Link between monsoon rainfall variability and agricultural drought in the semi-arid region of Maharashtra, India

Rahul S. Todmal*

Department of Geography, Vidya Pratishthan's ASC College, Baramati 413 133, India

The monsoon rainfall variability in semi-arid regions affects all economic activities in general and agriculture in particular. The present study, therefore, analyses monsoon rainfall variability and its connection with El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and agriculture in the semi-arid region of Maharashtra, India during 1980–2014. Linear correlation and regression analysis were carried out to evaluate the role of ENSO and IOD in rainfall variability. The standardized precipitation index (SPI), standardized cropped productivity index (SCPI) and standardized crop area index (SCAI) were used to compare the agro-meteorological variability. The dependency of agricultural cropped area on rainfall was verified using satellite data (NDVI). The El Niño events and positive phase of IOD were mainly responsible for below-average rainfall over the study region. This highlights the need to incorporate the ENSO and IOD for precise forecasting of monsoon rainfall. Rainfall variability (up to 33%) over the study basins causes meteorological droughts and eventually results in agricultural droughts. The agricultural productivity of rainfed as well as irrigated crops was significantly affected by rainfall variability. Particularly, during the severe meteorological droughts (1985–86, 2002–03 and 2012), agricultural productivity and cropped area were significantly reduced. Under the future climate change scenario, a rise in temperature will further add to the already difficult agricultural water management challenge. Therefore, agronomists and water resources managers have to design a judicial plan which can mitigate the water scarcity and sustain agricultural yield even in warming conditions.

Keywords: Agriculture, drought, future climate change, monsoon rainfall, semi-arid regions.

IT is a well-established fact that variability in monsoon rainfall severely affects the Indian economy[1]. The extreme decline in rainfall causes drought, which is a recurring and multifaceted climatic disaster affecting the socio-economic activities, including agriculture. The deficiency of water for prolonged periods primarily reduces agricultural yield[2] and eventually a collapse in the agrarian economy of a region[3]. Under the climate change scenario, an increase in frequency and intensity of extreme climatic events is estimated over the semi-arid regions of the world[4]. Therefore, rainfed agriculture in such regions is more vulnerable to the adverse effects of drought[5] and flood.

The water resources management and mitigation of hydrological disasters are heavily dependent on climate variability[6]. Moreover, variation in rainfall (and temperature) can have a pronounced effect on the cropping pattern and agricultural productivity[7]. In this context, several efforts have been made to understand the variability, pattern and associated factors with monsoon rainfall over India. Kripalani *et al.*[8] have used standardized precipitation index (SPI) to understand rainfall variability at the all-India level. They found that there are distinct periods of above- and below-average monsoon rainfall. In the case of Maharashtra, India, the Marathwada and Madhya Maharashtra Sub-divisions had highest rainfall variability[9]. Particularly, the districts with low rainfall (including the present study area) had higher variability[10]. El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are the two major climatic phenomena in the Indo-Pacific sector, which determine the variability in rainfall over India[11]. At the regional and national levels, a reasonably good connection between El Niño events and rainfall was observed[12]. Kale *et al.*[13] reported a similar link for the rain-shadow zone of western Maharashtra. Obviously, ENSO influences the production of major crops[14]. Similarly, the positive and negative phases of IOD are in good agreement with rainfall variability, particularly over western India[11]. It was also observed that the occurrence of positive phase of IOD reduced the intensity of ENSO-induced droughts over western Maharashtra[3].

Rainfall variability primarily caused water scarcity and eventually affected agriculture in the semi-arid regions of Maharashtra. Majority of districts in the state experience drought conditions once in four years[15,16]. Although agriculture in Maharashtra contributes a marginal share to the state domestic production, about two-thirds of the state population depends on it for their livelihood[17]. Owing to this economic character, Maharashtra is highly vulnerable

*e-mail: todmalrahul@gmail.com

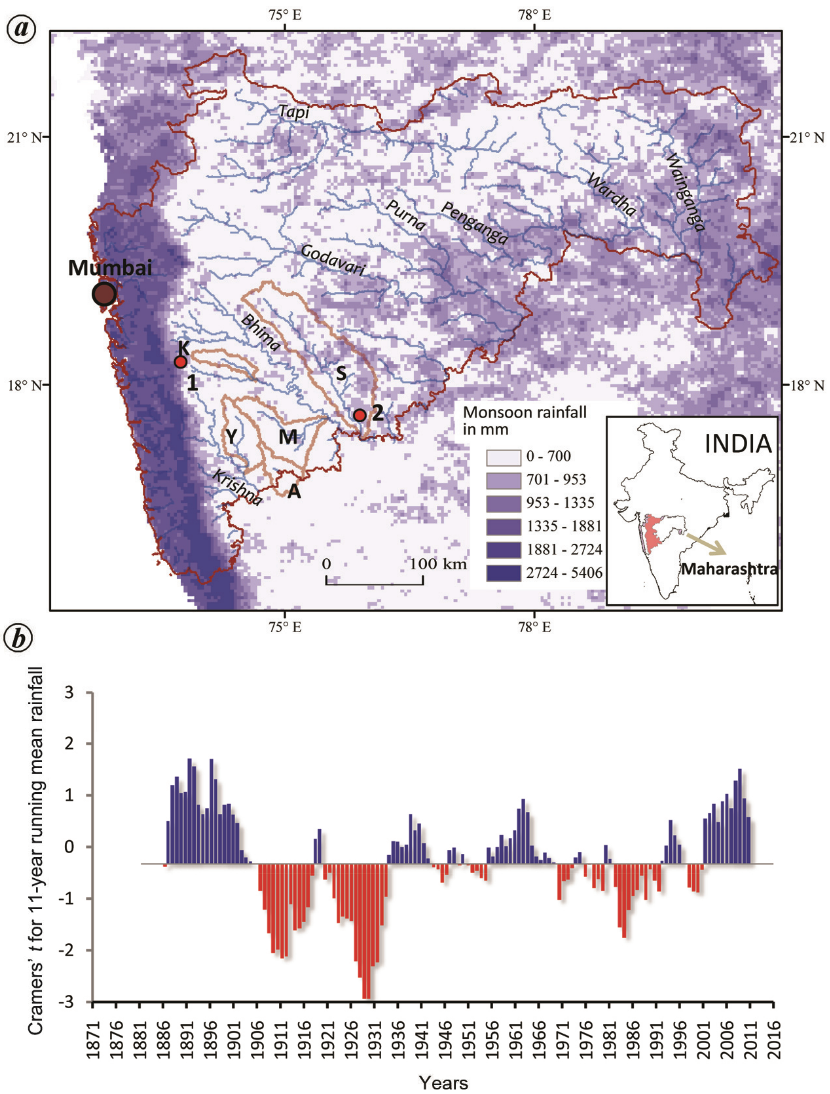

Figure 1. ***a***, Location of study basins and distribution of monsoon rainfall over Maharashtra, India. Rainfall classes are based on natural breaks. (Inset) Map shows the Madhya Maharashtra Sub-division. S, Sina; M, Man; K, Karha; Y, Yerala and A, Agrani basins. 1, Pune and 2, Solapur. ***b***, Above- and below-average epochs in monsoon rainfall over Madhya Maharashtra. Source of TRMM data: http://www.geog.ucsb.edu/~bodo/TRMM/.

to climatic variability. Frequent drought conditions have triggered agricultural poverty and distress as reflected from the suicide of more than 14,000 farmers since 1994 (refs 18–20). On the other hand, extreme hydrological conditions severely damage the economy of the state, as the recent drought and flood events (in 2003 and 2005 respectively) have consumed the entire planned budget (for 2002–2007) of the agriculture and rural sectors in Maharashtra[21]. Under the climate change scenario, such extreme events (extreme rainfall and rise in temperature) are likely to occur over the semi-arid regions of Maharashtra[9,17,21], which may lead to a collapse of the agrarian economy of the state.

In this background, the present study analyses the variability in monsoon rainfall over the semi-arid region of Maharashtra and its relation with ENSO and IOD. As meteorological droughts in the study area directly affect agriculture[3], an examination of the linkage between the monsoon rainfall and agriculture (productivity and cropped area) is another objective of this study. Moreover, with the projected rainfall and temperature data, future climatic variability over the rainshadow zone of Maharashtra is also highlighted.

Study area

The selected river basins, namely Sina, Karha, Yerala, Agrani and Man are part of the rainshadow zone in Maharashtra, and cover about 24,000 sq. km area of the state (Figure 1 *a*). These basins are characterized by semi-arid

Table 1. Details of data used in the present study

Parameter	Details	Stations/talukas/ pixel size	Length of records (duration)	Source
Monsoon rainfall	Well-distributed stations over the selected basins	40	1981–2013 (33 years)	IMD, ADMS, HDUG
Taluka-wise agricultural cropped area and productivity data for selected basins (sorghum, pearl millet, sugarcane, wheat and gram)	Sina Basin	20 (14)	Cropped area 1980–2010 (31 years)	ADMS
	Man Basin	6 (9)		
	Yerala Basin	5 (7)	Productivity (33 years)	
	Agrani Basin	2 (5)		
	Karha Basin	4 (5)		
Temperature	AMT, AMXT, AMNT	2	1981–2015 (35 years)	IMD
Projected temperature (CORDEX RCA4)	Annual mean	0.25° × 0.25°	2015–2050 (36 years)	IITM
Projected monsoon rainfall (CORDEX RCA4)	Yearly total rainfall between June and October	0.25° × 0.25°	2015–2050 (36 years)	IITM
Satellite data Landsat-5 TM	Winter season (December)	30 m	1998 and 2002	On-line

Numbers in the third column and those within brackets denote talukas in each river basin and selected rainfall stations respectively. IMD, India Meteorology Department; HDUG, Hydrological Data Users Group; ADMS, Agriculture Department of Maharashtra State; IITM, Indian Institute of Tropical Meteorology; AMT, Annual mean temperature; AMXT, Annual maximum temperature and AMNT, Annual minimum temperature.

tropical monsoon climate (Koppen classification Bsh) and receive annual rainfall between 400 and 800 mm, about 85% of which falls during the monsoon period (June–October). The interannual variations in monsoon rainfall over the study basins were observed to be between 24% and 57% (ref. 9). The high annual temperature throughout the year results in a higher rate of potential evapotranspiration (PET; >1600 mm). On account of these conditions, the study area is characterized by annual water deficiency of >900 mm (ref. 22) and higher drought frequency (once in 3–5 years)[23]. During the period between 1871 and 2016, more than 20 region-wide droughts were observed which had adversely affected agriculture in western Maharashtra[3]. As the Cramer's *t* values for 11-year running mean identify short-term epochal variability in rainfall[24], Figure 1 *b* displays epochs in monsoon rainfall over western Maharashtra. Phases of above-average rainfall were experienced during 1876–1996, 1926–1936, 1951–1966 and 2001–2016, whereas during 1896–1930 and 1966–1991 rainfall was observed to be below average.

Agro-climatologically, the study area falls in the scarcity zone[24], where about 80% of the agricultural area depends on rainfall and groundwater resources[19]. Cultivation of short-duration and low water-requiring crops such as sorghum, pearl millet, gram and pigeon pea is the chief characteristic of agriculture[23,25]. Sorghum and pearl millet are the principal rainfed crops that cover more than 60% of the agricultural area. However, in the areas where surface irrigation facilities are well-developed, high water-requiring crops (sugarcane, maize and onion) are also preferred.

Data and methods

The present study is based on the climatic (rainfall and temperature), agricultural (cropped area and crop productivity) and satellite data. Table 1 provides details of data used in this study. The rainfall data of 40 well-distributed rainfall stations over the selected basins were acquired from various Government agencies (Table 1). Using the Thiessen polygon method, year-wise average basin monsoon rainfall values were calculated. The SPI developed by McKee *et al.*[26] was used to identify the wet, normal and drought years during the study period. Basin-wise SPI values were calculated for the yearly total monsoon rainfall data. For this, the methodology explained by Naresh Kumar *et al.*[27] was adopted. In order to normalize the rainfall data, probability distributions from the Gamma family were fitted. Temperature data of the Pune and Solapur stations were considered to evaluate its effect on crop productivity (Figure 1 *a*). To understand the near-term future monsoon rainfall and temperature (annual mean) variability over the study basins, the CORDEX RCA 4 modelled data were also considered. CORDEX South Asia data include simulations performed by the Swedish Meteorological and Hydrological Institute (SMHI), Rossby Centre RCM Rossby Center Atmospheric Model version 4 (RCA4). The SPI and standardized temperature index (STI) values for the projected rainfall and annual mean temperature data were also derived using the above methodology.

It has been reported that the link between monsoon rainfall and El Niño is weakening at the all-India level[28,29]. Therefore, in the present study we made an effort to verify this linkage concerning selected basins. To achieve this objective, the monthly southern oscillation index (SOI) and IOD Mode Index data were collected from the National Oceanic and Atmospheric Administration (NOAA), USA, website. The lower SOI values (negative values) indicate weak to strong El Niño events and vice versa[30]. The relationship of monsoon rainfall with SOI and IOD was derived using the bivariate and multivariate correlation and regression techniques.

Table 2. Classification of meteorological and agricultural drought

Index values	Standardized precipitation index (SPI)	Standardized cropped productivity index (SCPI)/standardized crop area index (SCAI)
<–2.0	Extremely dry	Extreme agricultural drought
–2.0 to –1.5	Severely dry	Severe agricultural drought
–1.5 to –1.0	Moderately dry	Moderate agricultural drought
–1.0 to 1.0	Near normal	Near normal
1.0 to 1.5	Moderately wet	
1.5 to 2.0	Very wet	
>2.0	Extremely wet	

SPI classes after ref. 51.

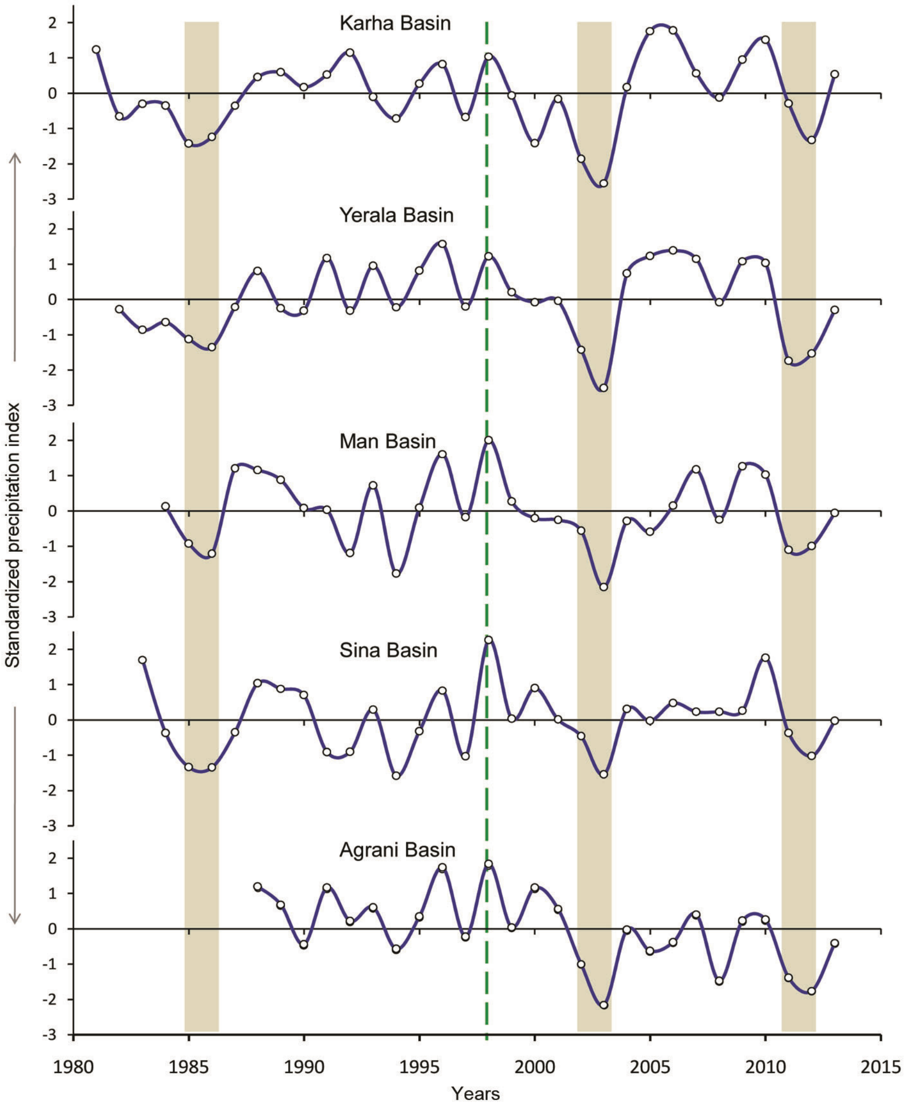

Figure 2. Basin-wise SPI between 1981 and 2013. Grey bands highlight consecutive drought years (1985–86, 2002–03 and 2011–12). Dashed line denotes wettest monsoon year (1998).

To evaluate the connection between rainfall variability and agriculture was another objective of this study. For this, the talukas (administrative sub-division of a district) which cover the entire basin area were selected (basin-wise number of talukas is given in Table 1). The agricultural cropped area and productivity data were obtained for the major rainfed and high-water requiring crops (Table 1). To maintain the comparable character of the methodology, the standardized crop productivity index (SCPI) and standardized crop area index (SCAI), which are based on the SPI methodology, were used to detect agricultural droughts[3]. The indices were computed using the formulae

$$\mathrm{SCAI} = (A_j - A_m)/\sigma, \tag{1}$$

where A_j is the area under a particular crop at the jth observation, A_m its long-term mean and σ is its standard deviation. SCAI is negative when the area under a crop declines.

$$\mathrm{SCPI} = (P_j - P_m)/\sigma, \tag{2}$$

where P_j is the productivity of a crop at the jth observation, P_m its long-term mean and σ is its standard deviation. Negative SCPI values denote agricultural drought conditions (Table 2). With the use of bivariate and multiple regression analysis, we evaluated the role of rainfall, temperature SOI and IOD to determine SCPI.

In order to verify the difference between agricultural cropped area/vegetation area in normal/wet monsoon years and drought years, digital satellite images of the post-monsoon period (November and December) were downloaded. From these images, the normalized difference vegetation index (NDVI) values were calculated for each river basin. This is the difference between near-infrared (NIR) and red (R) spectral reflectance, normalized by their sum. The NDVI values range between –1.0 and +1.0. High positive values of NDVI indicate dense and healthy vegetation (including agriculture) cover, and vice versa.

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R}). \tag{3}$$

Unfortunately, error-free, cloud-free and freely accessible Landsat-5 images for all the five semi-arid basins for the winter months (October to December) were not available for many years during the study period, including 2003 extreme drought year, 2010 wet year and 2005–2007 normal monsoon years. Notwithstanding these difficulties, to ascertain link between monsoon rainfall variability and vegetation (including agriculture) within the five semi-arid river basins, the best available Landsat-5 images for December were downloaded and processed for two representative years (1998 and 2002). Although October to December is the post-monsoon period, the agricultural crops and vegetation cover during these months clearly indicate monsoon condition. The obtained basin-wise NDVI values in 1998 (wet year) and 2002 (dry year) were graphically compared. To verify the difference between NDVI during these two years, Student's t test was applied.

Results and discussion

Monsoon rainfall variability

Figure 2 shows the basin-wise SPI values for the period between 1981 and 2013. All the basins under consideration exhibit consistent spatial variation in monsoon rainfall, especially during the wet and dry years. The highest interannual variability in annual as well as monsoon rainfall in Maharashtra was observed over the present study area[9]. Analysis shows that the study basins have coefficient of variation for the monsoon rainfall between 27% and 33%. Among them, the Karha Basin has the highest rainfall variability (33%), followed by the Agrani and Man basins (29%). It should be mentioned here that

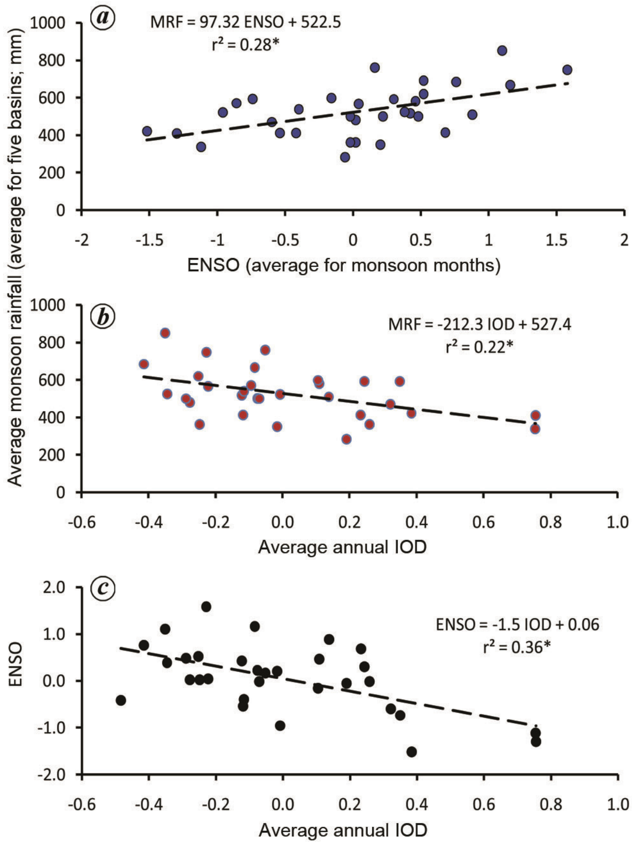

Figure 3. Linear relationship between monsoon rainfall (average of five basins) and (***a***) El Niño southern oscillation (ENSO) (average for monsoon months) and (***b***) average annual Indian Ocean Dipole (IOD). (***c***) Linear relationship between ENSO and average annual IOD. Asterisks (*) denotes significant relationships at 95% confidence level. Relationships are significant by excluding the IOD value for 1992.

Table 3. Basin-wise coefficient correlation El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) with SPI

	Sina	Man	Yerala	Karha	Agrani
ENSO	**0.60**	**0.35**	0.21	0.32	0.26
IOD	**–0.41**	–0.32	–0.16	**–0.34**	**–0.35**

Bold values denote statistically significant relationships at 95% confidence level.

during the last few decades, significant warming with rainfall extremes has increased over western Maharashtra[6,31–33]. Perhaps due to this, the semi-arid regions of the state have experienced a higher frequency of drought events[25], particularly after 2000 (ref. 3). The basins under study had experienced severe to extreme region-wide drought conditions during 1985–86, 2002–03 and 2011–12 (Figure 2). It should be noted that these major droughts had covered about 45%, 89% and 35% area respectively, of the Upper Krishna Basin (including the study basins)[34]. Another noteworthy characteristic of these droughts is that they occurred consecutively for two years. Obviously, during the succeeding drought years (1986, 2003 and 2012 respectively), water scarcity and its socio-economic effects were amplified, irrespective of drought intensity. Based on SPI intensity, these events were classified as severe to extreme meteorological droughts estimated to occur once in 10, 50 and 28 years respectively[3]. Such deficit monsoon conditions have the potential to hinder the productivity of rainfed crops and high-water requiring crops. Among these three major droughts, that of 2002–03 was the worst after the drought of 1972 in Maharashtra[34]. On the other hand, 1998 was observed to be the wettest monsoon year during the study period (Figure 2), as each of the study basins exhibited highest SPI value.

SPI vis-à-vis ENSO and IOD

Although at the All-India level, rainfall has a weaker relationship with ENSO[29], it was observed that rainfall over the semi-arid regions of Maharashtra had considerable connection with ENSO[3,5]. The present study confirms this finding, as the selected river basins in the rainshadow zone of Maharashtra exhibit a significant connection, particularly the Sina and Man Basins (Table 3). Rainfall over the remaining three basins in the study area had a weak linkage with ENSO. The Sina and Man basins cover about 70% of the study area. Perhaps due to this, the average monsoon rainfall for the entire study area shows a significant relationship with ENSO (Figure 3 *a*). The negative values of ENSO denote moderate to extreme El Niño conditions which retard the monsoon over western Maharashtra[5]. In other words, the El Niño condition is accountable for the occurrence of droughts in the study area to a great extent. However, the region-wide severe droughts of 2003 and 2012 were experienced in a neutral phase of ENSO. It should also be mentioned here that the wet monsoon years (1998 and 2010) have ENSO index values >1.0, which denotes La Niño conditions. Broadly, it suggests that ENSO has notable control over the monsoon. It should be noted that the present study carried out multiple regression analysis to ascertain the combined effect of SOI and IOD on monsoon rainfall. However, the strength of relationship is insufficient to formulate a model based on these variables.

It is well-established that IOD and El Niño are associated with deficient rainfall over Australia[35–37] and eastern South Asia. In the context of the semi-arid regions of Maharashtra, apart from ENSO, IOD plays a crucial role in determining monsoon rainfall variability, as the Sina, Karha and Agrani basins (about 64% of the study area) reveal considerable connection between the two (Table 3). Obviously, the average monsoon rainfall over the entire study area shows a significant relationship with IOD (Figure 3 *b*). It can be noticed that IOD has an inverse relationship with rainfall over each of the selected basins, albeit, it is not significant in the case of Man and Yerala basins. This suggests that the positive phase of IOD is associated with deficient monsoon over the study area. Particularly, in the Sina, Karha and Agrani basins, the positive IOD events significantly determine the intensity and occurrence of meteorological droughts. Thus precise predictions of IOD phases have implications in the planning of water resources and agriculture for the semi-arid regions of Maharashtra[38]. Figure 3 *c* reveals significant linkage between ENSO and IOD. The inverse relationship suggests that the warmer phase of ENSO mostly occurs when the sea surface temperature (SST) of the western Indian Ocean is below average. Interestingly, the occurrence of the positive phase of IOD (warmer SST) during the El Niño year minimizes the effect of El Niño over India in general[11], and particularly over the semi-arid regions of Maharashtra[3]. It is evident that the effect of El Niño events in 1994 and 1997 was minimized likely due to the occurrence of the positive phase of IOD. In a nutshell, ENSO, IOD and monsoon rainfall over the study area have considerable inter-linkages which can be incorporated to precisely forecast monsoon variability.

Monsoon rainfall and agricultural productivity

The monsoon rainfall chiefly determines agricultural yield in Maharashtra[25], particularly for rainfed agriculture[3]. Table 4 summarizes basin-wise relationships between rainfall and productivity of major crops. In the present study area, the productivity of rainfed as well as irrigated crops is significantly associated with monsoon rainfall. This can be observed in the Sina, Man and Yerala basins, which collectively cover about 87% of the study area. As about 80% of the agricultural area depends on monsoon rainfall[25] and groundwater resources[19], it is obvious that there is a significant linkage between rainfall and agricultural yield. In the case of Karha and Agrani basins, the yield of rainfed crops (sorghum and gram) exhibited significant connection with rainfall. It should be mentioned here that during the last three decades, a large number of surface water impoundment structures were constructed in the Karha Basin[33]. Perhaps due to this, pearl millet, wheat and sugarcane crops are not affected by rainfall variations. The predictive model

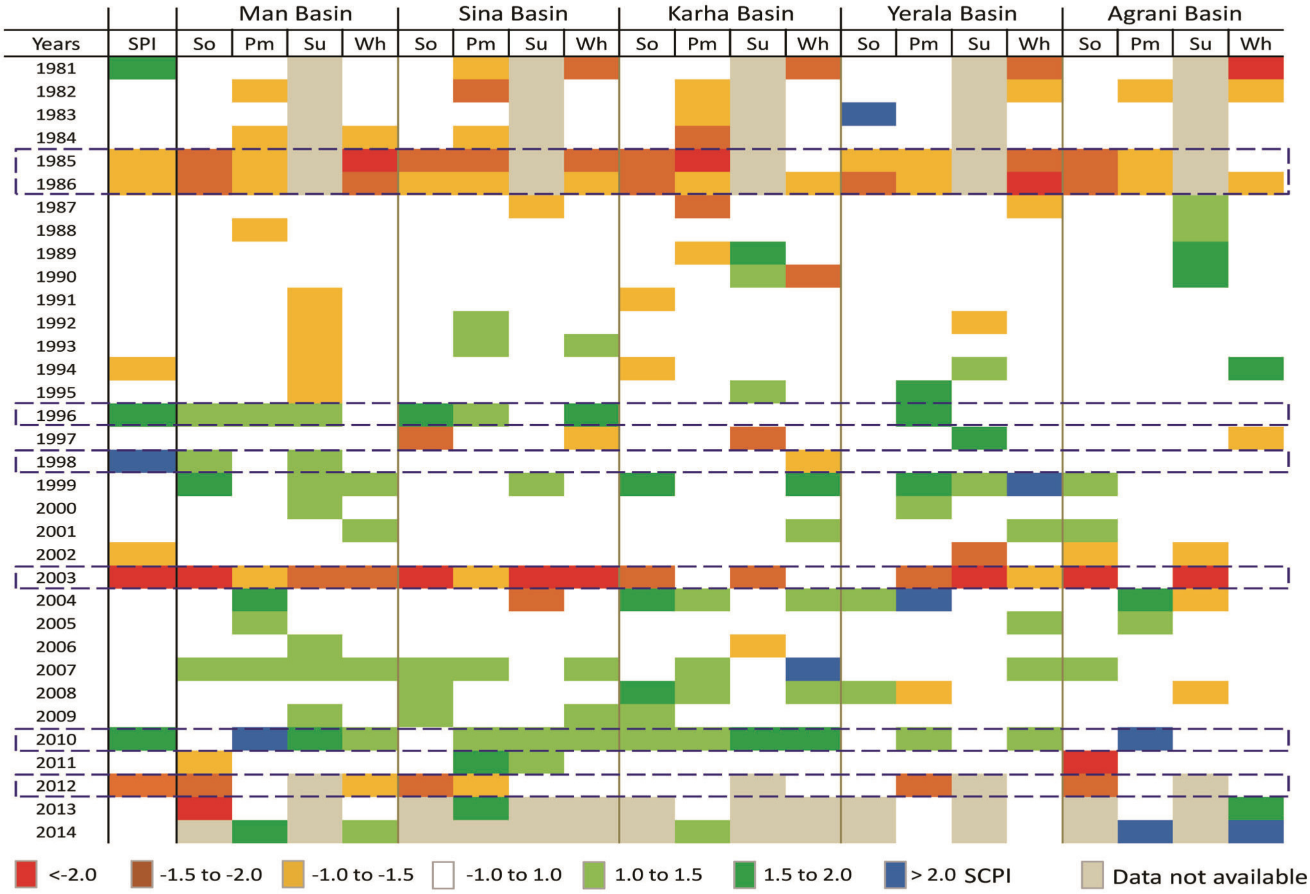

Figure 4. Basin-wise standardized cropped productivity index for sorghum (So), pearl millet (Pm), sugarcane (Su) and wheat (Wh) from 1981 to 2014. Dashed boxes highlight major drought years (1985–86, 2003 and 2012) and wet monsoon years (1998 and 2010).

Table 4. Basin-wise correlation coefficient between SPI and SCPI

	Rainfed crops			Irrigated/cash crops	
River basin	Sorghum	Pearl millet	Gram	Wheat	Sugarcane
Sina	**0.43**	**0.17**	**0.42**	**0.38**	**0.21**
Man	**0.39**	**0.17**	**0.23**	**0.27**	**0.42**
Karha	**0.23**	0.09	**0.15**	0.08	0.08
Yerala	0.07	**0.41**	**0.62**	**0.44**	**0.16**
Agrani	**0.38**	0.05	**0.15**	0.08	**0.37**

Basin-wise SPI values are denoted. Bold values indicate significant relationship at 95% confidence level.

which explains the variations in agricultural productivity cannot be formulated, as the relationships of monsoon rainfall, temperature (annual mean temperature (AMT), annual maximum temperature (AMXT) and annual minimum temperature (AMNT)), ENSO and IOD with crop-wise SCPI are not considerable. During the recent period, agricultural productivity is notably influenced by water availability, use of high-yield variety seeds, fertilizers, pesticides and insecticides, etc. Perhaps due to this, the above-considered variables explain marginal variations in crop yield.

Figure 4 displays spatial variations (basin-wise) in crop productivity vis-à-vis average SPI for the entire study area. Agricultural crop productivity of sorghum, pearl millet, sugarcane and wheat has considerable connection with monsoon rainfall, as most of the time it follows rainfall patterns. A remarkable decline in agricultural yield can be noticed during the 1985, 1986 and 2003 drought years. Compared to 1998, in 1996 and 2010 (wet monsoon years), the monsoon rainfall received was lower; however, all the basins registered above average agricultural crop yield. This suggests that in the dry farming

Table 5. Monsoon rainfall and SCAI values for the entire study area during drought and wet years

	Drought years				Wet years
	1985	1986	2002	2003	2010
Monsoon rainfall (%)	69	66	78	54	142
Sorghum	0.59	0.58	**–0.25**	**–2.28**	0.82
Pearl millet	0.02	**–0.13**	**–1.17**	**–1.92**	1.56
Sugarcane	**–1.41**	**–1.37**	0.91	**–0.11**	1.92
Wheat	**–1.18**	**–1.19**	**–1.17**	**–2.12**	2.03

Bold values denote a notable reduction in cropped area.

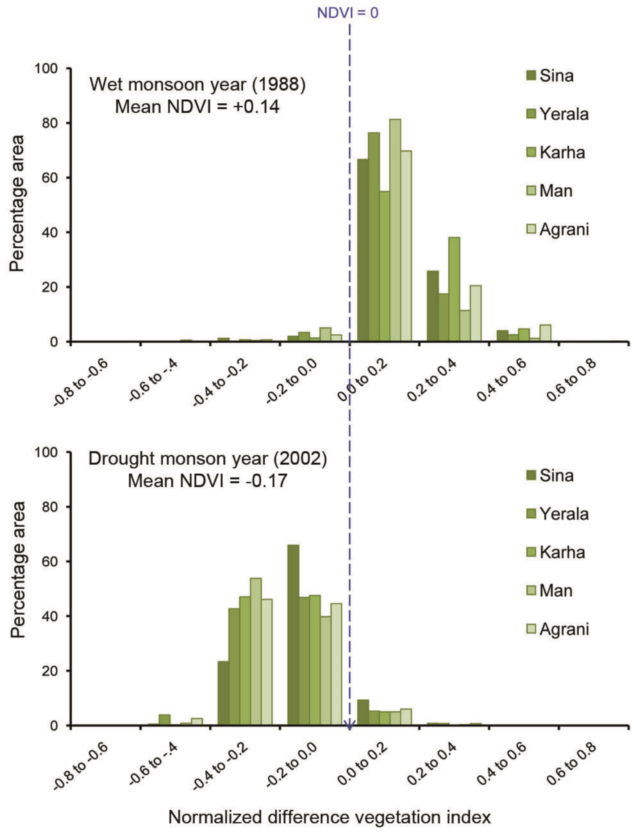

Figure 5. Histograms showing percentage area under different normalized difference vegetation index (NDVI) classes in winter (December) for 1998 and 2002.

track of Maharashtra, excess soil moisture may result in low crop yield. Perhaps due to this, in spite of surplus rainfall in 1998, almost all the basins registered near-normal crop yield. Figure 4 also reveals that the productivity of selected crops before 1994 was mostly below average. This suggests that crop productivity has gradually increased from 1980 to 2014. It is obvious to have an increase in agricultural yield with the adoption of high-yield varieties (HYV), development in irrigation facilities, use of chemical fertilizers, pesticides, etc. In spite of this, severe water scarcity can notably reduce agricultural yield in the study area. The sharp and region-wide decline in productivity of major crops during the 2003 drought corroborates this argument. During the last few years, the rainfed as well as irrigated crops show above-average productivity (Figure 4), although monsoon rainfall is near-normal. Among the selected crops, sorghum and pearl millet are the most sensitive to water deficiency. Therefore, even moderately low rainfall condition results in a considerable decline in the productivity of these crops (Figure 4). It should be noted that all the selected crops, except pearl millet, are sown during the late or post-monsoon season. Therefore, the present study could not ascertain the effect of inter-seasonal rainfall variability on crop yield.

Monsoon rainfall and agricultural cropped area

Table 5 gives the average SCAI values (for the entire study area) in the major drought and wet events over the study area. Monsoon precipitation during the drought and wet years was remarkably below average (<78%) and above average (>140%) respectively. As the water requirement of sugarcane and wheat is higher, areas under irrigated crops were notably reduced due to water deficiency, particularly, during the severe droughts years (1985, 1986, 2002 and 2003). On the other hand, area under all the selected crops was observed to be above average in the wet year of 2010 (Table 5). It should be noted that the Government agencies collect data on the area under different crops after the time of sowing and not at the time of harvesting. Therefore, the effect of mild to moderate drought (1985–86) is not reflected in the present cropped area data. Moreover, sorghum and pearl millet are cultivated during the monsoon season, however wheat and sugarcane are post-monsoon crops. The decision of wheat and sugarcane sowing is taken according to water availability (monsoon performance). While the cropped areas under sorghum and pearl millet are almost the same irrespective of yearly monsoon performance. In this situation, the effect of water scarcity can only be reflected in the agricultural yield. As mention earlier, the 2003 drought was the worst one after 1972, with significant decline in cropped area under rainfed as well as irrigated crops. Almost comparable effect of water deficiency on crops was exhibited from the SCAI values in 2002. On the other hand, 2010 was the wet monsoon year which exhibited positive SCAI values for all crops. The area under

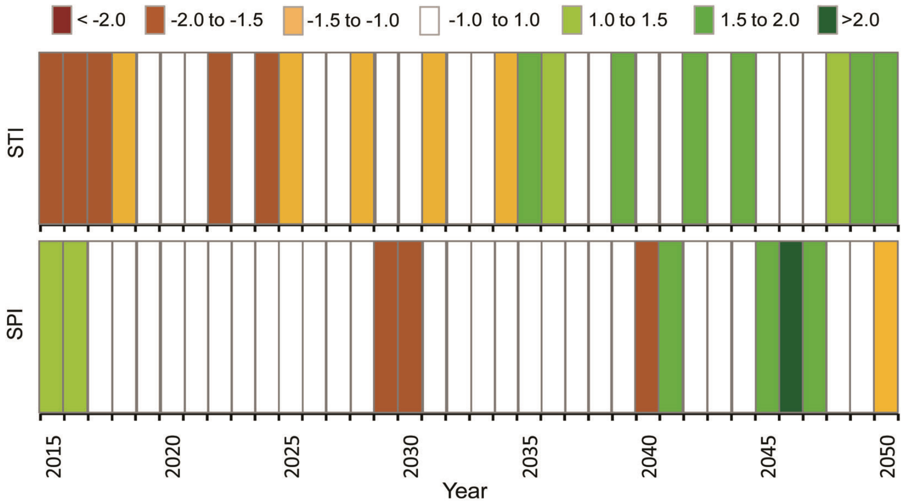

Figure 6. Standardized temperature index (STI) and SPI for the entire study area between 2015 and 2050. Negative values of SPI indicate drought events and positive values of STI denote above-average annual mean temperature, and vice versa.

irrigated crops was notably increased during the wet year. Broadly, rainfall variability has a pronounced effect on agricultural cropped area.

It is a well-established fact that monsoon performance determines the vegetation cover, including agriculture[39]. It was reported that NDVI and SIP over the Upper Krishna Basin had a significant positive correlation[40]. The available error-free satellite images for the wet (1998) and drought (2002) years were analysed to confirm the same relationship over the study area. Figure 5 presents the results of NDVI graphically. It is evident that the negative NDVI values have higher frequencies during drought years, and vice versa. As monsoon rainfall increases, the frequency peak shifts toward the right (positive side). Moreover, the linear relationship between basin-wise average NDVI and SPI is statistically significant. In addition to this, the Student's *t* test suggests a significant difference between the agricultural (NDVI) condition during the wet (1998) and drought (2002) years. These results revealed that monsoon rainfall has considerable control over the vegetation cover, including agriculture in the study area. There are other factors that govern variations in cropped area. Broadly, the role of Government subsidies to increase cropped area was reported to be marginal[41]. The availability of surface water and uninterrupted electricity are the other factors which determine agricultural cropped area in Maharashtra[42]. Moreover, the recent market prices also influence cropping pattern, as the economic perspective among farmers is growing, particularly after liberalization[33,43].

Near-term future climate variability

IPCC[4] has reported that the future climatic changes over South Asia are likely to aggravate water scarcity, particularly in the semi-arid regions. As the agriculture in the study area chiefly depends on monsoon rainfall, to understand the same we determined the future (up to 2050) variations in annual mean temperature and monsoon precipitation (Figure 6). Although majority of the year show near-normal rainfall conditions by 2050, severe droughts are expected to occur in 2029–30, 2040 and 2050 (Figure 6). Similarly, wet monsoon events are also likely between 2041 and 2047. The future monsoon rainfall variations do not show any typical pattern. However, annual mean temperature over the study basins exhibits a notable increase after 2035, which suggests future warming. A significant rise in temperature may amplify agricultural water demand in the future[3]. Under such circumstances, it will be a challenge to manage water scarcity, particularly during the severe drought years.

Apart from monsoon variability, increase in temperature has the potential to adversely affect agricultural yield[21,44]. Studies have predicted a decline in the productivity of cereal crops such as sorghum[45], pearl millet[46] and wheat[44]. Apart from this, with an increase in annual mean temperature by <2.5°C, a significant reduction in the yield of cash crops, including sugarcane[47], rice[48,49], cotton[50] is expected. Therefore, it is worthwhile to consider future trends in temperature and variability in rainfall together in agricultural planning.

Conclusion

The present study confirms that the monsoon rainfall over the semi-arid regions of Maharashtra has notable interannual variability, which may have resulted in a higher frequency of droughts. It is also clear that the spatial consistency in rainfall deficiency has the potential to develop a region-wide drought condition, such as that experienced in 1985–86, 2002–03 and 2011–12. It is, therefore, pertinent to incorporate rainfall variability while forecasting monsoon performance over the study area. Moreover, the study has highlighted another facet of regional climate that the variability in rainfall has a significant linkage with ENSO and IOD. Further studies, as well as water resources and agricultural policies, have to consider this while formulating a judicial plan. On the other hand, it is established that monsoon precipitation prominently controls agricultural productivity and cropped area. The meteorological droughts over the semi-arid regions of Maharashtra cause agricultural drought conditions. Thus agronomist and water resources managers must design a plan which restricts the transformation of meteorological drought into agricultural drought. It is also advisable to consider the future climate change (temperature rise) over the study area, as it may aggravate agricultural distress.

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