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A drought indicator reflecting ecosystem responses to water availability: The Normalized Ecosystem Drought Index

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ABSTRACT

Drought, one of the most destructive natural disasters is projected by numerous studies to become more severe and widespread under climate change. These water limitations will have profound effects on terrestrial systems across the globe. Yet, most of the existing drought monitoring indices are based on drought stress derived from environmental conditions rather than ecosystem responses. Here, we propose using a new approach, the Normalized Ecosystem Drought Index (NEDI), coupled with modified Variable Interval Time Averaging (VITA) method, to quantify drought severity according to ecosystem transitional patterns with water availability. The method is inspired by Sprengel's and Liebig's Law of the Minimum for plant nutrition. Eddy covariance measurements from 60 AmeriFlux sites that cross 8 International Geosphere–Biosphere Programme (IGBP) vegetation types were used to validate the use of NEDI coupled to VITA. The results show that NEDI can reasonably depict both drought stress posed by the environment and drought responses presented by various ecosystems. Water availability becomes a dominant limiting factor for ecosystem evapotranspiration when NEDI falls below zero, and normalized evapotranspiration strength generally decreases with decreasing NEDI under this regime. The widely used self-calibrating Palmer Drought Severity Index (sc-PDSI) and Standardized Precipitation Index (SPI) have difficulty capturing ecosystem responses to water availability, although they can reasonably represent drought conditions detected in the environment. The normalization feature employed in NEDI makes it feasible to compare drought severity over different regions, seasons and vegetation types. The new drought index also provides a valuable tool for irrigation and water distribution management practices which may enhance water conservation efforts as drought conditions become more prevalent.

1. Introduction

Drought is one of the most devastating natural disasters that can cause serious agricultural, economic and social impacts in the world (Wilhite, 2000). Several studies project increased aridity over land and more widespread droughts associated with changing climate, which could have profound impacts on agriculture, ecosystem structure and function, and human welfare (Mpelasoka et al., 2008; Feyen and Dankers, 2009; Seager et al., 2007, 2009; Dai, 2011a,b). Therefore, it is imperative to define more robust drought measures that can objectively quantify its characteristics, such as onset, severity and duration. Current drought measures often label drought into four categories: meteorological or climatological drought, agricultural drought, hydrological drought, and socioeconomic drought (Wilhite and Glantz, 1985; Heim, 2002; Dai, 2011a,b).

Several drought indices have been developed to consider drought monitoring demands across diverse group of users. Some drought indices define droughts as the departures of soil water balance from normal conditions, such as the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the self-calibrating Palmer Drought Severity Index (sc-PDSI) (Wells et al., 2004) and the Soil Moisture Deficit Index (SMDI) (Narasimhan and Srinivasan, 2005). Other drought indices define droughts as the deviations from normal precipitation patterns, such as the Standardized Precipitation Index (SPI) (McKee et al., 1993), and fractional decreases in precipitation compared to climatological averages (Shi et al., 2014; Hoover and Rogers, 2016). The Standardized Precipitation Evapotranspiration Index (SPEI) includes the effect of evapotranspiration demand caused by temperature variability into the

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SPI framework, which combines the features in PDSI and SPI (Vicente-Serrano et al., 2010; Beguería et al., 2014).

These drought indices can serve as useful tools for drought monitoring, although these approaches may only reflect potential drought stress imposed on an ecosystem rather than actual drought responses. Thus, such drought indices may miss potential phenological and morphological impacts on ecosystems, since ecosystems can have various adaptation and acclimation mechanisms in regards to limited water availability (Lu and Zhuang, 2010; Liu et al., 2011; Starr et al., 2016). At the canopy scale, stomatal conductance could decrease to reduce water loss from a water stressed ecosystem (Reichstein et al., 2002; Ponce Campos et al., 2013). Total leaf area and net primary production of an ecosystem could be regulated in response to limited water availability (Huxman et al., 2004; Saleska et al., 2007; Zhao and Running, 2010). This reduction in leaf level physiological activity in evergreen systems has been observed at least a year following the alleviation of the water stress (Starr et al., 2016). Water use efficiency was found to increase with moderate drought and decrease under severe drought (Lu and Zhuang, 2010).

At the biome scale, a particular ecosystem found at any location has an assemblage of species that are in their specific ecological niche (Peterson, 2003), and has experienced climatological conditions like periodic droughts. These ecosystem responses are able to regulate local and regional circulation patterns, which could have significant influence on water cycles (Foley et al., 2003; Levis 2010). Failure to represent this type of ecosystem regulation may increase the uncertainty in quantifying drought characteristics for real time monitoring and future prediction. In addition to the regulations of soil water availability, ecosystem water and carbon fluxes are also controlled by atmospheric demand for water, indicated by vapor pressure deficit (Whelan et al., 2013; Novick et al., 2016). Therefore, drought index development should not only focus on environmental dryness, but also on ecosystem responses to different limiting factors. Novick et al. (2016) presented a synthesis analysis of drought effects on ecosystem responses, but the dryness index used in their study was based on the ratio of annual potential evapotranspiration and annual precipitation that represents ecosystem characteristics rather than ecosystem transitional responses.

Here, we propose an ecosystem drought indicator called the Normalized Ecosystem Drought Index (NEDI) that can measure drought severity to relate to the effects of ecosystem responses to limited water availability. The NEDI provides a measure of ecosystem responses to drought, which is often not discussed in current drought perspectives (Wilhite and Glantz, 1985). The main difference that distinguishes NEDI from the existing drought indices is the use of normalized surface water balance in quantifying drought conditions, which incorporates ecosystem characteristics in drought severity estimation. With the incorporation of these ecosystem characteristics, we hypothesize that the inclusion of normalization feature can facilitate the inter-comparison of drought severity across different geographical regions and ecosystem types. Ecosystem responses to drought are depicted by the measured changes in normalized evapotranspiration strength (hereafter K) defined as the ratio between actual evapotranspiration (hereafter ET) and potential evapotranspiration (Thornthwaite, 1948). The K defined here is conceptually similar to the Evaporative Stress Index (*ESI*, Anderson et al., 2007), and the crop coefficient K_c (Allen et al., 1998). A modified Variable Interval Time Averaging (VITA) technique traditionally used in detecting turbulence ramp events (Blackwelder and Kaplan, 1976) is applied to identify ecosystem responses to water availability and determine drought severity. The variations of K are analyzed by the modified VITA in drought index domain to illustrate the relationship between measured ecosystem drought response and estimated drought severity. We examined the applicability of NEDI with field measurements taken at 60 AmeriFlux eddy covariance (EC) towers (489 site years in total) across 8 different vegetation types that were defined by the International Geosphere–Biosphere Programme classification (IGBP). The drought conditions commonly identified by sc-PDSI, SPI1 and SPI12 were analyzed and compared with the NEDI to determine the differences among the indices, and show the importance of ecosystem function in quantifying drought severity.

2. Methodology

2.1. Normalized Ecosystem Drought Index (NEDI)

We use the difference between monthly precipitation (P) and monthly potential evapotranspiration (hereafter PET) to estimate water availability (W), similar to the Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2010), and related to the Reconnaissance Drought Index (Tsakiris and Vangelis, 2005). However, we represent water supply with total precipitation collected in the previous months (j = 1 for 1 month lag, j = 2 for 2 months lag, and so forth) instead of the value in the current month to account for legacy effects for precipitation to become an available water source. Therefore, the water availability for the month i can be represented as

$$W_i = P_{i-j} - PET_i, \tag{1}$$

which is positive with water surplus, neglecting groundwater storage and runoff. The monthly NEDI is then defined by normalizing the W_i series with the maximum absolute value of water availability shown in the W_i series of I months, which can be represented as

$$NEDI_i = \frac{W_i}{\max(abs(W_{i=1,I}))}. \tag{2}$$

NEDI can quantify water availability at each ecosystem from −1.0 (driest condition; maximum water shortage) to 1.0 (wettest condition; maximum water surplus).

The Thornthwaite PET (Thornthwaite, 1948), which requires only the mean monthly surface air temperature and latitude, was used to estimate the monthly water demand required in NEDI. Despite its limitations (Jensen et al., 1990; Donohue et al., 2010; van der Schrier et al., 2011), Dai (2011a) showed that using the more sophisticated Penman-Monteith PET only reduced uncertainties slightly in the PDSI calculation. Therefore, the Thornthwaite PET was used in our NEDI calculation to bypass the extensive amount of data required for using Penman-Monteith PET, allowing us to examine NEDI with a greater number of eddy covariance stations.

2.2. Modified Variable Interval Time Averaging (VITA)

Based on a running variance concept, VITA (Blackwelder and Kaplan, 1976) has been widely applied to detect turbulence characteristics in unsteady flows (Shaw et al., 1989). The localized variance used in VITA for each time interval window T is calculated as

$$var(t_i, T) = \frac{1}{T}\int_{t_i-T/2}^{t_i+T/2} p(t)^2 dt - [\frac{1}{T}\int_{t_i-\frac{T}{2}}^{t_i+\frac{T}{2}} p(t)dt]^2, \tag{3}$$

where p and t_i stand for the variable to be used for detection of some phenomenon and observation time, respectively. When the streamwise velocity is used for the variable p, turbulence patterns are identified if rapid changes are detected in the localized variance, suggesting the existence of high velocity fluctuations associated with coherent turbulent structures, as originally used by Blackwelder and Kaplan (1976).

We extend this running variance concept to drought monitoring by using NEDI values in place of time (the variable t_i in Eq. (3)), that is NEDI (the variable n_i in Eq. (4)) was used instead of the time on the abscissa. The variable to be used in detection is then labeled and sorted by the corresponding NEDI value, instead of sorted by time series. This modified VITA is thus defined as