to the meteorological type because meteorological variables have been used as input (precipitation and temperature) and we deal with a medium-term rainfall accumulation period (12 months), a compromise that allows representing water shortages caused by lack of precipitation and/or hot temperatures over an entire year. However, according to the strict use of definitions, such accumulation period is also referred to drought events that cause hydrological impacts (Mishra and Singh, 2011).

In the last six decades, drought patterns have shown a slightly increasing tendency at a global level (Dai, 2011a; Sheffield et al., 2012; Spinoni et al., 2014a), partly due to global warming (Trenberth et al., 2014). Europe is considered as a climate change hotspot (Giorgi, 2006) and a positive drought trend seems to be more evident in Southern Europe (Briffa et al., 2009), in particular in the Mediterranean area (Hoerling et al., 2012), where the temperature increase is more evident (IPCC, 2014).

In the recent scientific literature, the most relevant meteorological drought climatologies regarding Europe are usually based on single indicators (e.g., van der Schrier et al., 2006), focused on some regions

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only (e.g., Vicente-Serrano et al., 2014), not up-to-date (e.g., Lloyd-Hughes and Saunders, 2002), or derived from global maps (e.g., Vicente-Serrano et al., 2010a). This study aims at identifying the European drought hotspots and evaluating trends in meteorological drought frequency, duration, and severity during the period 1950–2012 through a multi-indicator approach and at a high spatial resolution (0.25° × 0.25°). Providing a complete picture of the areas that suffered frequent and severe droughts in the past could help scientists, politicians, and stakeholders in responding to drought challenges (Wilhite, 1997; EC, 2007). Moreover, this might push towards the development of better frameworks for drought assessment, adaptation, and mitigation, in a possibly drier future (Sherwood and Fu, 2014).

In Section 2, we describe the input datasets and the methodologies used to compute the indicators and the derived quantities. In Section 3 we list the European drought hotspots in the periods 1951–1970, 1971–1990, and 1991–2010, we discuss the drought tendencies over the last six decades at grid point and country level, and we investigate the drivers of meteorological droughts. In Section 4 we summarize the most important outcomes of this study.

2. Data and methods

2.1. Precipitation and temperature gridded data

As input data, we used daily precipitation (P) and mean temperature (T_M) data from the latest version of the E-OBS grids (version 10) of the European Climate Assessment and Dataset (ECA&D; Haylock et al., 2008) of the Royal Netherlands Meteorological Institute (KNMI). This dataset encompasses the whole of Europe with a spatial resolution of 0.25° × 0.25°. The period analyzed is 1950–2012.

Regarding mean temperature, we transformed the daily values of a given month into a monthly average if no more than three values were missing; regarding precipitation, we transformed the daily values into a monthly sum if no more than one value was missing. Though the latest versions of the E-OBS– are based on more in situ station data than previous versions – in particular versions 9 and 10 strongly improved the situation in Scandinavia and corrected the biases in Romania – the spatial distribution is still uneven, especially regarding the South-Eastern Mediterranean area and Eastern Europe. Consequently, to avoid introducing spatial inhomogeneities, the gridded monthly series have been quality-checked and tested for homogeneity with the latest version of the Multiple Analysis of Series for Homogenization software (MASHv3.02; Szentimrey, 1999). If a grid point failed the tests, we used a weighted combination of the surrounding grid points. We had to exclude a few points in Iceland, Scotland, Central Italy, Albania, Macedonia, Southern Greece, and Central Turkey from the analysis, because neither they nor the surrounding points passed the tests.

We computed potential evapo-transpiration (PET) from gridded T_M, at a monthly scale, using a new version (van der Schrier et al., 2011) of the Thornthwaite's model (Thornthwaite, 1948).

2.2. Meteorological drought indicators: SPI, SPEI, RDI, and the combined indicator

Many indicators are commonly used to analyze meteorological droughts (see Keyantash and Dracup, 2002, for a review). Globally, two indicators have been applied the most: the Palmer Drought Severity Index (PDSI: Palmer, 1965; e.g., applied by Dai et al., 2004), and the Standardized Precipitation Index (SPI: McKee et al., 1993; e.g., applied by Spinoni et al., 2013). Among them, we selected the SPI, for it requires only precipitation data as input, while the PDSI and its modified version, the self-calibrated PDSI (sc-PDSI: Wells et al., 2004), rely on many assumptions and variables that can be hardly retrieved at a high spatial resolution or for extended regions like Europe. However, they show similar results in Europe when the SPI is computed for 9 or 12-month accumulation periods (Lloyd-Hughes and Saunders, 2002). Moreover, we did not compute the PDSI or the sc-PDSI because one of our basic assumptions was to base this study on a single source dataset to avoid introducing biases from the harmonization of datasets with different spatial and temporal resolutions. It follows that we have to discard the PDSI and the sc-PDSI because some of their input variables are not part of the E-OBS gridded products.

Given the current global warming (IPCC, 2014), we assume that it is important to consider the effect of temperature, and therefore added the Standardized Precipitation Evapo-transpiration Index (SPEI: Vicente-Serrano et al., 2010b) to our analysis. The SPEI has been increasingly applied worldwide (Beguería et al., 2014) and is based on the difference between P and PET. If computed for 6 to 12-month accumulation periods, it proved to be highly correlated with the sc-PDSI in Europe (Vicente-Serrano et al., 2010b).

Finally, we selected a third indicator, the Reconnaissance Drought Indicator (RDI: Tsakiris and Vangelis, 2005), that is based on the ratio between P and PET and is frequently applied in South-Eastern Europe (Tsakiris et al., 2007). The three indicators have been recently applied simultaneously in China (Gao et al., 2012) and Eastern Europe (Spinoni et al., 2013). Though all the mentioned indicators have been successfully useful in a lot of drought studies, we should stress that the SPEI and the RDI are based on potential evapo-transpiration (PET) that is of course different than actual evapo-transpiration (AET) and, in moisture stressed areas, PET is likely to increase (higher temperatures but lower humidity), while AET decreases. This has found to amplify the drought signal in the SPEI (Brutsaert and Parlange, 199898). Recently, Beguería et al. (2014) also discussed that, at global scale, the choice of the PET parameterization is fundamental in some regions, however they are very rare in Europe.

We computed all three indicators at monthly scale and for a 12-month accumulation period (SPI-12, SPEI-12, and RDI-12), from 1950 to 2012. We fitted the cumulated P by Gamma distribution (Thom, 1958) for the SPI-12, the cumulated difference P-PET by log–logistic distribution (Shoukri et al., 1988) for the SPEI-12, and the cumulated ratio P/PET by log–normal distribution (Heyde, 1963) for the RDI-12, following the approaches of the authors who originally presented such indicators. All the available data in the period 1950–2012 have been used to fit the distributions.

There are three main reasons behind the choice of 12-month accumulation period. Firstly, we wanted to produce results that can be compared to already published drought climatologies, as the global drought maps presented by Spinoni et al. (2014a) based on the SPI-12. Moreover, we reported above that the SPI and the SPEI proved to be comparable with the PDSI or the sc-PDSI if using a medium–long accumulation period (Lloyd-Hughes and Saunders, 2002; Vicente-Serrano et al., 2010b). Secondly, the choice of 12-month accumulation avoids the presence of too many 0 values – that are indeed present using 3-month scale – in the computation of the SPI, in particular in arid or semi-arid Mediterranean regions. The high presence of 0 values could bias the outputs as they may cause problems in the computation of the underlying distributions of the SPI. Furthermore, excluding a few rare exceptions in Greece, Cyprus, and Turkey, the use of 12-month accumulation period that always leads to positive P-PET values and negative values may cause problems for computing the SPEI; similarly this leads to PET values always greater than 0 also in the northernmost European regions and 0 or very low PET values cause problems in the computation of the RDI, based on the ratio between P and PET. Thirdly, we planned to separately analyze a combined indicator based on a 3-month accumulation period in order to study the European trends of seasonal droughts and rank them for severity on a regional scale.

For a given month and grid point, we finally calculated a combined indicator (*Z-12*) based on the SPI-12, the SPEI-12, and the RDI-12. The *Z-12* is not a simple average but is focused on the drought conditions and structured to favor the predominance of one condition (Table 1). If two or more (2 + in Table 1) indicators suggest drought conditions, so the combined indicator does; oppositely, if two or more indicators