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Response of ecosystem productivity to dry/wet conditions indicated by different drought indices

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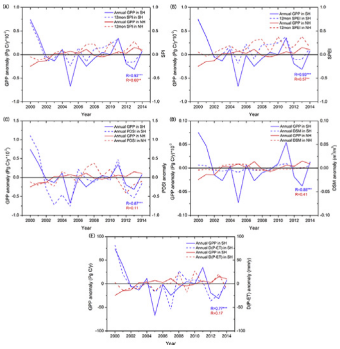
HIGHLIGHTS

- The sensitivity of GPP to five drought indices was comprehensively evaluated.
- Reduced global drought condition and increased GPP were observed from 2000 to 2014.
- Semi-hemisphere as a whole, GPP anomalies are more sensitive to SPI and SPEI than other indices.
- On a regional scale, GPP anomalies are most sensitive to DSM and PDSI.

GRAPHICAL ABSTRACT



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ABSTRACT

Various climatic and hydrological variables such as precipitation, soil moisture, stream flow, and water level can be used to assess drought conditions, however, the response of ecosystem productivity to such metrics is not very clear. In this study, we examined the sensitivity of GPP anomalies to five drought indicators: the Standardized Precipitation Index (SPI), the Standardized Precipitation–Evapotranspiration Index (SPEI), Palmer Drought Severity Index (PDSI), deficit of soil moisture (DSM), and the difference between precipitation (P) and evapotranspiration (ET) (D(P-ET)). The global spatial distributions of drying and wetting trends from 2000 to 2014 determined by these five indices were similar. Additionally, the percent of drought-impacted areas decreased over the study period, indicating a reduction in drought conditions. GPP increased over the study period in the Northern Hemisphere (NH) but decreased in the Southern Hemisphere (SH), resulting in a net increase in global GPP. GPP anomalies were more sensitive to drought indices in the SH than in the NH. Among the five indices, GPP anomalies were most closely correlated with SPI in the NH ($R = 0.60$, $P < 0.05$) and SPEI in the SH ($R = 0.93$, $P < 0.01$). Regionally speaking, annual and seasonal GPP anomalies were most sensitive to DSM and PDSI, highlighting the importance of soil moisture observations to regional drought monitoring and assessment. The results of this study are important for evaluating the impacts of drought on ecosystem production and the global carbon cycle.

1. Introduction

Drought influences ecosystem production by limiting vegetation growth, causing tree mortality, inducing wild fires, etc., and therefore can impact the global carbon cycle (Chen et al., 2013; Ciais et al.,

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2005; Huang et al., 2016b; Lewis et al., 2011; Mantgem et al., 2009; Reichstein et al., 2013; Westerling et al., 2006). Observations have suggested that drought reduces ecosystem NPP and enhances global CO_2 concentrations (Zhao and Running, 2010). Drought-induced ecosystem carbon loss and potential biosphere–atmosphere feedback have raised concerns related to climate change (Reichstein et al., 2013). Understanding the response of ecosystem production to drought facilitates the prediction of ecosystem dynamics under future climate scenarios.

Drought is a complex issue and still has no uniform definition (Van Loon et al., 2016). This may be one of the reasons behind the controversy of whether drought conditions have become aggravated over the past few decades. Some studies have claimed a pronounced increase in drought events and drought-impacted areas since the 1950s (Dai, 2013), whereas other studies have reported opposite results (Sheffield et al., 2012a). Uncertainties in climate datasets, use of different drought indicators or evapotranspiration models, natural climate variability, and so forth have all contributed to divergences in historical drought trends (Donohue et al., 2010; Mcvicar et al., 2012; Trenberth et al., 2013). Several studies have found that the effect of CO_2 on vegetation may reduce drought intensity by enhancing ecosystem water use efficiency and reducing evaporative loss, and suggested that this effect should be included in drought assessments (Burke, 2011; Burke and Brown, 2008; Roderick et al., 2015; Swann et al., 2016; Yang et al., 2016). Hence, selecting an appropriate drought indicator is necessary to access drought conditions and evaluate the impact of drought on ecosystem productivity.

Numerous drought indices have been developed over the past several decades. Among these, the Standardized Precipitation Index (SPI) (Mckee et al., 1993), the Palmer Drought Severity Index (PDSI) (Palmer, 1965), and the Standardized Precipitation–Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010a) are most commonly used. The multi-timescale drought index SPI is calculated based on precipitation; it is simple to calculate and reflects drought conditions over different timescales. PDSI and SPEI are based on the theory of water balance and incorporate the impact of precipitation on drought as well as the influences of other climatic variables such as temperature, wind speed, and solar radiation (Dai et al., 2009; Vicente-Serrano et al., 2010a). Compared with SPI, PDSI and SPEI more realistically reflect soil moisture conditions and have been extensively used in agricultural drought assessments.

Soil moisture contributes to approximately half of global terrestrial ecosystem production (Chen et al., 2014). Despite the importance of soil moisture in regulating land surface ecological process, investigations of soil moisture dynamics and their influences on vegetation growth typically have been confined to local scales due to scarcity of in-situ observations. Over the past decade, a series of satellite based soil moisture datasets have been produced to satisfy needs of large scale investigations, such as soil moisture products generated from SMOS (Soil Moisture and Ocean Salinity) mission (Marczewski et al., 2010), from SMAP (Soil Moisture Active Passive) mission (Entekhabi et al., 2009), from ASCAT (Advanced Scatterometer) sensor (Naeimi et al., 2012), from AMSR-E (Advanced Microwave Scanning Radiometer - Earth Observing System) mission (Koike et al., 2004; Paloscia et al., 2006) and AMSR-2 mission (Forbes, 2014), etc. Among these dataset, the satellite-based soil moisture product (CCI SM) issued by the European Space Agency (ESA) provides long-term, global coverage of soil moisture conditions (Dorigo et al., 2012; Liu et al., 2012). This product has been extensively implied in study fields of hydrology, land-atmosphere interactions, global biogeochemical cycles, weather prediction, climate change, etc. (Dorigo and Jeu, 2016; Dorigo et al., 2017). Relying on this product, some studies have evaluate the response of vegetative growth to changes in soil moisture (Barichivich et al., 2014; Chen et al., 2014; Mcnally et al., 2016; Muñoz et al., 2013; Nicolai-Shaw et al., 2017). For example, Chen et al. (2014) investigated the impact of soil moisture on vegetative growth in mainland Australia and found a sensitive and lagged response of vegetative growth to soil moisture conditions. However, seldom of them have examined the sensitivity of vegetative growth to soil moisture dynamics on a global scale.

Previous studies have employed various drought indices to assess the impact of drought on ecosystems (Lotsch et al., 2003; Narasimhan and Srinivasan, 2005; Vicente-Serrano et al., 2013; Zhao and Running, 2010), but few have explored differences in the sensitivity of ecosystem productivity to these indices. In this study, we explored the sensitivity of global primary productivity (GPP) simulated based on Moderate Resolution Imaging Spectroradiometer (MODIS) retrieves to five drought indices. Three meteorological (SPI, SPEI and PDSI) and two surface water based (deficit in soil moisture, DSM, and the difference between precipitation and actual evapotranspiration, D(P-ET)) indices were selected. Annual and seasonal trends of these five indices were evaluated, and the sensitivity of GPP to each index was examined and compared.

2. Material and methods

2.1. Datasets

Monthly GPP and ET products (from 2000 to 2014) with a spatial resolution of 1 km were retrieved from MODIS. These two products were produced by the Numerical Terradynamic Simulation Group (http://www.ntsg.umt.edu/) and can be obtained freely. The GPP product (MOD17A2) was simulated using a light use efficiency model (Running et al., 2004; Zhao et al., 2005; Zhao et al., 2010). Its accuracy had been validated by many studies, and it is comparable with in-situ observations (Gebremichael and Barros, 2006; Heinsch et al., 2006; Turner et al., 2006). The ET product (MOD16) was estimated based on the Penman–Monteith model using satellite-retrieved surface parameters (e.g., land cover, FPAR, albedo, and LAI) as inputs (Mu et al., 2007; Mu et al., 2011). Validation studies using station flux tower data and modeling data have suggested a reasonable accuracy of this product (Lu and Zhuang, 2010; Mu et al., 2011; Ruhoff et al., 2013; Velpuri et al., 2013), despite relative large biases have been observed in some regions, such as Africa, tropics and subtropics (Miralles et al., 2016; Ramoelo et al., 2014).

The global CCI_SM product with a resolution of 0.25°, which was merged with retrievals from four passive (TMI, SSM/I, SMMR, and AMSR_E) and two active (ASCAT and ERS AMI) microwave sensors with the support of the Climate Change Initiative (CCI) project (Liu, 2010; Liu et al., 2012). This product provides daily soil moisture conditions since 1979, and data from 2000 to 2014 were selected to match the time scale of the GPP data. CCI_SM measures soil moisture at shallow depths (Rebel et al., 2012) and can capture soil moisture dynamics at the root zone layer, which are crucial to vegetative growth (Barichivich et al., 2014; Dorigo et al., 2012; Muñoz et al., 2013; Nicolai-Shaw et al., 2017).

SPEI was developed based on SPI (Vicente-Serrano et al., 2010a). This index retains the flexible timescale of SPI and, similar to PDSI, derives drought based on water balance theory. This new drought index has been widely used for drought monitoring and assessments. Global 0.5° SPEI data was obtained from SPEIbase v2.41 (http://sac.csic.es/spei/database.html) (Beguería et al., 2014; Beguería et al., 2010; Vicente-Serrano et al., 2010b). This dataset was produced based on the Climate Research Unit (CRU) Time-Series Version 3.23 (TS-3.23) dataset and provides SPEI values over timescales ranging from 1 to 48 months from 1901 to 2014.

PDSI is one of the most popular drought indices, accounting for the balance of precipitation, runoff and ET (Dai et al., 2009; Trenberth et al., 2014). In this study, a self-calibrating version of PDSI (Wells et al., 2004), the scPDSI was used. Global 2.5° scPDSIpm dataset (Dai, 2013; Dai et al., 2004; Dai et al., 2009) from 1950 to 2014 was obtained from http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html. The detailed information on this dataset can be found in Dai's (2011 and 2013) studies.