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On the observed variability of monsoon droughts over India

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ABSTRACT

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.

$$D = P - \mathrm{PET} \tag{1}$$

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:

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

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 (1×1 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 availability were considered in order to minimize the risk of generating temporal inhomogeneities in the gridded data due to varying station densities. Multi-stage quality control of observed rainfall data was carried out including checks for homogeneity before interpolating station rainfall data into regular grids. For interpolating station data into regular grids, a modified version of Shepard's angular distance weighting algorithm was used. More details of the gridded rainfall data set are available in Rajeevan et al. (2006, 2008).

For temperature for the same period, 1901–2004, the IMD gridded temperature data (Srivastava et al., 2009) was used. This temperature data set is based on 395 stations and gridded data was developed by interpolating station data into regular grids using modified version of Shepard's angular distance weighting algorithm (Srivastava et al., 2009). Before the gridded analysis, station data were subjected to multi-quality controls including checks for homogeneity. For examining the linkages to the global sea surface temperatures, the Hadley Centre SST dataset (⟨http://www.metoffice.gov.uk/hadobs/hadisst/⟩) has been used. This data set (Rayner et al., 2003) is available at 1 × 1 degree resolution. The calculated monthly SPEI was aggregated for different time scales, 6, 12, 18 and 24 months to examine multi-scalar characteristic of the monsoon droughts. In this study, we discuss these aggregated drought indices as SPEI (6), SPEI (12), SPEI (18) and SPEI (24). The 6 month SPEI will signify the effect of southwest and northeast monsoons. The 12 month SPEI will signify the rainfall contribution of winter and pre-monsoon months also in addition to the southwest and northeast monsoons. The 18 and 24 months SPEI will signify multi-year droughts.

3. Results and discussion

3.1. *Observed variability of droughts*

In this section, the observed variability of monsoon droughts at different time scales is discussed. Fig. 1a–d shows the time series of SPEI calculated for 6, 12, 18 and 24 months correspondingly. The time series of SEPI (6) resembles the all-India monsoon seasonal rainfall variations, even though there are variations. The time series however shows significant inter-annual and multi-decadal variations. The years, 1918 and 2002 were the worst droughts over India. If we assume all-India averaged SPEI < -0.50 as moderate drought years, with SPEI (6), there were 21 drought years during the period 1901–2010, thus making a probability of about 19%. With the same criterion, the probability of moderate drought with SPEI (12), SPEI (18) and SPEI (24) are 15%, 15% and 14% respectively.

In the whole data period, three consecutive droughts have occurred only once, 2000–2002. This prolonged drought had an adverse effect on the agricultural and water resources sectors over the country, which will be discussed later. The filtered SPEI time series with a 13 point smoother (IPCC 2007) is also shown in Fig. 1. This 13-point filtering is done to remove the sub-decadal fluctuations. The filtered time series shows significant decadal variations. In addition, a decreasing trend of SPEI (increasing drought intensity) from 1951 to 2010 is also observed. The time series of SPEI (12), SPEI (18) and SPEI (24) also shows significant inter-annual, decadal and long term trends. If there are two or more consecutive years with deficient southwest monsoon season, the effect will be seen in SPEI (18) and SPEI (24). If we look at the time series of SPEI (24), we observe higher frequency of multi-year droughts (24 months) during the period 1951–2010. For example, during the period 1951–2010, there were 12 multi-year droughts (24 months), while during the period 1901–1950, there were only three such long-lived droughts.

To examine the spectral characteristics of drought index at different time periods, a Morlet wavelet analysis (*For details refer* Torrence and Compo (1998) and Grinsted et al. (2004)) was performed on the SPEI time series and the results are shown in Fig. 2. The results suggest some interesting characteristics of the drought index at different time periods. The short term drought (SPEI (6)) is characterized by strong periodicity at quasi-biennial (2–4 years) and decadal (12–16 year) time scales. The longer duration drought, especially SPEI (18) and SPEI (24) are characterized by the influence of El Nino/Southern Oscillation (ENSO) with a peak around 4–8 year time scale. However, this spectral characteristic with ENSO showed epochal variations. It was stronger during the period 1940–1990, with a weakening during the recent years, which is similar to the weakening relationship between Indian monsoon rainfall and ENSO reported earlier (Kumar Krishna et al., 1999). In addition, strong periodicity is also observed on 8–10 year time scale till about 1940s, which then moved to higher time scale

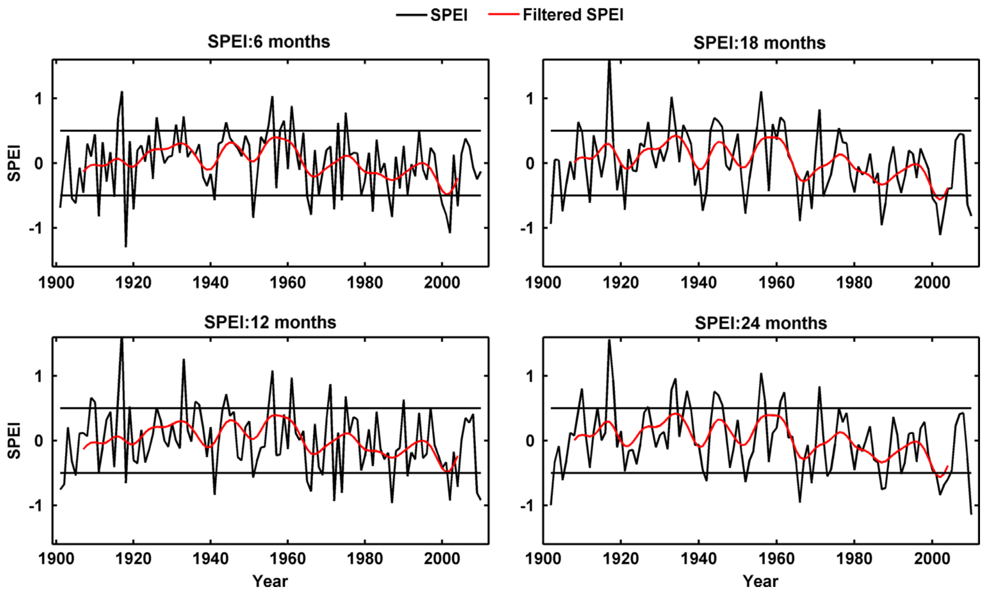

Fig. 1. Time series of SPEI for different accumulated periods 6, 12, 18 and 24 months for the period 1901–2010. The smoothed variation of SPEI after removing the sub-decadal variations using a 13-point filter is shown as red line.

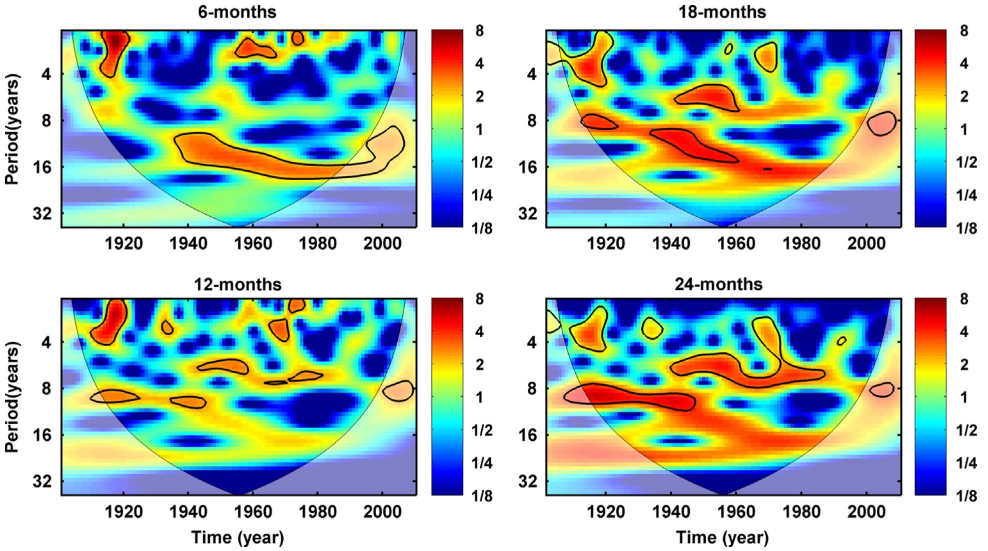

Fig. 2. Wavelet (Morelet) analysis of SPEI at different accumulated periods 6, 12, 18 and 24 months.

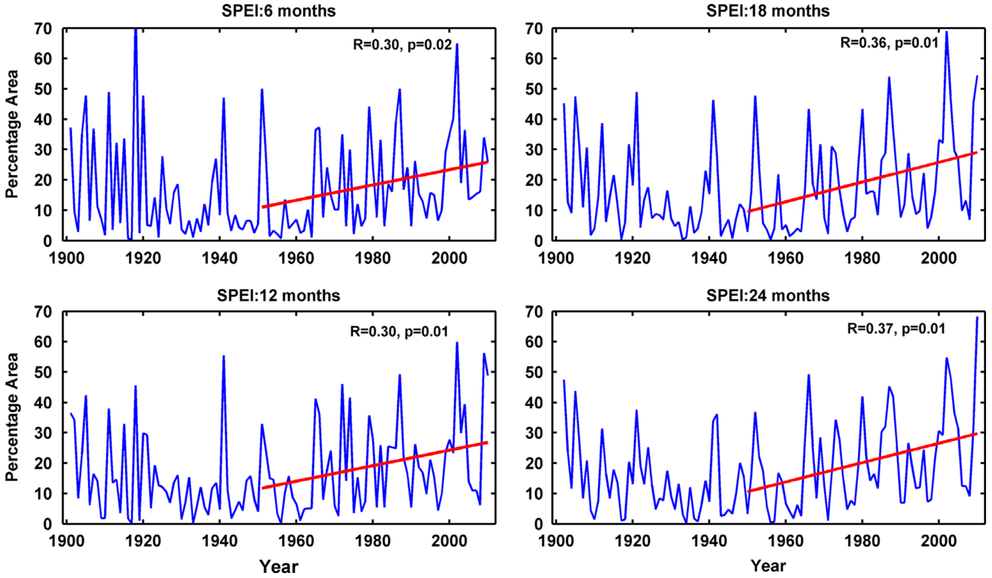

Fig. 3. The time series percent area affected by moderate drought (SPEI < -1.0) at different accumulated periods for the period, 1901–2010. The trend lines calculated using the data of 1951–2010 are shown as red lines. The statistical significance levels of trend values are shown as *p* values for each figure. All the trends are statistically significant at least at 95% significance level.

of 12–16 years during the later years. Similar decadal component has been found in the spectral characteristics of the European droughts also (Ionita et al., 2012). This decadal component may be intrinsic to the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO). More detailed analysis is however required to further explore this relationship on decadal time scale.

Fig. 3 shows the time series of percent of the country experiencing moderate droughts with different time periods. To calculate these time series, only the plains of India was considered and northeast India and extreme northern parts of India with higher topography were excluded. For calculating percent of area affected by drought, the grid points with SPEI less than -1.0 (moderate drought) were considered. It may be mentioned that for area averaged drought index of SPEI for the country as a whole, a smaller threshold (-0.5) was considered. The grid points at which SPEI is < -1.0 were counted and their total area (after multiplying with cosine of the latitude) was considered to prepare the time series. On an average, about 17% of the total country is affected by moderate drought. These time series also show significant inter-annual and decadal variations like the time series of SPEI shown in Fig. 1. In years like 1918 and 2002, more than 60% of the country was affected by moderate drought on shorter time scale (SPEI (6)). In some years like 1902, 1905, 1966, 1987, 2002, 2003 and 2010, multi-year droughts have affected more than 40% of the country. The most significant aspect is the observed increasing trends in percent area affected by moderate droughts. This is reflected in short-term drought like SPEI (6) as well as multi-year drought like SPEI (24). However, the significant increasing trends are observed from 1951 onwards, which are statistically significant at least at 95% significance level for all time periods.

An analysis of possible reasons revealed that these long term trends in SPEI are associated with increasing temperatures rather than decreasing precipitation. Fig. 4 shows the time series of annual mean temperature and precipitation averaged over the country. It shows significant increasing trends of temperatures from mid-1970s. The annual precipitation over the country is found to be very stable. This increasing trend in temperatures causes more evaporation and drying and thus increases the area affected by drought defined by SPEI. Dai (2011) examined the long term changes of global PDSI from 1900 to 2008, which suggested two modes of variability. The first mode represents a long-term trend of drying over Africa, south and east Asia and eastern Australia. The second mode is associated with the ENSO.

In Fig. 3, it was seen that the percent area of the country affected by the moderate drought has increased during the recent decades. To examine the spatial pattern of these changes, we have calculated the difference in frequency of moderate drought ($SPEI < -1.0$) between two periods, 1945–1977 and 1977–2010 for different SPEI indices. The results are shown in Fig. 5 in which the difference in frequency (percent) between the two epochs (1977–2010 and 1945–1977) is shown. In Fig. 5, the grid points where the difference is statistically significant at 95% level are only shown in different colors. The statistical significance of the differences between the two epochs was tested using a student's *t* test (Wilks, 2011). The results suggest an increase in drought frequency during the recent epoch, 1977–2010. The increase is more pronounced over central India and south peninsula including Kerala. A small decrease is noted over the north eastern parts of India. The increase in drought frequency is more evident in multi-year droughts like SPEI (18) and SPEI (24), which suggests that multi-year droughts are more frequent during the recent years.

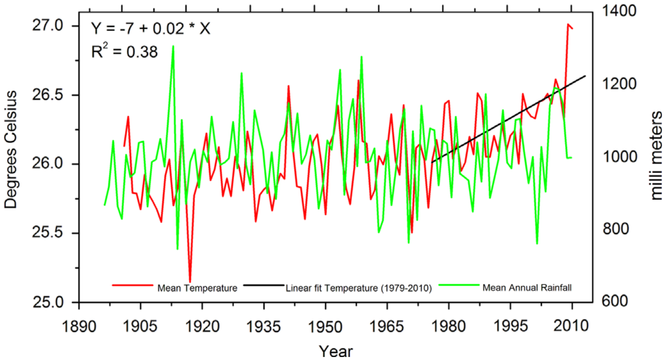

Fig. 4. Time series of annual rainfall and annual temperature averaged over the country for the period 1901–2010.

Agricultural crop production and the Gross Domestic Product (GDP) of the country are greatly influenced by the performance of monsoon rainfall (Gadgil and Gadgil, 2006). A large deficiency in the seasonal rainfall affects the agricultural production and also the GDP. The adverse effect of 2002 brought down the GDP of the country by 1% (approximately 5.22 billion dollars) (Gadgil et al., 2003). Fig. 6 shows the relationship between the agricultural crop production (Kharif season) in million tonnes with percent area of the country affected by moderate drought as defined by SPEI (6). The data of agricultural crop production for the Khariff season (only food grains) was taken from the Department of Agriculture, Government of India. The long term trend in crop production due to technological trend has been removed before this analysis. This is done by fitting a linear trend equation using the least square method and removing the trend equation from the overall data. The relationship between SPEI and agricultural crop production is found to be non-linear. Similar non-linear relationship has been found by Gadgil and Gadgil (2006) using only precipitation data. Drought area of less than 20% does not have an effect on the agricultural production. However, if the area of drought is more than 20%, then the agricultural crop production reduces sharply, but linearly. The large reduction of crop production in a severe drought year like 2002 is thus highlighted. The percent area affected by moderate drought (as defined by SPEI) explains almost 70% of the agricultural crop production in the country A further analysis with multi-year drought (SPEI (24)) shows that multi-year drought index which considers both precipitation and temperature explains more variance than the drought index which considers only precipitation (not shown). As we have seen in Fig. 1, the country experienced 3 years of consecutive droughts during 2000–2002 The cumulative adverse effect was however seen in the agricultural crop production. In 2002, total crop yield during the Kharif season was less than 50 million tones and the lowest in the period of data used (1966–2004). In July 2002, break monsoon conditions prevailed for almost the whole month, which caused abnormal day time temperatures during July 2002 (Rajeevan et al., 2010). The drying of soil moisture conditions during the July month might have added to the severity of the drought conditions in 2002 and thus also the agricultural crop production in the country. Further, Fig. 6b shows

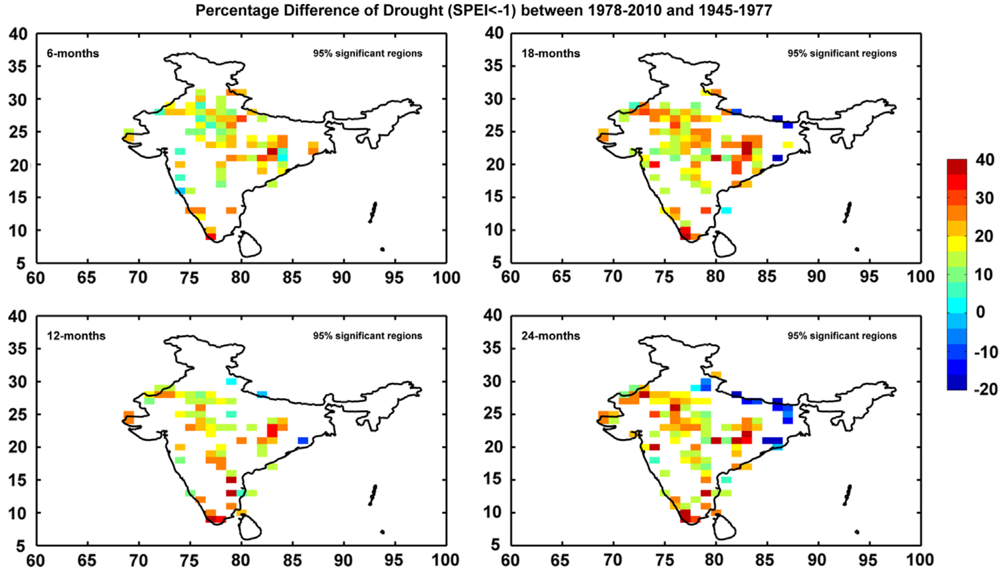

Fig. 5. Difference in frequency of droughts ($SPEI < -1.0$) in percent between two epochs, ((1978–2010) minus (1945–1977)). Differences which are statistically significant at 95% level are only shown. The magnitude and sign of the differences are shown in different colors.

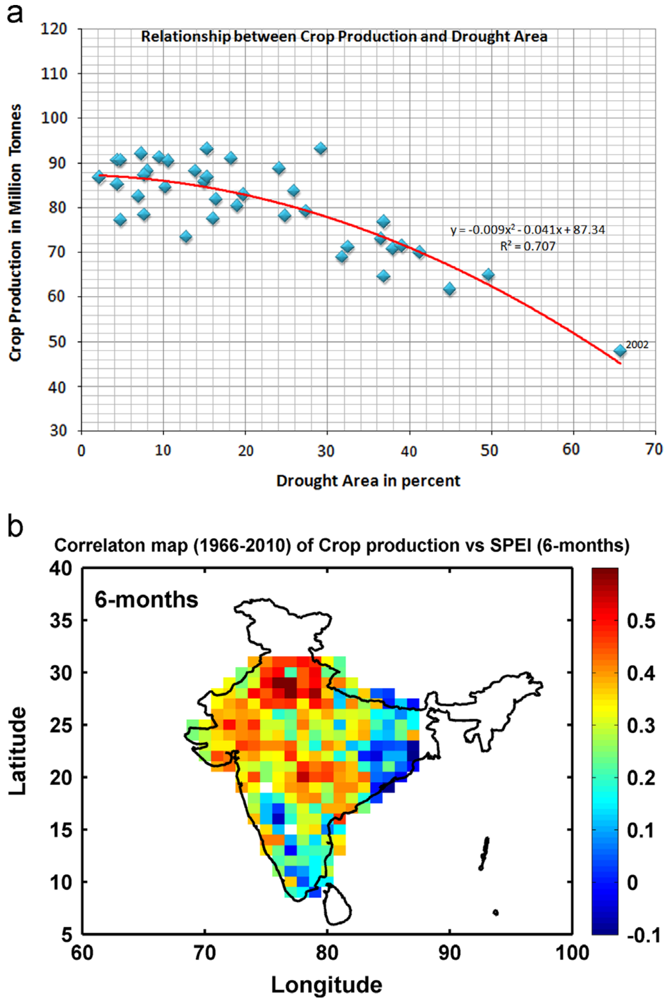

Fig. 6. (a) Scatter plot between agricultural crop production in the country (million tonnes) and percent area of the country affected by moderate drought as defined by SPEI (6), period: 1966–2010. (b) Spatial pattern of correlation between all-India agricultural crop production and SPEI (6) for the period 1966–2010.

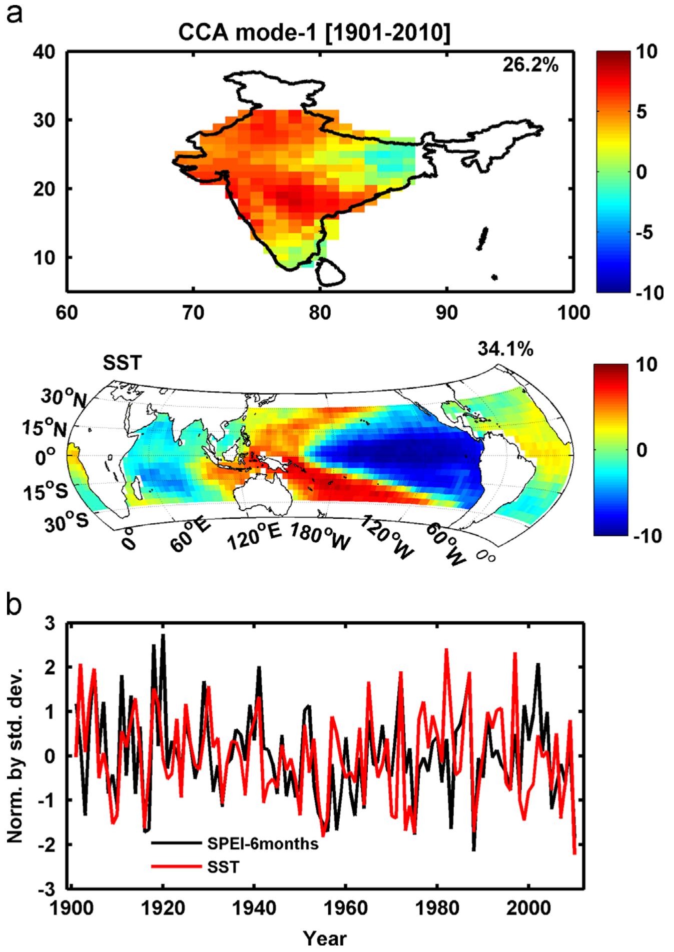

Fig. 7. (a) Spatial pattern of CCA mode-1 for SPEI (6) (above) and SST (below). The percent variance explained by the mode is also shown. (b) Time series of CCA mode-1 for SPEI (6) and SST for the period 1901–2010.

that drought conditions over central and northwest India have greater influence on the agricultural crop production over the country.

3.2. *Relationships with tropical sea surface temperatures (SST)*

Recent studies have shown that historical droughts are linked to SST variations in the tropics. Droughts in north America are associated with the La Nina SST anomalies in the tropical Pacific, while El Nino warming in the Pacific causes drought over India and East China (Dai, 2011). The southward shift of the warmer SSTs in the tropical Atlantic and warming in the Indian Ocean are the main causes of the recent droughts over Sahel. Land cover changes and local feedbacks may however enhance and prolong droughts triggered by tropical SSTs or other anomalies in atmospheric conditions.

In this section, the coupled mode of variability of droughts with tropical SSTs has been examined to understand the role of different ocean basins. To examine the coupled mode of variability, a canonical correlation analysis (CCA) was performed using the tropical SST data of the period, 1901–2010. Among other statistical methods, CCA has the advantage to select pairs of optimally correlated spatial patterns, which may lead to a physical interpretation of the mechanisms controlling the climate variability (Barnett and Preisendorfer, 1987). In this study, we have considered only the SPEI (6) for examining the coupled mode of variability. For the CCA, we considered tropical SSTs (30S to 30N) averaged during the period June–December and the SPEI (6).

Fig. 7a shows the first CCA mode associated with the SPEI (6). The first CCA spatial pattern explains 26.2% of the total variance and has a dipole-like structure with one pole covering central and northwest India and the other pole over the northeastern and southeastern parts of India. This pattern resembles very well the dipole structure associated with the active and break spells of the Indian summer monsoon (Rajeevan et al., 2010). The rainfall variability over northeast and southeast India is negatively correlated with the rainfall variability over central and northwest India. The first CCA spatial patterns associated with tropical SST (Fig. 7a) explains 34.1% of the total variance. This mode is dominated by the ENSO signal with larger loading over the equatorial Pacific Ocean. The familiar horseshoe pattern in the SST anomalies associated with the ENSO is clearly observed. This suggests that ENSO is the most prominent forcing of the variability of monsoon droughts over India. The associated time series of SPEI and SST show strong inter-annual variability (Fig. 7b). The correlation of Nino 3.4 SST time series with the SPEI time series for the period 1951–2010 is 0.57 and with SST time series, it is 0.92. However, the correlation with the ENSO index shows weakening during the recent years as suggested by Kumar Krishna et al. (1999). This weakening is however due to the year 1997 in which the ENSO warming was very large. However there was no adverse effect of the 1997 ENSO on the Indian summer monsoon. The analysis clearly suggests the predominant role of ENSO in causing monsoon droughts. The second CCA spatial pattern of SPEI (Fig. 8a, first panel) explains

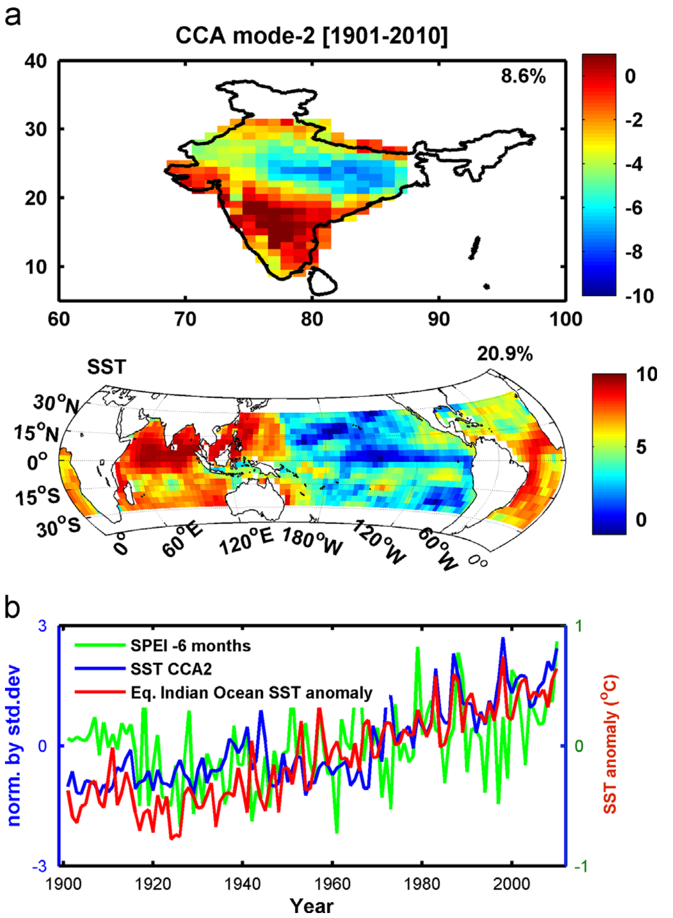

Fig. 8. (a) Spatial pattern of CCA mode-2 for SPEI (6) (above) and SST (below). The percent variance explained by the mode is also shown. (b) Time series of CCA mode-2 for SPEI (6) and SST for the period 1901–2010.The SST anomalies averaged over the equatorial Indian Ocean for the same period is also shown in red color.

8.6% of the total variance. It shows a spatial structure similar to the seasonal rainfall trends over the Indian sub-continent (Guhathakurta and Rajeevan, 2008). An analysis of rainfall trends using the data 1901–2003 showed significant negative trends over eastern parts of central India and southwest parts of south peninsula (Kerala) and increasing trends over western parts of central India (Guhathakurta and Rajeevan, 2008). The spatial pattern of the second mode of SPEI resembles the observed trends of seasonal monsoon rainfall. Fig. 8a (second panel) shows the spatial pattern associated with the second CCA which explains 20.9% of the total variance. The spatial pattern shows strong positive loadings in the equatorial Indian Ocean and South Atlantic Ocean. Strong negative loadings are also observed over the north Atlantic Ocean. The time series associated with SPEI and SST present strong interannual variability and a significant trend, especially after mid-1960s (Fig. 8b). The time series of monthly SST anomalies averaged over the equatorial Indian Ocean is also overlaid over the time series of CCA2 of SPEI and SST. This suggests a very close relationship between the second mode of variability of SPEI and the SST anomalies over the equatorial Indian Ocean. The results discussed in Section 3.1 suggested a long term increase in the percent area affected by moderate drought over the country. The second CCA mode explains this observed long term trend of drought and is related to the SST anomalies over the equatorial Indian Ocean. Since the second mode is related to the equatorial Indian Ocean SST anomalies, it is very likely that Indian Ocean SSTs could be the primary cause for the increasing trend of drought area over the country. An analysis of trends of sea surface temperatures over the tropical Indian Ocean suggests (Fig. 9) that over the years, the Indian Ocean has shown a warming trend. Many other studies (Alory et al., 2007; Deser et al., 2010; Ramesh Kumar et al., 2009) also highlighted the warming of the equatorial Indian Ocean during the recent decades. The observed warming over the equatorial Indian Ocean could be part of the global warming as the second SST mode is significantly correlated (0.75) with global mean temperatures. The warming of the equatorial Indian Ocean may affect the monsoon circulation by (a) enhancing convection over the equatorial Indian Ocean and (b) reducing the land-sea temperature contrast. However, a detailed analysis including climate model simulations is desired for better understanding of the physical causes of the relationship between the Indian Ocean SST anomalies and frequency of droughts.

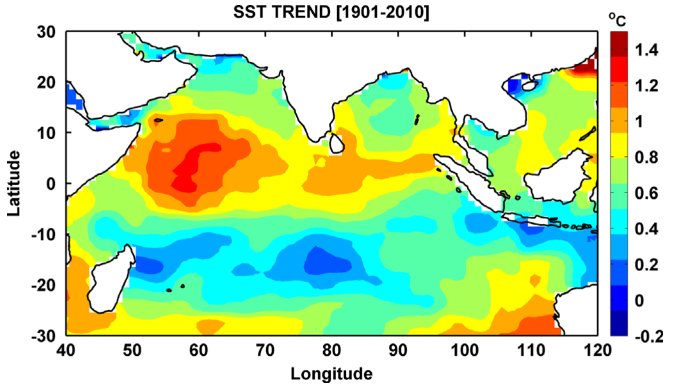

Fig. 9. Linear trends (°C/110 years) of SST averaged during June–December over the tropical Indian Ocean.

4. Conclusions

In the present study, the observed variability of droughts and future projections of frequency and intensity of droughts over India have been examined using a drought index. The drought index, Standardized Precipitation–Evapotranspiration Index (SPEI) considers both the effects of temperature and precipitation and it can also represent the multi-scalar characteristic of monsoon droughts. For calculating SPEI at different time periods, 6, 12, 18 and 24 months, long term (1901–2004) high resolution gridded data of monthly temperature and rainfall have been used. The results suggest the drought index, SPEI exhibits significant inter-annual, decadal and long term trends. The years 1918 and 2002 were the worst droughts, which affected the country. The observed time series of SPEI since 1951 shows a general decrease in SPEI and thus increase in intensity of monsoon droughts. Since 1951, there is an increase in percent area affected by moderate droughts over the country, which is mainly attributed to increase in surface air temperatures. The frequency of multi-year droughts (SPEI (24)) is much more (12) during the period, 1951–2004 compared to the frequency (only 3) during the period 1901–1950. The SPEI (6) is characterized by spectral peaks at quasi-biennial time scales. The multi-year droughts like SPEI (24) have, however, show spectral peaks in the ENSO (5–7 years) and decadal (10–16 years) time scales. Occurrence of moderate and severe droughts affect the agricultural crop production, the relationship is found to be non-linear. The adverse effect on the crop yield is observed when the area affected by moderate drought is more than 20%.

The variability of monsoon droughts over India is significantly caused by the tropical sea surface temperatures. The canonical correlation analysis reveals that the major portion of the drought variability over India is influenced by ENSO. The first coupled mode is significantly correlated with the central Pacific sea surface temperatures, suggesting the major influence of ENSO on monsoon droughts. This is consistent with the earlier studies linking

ENSO and monsoon droughts. The second coupled mode represents the long term trend of monsoon droughts. This mode has linkage to global warming and especially the warming of the tropical Indian Ocean. The recent warming of the tropical Indian Ocean may be responsible for the observed increase of moderate droughts over the country.

In view of the potential threat to important sectors like agriculture, water resources and social life and even the economy, a dedicated monitoring and prediction system needs to be implemented. The India Meteorological Department (IMD), the national weather agency in India is carrying out the operational monitoring of drought conditions over the country using a drought index based on precipitation only. The special drought monitoring mechanism implemented after the devastating subdued monsoon in 2002 helped the policy makers and the government to mitigate the adverse effect of the 2002 drought (Sikka, 2003). However a useful prediction system in predicting probability of occurrence of moderate or severe drought is essential. Many of the current climate models are capable of simulating the precipitation deficits during the recent droughts over North America and Africa (Dai, 2011). It is a big challenge for prediction of monsoon droughts on seasonal to decadal time scales. However, current coupled climate models still have large deficiencies in simulating mean monsoon circulation and rainfall (Rajeevan et al., 2011; Sperber et al., 2012). Substantial efforts will be required to improve the skill of coupled climate models to predict SST variations and associated drought occurrence on seasonal to decadal time scales. Also, we need to take adaptation measures to future climate changes by considering the widespread droughts anticipated in coming decades. Lessons learnt from the past droughts may be helpful for adaptation strategies for future droughts.

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