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A drought event composite analysis using satellite remote-sensing based soil moisture

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ABSTRACT

Drought is a globally relevant hazard, and while various studies have investigated the relationship between droughts and different climate and ecosystem variables, they are often not global or they do not make use of direct soil moisture observations. Here we use satellite derived soil moisture observations from the Climate Change Initiative of the European Space Agency to quantify the relation between soil moisture drought and temperature, precipitation, evapotranspiration and vegetation during the peak of the growing season. Furthermore, we follow the temporal evolution of the buildup and recovery surrounding the drought peak. We find that in many regions longer-term precipitation deficits are the driving factors of large negative soil moisture anomalies. At the peak of the dry period large anomalies are found for precipitation, evapotranspiration, and temperature, while vegetation indices often show a delayed response. This delay is likely related to the limited information contained in the remotely sensed soil moisture signal on the deeper root zone, thus underestimating the available soil moisture for plants. Anomalies over grasslands are generally larger than over forests, likely linked to the ability of trees to better access water at deeper depths, and to save water during dry conditions. These results illustrate the relevance of remote-sensing based soil moisture as a new independent observation for studying land-vegetation-atmosphere dynamics at the global scale.

1. Introduction

Drought is a globally relevant hazard which can lead to severe economical, agricultural and societal damages. A key feature of droughts is extremely low soil moisture availability, either due to reduced precipitation and/or increased evapotranspiration (Seneviratne et al., 2012b). An essential prerequisite for efficient drought mitigation and management is a detailed and quantitative assessment of both the processes leading to episodes of severely limited water availability together with the respective impacts on both ecosystems and societies. For this purpose, drought has historically been classified into four categories including meteorological drought, hydrological drought, agricultural drought and socio-economic drought (Mishra and Singh, 2010). While meteorological is usually defined through periods of anomalously low precipitation (McKee et al., 1993) and hence solely dependent on atmospheric processes, hydrological (surface water), agricultural (soil-moisture) and socio-economic (water supply systems) droughts are directly influenced by land-processes and often also subject to human management (Van Loon et al., 2016).

In this study, we focus on emerging opportunities for quantitatively assessing the impacts of agricultural drought using remotely sensed soil moisture (Liu et al., 2011, 2012; Wagner et al., 2012; Dorigo et al., 2015) at the global scale. Soil moisture drought is highly relevant for agriculture (McWilliam, 1986), plant health (Zscheischler et al., 2013, 2014), the intensification of heat extremes (Fischer et al., 2007b,c; Hirschi et al., 2011; Mueller and Seneviratne, 2012; Miralles et al., 2014; Whan et al., 2015) and, more generally, land-atmosphere feedbacks and temperature variability (Seneviratne et al., 2010, 2006a). Changes in soil moisture regimes also affect modifications of climate variability in a changing climate (Seneviratne et al., 2006b, 2013; Lorenz et al., 2016), originating from the direct influence of soil moisture on the water and energy cycles through land-atmosphere interactions (see e.g. Seneviratne et al., 2010, for a review).

Obtaining good soil moisture observations is, however, often a challenge (Seneviratne et al., 2010), and in practice many studies rely on soil moisture proxies to study the relationship between soil moisture drought and other variables. Process-based models of varying complexity usually try to incorporate the different effects of precipitation, temperature, evapotranspiration, land cover, and soil

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Table 1
Overview of the data sets used, indicating the original properties of the products.

Data set	Variable	Temp. cov.	Temp. res.	Spatial res.
ESA CCI	SM	1979–2015	Daily	0.25°
ERA-Interim/Land	SM	1979–2010	Daily	0.25°
GLEAM	ET	1980–2014	Daily	0.25°
ERA-Interim	Tx & P*	1979–2014	Daily	0.25°
NDVI3g	NDVI	1981–2015	Biweekly	1/12°
MODIS	LAI, FPAR	2000–2015	Every 8 days	1 km
ESA CCI	Landcover	2008–2012	Static	300 m

* Used to calculate a 3-month SPI.

type on soil moisture variability (Balsamo et al., 2009; Miralles et al., 2011; Orth and Seneviratne, 2015; Davis et al., 2017). Such models are widely used as observation-based proxies for soil moisture, to study soil moisture interactions with climate (Fischer et al., 2007c; Van den Hurk et al., 2010; Dirmeyer, 2011; Miralles et al., 2014) and vegetation (Reichstein et al., 2007, 2013; Zscheischler et al., 2013, 2015). Alternatively, there is a suite of commonly used indicators for soil moisture drought. For instance, the Standardized Precipitation Index (SPI, McKee et al., 1993) has been used extensively to study interactions between drought, climate, and vegetation (Hirschi et al., 2011; Mueller and Seneviratne, 2012; Zscheischler et al., 2014; Gudmundsson et al., 2014; Whan et al., 2015). However, the SPI is purely based on precipitation and thus strictly speaking an indicator for meteorological drought.

The soil moisture product from the European Space Agency's Climate Change Initiative (CCI-SM) (Liu et al., 2011, 2012; Wagner et al., 2012; Dorigo et al., 2015) offers a unique opportunity to study soil moisture drought and its implications at the global scale for a time period of more than two decades. The relevance of satellite-based soil moisture observations is underlined by a number of publications, highlighting recent advances in technology and validation of satellite-based soil moisture retrievals and their relevance for understanding Earth system processes (Dorigo and de Jeu, 2016; de Jeu and Dorigo, 2016). Studies using the CCI-SM dataset have focused on specific regions and specialized research questions (Bauer-Marschallinger et al., 2013; Chen et al., 2016; Fang et al., 2016; Qiu et al., 2016; Nicolai-Shaw et al., 2016; Shrivastava et al., 2017). In addition, the data set has also been used to evaluate Earth System Models (Lauer et al., 2017). The CCI-SM dataset is continuously improved and validated and the number of studies using this dataset is rapidly increasing (de Jeu and Dorigo, 2016).

Here we make use of the global extent of the CCI-SM dataset, and provide the first global-scale assessment of satellite-based soil moisture drought and its covariability with other climatic variables and vegetation indices. Our study focuses on soil moisture droughts during the peak of the growing season and illustrates the sensitivity of variables such as maximum temperature, precipitation, evapotranspiration, and three vegetation indices to extremely low levels of soil moisture. We further discuss the impact of the dominant vegetation classes on this sensitivity with a particular focus on the differences between forests and grasslands. Finally we compare remotely sensed soil moisture drought with modeled soil moisture by a land surface model and with the SPI.

2. Data sets and data preprocessing

2.1. Data sets

Below we describe the data sets used for the analysis, see Table 1 for a quick overview of the original properties.

2.1.1. Soil moisture

We use the remote-sensing based soil moisture data set developed in the framework of the European Space Agency Climate Change Initiative program on the global monitoring of Essential Climate Variables (CCI-SM). It has a 0.25° spatial and a daily temporal resolution, and is given in units of m^3/m^3 (Liu et al., 2011, 2012; Wagner et al., 2012; Dorigo et al., 2015). Over time the number of available satellites has increased, which in turn increased data availability and data quality (Dorigo et al., 2015, 2010). Here we use the merged data set (v03.2), derived from the collocated C-band scatterometer data set and the collocated multi-frequency radiometer data set. The analysis is based on the period 1992 to 2014, as 1992 is the first full year that includes scatterometer data. CCI-SM represents the upper few millimeters to centimeters of the soil (Kuria et al., 2007), to determine the influence of soil depth on drought anomalies ERA-Interim/Land soil moisture (ERA-SM) is used (Dee et al., 2011; Balsamo et al., 2015, 2012). ERA-SM has a daily temporal resolution and covers the period 1979 to 2010. The true spatial resolution is approximately 80 km, but here the 0.25° regridded product is used as it corresponds to the CCI-SM resolution. The top three layers of ERA-SM represent 0–7 cm, 7–28 cm, and 28–100 cm, and will be referred to as ERA-SM$_{0-7}$, ERA-SM$_{7-28}$, and ERA-SM$_{28-100}$ respectively.

2.1.2. Evapotranspiration

The Global Land Evaporation Amsterdam Model (GLEAM) consists of a set of algorithms which estimate the different components of land evaporation (Miralles et al., 2011; Martens et al., 2016). Here we use GLEAM_v3.0a, which spans the period 1980 to 2014 at a 0.25° spatial and a daily temporal resolution. For the analysis we use actual evapotranspiration (*ET*, mm/day), which is defined as the sum of transpiration, bare-soil evaporation, open-water evaporation, interception loss and snow sublimation.

2.1.3. Maximum temperature and precipitation

Temperature and precipitation data are taken from the ERA-Interim global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF, Dee et al., 2011). We use the interpolated 0.25° data set, the original resolution is approximately 80 km. Daily total precipitation in millimeters of water is produced by the forecasting model, and is defined as the sum of snowfall and rain (ERA-P). We further use the 6 hourly 2 m air temperature product from the analysis to define the maximum daily temperature (ERA-Tx).

2.1.4. Vegetation activity

As a proxy for vegetation activity, we use the Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) generated from NOAA's Advanced Very High Resolution Radiometer (AVHRR) data (Pinzon and Tucker, 2014). The data set is assembled from different AVHRR sensors, and the latest version spans the period July 1981 to December 2015 (3g.v1). The spatial resolution is 1/12°, and data is available twice monthly. In addition we use level-4 MODIS global Leaf Area Index (LAI) and the Fraction of Absorbed Photosynthetically Active Radiation (FPAR) as proxies for vegetation activity (MOD15A2). These data sets are available every 8 days at a 1-km resolution on a sinusoidal grid, and span the time period February 2000 to the present (Knyazikhin et al., 1999).

2.1.5. Land cover

We use the third epoch (2008–2012) of the global ESA CCI Land Cover data set (v1.6.1) which is centered on the year 2010. It has a 300 m spatial resolution with global coverage and uses the legend as defined by the UN Land Cover Classification System (LCCS). Differences between the epochs centered on 2000 and 2005 with the epoch centered on 2010 are negligible at the spatial scale of our analysis (0.25°).