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# Impact of soil moisture on extreme maximum temperatures in Europe

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ABSTRACT

Land-atmosphere interactions play an important role for hot temperature extremes in Europe. Dry soils may amplify such extremes through feedbacks with evapotranspiration. While previous observational studies generally focused on the relationship between precipitation deficits and the number of hot days, we investigate here the influence of soil moisture (*SM*) on summer monthly maximum temperatures (*TXx*) using water balance model-based *SM* estimates (driven with observations) and temperature observations. Generalized extreme value distributions are fitted to *TXx* using *SM* as a covariate. We identify a negative relationship between *SM* and *TXx*, whereby a 100 mm decrease in model-based *SM* is associated with a 1.6 °C increase in *TXx* in Southern-Central and Southeastern Europe. Dry *SM* conditions result in a 2–4 °C increase in the 20-year return value of *TXx* compared to wet conditions in these two regions. In contrast with *SM* impacts on the number of hot days (NHD), where low and high surface-moisture conditions lead to different variability, we find a mostly linear dependency of the 20-year return value on surface-moisture conditions. We attribute this difference to the non-linear relationship between *TXx* and NHD that stems from the threshold-based calculation of NHD. Furthermore the employed *SM* data and the Standardized Precipitation Index (SPI) are only weakly correlated in the investigated regions, highlighting the importance of evapotranspiration and runoff for resulting *SM*. Finally, in a case study for the hot 2003 summer we illustrate that if 2003 spring conditions in Southern-Central Europe had been as dry as in the more recent 2011 event, temperature extremes in summer would have been higher by about 1 °C, further enhancing the already extreme conditions which prevailed in that year.



## 1. Introduction

It is well established that the state of the land surface influences atmospheric conditions, including impacts on near-surface temperatures, boundary layer development, and possibly rainfall generation. Soil moisture is a key variable controlling several of these interactions (Seneviratne et al., 2010). As such, the relationships between surface moisture and temperature means and extremes have been studied extensively using both observational and model derived products (e.g., Koster et al., 2006; Seneviratne et al., 2006; Fischer et al., 2007; Mueller and Seneviratne 2012; Miralles et al., 2014). Most of the inferred impacts of soil moisture on the climate system are mediated by variations of evapotranspiration in soil moisture-limited regimes (Koster et al., 2004, Seneviratne et al., 2010), and these feedbacks also play an important role in the context of climate change, possibly leading to a shift in the location of hot spots of soil moisture-temperature coupling (Seneviratne et al., 2006).

Increases in climate extremes, due to changes in the mean, variance or shape of the distributions, can have larger impacts on ecosystems and society than changes in mean climate because it is often more difficult to adapt to changes in rare but high impact extreme events (e.g., IPCC, 2012; Reichstein et al., 2013). Several studies have shown that changes in the extremes do not always scale to changes in mean climate (see references in Seneviratne et al., 2012a). For instance, an extreme value analysis of the Central England daily mean temperature record has shown that hot summer extremes have evolved differently than mean summer temperature (Brabson and Palutikof, 2002). Furthermore, analyses of climate model projections also suggest that the warm tails of summer temperature

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distributions will warm more than mean temperatures in mid-latitude regions with substantial decreases in soil moisture content, in particular in Central Europe and the Mediterranean region (Orlowsky and Seneviratne, 2012). Accordingly, investigating the relationship between soil moisture anomalies and indices of temperature extremes in Europe is of high interest. Indices that have been developed to characterize temperature extremes (Zhang et al., 2011) include absolute indices (e.g., the hottest day of the year, season or month) and percentile indices that examine changes in the tails of the distribution (e.g., the number of days with maximum temperatures above the 90th percentile), among others. Many of these indices describe 'moderate' extremes with a re-occurrence time of one year (Seneviratne et al., 2012a).

Many studies have investigated the influence of land-atmosphere coupling on indices of extreme temperature. Antecedent surface moisture deficits estimated from the Standardized Precipitation Index (SPI) were related both to the number of hot days (i.e., the number of days with maximum temperatures above the 90th percentile) and the maximum heatwave duration (i.e., the maximum number of consecutive days with daily maximum temperature above the 90th percentile) in summer in Southeastern Europe (Hirschi et al., 2011). These results were confirmed in other studies for Europe (Quesada et al., 2012) and on the global scale (Mueller and Seneviratne, 2012), which identified other hot spots with a strong correlation between the number of hot days in the warm season and antecedent precipitation deficits. In these various studies, the relationship between antecedent moisture deficits and extreme temperature (assessed by the number of hot days) amplified for summers with a higher occurrence of hot days (Hirschi et al., 2011). On the other hand, the decreasing variability of hot extremes towards wetter conditions implies a higher predictability for the occurrence of hot days following wet rather than dry conditions. Indeed, wet spells are strictly followed by low numbers of hot days, but both high and low numbers of hot days can take place following dry conditions (Quesada et al., 2012; Mueller and Seneviratne, 2012). Hence, antecedent dry conditions were found to be a necessary but not sufficient condition for the occurrence of hot days. In addition, Quesada et al. (2012) considered the role of prevailing weather types in combination with spring moisture deficits in the occurrence of summer heat waves in Europe, identifying that both controls are important for the occurrence of hot days. The global analysis of Mueller and Seneviratne (2012) identified a relationship between precipitation deficits and the subsequent occurrence of hot extremes in a large fraction of the world, including many areas in North and South America, Europe, Australia and parts of China. In North America, these results are also consistent with previous findings of Durre et al. (2000), suggesting that the distribution of daily maximum temperature is shifted to higher values on days following low soil moisture anomalies (using soil moisture estimates from a water balance model), with the largest impacts at the warm end of the distribution.

In general, most studies of extremes examine changes or relationships in extreme indices (Vincent et al., 2005; Donat et al., 2013; McGree et al., 2013; Whan et al, 2013). Recently, however, more research uses extreme value theory to fit non-stationary generalized extreme value (GEV) distributions to precipitation and temperature data, with covariates used to explore relationships with large-scale climate drivers (e.g., Zhang et al., 2010; Sillmann et al., 2011; Photiadou et al., 2014). For instance, the relationship between hot spell duration, magnitude and frequency, and atmospheric blocking has been demonstrated for Europe using a non-stationary GEV model (Photiadou et al., 2014). A GEV analysis has the advantage of moving away from moderate extreme events and focusing on the far ends of the tails of the distributions. Robust predictions can even be made about the occurrence of rare events that have not (yet) been observed. To answer questions only related to extremes, it is preferable to fit distributions only to the tails using an extreme value analysis rather than to model the whole distribution (Cooley, 2009).

One way of understanding the influence of soil moisture on (subsequent) temperature extremes is to study temperature differences on days with wet soil moisture compared with all days, i.e., using composites. Using such a method, Brabson et al. (2005) demonstrated that additional soil moisture is associated with more moderate return values (RVs) for both summer maximum and winter minimum temperatures in Britain. In addition, it was shown that future hot spells are longer when the analysis is restricted to low soil moisture days. That study fitted a stationary GEV distribution to a subset of days (i.e., wet soil moisture days) rather than using a non-stationary approach with an index of soil moisture as a covariate. Also Mueller and Seneviratne (2012) used composites to derive the distributions for the number of hot days following dry or wet conditions in Texas in a non-GEV application.

Despite the large body of research about the influence of land-atmosphere coupling on temperature, several questions remain. For instance, it is difficult to obtain continental scale observed soil moisture data sets (Koster et al., 2006; Seneviratne et al., 2010, Dorigo et al., 2013). Therefore, many observational studies use proxies for soil moisture (Hirschi et al., 2011; Mueller and Seneviratne, 2012; Zscheischler et al., 2014a) as data basis, while others used soil moisture derived from meteorological inputs to a water balance or land surface model (Durre et al., 2000, Orth and Seneviratne, 2014). A recent study alternatively used remote sensing estimates of soil moisture retrieved from microwave measurements, but also these data have some shortcomings, mostly because they only measure moisture in the top few centimetres of the soil (Hirschi et al., 2014). Hence, it is relevant to investigate how inferred relationships between surface moisture deficits and temperature extremes may depend on the use of the SPI compared to model-based soil moisture. The relationship between the number of hot days and the block maxima of maximum temperature also requires further analysis, because a direct translation from temperature extremes into the number of hot days cannot be expected. Finally, no previous research has examined the nature of soil moisture—extreme temperature relationship within a GEV framework.

In order to answer the above questions, we focus on the relationship between extreme temperature and a newly derived model-based soil moisture data set using an extreme value theory methodology. We concentrate on the summer months (June, July and August) and domains in Southeastern and Southern-Central Europe (SEE and SCE, respectively). These regions were chosen because SEE has been identified as a hot spot of soil moisture-temperature coupling (Hirschi et al., 2011; Mueller and Seneviratne, 2012) and because SCE was the main region affected by the 2003 heatwave (e.g., Schär et al., 2004; Fischer et al., 2007). The SCE domain is substantially different from the Central European domain considered in Hirschi et al. (2011), which only included Austria and the Czech Republic, while the SCE domain in the present study covers most of Southern France and Northern Italy (in addition to Austria and Southern Germany), and thus a large fraction of its area is located in a Mediterranean climate regime. The latter is expected to be associated with a soil moisture-limited evapotranspiration regime (Teuling et al., 2009) and thus a stronger impact of soil moisture availability on temperature on the interannual time scale (Seneviratne et al., 2010).

## 2. Data and methods

### 2.1. Study area and data sets

We focus our analysis on Europe (−9.75 to 49.75°E and 35.25 to 69.75°N) and the period 1984–2013 to coincide with the extent