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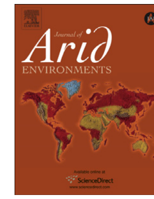

Study on inter-seasonal and intra-seasonal relationships of meteorological and agricultural drought indices in the Rajasthan State of India

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ABSTRACT

Use of rainfall anomaly based Standardized Precipitation Index (SPI) and satellite-derived Vegetation Condition Index (VCI) are becoming common to assess the impacts of drought on crops. This study analysed spatio-temporal intra-seasonal and inter-seasonal relationships for 24 years between rainfall and NDVI and between SPI and VCI to understand crop response to water availability in the Rajasthan State, India. To separate the effect of weather and technology on crop growth over time, a modification in VCI was proposed and called "Trend Adjusted VCI" (VCI_{Tadj}). The VCI_{Tadj} was computed for early, mid, late and whole crop seasons by deriving pixel wise crop phenology metrics from NDVI profile. Significant linear relationships were found between NDVI and rainfall but phase of crop season affected the strength of this relationship. The SPI and VCI_{Tadj} were linearly related in all the four seasons, the strength of relationship improved with the progress of crop season and these relationships were stronger than between rainfall and NDVI. These relationships broke down in irrigated croplands. As a result, the anomaly indices of SPI and VCI_{Tadj} and their intra-seasonal relationships can be used to study the response of crops to water availability for early detection and better prognosis of agricultural drought.

1. Introduction

Droughts are recurring climatic events that often affect South Asia, bringing significant water shortages, economic losses and adverse social consequences. In the literature, many definitions of drought exist but the central theme in the definitions of a drought is the concept of a water deficit. Drought is broadly categorised as being meteorological, hydrological, agricultural or socioeconomic (Boken, 2005; Lloyd-Hughes and Saunders, 2002). Agricultural droughts in India are also classified according to the timing of rainfall deficiency during a crop season: early, mid and late season droughts (Kumar et al., 2009). Early season droughts are associated with delay in commencement of the monsoon resulting in no or delayed sowing of crops. Mid-season droughts are associated with breaks in southwest monsoon and coincide with vegetative growth stage of crops. Late season droughts coincide with the reproductive stage of crop leading to forced maturity. The relationships between different types of drought are complex and their understanding is important for prognosis of impacts.

Among the several proposed meteorological drought indices for drought monitoring, the Standardized Precipitation Index (SPI) has found wide-spread application (Heim, 2000; McKee et al., 1993; Rossi and Cancelliere, 2002; Wilhite et al., 2000). Guttman (1998) and Hayes et al. (1999) compared SPI with Palmer Drought Severity Index (PDSI) and concluded that the SPI has advantages of statistical consistency, and the ability to describe both short-term and long-term drought impacts through the different time scales of precipitation anomalies. Also, due to its intrinsic probabilistic nature, the SPI is the ideal candidate for carrying out drought risk analysis (Guttman, 1999). An evaluation of common indicators, according to six weighted evaluation criteria of performance (robustness, tractability, transparency, sophistication, extendibility, and dimensionality), indicated strengths of the SPI over the PDSI (Keyantash and Dracup, 2002).

Satellite-based vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), have been used extensively for vegetation drought monitoring (Kogan, 1997; Bayarjargal et al. 2006; Mcvicar and Bierwirth, 2001; Prathumchai and Honda, 2001; Rabab, 2002; Ji and Peters, 2003a; Vicente-Serrano et al., 2006). NDVI – based Vegetation Condition Index (VCI) (Kogan, 1995) has proven to be useful for detecting vegetation drought onset and measuring the intensity, duration, and impact of drought

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in regions around the world (Anyamba et al., 2001; Ji and Peters, 2003a; Kogan, 1995; Nicholson and Farrar, 1994; Seiler et al., 2000; Unganai and Kogan, 1998; Wang et al., 2001). One of the main advantages of the VCI is that, because it is a satellite-based drought product, it can provide near real-time data over the globe at a relatively high spatial resolution. In addition, the VCI uses a completely independent methodology for monitoring drought, while all of the other meteorological indices rely, to some extent, on station-based meteorological data.

Nicholson and Farrar (1994) studied the relationship between NDVI and rainfall at 26 weather stations in Botswana (1982–1987) and found a linear relationship between NDVI and rainfall when rainfall was below the 'saturation' threshold. Once precipitation exceeded this threshold, NDVI only increased slightly with additional rainfall. Wang et al. (2001) examined the relationship between NDVI and precipitation variability in Kansas. During the summer, the correlation was strongest when precipitation was averaged over the most recent 1–2 months. They found that strength of the correlation between precipitation and NDVI varied by land cover type. Ji and Peters (2003b) also examined the relationship between the NDVI and precipitation (e.g., SPI) during the growing-season over the northern and central US Great Plains (1989–2000). They found that the 3-month SPI was most strongly correlated with the NDVI due to the lag between the occurrence of precipitation and vegetation response. The strength of the correlations between the NDVI and SPI varied both spatially and temporally. The strongest (weakest) correlations were found in regions with low (high) soil water holding capacities and during the middle (beginning/end) of the growing-season. The authors concluded that while NDVI is a useful variable for monitoring vegetation conditions, the nature of the relationship between the NDVI and drought conditions varies based on the seasonal timing and variations in vegetation and soil type. Méndez-Barroso et al. (2009) also found strong relationship between seasonal precipitation and Enhanced Vegetation Index (EVI) derived greenness intensity across the regional ecosystems in the North America Monsoon region in northwestern Mexico.

Singh et al. (2003) used the VCI and Temperature Condition Index (TCI) for drought monitoring in India and they noted that low VCI values can occur from flooding as well as from drought and therefore concluded that using the VCI alone is not suitable for drought monitoring. Bhuiyan et al. (2006) compared the response of the SPI, VCI, and a ground water index in northern India. Their findings were in agreement with Singh et al. (2003) as they also found that the VCI was only weakly correlated with the meteorological and hydrological drought indices. Further, Bhuiyan et al. (2006) found that the correlation between the VCI and SPI increased during the monsoon season because vegetation health is entirely dependent on precipitation, while during the rest of the year it is partly controlled by irrigation. They concluded that the identification and classification of drought are strongly controlled by the monitoring method (e.g. drought index). Very few studies in literature have specifically studied intra-seasonal variations in relationships between meteorological and agricultural drought indices at regional scales.

The present study is aimed at analysing the spatio-temporal intra and inter-seasonal relationships between meteorological drought indices and satellite derived agricultural drought indices to determine the crop response to water availability and its regional characteristics. The results should improve our understanding of interaction between crop and climatic factors which may improve the technique of drought detection and monitoring using satellite data.

2. Material and methods

The study was conducted for the Rajasthan State (Fig. 1), situated in the north-western part of India exhibiting arid to semi-arid climate in different parts. The mean annual rainfall in the west varies from 100 to 400 mm while it ranges between 557 mm and 1000 mm in the east with annual average value of 574.3 mm for the whole State. About 90% of annual rainfall is received by south-west monsoon during June to September months. The total cultivated area of the State encompasses about 20 million hectares and out of this only 20% of the land is irrigated (State Government of Rajasthan: http://www.krishi.rajasthan.gov.in). The State has principally two crop seasons, viz., *Kharif* (June to October) and *Rabi* (November to March). The *kharif* crop season corresponds to monsoon period and major crops grown during *kharif* are pearl millet, sorghum, pulses, maize and groundnut.

The datasets used and steps followed in this study are represented as schematic diagram in Fig. 2. This study used gridded monthly precipitation time series data constructed by Climatic Research Unit (CRU TS 3.0) at a spatial resolution of 0.5 × 0.5° for 1951–2006 time period (Mitchell and Jones, 2005; New et al., 2000). Gridded data was preferred over station data as it is more amenable to spatial analysis. The comparison of gridded monthly rainfall data with station data for four locations in the study area over 40 years showed a good correspondence between the two with R^2 values ranging between 0.87 and 0.97 and RMSE ranging between 6.9 and 16.8 mm. Time series of NOAA-AVHRR bimonthly NDVI composite dataset having a spatial resolution of 8 km for 1982–2006 period was used to study the crop dynamics. The NDVI dataset was downloaded from the University of Maryland Global Land Cover Facility Data Distribution centre website (http://ftp.glcf.umd.edu/data/gimms/).

2.1. Standardized Precipitation Index (SPI)

The Standard Precipitation Index (SPI) is a tool developed by Mckee et al. (1993) to detect and compare meteorological drought across time and space scales. Technically, SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable i.e. Z-variate. Mathematically, SPI for period *i* is calculated as:

$$\mathrm{SPI}_i = (X_i - X_{\mathrm{mean}})/\sigma \quad (1)$$

where, X_i is standardized rainfall of station for period i; X_{mean} and σ are long-term mean and standard deviation of standardized rainfall for the same period. Since precipitation is not normally distributed, the long-term precipitation record is first fitted to an incomplete-gamma probability distribution, which is then transformed into a normal distribution such that the mean of SPI for the location and desired period is zero.

Using monthly gridded rainfall data of 56 years, SPI for study grids at different time-scales was calculated. SPI was computed spatially (pixel wise) at four time scales during the main summer crop season (*kharif*), namely, tri-monthly SPI_JJA (June, July, August), bi-monthly SPI_AS (August, September), bi-monthly SPI_SO (September, October) and penta-monthly SPI_JJASO (June to October) corresponding to early, mid, late and whole *kharif* crop seasons, respectively.

2.2. Vegetation Condition Index (VCI)

VCI was calculated in this study from NDVI time series data as described in following sub-sections.