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Monitoring vegetative drought dynamics in the Brazilian semiarid region

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ABSTRACT

Drought is a complex natural phenomenon that can lead to reduced water supplies and can consequently have substantial effects on agriculture and socioeconomic activities that cause social crises and political problems. Different drought indicators are used for identifying droughts. This work explored the applicability of a near-real time drought monitoring methodology using Terra-MODIS Normalized Difference Vegetation Index (NDVI) and land surface temperature (LST) products. This approach is called the Vegetation Supply Water Index (VSWI), which integrates land surface reflectance and thermal properties. The results indicate that during a major drought event from 2012 to 2013, approximately 85% of the Brazilian semiarid region was affected. The number of days of soil moisture deficit, which was derived from a simple water balance model and the daily interpolated precipitation, were used to verify the results. A correlation analysis of VSWI, precipitation and soil moisture deficit shows that VSWI is closely related to rainfall and soil water content, especially under dry conditions, and indicates that the use of VSWI can be a suitable near-real time drought monitoring approach. The evaluation of the 2012–2014 drought considering the VSWI index highlighted two major characteristics of vegetation response to drought conditions, i.e., the recovery and memory effects of vegetation.

1. Introduction

Drought is basically defined as an extended period of months or years, in which precipitation is less than the annual average, resulting in water scarcity. Generally droughts are classified as either a meteorological drought (lack of precipitation over a region for a period of time), hydrological drought (deficiencies in surface and subsurface water supplies), agricultural drought (deficiency in water availability for crop or plant growth) or socio-economic drought (failure of water resources systems to meet water demands, which impacts human activities both directly and indirectly) (Wilhite, 2000; Yang, 2010; Son et al., 2012; Udmale et al., 2014). Although precipitation deficiencies are important, agricultural drought severity is usually more closely associated with deficiencies in soil moisture. The areas affected by drought evolve gradually as the symptoms of moisture stress in plants often develop slowly. These impacts of drought on vegetation are here referred as vegetative drought (Rulinda et al., 2012). Several studies have documented that uneven temporal distributions of precipitation and rising temperatures have caused vegetation shifts, and these studies have shown a newly directional change pattern of vegetation communities in response to climate change and the consequent dryness (Zhou et al., 2011, 2013a,b, 2014).

Drought is considered to be among those natural disasters that can cause the most serious global economic and social losses (Carolwicz, 1996) and affects more people than any other natural disasters (Keyantash and Dracup, 2002). The effects of drought often accumulate slowly over a considerable period of time and may linger for years after the termination of the event, and both the onset and end of drought are difficult to determine (Tannehill, 1947).

In recent decades, droughts have increased in frequency and intensity over much of the planet and can be related to climate change (Marengo et al., 2009; Zhou et al., 2011). The percentage of area that is affected by drought has doubled from the 1970s to the early 2000s (Nagarajan, 2009). In Brazil, this phenomenon has occurred mainly in the semiarid area of Northeast Brazil (SANEB) due to uneven precipitation in space and time. Seasonal droughts usually occur in the winter and spring and have a significant impact on agricultural harvests. The severe droughts that are caused by climactic variations harm the growth on plantations and cause serious social problems because a large number of people who inhabit the region truly live in a situation of extreme poverty (Marengo et al., 2009). More than 80% of the agricultural establishments in

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Northeast Brazil consist of smallholder farmers that practice subsistence agriculture (IBGE, 2009). Thousands of subsistence farmers have seen their livelihoods wither away during drought episodes. Other consequences of large droughts are starvation, malnutrition, misery and migration to urban centers (rural exodus). Thus, the livelihood and food security of millions of smallholder farmers are exposed to profound risk from drought.

In Brazil, from 1980 to 2010 approximately 15% of natural disasters were related to drought conditions in the Northeast Region (NEB). Drought affects more people than any other natural disaster; since 1980 more than 50 million people have been affected by drought (Sapir and Below, 2014). The recent drought of 2012/2013 reached approximately 1300 municipalities and affected approximately 10 million people in Brazil. Drought is, on average, Brazil's most costly natural hazard, primarily because it causes hard impacts on agriculture and livestock production. For example, the 2012/2013 drought resulted in economic losses of US $1.6 billion for the 10 most important crops (beans, rice, corn, cotton, bananas, sugar cane, cassava, soybeans and coffee), US $1.5 billion due to cattle mortality and costs of greater than US $1.5 billion in insurance claims, according to the Brazilian Institute of Geography and Statistics (IBGE).

The quantification of drought is usually determined by remotely sensed spectral indices and water balance simulations. Drought indices are particularly useful for monitoring the impact of climate variability on vegetation because the spatial and temporal identification of drought episodes is extremely complex. A number of drought indices, including meteorological (Wilhite and Glantz, 1985), remote sensed, hydrological and other indicators, have been used to measure drought impacts (Palmer, 1965, 1968; Gibbs and Maher, 1967; Shafer and Dezman, 1982; Kogan, 1990, 2002; McKee et al., 1993; Keyantash and Dracup, 2004; Bhuiyan et al., 2006; Yagci et al., 2011; Zhou et al., 2012; Du et al., 2013; Yang et al., 2013; Abbas et al., 2014; Nichol and Abbas, 2015). Traditional methods of drought assessment and monitoring rely on rainfall data (e.g., the Palmer drought severity index (PDSI) and Standardized Precipitation Index (SPI)). However, in a region where the density of meteorological stations as well as the temporal scale of the data are insufficient, it is impossible to monitor drought using indices that are based on rainfall data. In contrast, satellite-sensor data are consistently available and can be used to detect the onset of drought, its duration and magnitude across large areas (Thiruvengadachari and Gopalkrishna, 1993). Remote sensing has proven to be a powerful tool for evaluating the temporal and spatial aspects of drought conditions (Johnson et al., 1993; Peters et al., 2002).

Moderate Resolution Imaging Spectroradiometer (MODIS) data play an increasingly important role in drought monitoring and assessment (Wan et al., 2004) because of their associated rich spectral information, high temporal repeat cycle and convenient means of data access. The Normalized Difference Vegetation Index (NDVI), which provides a general measure of the state and health of vegetation, was one of the first remote sensing-based indicators that was used for drought detection and monitoring. Many studies have reported relationships between vegetation indices, rainfall and soil moisture (Davenport and Nicholson, 1993; Herrmann et al., 2005; Liu et al., 2013; Ibrahim et al., 2015). This is an important reason why NDVI is widely used in agricultural drought monitoring (Henricksen and Durkin, 1986; Tucker and Choudhury, 1987; Tucker, 1989; Gutman, 1990). On the other hand, vegetation cover condition, as sampled by vegetation index, is a relatively slow response variable that typically adjusts only after notable crop damage has already occurred. In contrast, land surface temperature (LST) derived from thermal infrared (TIR) information can be considered to be a rapid response variable. LST is a good indicator of the energy balance at the Earth's surface because it is one of the key parameters in the physics of land-surface processes on regional and global scales. Researchers have concluded that the combination of vegetation and temperature conditions is a good indicator of soil moisture content.

A large number of vegetation health and drought indices are based on the LST–NDVI space such as Vegetation Health Index (VHI, Kogan, 1990, 1997), Temperature-Vegetation Drought Index (TVDI, Sandholt et al., 2002), Vegetation Supply Water Index (VSWI, Carlson et al., 1990, 1994), and Drought Severity Index (DSI, Mu et al., 2013). These drought indices are often applied for arid or semi-arid regions, and their use in humid–semi humid regions are limited (Rhee et al., 2010). The NDVI–LST relationship, which characterizes moisture and thermal conditions and the entirety of vegetation health, has been used successfully for early drought detection and the estimation of crop and pasture production losses for winter wheat in the USA (Kogan, 1997). The potential for stress exists when the water stored in soil is insufficient to sustain the current growth. In the vegetation covering areas, LST can be considered equal to the temperature of vegetation canopy (Liu et al., 2013). The canopy temperature response can occur even when the plants are green because stomata closure to minimize water loss by transpiration results in a decreased latent heat flux (Berliner et al., 1984; Carlson et al., 1994; Yang and Merchant, 1997).

Because of the territorial expansion of the Northeast region of Brazil, it is necessary to develop methods for large-scale vegetative drought assessment. To direct the emergency actions of the government that are taken to mitigate the effects of drought, it is crucial to determine an appropriate and user friendly index that reflects the direct impact of drought on livestock and subsistence agriculture. Thus, the main objective of this study is to evaluate possible indicators to monitor the impacts of drought on vegetation over the NEB. In this paper, the Vegetation Supply Water Index (VSWI) performance is compared with precipitation data and soil water deficit. This study focuses on the diagnosis of a remote sensing indicator that is responsive to short-term environmental changes because early warning capabilities are limited in current drought monitoring systems.

2. Materials and methods

The study area (Fig. 1a) is located in the equatorial zone (1–21° S, 32–49° W) and covers an area of 1,800,555 km^2, which represents approximately 20% of Brazil's territory. The limits of the study area were defined by the "Superintendence for the Development of the Northeast (SUDENE)".

The semiarid area of Northeast Brazil covers an area of 980,323 km^2 and consists of 1133 municipalities and a population of approximately 22 million people (approximately 12% of the national population). These numbers make the Brazilian semiarid region the most populated semiarid region in the world. In the SANEB, rural areas in the interior are generally used for subsistence agriculture that is primarily comprised of beans, manioc, potatoes and other crops (Cavalcanti et al., 1999). Most of the study area is covered by mixed grasslands–croplands (Fig. 1b). Other land cover types are *caatinga* (closed and open shrublands) and savanna (not shown). In 2010, the total area of pasture and agricultural activities was 1,024,621 km^2, which represents 57% of the NEB territory (Vieira et al., 2013).

Northeast Brazil is characterized by a variable and irregular spatio-temporal distribution of precipitation. The rainfall ranges from less than 800 mm/year in the semiarid interior to more than 1500 mm/year in the rainy climatic zone that is mainly on the east coast (Fig. 2a). Different rainfall regimes have been identified in the NEB (Fig. 2b). (i) In the South-Southwest sector, the main rainy season is from November to February, and the rainfall is associated with cold fronts traveling from the South Region of Brazil. (ii) In the