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Modeling drought impact occurrence based on meteorological drought indices in Europe

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SUMMARY

There is a vital need for research that links meteorological drought indices with drought impacts felt on the ground. Previously, this link has been estimated based on experience or defined based on very narrow impact measures. This study expands on earlier work by showing the feasibility of relating user-provided impact reports with meteorological drought indices, the Standardized Precipitation Index and the Standardized Precipitation-Evapotranspiration Index, through logistic regression, while controlling for seasonal and interannual effects. Analysis includes four impact types, spanning agriculture, energy and industry, public water supply, and freshwater ecosystem across five European countries. Statistically significant climate indices are retained as predictors using step-wise regression and used to compare the most relevant drought indices and accumulation periods across different impact types and regions. Agricultural impacts are explained by 2–12 month anomalies, though anomalies greater than 3 months are likely related to agricultural management practices. Energy and industrial impacts, typically related to hydropower and energy cooling water, respond slower (6–12 months). Public water supply and freshwater ecosystem impacts are explained by a more complex combination of short (1–3 month) and seasonal (6–12 month) anomalies. The resulting drought impact models have both good model fit (pseudo-$R^2 = 0.225$–0.716) and predictive ability, highlighting the feasibility of using such models to predict drought impact likelihood based on meteorological drought indices.

1. Introduction

With recent progress in participatory approaches to drought management, the common hazard-focused view of meteorological drought has been criticized and strong claims have been made for ground-truthing the numerous meteorological drought indices with respect to the drought impacts they cause (Steinemann, 2014; Kallis, 2008). This study aims to address this issue by empirically examining the linkage between meteorological drought indices and the various drought impacts they are meant to describe in a rigorous and quantitative manner. It therefore starts with the assumption that drought definitions, and hence indices to be used e.g. for risk assessment, should consider water management practices employed (Lloyd-Hughes, 2013).

Of the available meteorological drought indices (Keyantash and Dracup, 2002), the Standardized Precipitation Index (SPI, McKee et al., 1993; Guttman, 1999) and the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010; Beguería et al., 2013) were selected as candidate drought indices for this study. The Standardized Precipitation Index (SPI) was selected because it is the predominant meteorological drought indices used in Europe and is recommended by the “Lincoln declaration on drought indices”, which encourages Meteorological and Hydrological Services around the world to use the SPI (Hayes et al., 2011). The SPEI is a newer index, which uses a similar methodology, but includes a more comprehensive water balance, which may better quantify drought (Beguería et al., 2013). The SPI and SPEI normalize accumulated precipitation (P) and climatic water balance (P – PET), respectively, where PET represents potential evapotranspiration. The popularity of these indices is related to their simple interpretation, low data requirements satisfied by most climate data products, and their multiscalar flexibility. This multiscalar characteristic, allowing for short or long accumulated anomalies, is viewed as a major benefit, allowing the user to approximate agricultural, hydrological, and socioeconomic drought by adjusting the accumulation period of the indices (Vicente-Serrano et al., 2012; Hayes et al., 2011). However, this claim is rarely tested, with few studies identifying the most

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appropriate drought index and accumulation period for different drought impact types. Without empirical evidence showing the link between drought impact occurrence and indices, drought monitoring agencies such as the European Drought Observatory (edo.jrc.europa.eu) and the US Drought Monitor (droughtmonitor.unl.edu) base their risk estimates on experience, assuming that short SPI aggregation periods explain agricultural impacts and longer SPI periods explain water resources impacts (personal communication, National Drought Mitigation Center).

Drought impacts are broadly defined as the negative environmental, economic, or social consequences of drought conditions (Knutson et al., 1998). Previous studies exploring the link between drought impacts and meteorological drought indices have primarily focused on correlating drought indices with quantitative measures of production, e.g. crop yield or hydropower generation. In Europe, such studies typically focus on agricultural impacts quantified by crop yield, particularly in southern and eastern Europe (e.g. Vicente-Serrano et al., 2006; Hlavinka et al., 2009; Rossi and Niemeyer, 2010; Tsakiris et al., 2010; Ceglar et al., 2012; Sepulcre-Canto et al., 2012). Alternatively, some studies have related meteorological drought indices with vegetation response, typically through remotely sensed measures like NDVI (Ji and Peters, 2003; Jain et al., 2010) or tree ring measurements (Vicente-Serrano et al., 2012). Low flows and hydrological drought have also been correlated with meteorological drought indices (Szalai et al., 2000; Vicente-Serrano and López-Moreno, 2005; Wong et al., 2013; Haslinger et al., 2014), though low flows are not considered drought impacts, as previously defined. Such correlation studies produce useful relationships; however, they do not focus on drought impacts alone. Using agriculture as an example, a correlation study may find a link between the 3 month SPI and wheat production. However, this link is based on the entire range of production values, including periods when harvests were successful and water was plentiful. Drought impacts represent only a small fraction of the time series, and therefore the most relevant drought index may be masked by correlations during non-drought periods.

In this study, analysis is solely based on drought impact occurrence rather than correlation and is facilitated by the European Drought Impact report Inventory (EDII, www.geo.uio.no/edc/droughtdb/), a pan-European database of drought impact reports. The EDII was developed for the purpose of cross-disciplinary drought research (Stahl et al., 2015). Its objective is to compile knowledge on the impacts of historic and recent drought events from a variety of information sources. Following the basic definitions of a drought impact by Knutson et al. (1998), which is also used by the US-Drought Impact Reporter (National Drought Mitigation Center; http://public.droughtreporter.unl.edu/), the EDII has collected reports on negative environmental, economic or social effects which have occurred due to drought conditions. Impact reports in the EDII can be based on quantitative indices, like crop production, or can include qualitative findings that would not otherwise be included in correlation analysis. This expands the scope of the study to include any agricultural consequence of drought rather than narrowly defined measures typically used in correlation analysis.

This study attempts to "move from the skies ... to the ground" (Kallis, 2008), using drought impact reports as a means to evaluate the relevance of meteorological drought indices with respect to impacts. The study approach uses logistic regression to model the extent to which drought indices can predict drought impact occurrence based on impact reports from the EDII. This builds on previous research (Blauhut et al., 2015) that examined annual drought impacts, but introduces novel methods, which include modeling impacts at the monthly scale by accounting for seasonality, incorporating interannual trends to account for sampling bias, and allowing for non-linear effects. All of these improvements better control for extraneous variables, producing a more accurate, isolated estimate of the link between drought and resulting impacts. This study tests all possible combinations of SPI and SPEI (1–24 month) separately for four general impact sectors (agriculture and livestock farming, energy and industry, public water supply, and freshwater ecosystems) and five European countries (Bulgaria, Germany, Norway, Slovenia, and the United Kingdom). The resulting drought impact models are then used to determine:

1. the most relevant drought indices and accumulation periods for each impact type and region,
2. the portion of impact likelihood explained by precipitation (SPI) or water balance (SPEI) anomalies,
3. and any consistent patterns across countries and impact types.

2. Data and methods

To determine the relevant drought indices and compare across impact types and countries, the best logistic regression model for each country and impact type is determined by stepwise regression. SPI and SPEI accumulation periods (n) of 1, 2, 3, 6, 9, 12, and 24 months are considered as potential predictor variables, as well as the joint influence of SPI-n and SPEI-n.

2.1. Drought indices (SPI/SPEI)

The Standardized Precipitation Index (SPI, McKee et al., 1993; Guttman, 1999) is calculated based on precipitation (P), while the alternative Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010; Beguería et al., 2013) uses the climatic water balance, measured as precipitation (P) minus potential evapotranspiration (PET). For each index, the quantities are summed over n months, termed accumulation periods and normalized to the standard normal distribution ($\mu = 0, \sigma = 1$) by fitting a parametric statistical distribution to the time of year during a reference period, from which non-exceedance probabilities can be calculated (McKee et al., 1993; Guttman, 1999; Lloyd-Hughes and Saunders, 2002). SPI and SPEI therefore allow for objective, relative comparisons across locations with different climatologies and highly non-normal precipitation distributions. In addition, index values are statistically interpretable, representing the number of standard deviations from typical conditions for a given location and time of year.

This study calculated SPI and SPEI for 1, 2, 3, 6, 9, 12, and 24 months, using a 30 year standard period, 1970–1999, as a reference period. Common nomenclature is used, so that SPI-6 corresponds to an SPI with a 6 month accumulation period. Index values were fitted by maximum likelihood estimation and normalized using the two parameter gamma distribution for the SPI and generalized extreme value (GEV) distribution for SPEI, following the recommendations for this dataset outlined in Stagge et al. (2015). Also, as in Stagge et al. (2015), index values are constrained to the range between -3 and 3, inclusive, to ensure reasonableness. Index values were extracted for each country using the area-weighted mean.

2.2. Climate data

The underlying climate data used to calculate the SPI and SPEI is based on the Watch Forcing Dataset (WFD) and the Watch Forcing Data ERA-Interim (WFDEI), which are gridded historical climate sets of subdaily climate data with a $0.5 \times 0.5^\circ$ resolution, originally intended to provide comprehensive historical climate data to force global climate models (Weedon et al., 2011, 2014). Both datasets have undergone significant review and validation (Weedon et al.,