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# On the observed variability of monsoon droughts over India

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In the present study, the observed variability of monsoon droughts over India has been examined using a drought monitoring index, namely the Standardized Precipitation Evapo-transpiration Index (SPEI). For calculating the SPEI over different time periods, long term (1901–2010), high resolution, monthly gridded temperature and rainfall data sets have been used. The drought time series shows significant interannual, decadal and long term trends. The analysis suggests a general increase in the intensity and percent area affected by moderate droughts during the recent decades. In particular, the frequency of multi-year (24 months) droughts has shown a statistically significant increase, which is attributed to increase in surface air temperatures and thus drying of the atmosphere. The wavelet analysis of SPEI suggests significant spectral peaks at quasi-biennial (2–3 years), ENSO (5–7 years) and decadal (10–16 years) time scales, with significant multi-decadal variations. The variability of monsoon droughts over India is significantly influenced by the tropical sea surface temperature anomalies. The Canonical correlation analysis (CCA) suggests that the major portion of the drought variability is influenced by the El Nino/Southern Oscillation (ENSO). Global warming, especially the warming of the equatorial Indian Ocean represents the second coupled mode and is responsible for the observed increase in intensity of droughts during the recent decades.



## 1. Introduction

Southwest monsoon season (June–September) is the primary rainy season over India which contributes 70–90% of the annual mean rainfall. Monsoon seasonal rainfall exhibits large year to year variability which is around 10% of the long term mean. The interannual variability of monsoon rainfall is linked to the El Nino/ Southern Oscillation (ENSO), the equatorial Indian Ocean anomalies (Gadgil et al., 2003), and the Atlantic Ocean climate anomalies (Rajeevan and Sridhar, 2008). A detailed review of the monsoon teleconnections is given in Gadgil Sulochana et al., 2007. A particular year is termed as an all-India drought year if the seasonal rainfall anomaly averaged over the country as a whole is less than −10% of its long period average. Based on this criterion, 17% of the years during the period 1901–2010 were drought years. Monsoon droughts had catastrophic effects on agriculture, water resources, food security, economy and social life in the country. In spite of technological advancements and improved drought mitigation measures droughts cause adverse effect on the economy of India. For example, the severe drought of 2002 had an adverse effect on the Indian economy by pulling down the Gross Domestic Product (GDP) of the country by almost 1% (Gadgil et al., 2003). To improve drought mitigation and preparedness, we need to improve our present knowledge about the spatial and temporal variability of droughts.

There are many studies on the general characteristic of droughts over India (Sikka, 1999; Bhalme and Mooley, 1980; Parthasarathy et al., 1987; Rao, 1981) and case studies on the specific drought years like 1987, 2002, 2004 and 2009 (Krishnamurti et al., 1989; Gadgil et al., 2003; Sikka, 2003; Francis and Gadgil, 2010; Krishnamurti et al., 2010; Neena et al., 2011). In general, the previous studies of Indian droughts were based on only rainfall data (Chowdhury et al., 1989, SinhaRay and Shewale, 2001; Guhathakurta, 2003). Recently, Pai et al. (2011) examined district-wide drought climatology over India for the southwest monsoon season (June–September) using two simple drought indices; Percent of Normal Precipitation (PNP) and Standardized Precipitation Index (SPI). Gregory (1989) studied the changes in drought frequency over India for the period 1871–1985. Using the SPI and PDSI as drought indices, Benjamin and Saunders (2002) examined the 20th century drought climatology over Europe. Their study revealed that proportion of Europe experiencing extreme and/ or moderate drought conditions has changed insignificantly during

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the 20th century. Dai et al. (1998, 2004) examined global variations of dry and wet spells using PDSI as the monitoring index. Ummenhofer et al. (2012) examined the links between Indo-Pacific climate variability and drought using the Monsoon Asia Drought Atlas.

Several drought indices were developed during the 20th century based on a range of variables and parameters. For the details, Heim (2002), Mishra and Singh (2010) and Sivakumar et al. (2011) may be referred. However, no single index has been able to adequately capture the intensity and severity of drought and its potential impacts on such a diverse group of users (Wilhite and Glantz 1985). Among various drought indices, the palmer drought severity index (PDSI, Palmer 1965) is one of the most widely used. PDSI is a climatic water balance index that considers precipitation and evapo-transpiration anomalies and soil water-holding capacity. Many of the deficiencies in PDSI are resolved by the self-calibrated PDSI. The PDSI is the most prominent index of meteorological drought used in the United States (Dai, 2011). It has been used to quantify long term changes in aridity (Dai et al., 1998) and in tree-ring based reconstructions of past droughts (Cook et al., 2004). However, the PDSI has a fixed time scale and does not allow different drought types (Vicente-Serrano et al., 2010a). Since drought is a multi-scalar phenomenon (McKee et al., 1993), the PDSI is not a good choice to represent drought conditions. Drought is a phenomenon which may occur simultaneously across multiple temporal scales. For example, a short period of particular dryness may be embedded within a long-term drought. In this case, multi-scalar refers to numerous temporal periods which may or may not overlap (Vicente-Serrano et al., 2010a). The response of various hydrological systems (including soil moisture) to precipitation can vary markedly as a function of time.

Moreover, a shortcoming of PDSI values is that it may lag behind emerging droughts by several months. This limits its applications in areas of frequent climatic extremes like the Indian monsoon region. Another major problem associated with using PDSI is that its computation is complex and required substantial input of meteorological data and therefore its application is limited where observational networks are scarce (Smakhtin and Hughes, 2004).

On the other hand, the Standardized Precipitation Index (SPI) developed by McKee et al. (1993) considers the multi-scalar nature of droughts. However, SPI also has an important shortcoming since it is based only on precipitation data and does not consider other critical variables, especially temperatures. Empirical studies have shown that temperature rise markedly affects the severity of droughts (Abramopoulos et al., 1988). The role of temperature was also evident in the devastating central European drought during the summer of 2003. Although previous precipitation was lower than normal, the extremely high temperatures over most of Europe during June and July caused the greatest damage to cultivated and natural systems and dramatically increased evaporation rates and water stress (Ciais et al., 2005; Fischer et al., 2007). For examining the future projections of droughts in the global warming scenario, drought indices that consider precipitation only will not be sufficient. The index should account for changes in atmospheric demand for moisture due to increased surface warming (Dai, 2011). Recently a new drought index, the Standardized Precipitation–Evapotranspiration Index (SPEI) has been proposed (Begueria et al., 2010; Vicente-Serrano et al., 2010a, 2010b) to quantify the drought condition over a given area. The SPEI considers not only precipitation but also temperature data in its calculation, allowing for a more complete approach to explore the effects of climate change on drought conditions.

The objective of the present study is to examine the variability of monsoon droughts over India using a long term data set of 1901–2010 using the SPEI as the drought index. The present study in particular examines (a) spatial and temporal variations of observed droughts and long trends and (b) co-variability of monsoon droughts with tropical sea surface temperatures (SST). In Section 2, data and methods are described. The results are discussed in Section 3 and the conclusions are drawn in Section 4.

## 2. Data and methods

In this study, we preferred to use the SPEI as an indicator for drought as it represents the multi-scalar aspect and also includes the effect of temperature. Since the SPEI includes the effect of the evaporative demand on its calculation, it is more suited to explore the effects of warming temperatures on the occurrence of droughts. The SPEI can be calculated at several time scales to adapt to the characteristic times of response to drought of target natural and economic systems. The SPEI combines the sensitivity of PDSI to changes in evaporation demand (caused by temperature fluctuations and trends) with the simplicity of calculation and the multi-temporal nature of the SPI. The new index is particularly suited to detecting, monitoring and exploring the consequences of global warming on drought conditions (Vicente-Serrano et al., 2010a).

The SPEI is based on a monthly climatic water balance (Precipitaiton minus potential evapotranspiration (PET)) and it is expressed as a standardized Gaussian variate with a mean of zero and a standard deviation of one. The SPEI uses the monthly difference between precipitation and PET. But unlike other water balance-based drought indices such as the PDSI, the SPEI does not rely on the water balance of a specific system (the soil system) (Begueria et al., 2010). It can be calculated for different time scales, and hence the SPEI has a much wider range of applications than the PDSI (Begueria et al., 2010).

Details of the SPEI calculations are given in Vicente-Serrano et al., (2010a, 2010b). The SPEI is based on the climatic water balance, the difference between precipitation and PET.

$$D = P - \mathrm{PET} \quad (1)$$

where $P$ is the monthly precipitation (mm) and PET (mm) is calculated according to the method of Thornthwaite (1948) which only requires data on mean monthly temperature and the geographical location of the region of interest. The calculated $D$ values were aggregated at various time scales:

$$D_n^k = \sum_{i=0}^{k-1} (P_{n-i} - \mathrm{PET}_{n-i}), \quad n \geq k \quad (2)$$

where $k$ (months) is the timescale of the aggregation and $n$ is the calculation number. The $D$ values are undefined for $k > n$. A log-logistic probability distribution function was then fitted to the data series of $D$ as it adapts very well to all time scales. The complete calculation procedure for the SPEI can be found in Vicente-Serrano et al. (2010a).

This represents a simple climatic water balance that is calculated at different time scales to obtain the SPEI. Typical values of the SPEI range between $-2.5$ and 2.5 corresponding to exceedance probabilities of approximately 0.006 and 0.994 respectively, although the theoretical limits are $(-\infty, +\infty)$. The software to calculate the SPEI is available in the Web repository of the Spanish National Research Council (available online at ⟨http://digital.csic.es/handle/10261/10002⟩). We have used this software to calculate the SPEI.

For calculating SPEI, both monthly precipitation and temperature data are required. For this purpose, the gridded ($1 \times 1$ degree) rainfall data over the Indian region (Rajeevan et al., 2006, 2008) developed by the India Meteorological Department (IMD) for the period 1901–2010 have been used. For developing the gridded rainfall data set, 1384 stations which had minimum 70% data