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El Nino/La Nina and IOD impact on Kharif season crops over western agro-climatic zones of India

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Abstract

Climate modes like ENSO (El Nino Southern Oscillation) and IOD (Indian Ocean Dipole) produce an impact on the monsoon rainfall over India. Monsoon rainfall is extremely important for the agriculture of our country. The impact of these climate modes on monsoon rainfall thus in turn affects the rain-fed crops (kharif). In this study, four kharif season crops namely rice (*Oryza sativa*), maize (*Zea mays*), pulses and sugarcane (*Saccharum officinarum*) are chosen over four arid/semi-arid agro-climatic zones of western India to study the effect of the climate modes on selected crops. The detailed analysis has been carried out to show the impact of rainfall in the El Nino/La Nina (phases of ENSO) and IOD years on the crop productions over the mentioned zones viz. (Central plateau and hills region; Western plateau and hills region; Gujarat hills and plains region; Western dry region) from 1966–2011. The results show that rice productions which require hot and humid conditions have been largely affected during drought years associated with El Nino which results in poor rainfall over all the zones. The production of pulses which does not require excess humid conditions shows marginal improvement during the neutral years or non-El Nino/non-La Nina years. Maize production seems to be better in La Nina years and worst in the El Nino years as La Nina years are responsible for good rainfall in all zones. El Nino years provide a minor impact on sugarcane productions in different zones. La Nina years are well suited for sugarcane production in all zones of our study as sugarcane requires a good amount of moisture. Positive IOD years are associated with poor crop productions as compared to negative IOD years mostly in all zones as most of the positive IOD years happen to be El Nino years. El Nino-rainfall relation being dominant than positive IOD-rainfall relation is, therefore, responsible for negative rainfall anomalies over the selected zones.

1 Introduction

Agriculture plays a vital role in shaping the economy of the developing countries like India. Agriculture along with its allied sector is the largest source of livelihoods in India particularly the rural populations. It provides them the main source of food, income and employment. India is the largest producer (25% of global production), consumer (27% of world consumption) and importer (14%) of pulses in the world (Mohanty and Satyasai 2015). India is the second largest producer of sugarcane after Brazil in the world and accounts for about 25% of the world's production (Upreti and Singh 2017). Climatic conditions such as temperature, rainfall, humidity and sunshine have an impact on agriculture. India mostly receives rainfall during the summer monsoon season and some parts of the Northern India and Gangetic plains receive rainfall from the Western Disturbances. Indian monsoon rainfall varies both spatially as well as temporally. Spatial variations are mainly due to the geography of India. But temporal variations especially year-to-year (annual) variations in Indian monsoon rainfall mainly depend on El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) which are the important predictors of Indian summer monsoon rainfall. There are several climate modes that have an impact on Indian monsoon through teleconnections. But the prime contribution is of ENSO. This phenomenon can lead to an increase or decrease in rainfall, cloudiness, humidity, etc. and hence, affecting the crops.

Indian monsoon rainfall is extremely important for the agriculture of our country. Kharif crops are very much dependent on the summer monsoon rainfall and thus get affected due to the variation or fluctuations in the rainfall

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(Parthasarathy et al. 1988; Gadgil 1996; Webster et al. 1998). These crops get terribly affected by the floods and the droughts that are associated with the mentioned climate modes in the different zones. It has been found that post 1980, there are lots of variability in the Indian summer monsoon rainfall prediction. Post 1988, the models even could not predict the Indian summer monsoon rainfall accurately (Wang et al. 2015). It has been found that the inverse relationship between El Nino (warm phase of ENSO) and the Indian summer monsoon rainfall has weakened post 1980s (Krishna Kumar et al. 1999). The prime reason is that there is a shift in the ENSO circulation to the south east or southward of its original position in the recent decades as compared to that before the 1980s. This south eastward or southward shift in the walker circulation results in the descending motion to weaken over the Indian subcontinent as the zone of strong subsidence has shifted southwards away from India. This results in an increment in the Indian summer monsoon rainfall even when the phase is El Nino (Krishna Kumar et al. 1999). Even in the La Nina years after 1980, the rainfall over the central India has also decreased as compared to pre 1980s (Samanta et al. 2020). After the 1980s, La Nina tends to weaken the Walker circulation that has resulted in anomalous subsidence over the Indian subcontinent. As a result, there is inhibition of deep convection that drives Indian summer monsoon rainfall (Samanta et al. 2020). Another leading mode of ENSO has appeared since 1990, i.e. the Central pacific ENSO (CP-ENSO). It has been found out that the phases of CP-ENSO are responsible for the drought and flood events in India (Krishna Kumar et al. 2006). Some more research have emerged based on the observations of other teleconnections or events in the recent decades. It has been observed that the Eurasian snowfall has decreased during the recent decades, particularly the El Nino years. This decrease in snowfall has resulted in a rise in the temperature of the surface that in turn led to the further deepening of the heat low during the pre-monsoon seasons of the El Nino years resulting in good monsoons (Krishna Kumar et al. 1999).

Indian summer monsoon rainfall over India has been changed due to the variation in the ENSO in the recent years. The change in the rainfall pattern affects the growth as well as the production of the crops, specifically the kharif crops which grows during the summer monsoon season. Crops mostly get affected in the drought or the flood years. The association of drought/flood with El Nino/La Nina has been described and studied over all India and East Uttar Pradesh (Bhatla et al. 2016a, b). In the recent times, there are certain anomalous El Nino flood years as well as La Nina drought years in certain zones that have affected the crop production. The present study has shown the association of drought or flood years with El Nino and La Nina years as well as the effect of these flood or drought years on the agricultural crops over the agro-climatic zones of western India. It is thought that the IOD has a connection with ENSO events through an extension of the walker circulation to the west of and associated Indonesian flow of warm tropical ocean water from the Pacific into the Indian Ocean. Hence, positive IOD events are often associated with El Nino and negative events with La Nina in the same year (Saji et al. 1999). The IOD which is induced can also provide feedback to the developing phase of ENSO (Behera and Yamagata 2003; Annamalai et al. 2005). When the IOD and ENSO are in phase, the impacts of El Nino and La Nina events are often most extreme over Australia, while when they are out of phase, the impacts of El Nino and La Nina events are very less.

In the recent decades, particularly the positive IOD years, the Indian summer monsoon precipitation has increased as compared to the negative IOD years. Although, it has also been found out that both the phases of IODs give a significant increase or decrease in monsoon rainfall over the southern peninsular India (Bala and Singh 2008). It shows very weak correlations over other zones. Ashok et al. (2001) have shown that the weakening of the ENSO-ISMR relationship is apparently due to the frequent occurrence of strong positive IOD events that have neutralised the impact of ENSO; this is because the ISMR is positively correlated to the IOD mode index. IOD and ENSO variabilities during monsoon months (JJAS) indeed influence the monsoon variability (Ashok and Saji 2007). The effect of these climatic modes such as ENSO on the crops has been studied over the IGP region (Bhatla et al. 2020) but the effects of the ENSO over the western agro-climatic zones of India have not been studied. The effect of IOD on crop productions over agro-climatic zones of India has never been studied. India is divided into fifteen agro-climatic zones based on the physiography, soil, climate, cropping patterns and geological formation and development of irrigation and mineral resources for broad agricultural planning and developing future strategies. The present study is on the effects of El Nino, La Nina and the IOD on the kharif crops over the four arid/semi-arid agro-climatic zones of Western India from 1966 to 2011.

2 Data and methodology

This study is based on the district-wise agricultural data from 1966 to 2011 for four crops namely rice, maize, pulses and sugarcane over four different western and central agro-climatic zones (ACZ) of India. These four agro-climatic zones are the Central plateau and hills region (ACZ-8), Western plateau and hills region (ACZ-9), Gujarat plains and hills region (ACZ-13) and Western dry region (ACZ-14). The names given to ACZ-8, 9, 13 and 14 are CPHR, WPHR, GPHR and WDR respectively. The districts of the states in each zone are shown in Table 1. Several hot arid

Table 1 Districts included in the different agro-climatic zones of our study

Agro-climatic zones	States	Regions covered
CPHR (Central plateau and hills region) Average monthly monsoon rainfall: 629.85 mm	Madhya Pradesh, Rajasthan and Uttar Pradesh	Districts: Ajmer, Alwar, Banswara, Bharatpur, Bhilwara, Bundi, Chittorgarh, Dungarpur, Kota, Pali, Sawai Madhopur, Sirohi, Udaipur, Jabalpur, Chhindwara, Narsinghpur, Seoni, Mandla, Sagar, Tikamgarh, Chhatarpur, Panna, Rewa,Sidhi, Satna, Gwalior, Shivpuri,Guna, Datia, Morena, Bhind, Sehore, Raisen, Vidisha, Betul, Hoshangabad, Jalaun, Hamirpur, Banda
WPHR (Western plateau and hills region) Average monthly monsoon rainfall: 760.04 mm	Madhya Pradesh and Maharashtra	Districts: Indore, Ratlam, Ujjain, Mandsaur, Dewas, Dhar, Jhabua, Khaegone, Khandwa, Rajgarh, Shajapur, Nasik, Dhulia, Jalgaon, Ahmednagar, Pune, Satara, Sangli, Solapur, Kolhapur, Aurangabad, Parbhani, Beed, Nanded, Osmanabad, Buldhana, Akola, Amaravati,Yeotmal,Wardha, Nagpur
GPHR) (Gujarat plains and hills region) Average monthly monsoon rainfall: 210.59 mm	Gujarat, Dadra and Nagar Haveli, Daman and Diu	Districts: Ahmedabad,Amreli,Banaskanth,Broach,Vadodara,Bhavnagar,Valsad,Dang,Jamnagar,Junagarh,Kaira,Kheda,Kutch,Mehsana,Panch-Mahal,Rajkot,Sabarkantha, Surat, Surendranagar
WDR (Western dry region) Average monthly monsoon rainfall: 65.34 mm	Rajasthan	Districts: Barmer, Bikaner,Churu, Jaisalmer,Jalore, Jhunjhunu, Jodhpur, Nagaur, Sikar

and semi-arid regions are considered. Here, we want to study about the impact of El Nino, La Nina and IOD on the semi-arid and arid zones of the western India. The yearly agriculture data have been obtained from International Crops Research Institute in Semi-Arid Tropics (ICRISAT-IN). El Nino and La Nina conditions are found by the observations of SST anomalies at the Nino 3.4 region of the Pacific Ocean. Nino 3.4 region is from 5° N-5° S, 170° W-120° W (Fig. 1). Anomalies are the deviations from the mean SST of the data for each month of all the 46 years of our study. Since we are dealing with the kharif season crops, we are rather more interested in the ONI (Ocean Nino Index) for the monsoon months (JJAS). The ONI data is taken from NOAA, Climate Prediction Centre (www.cpc.ncep.noaa.gov). The El Nino and La Nina years are found based on the basis of 5 or more consecutive seasons having 3 months mean of SST

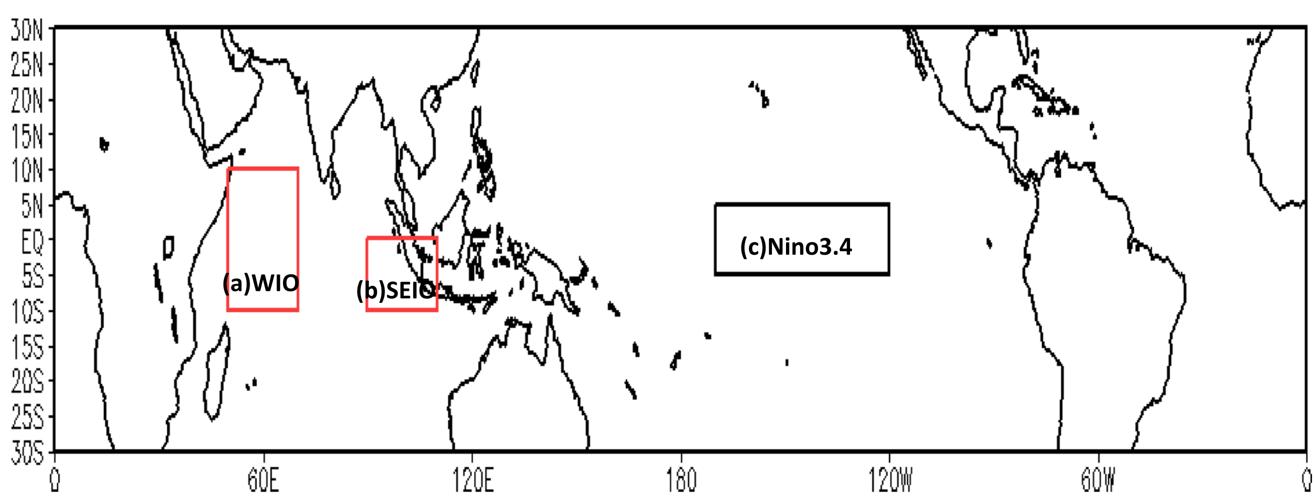


Fig. 1 Region for dipole mode index (DMI) for Indian Ocean (**a**) western equatorial Indian Ocean (WIO) (50° E-70° E and 10° S-10° N) (**b**) south-eastern equatorial Indian Ocean (SEIO) (90° E-110° E and 10° S-0° N) and the El Nino and La Nina time series are measured by observed SST anomalies over (**c**) Nino 3.4 region (5° N -5° S, 170° W-120° W) of the Pacific Ocean

3.4 anomalies is greater than/equal to + 0.5 °C or lesser than/equal to – 0.5 °C respectively are listed in Table 2.

The rainfall data considered for the study over the different regions are taken from the Indian Institute of Tropical Meteorology (IITM), Pune (www.tropmet.res.in). IITM rainfall data is chosen for the rainfall in this study because most of the rain gauge stations used for calculating IITM rainfall data happen to be the districts of each agro-climatic zones of our study. Also, this data is prepared by assigning the area of the district as the weight for each rain gauge stations. The drought and the flood years are calculated from the rainfall data by standardising the rainfall. If the standardisation of rainfall is greater than + 0.5, then the year is a flood year and if it is less than – 0.5, it is a drought year (Yuheng et al. 2019). The list of flood and the drought years are shown in Table 3 for all the four zones.

Table 2 List of El Nino, La Nina, neutral, positive IOD and negative IOD years. Positive IOD years associated with El Nino are shown in red and negative IOD years associated with La Nina are shown in blue

La Nina	El Nino	Neutral	IOD positive	IOD negative
1970	1969	1966	1972	1974
1971	1972	1967	1982	1981
1973	1977	1968	1983	1989
1974	1982	1976	1994	1992
1975	1987	1978	1997	1996
1985	1991	1979	2006	1998
1988	1994	1980		2010
1995	1997	1981		
1998	2002	1983		
1999	2004	1984		
2000	2006	1986		
2007	2009	1989		
2008		1990		
2010		1992		
2011		1993		
		1996		
		2001		
		2003		
		2005		

The positive and negative IOD intensity is represented by anomalous SST gradient between the western equatorial Indian Ocean (50° E-70° E and 10° S-10° N) and the south eastern equatorial Indian Ocean (90° E-110° E and 10° S-0° N). The regions are shown in Fig. 1. This gradient is named as Dipole Mode Index (DMI). The DMI values are taken from NOAA, Physical Science Laboratory (www.psl.noaa.gov). The positive and negative IOD events during monsoons were calculated and verified with IOD years mentioned on the website of the Bureau of Meteorology (BOM), Australia (http://www.bom.gov.au/climate/iod/). The DMI are averaged for the positive and negative IOD years only for the monsoon months (JJAS). Its correlation with the crops of the different zone and with the rainfall in each zone is studied. The crop production data for the entire period 1966–2011 was de-trended each time by taking the difference, $Z_i = Z_i - Z_{i-1}$ between the value Z in each year i, and the value in the previous year $i-1$ (Box and Jenkins 1976). Trend analysis is also done for the crop production for the entire time series from 1966–2011 using the Mann–Kendall trend test. The significance test of the correlation coefficients is also done using the Student *t*-test.

3 Result and discussion

3.1 Distribution of crop production and variation over different zones

The variation in production of the crops over the Central plateau and hills regions (CPHR) in the period of 1966–2011 are shown in Fig. 2a. From this figure, it is clearly seen that pulses are the majorly grown crops. Other than that, maize and rice crops are also grown well in this region, but the quantity of its productions is not as high as compared to the pulses. Sugarcane production is minimum in this region. This zone includes the regions of eastern Rajasthan and Madhya Pradesh which usually receives sufficient rainfall during the monsoon season and

Table 3 Drought and the flood years at different zones (red colour indicating El Nino years and blue colour indicating La Nina years)

Zones	Drought years	Flood years
01	**1966,1968,1972,1974,1979,1985,1986,1987,1989,1991,2000,2002,2004,2007,2009**	**1967,1969,1970,1971,1973,1975,1977,1978,1983,1990,1994,1996,1999,2003,2011**
02	**1968,1971,1972,1974,1982,1984,1985,1987,1995,1997,2001,2002,2004,2009**	**1969,1970,1973,1975,1981,1983,1988,1990,1994,1998,2005,2006,2007,2010**
03	**1968,1969,1972,1974,1979,1982,1985,1986,1987,1991,1995,1999,2000,2002,2009**	**1970,1973,1975,1976,1977,1983,1984,1988,1994,1997,2003,2005,2006,2007,2010**
04	**1968,1969,1971,1972,1974,1980,1982,1984,1985,1986,1987,1991,1999,2002,2004,2005,2009**	**1970,1973,1975,1976,1977,1978,1983,1990,1992,1994,1995,1996,2006,2010,2011**

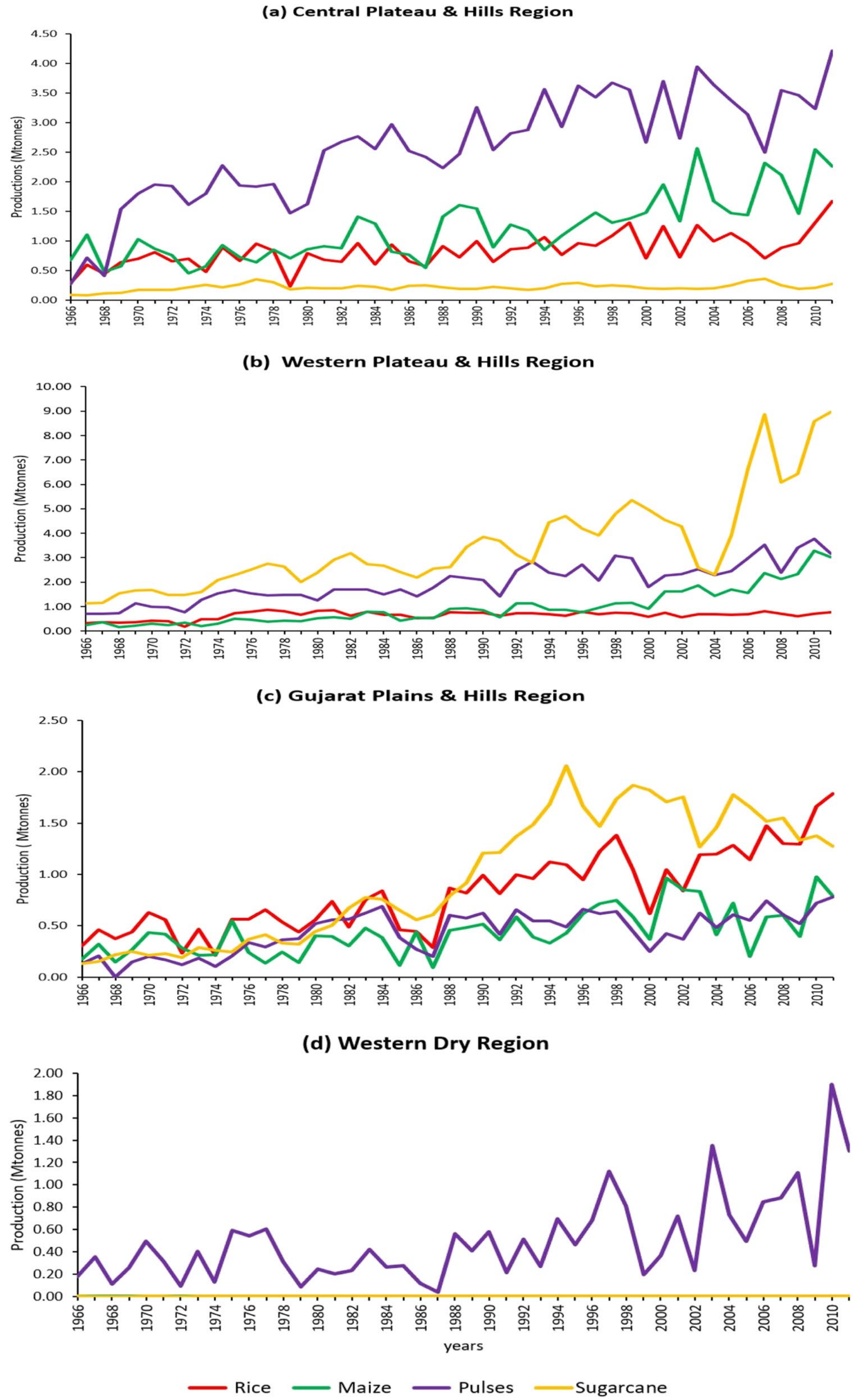


Fig. 2 **a–d** Crop production variation over **a** Central plateau and hills region, **b** Western plateau and hills region, **c** Gujarat plains and hills region **d** Western dry region during 1966–2011

remains mostly dry otherwise and hence are perfectly suitable for the pulses production. It is known that the pulses are mostly found in the semi-arid zones of India. This agro-climatic zone is also a hot semi-arid zone. Cloudy weather or rains at flowering and fruiting stages of the pulses can result in poor pod setting and seed filling and hence lead to increased damage by pod borers (Sardana et al. 2010). The Mann–Kendall trend test shows that there is a monotonic increasing trend with more than 99% confidence (p-values $< < 0.01$) for all the crops in this zone (Table 4).

Figure 2b depicts the variation in the crop production over the Western plateau and hills region (WPHR) from 1966–2011. In this zone, climatic conditions are moderately humid as well as very hot. The regions include southern parts of Madhya Pradesh and central and eastern parts of Maharashtra which receives a good amount of rainfall during the monsoons. In other seasons, it is usually dry. This region receives about 50–100 cm of rainfall (Rainfall statistics of India 2016). From the figure, it is clear that sugarcane is the majorly grown crop in this zone. Hot (> 30 °C) and rainfall between 70 and 100 cm are very ideal for the sugarcane production (Shukla et al. 2017). Pulses are also grown well in this region. Rice and maize productions are not very high. The Mann–Kendall trend test shows that all the crops except rice have a monotonic increasing trend over this region with more than 99% confidence whereas the rice crop has a monotonic increasing trend with a 98% confidence level (Table 4). Figure 2c shows the variation in crop productions over Gujarat plains and hills region (GPHR). The name itself suggests that the region in this zone is Gujarat. Most of the parts of Gujarat receive an annual rainfall between 50 and 100 cm. Sugarcane and rice are the majorly grown crops in this zone. After 1980, the production of sugarcane has increased as compared to rice. Maize and pulses are also grown well in this zone. All the crops have a monotonic increasing trend at more than 99% confidence level (Table 4). Figure 2d depicts the variation in crop productions over the Western dry region (WDR). This zone includes the region of western Rajasthan. The climatic conditions are very dry throughout the year. Monsoon rainfall is also quite low in this zone. Pulses are majorly grown in this zone as it requires slightly dry conditions with high temperatures. The water remains available through the Indira Gandhi Canal which is there over the Western Rajasthan and the rainfall that the zone receives during the monsoon. There are negligible productions of other crops. Using the Mann–Kendall trend test, it is seen that pulses have a monotonic increasing trend at more than 99% significance level (Table 4).

The percentage contributions of the crop production at the four different agro-climatic zones over the period of -2011 are shown in Fig. 3. The percentage contribution of rice production at CPHR, WPHR and GPHR is 17%, 9% and 31% respectively. At WDR, rice production is negligible. Maize production percentage contributions over CPHR, WPHR and GPHR are 25%, 13% and 17% respectively. Over WDR, the maize productions are also negligible. Pulses are the majorly grown crops over CPHR and WDR with percentage contribution of 53% and approximately 100% respectively. At WPHR and GPHR, the percentage contribution of pulses is 28% and 16% respectively. Sugarcane is the majorly grown crops over WPHR and GPHR with percentage contribution of 50% and 36% respectively. Sugarcane productions are very negligible over WDR and at CPHR, the percentage contribution is 5%.

3.2 Association between crop productions with ONI/DMI and rainfall during El Nino, La Nina and positive/negative IOD years

Agricultural crops are highly dependent on Indian summer monsoon rainfall (June to September). The correlations of the crops with ONI (Ocean Nino Index) and with the rainfall during El Nino, La Nina, positive IOD and negative IOD years are shown in Tables 5, 6, 7 and 8 respectively. Since we are studying the impact of the climate modes such as ENSO and IOD on kharif season crops, we, therefore, tried to find whether any direct statistical correlations exist between them or not. Although, it is clear enough that climate modes will change the regional rainfall amount and hence impacting the crop productions. In general, "r" is representing correlation coefficients. Student's t-test has been performed to check the confidence level of the correlations. "+" sign represents a confidence level of more than or equal to 90%, "+ +" sign refers to the confidence level of more than 95%.

Table 5 shows that during El Nino years, the rice crop has the strongest correlation with rainfall with more than 95%

Table 4 P-values for different crops at four agro-climatic zones using the Mann–Kendall trend test (with trend shown in up arrow represents the positive trend whereas the down arrow showing negative trends. Red colour represents the p-values greater than 0.05, i.e. insignificant)

Zone	Rice (p-values)	Maize (p-values)	Pulses (p-values)	Sugarcane(p-values)
01	1.511×10^{-6} ⇧	3.881×10^{-9} ⇧	6.445×10^{-11} ⇧	0.007585 ⇧
02	0.02672 ⇧	5.286×10^{-16} ⇧	3.089×10^{-13} ⇧	1.079×10^{-12} ⇧
03	1.208×10^{-11} ⇧	1.023×10^{-5} ⇧	1.053×10^{-6} ⇧	2.445×10^{-12} ⇧
04	0.4437 ⇧	1.425×10^{-5} ⇩	5.07×10^{-5} ⇧	0.04064 ⇩

P-values = 0.02: 98% confidence level; p-values = 0.01: 99% confidence level; p-values = 0.05: 95% confidence level

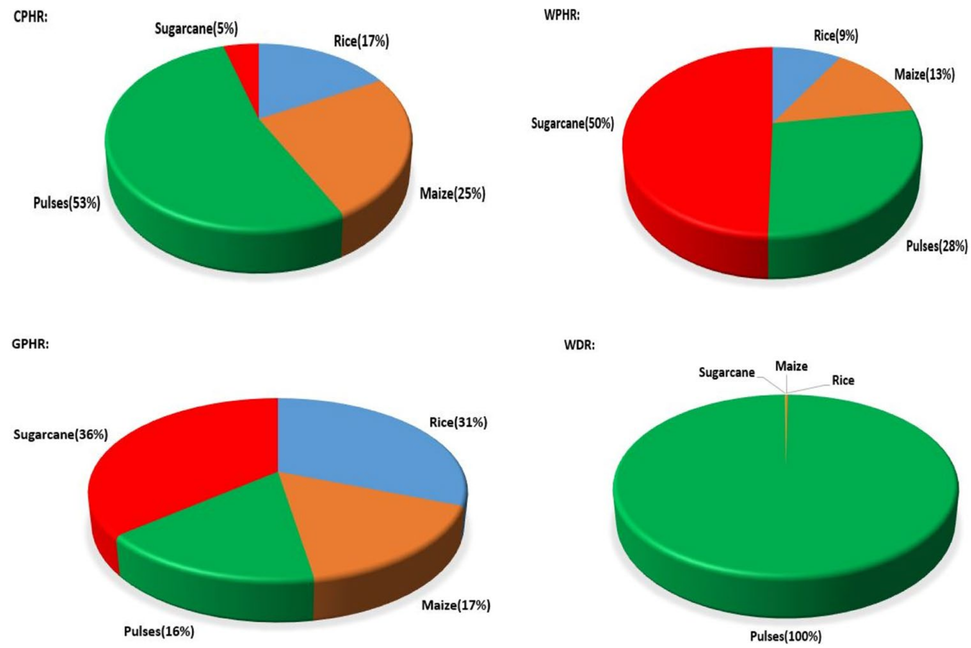


Fig. 3 Percentage contribution of crop productions in four zones during 1966–2011

Table 5 Correlation coefficients for four crops at 4 different zones with ONI and rainfall during El Nino years [more than or equal to 90% confidence level: +, more than or equal to 95% confidence level: + +

Crops	Zone 1		Zone 2		Zone 3		Zone 4	
	ONI	Rainfall	ONI	Rainfall	ONI	Rainfall	ONI	Rainfall
Rice	−0.44	0.51+	−0.30	0.34	−0.32	0.67++	−0.23	0.37
Maize	−0.10	−0.28	−0.27	0.00	0.25	0.08	0.46	0.32
Pulses	−0.04	0.00	−0.31	0.22	−0.13	0.59++	−0.11	0.73++
Sugarcane	−0.14	0.26	−0.34	0.33	−0.19	0.55+	0.14	0.19

Table 6 Correlation coefficients for four crops at 4 different zones with ONI and rainfall during La Nina years (more than or equal to 90% confidence level: +, more than or equal to 95% confidence level: ++)

Crops	Zone 1		Zone 2		Zone 3		Zone 4	
	ONI	Rainfall	ONI	Rainfall	ONI	Rainfall	ONI	Rainfall
Rice	−0.24	0.28	−0.17	0.21	−0.02	0.44+	0.12	0.18
Maize	0.05	−0.30	0.03	0.10	−0.29	0.51++	0.03	−0.09
Pulses	0.18	−0.15	−0.14	0.12	−0.01	0.39	−0.13	0.46+
Sugarcane	0.24	−0.27	0.12	−0.01	0.21	−0.13	0.10	−0.18

Table 7 Correlation coefficients for four crops at 4 different zones with DMI and rainfall during positive IOD years (more than or equal to 90% confidence level: +, more than or equal to 95% confidence level: ++)

Crops	Zone 1		Zone 2		Zone 3		Zone 4	
	DMI	Rainfall	DMI	Rainfall	DMI	Rainfall	DMI	Rainfall
Rice	−0.06	0.84	−0.52	0.78+	−0.16	0.92++	−0.25	−0.54
Maize	−0.58	0.06	−0.58	0.73+	0.26	0.21	0.63	−0.48
Pulses	−0.06	0.74+	−0.57	0.73+	−0.50	0.69	−0.10	0.62
Sugarcane	−0.80++	0.16	−0.52	0.65	−0.16	0.90++	−0.39	0.10

confidence level having $r = 0.67$ over GPHR. Pulse crop on the other hand has the strongest correlation with rainfall over WDR with a 95% confidence level having $r = 0.73$. From Table 6, it can be seen that there are no significant correlations with ONI in any zones during the La Nina years. But rice and maize have positive correlations with rainfall at GPHR with $r = 0.44$ having more than 90% confidence and $r = 0.51$ having more than 95% confidence level respectively. In Table 7, during the positive IOD years, sugarcane have the strongest negative correlations with DMI (Dipole mode

Table 8 Correlation coefficients for four crops at 4 different zones with DMI & rainfall during negative IOD years (more than or equal to 90% confidence level: +, more than or equal to 95% confidence level: ++)

Crops	Zone 1		Zone 2		Zone 3		Zone 4	
	DMI	Rainfall	DMI	Rainfall	DMI	Rainfall	DMI	Rainfall
Rice	0.43	0.50	−0.32	0.76++	0.38	0.88++	0.72+	0.44
Maize	0.53	0.13	0.62	0.55	0.43	0.82++	−0.76	0.06
Pulses	0.06	0.79++	0.48	0.61	−0.08	0.89++	0.63++	0.65
Sugarcane	0.00	0.62	0.68+	0.65	−0.03	0.54	−0.54	−0.33

index) over CPHR with more than 95% confidence level having $r = -0.80$ and have a strong correlation with rainfall over GPHR with more than 95% confidence level having $r = 0.90$. Pulses have the strongest correlation with rainfall at CPHR with more than 90% confidence level having $r = 0.74$. Maize has the strongest correlation with rainfall over WPHR having $r = 0.73$ with more than 90% confidence level. The rice crop is having the strongest correlation with rainfall over GPHR with $r = 0.92$ with more than 95% confidence level. From Table 8, during the negative IOD years, rice crops have the strongest correlations with rainfall over GPHR with $r = 0.88$ having more than 95% confidence level. The maize crop is also having the strongest correlation with the rainfall over the same zone with more than 95% confidence level having $r = 0.82$. Pulses have the strongest correlation with DMI with more than 95% confidence level over WDR having $r = 0.63$ and rainfall having more than 95% confidence level with $r = 0.89$ over GPHR. A negative correlation with DMI (negative for negative IOD years) means that when the DMI are strongly negative, crop production increases. Sugarcane has a strong correlation with DMI with more than 90% confidence level having $r = 0.68$ over WPHR. At CPHR, WPHR and GPHR, all the crops are showing positive correlations with rainfall during positive as well as negative IOD years. During El Nino years, over CPHR and WPHR, all the crops are negatively correlated with ONI.

3.3 Impact of deviation of crop production from its previous year (detrending of production) during El Nino, La Nina, positive and negative IOD years

Figure 4a–d shows the variation in the crop productions as compared to the previous year (detrending) for all the zones from 1–4 for rice, maize, pulses and sugarcane respectively. In the figure, the "E" represents El Nino year, "L" represents La Nina year, "+" represents a positive IOD year only and "(−)" represents negative IOD years only. Combined El-Nino positive years are denoted by "E+" and combined La Nina negative IOD years are denoted as "L−".

There are total of 12 El Nino years and 15 la Nina years and 19 neutral years. But, here, 18 neutral years are to be considered as the detrending analysis does not include 1966 which is a neutral year. From Fig. 4a, i.e. for rice productions, it is observed that over CPHR, i.e. Central plateau and hills region, 4 out of 12 El Nino years are giving positive production of rice, i.e. increment in production as compared to the previous year. This is about 33% of the total number of El Nino years. The remaining 67% of the total El Nino years are severely impacting the rice production. There are 6 El Nino drought years out of which only 1 year is giving positive production of rice. There are 3 combined El Nino flood years, in all these, there is an increment in rice production from the previous year. Rainfall and the crop productions are positively correlated during the El Nino years with more than 90% significance level with ($r = 0.51$). There are total of 15 La Nina years out of which 4 La Nina years are negatively associated with rice production. This is only 27% years of the total La Nina years and hence is giving a clear indication that rice production is mostly high in La Nina years. There are a total of 6 La Nina flood years in which, the rice production has increased w.r.t its previous year. There are only 4 combined La Nina drought years out of which there are 3 years when the rice production is negatively associated. Eight out of 18 neutral years are associated negatively with rice production. Out of 6 positive IOD years, 2 years are positively associated with rice production. The other 4 years are combined El Nino and positive IOD years. In these years, the impact of El Nino is more than the impact of positive IOD on rainfall and hence affects the rice production as the crop is strongly dependent on rainfall. It has been found out that in the combined El Nino and positive IOD years, the correlation between positive IOD and rainfall is $r = 0.10$ (not significant) and the correlation between El Nino and rainfall is $r = -0.59$ (albeit insignificant) (Table 10). Three out of 7 negative IOD years are associated with negative rice production. Out of these 3 years, 2 years are complete negative IOD years.

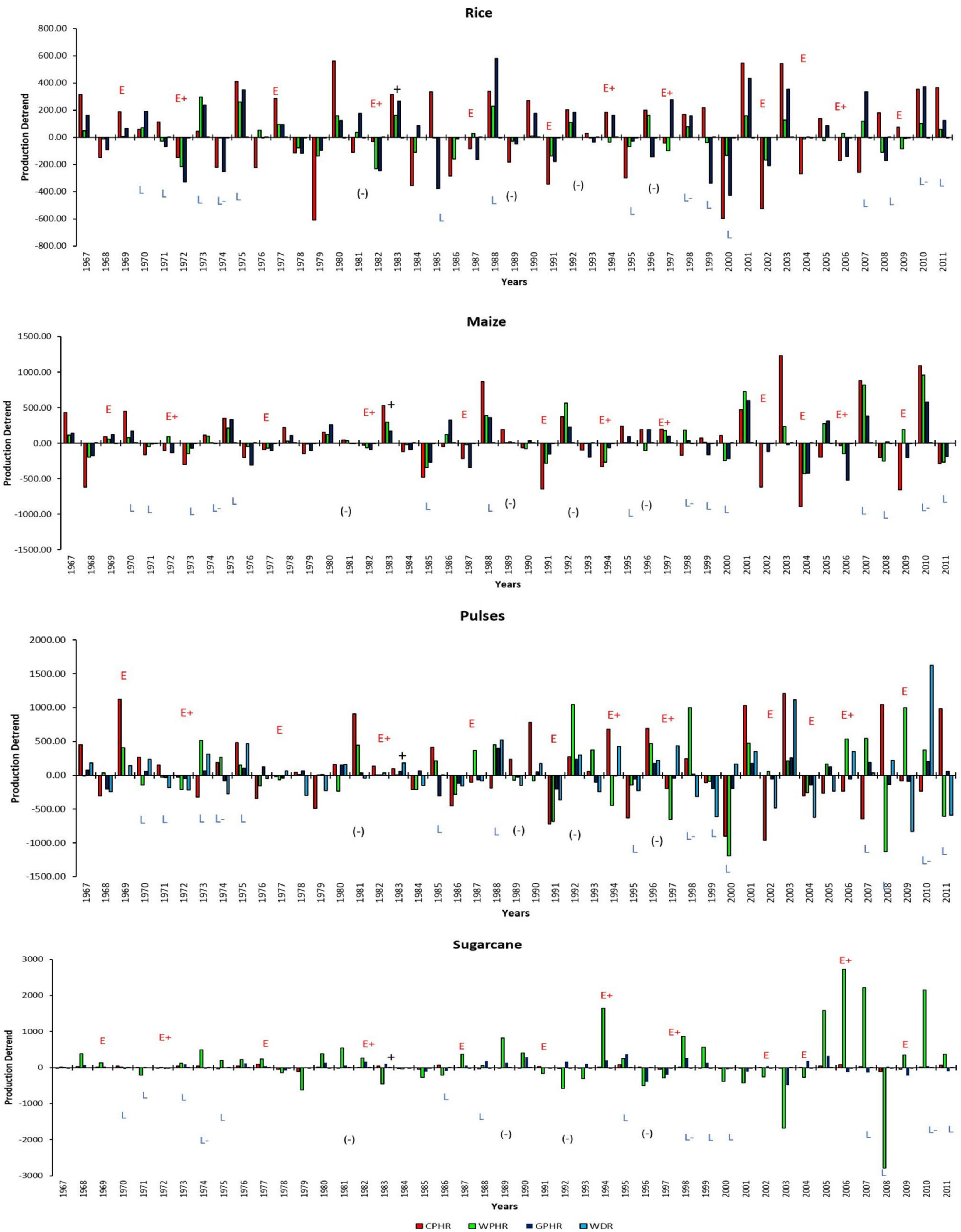
Moving on towards the Western plateau and hills region (WPHR), out of 12 El Nino years, only 4 years are associated with the positive production of rice. This suggests that the El Nino years are giving a negative impact on the rice production in the mentioned zone. One year out of 7 combined El Nino and drought years are associated with the increment in rice production. Two out of 3 combined El Nino and flood years are associated with positive production of rice. Seven years out of 15 La Nina years are associated negatively with the rice production. The remaining 8 years are related positively to the rice production. All the 7 combined La Nina and flood years are positively associated with the production of rice. In the 4 years that are combined La Nina but drought years, the rice production has decreased. Eight out of 18 neutral years are negatively associated with the rice production. Four out of 6 IOD-positive years have a negative impact on the rice production. All these 4 years are El Nino years. Correlations between ONI and rainfall during the El Nino combined with positive IOD years is $r = -0.80$ (significant up to 90% confidence level); on the other hand, the correlation between DMI and rainfall is $r = -0.51$ (insignificant) (Table 10). This indicates El Nino has more impact on the rainfall than positive IOD in the combined years. Two out of 7 IOD negative years are associated with a decrement in rice production as compared to its previous years. One is a pure negative IOD year. There are 3 La Nina years associated with negative IOD years in which 2 years have positive production and 1 year have decrement in rice production.

Over GPHR, i.e. Gujarat hills and plains region, rice crop has a maximum increasing trend of 25.27 kT/year during 1966–2011 (Table 9 and Fig. 5). In this zone, out of 12 El Nino years, there are 5 years in which the rice production has increased from the just previous year. One out of 7 El Nino and drought combined years are positively associated with rice production. Three out of 4 combined El Nino flood years are showing an increment in rice production. This is also justified as the rainfall is positively correlated with the rice production ($r = 0.67$) up to more than 95% confidence level. There are 7 La Nina years out of 15 years, in which the rice production has decreased from its previous year. Combined La Nina and flood years are positively associated with the rice production. All the 5 combined La Nina drought years are negatively associated with the rice production. There are in total 8 neutral years out of total of 18 years, when the rice production has decreased from the previous year. Looking at the positive IOD years, 3 positive IOD years are associated negatively with the rice production. These are all El Nino years as well. The effect of the El Nino-rainfall correlation, i.e. ONI and rainfall, is $r = -0.44$ (although not significant) and is dominant as compared to the IOD rainfall (DMI and rainfall) whose correlation is $r = -0.13$ (not significant) (Table 10). In the negative IOD years, 3 out of 7 negative IOD years are associated with a decrement in the production of rice. Out of all these 3 years, 2 years are pure negative IOD years. It is known that negative IOD years usually results into negative rainfall anomaly in most of the places of our country (Ashok et al. 2004). There are 14 drought years out of 15 years when the rice production shows a decrement from the just previous year. There are 2 flood years out of 15 years are associated with the decrement in the rice production. At WDR, i.e. Western dry region, rice is hardly grown.

Figure 4b represents the effect of El Nino, La Nina, positive IOD and negative IOD years on the maize production. Over CPHR, i.e. Central plateau and hills region, out of total of 12 El Nino years, 2 are positively associated with the maize production that is nearly 17% of the total El Nino years. El Nino is giving a strong negative impact on maize production. All the 6 El Nino and drought combined years are associated with negative production of the maize. Two combined El Nino flood years are negatively associated with maize production out of 3 years. Six out of 15 La Nina years are associated with a decrement in the production of maize. Three out of 6 La Nina flood years are associated with the negative production of maize. Three years out of 4 combined La Nina drought years are positively associated with maize production. Eight out of 18 neutral years are affecting maize production. Two out of 6 positive IOD years are positively associated with maize production. All the four positive IOD years are El Nino years. As already discussed, El Nino seems to affect the rainfall more than the positive IOD and hence production decrement is seen (Table 10). Only 1 out of 7 negative IOD years are negatively associated with the maize production.

Maize crop production shows a maximum increasing trend of 48.73 kT/year over the period from 1966 to 2011 (Table 9, Fig. 5) over WPHR, i.e. Western plateau and hills region. There are 4 El Nino years in which the maize production is positively associated, i.e. w.r.t the previous year the production has increased. The remaining El Nino years have a negative association. Three out of 7 combined El Nino and drought years are positively associated with the maize production. One out of 3 combined El Nino flood year is positively associated with maize production. There are 6 La Nina years out of 15 where the maize production has decreased as compared to its previous year. The remaining years are positively associated, i.e. the maize production has increased as compared to the previous year. Two out of 4 combined La Nina and drought years are negatively associated with maize, and 1 out of 7 combined La Nina and flood years is negatively associated with the maize production. Seven out of 18 neutral years are negatively associated with maize production. There are 3 years out of 6 positive IOD years when the maize productions are severely affected. All these 3 years are combined El Nino positive IOD years. Over WPHR also, the El Nino-rainfall correlations are stronger than the positive IOD–rainfall correlations (Table 10). Only 1 year out of 7 negative IOD years is there in which maize productions has been affected.

Over Gujarat hills and plains region (GPHR), only 2 years out of 12 El Nino years are associated with the positive production (increase from the previous year). One out of 7 combined El Nino drought years is positively associated


Rice
Production Detrend
Years
Maize
Production Detrend
Years
Pulses
Production Detrend
Years
Sugarcane
Production Detrend
Years
CPHR
WPHR
GPHR
WDR

◂**Fig. 4** Time series bar plot representing the detrending of **a** rice, **b** maize, **c** pulses and **d** sugarcane during El Nino, La Nina, positive IOD and negative IOD years. Note: El Nino: E, La Nina: L, El Nino + positive IOD: E+, La Nina + negative IOD: L-, positive IOD: + and negative IOD: (−)

with the maize production. Three out of 4 combined El Nino flood years are negatively associated with maize production. Six years out of total of 15 La Nina years are negatively affecting the crop production. Three out of 5 combined La Nina drought years are negatively associated with the maize production, and 1 out of 6 combined La Nina flood years is negatively associated with maize. There are 7 neutral years out of 18 that are negatively associated with the maize production. There are 4 positive IOD years out of 6 years which are associated with a decrement in maize production. These all are combined El Nino-positive IOD years. The reason may be El Nino is affecting the production as compared to positive IOD (Table 10). There is only 1 negative IOD year out of 7 years which is negatively affecting the maize production, i.e. 1981. Over WDR, i.e. the Western dry region, maize production is very negligible.

Figure 4c shows the impacts of the climate modes on pulse productions. It is observed that in CPHR, i.e. Central plateau and hills region, pulses production shows a maximum increasing trend of 58.08 kT/year from 1966 to 2011 (Table 9, Fig. 5). Out of 12 El Nino years, 3 El Nino years are associated with positive production of pulses. Two years out of 3 El Nino years as mentioned are flood years. This indicates that 75% of the El Nino years are impacting negatively in the pulse production. There are 6 El Nino and drought combined years in which the pulse production has been negatively impacted. One out of 3 El Nino flood year is negatively associated with pulse production. But 7 out of 15 La Nina years are negatively associated with pulse production. Excessive rainfall during La Nina years may affect the production. Cloudy weather or rains at flowering and fruiting stages of the pulses can result in poor pod setting and seed filling leading to crop damage (Sardana et al. 2010). Two La Nina and flood combined years out of 6 are negatively associated with pulse production. Out of 4 combined La Nina drought years, 2 years are associated with a decrement in pulse production. Six out of 18 neutral years are negatively associated with the pulse production. Three out of 6 positive IOD years are positively associated with pulse production. The other 3 are combined El Nino and positive IOD years. In these years, over this region, El Nino has a greater impact on rainfall than IOD (Table 10). Only 1 out of 7 negative IOD years are negatively associated with pulses production. Pulse is the majorly grown crop out of all other crops in this zone. Three out of 14 drought years are associated positively with the pulses, i.e. the major grown crops. Three out of 15 flood years are negatively associated with the negative pulse production. Drought years in this zone are decreasing the production of the crops.

Over the Western plateau and hills region (WPHR), half (6/12) of the El Nino years are positively associated with the pulses production. Six years out of 15 La Nina years are negatively impacting the pulses production. The decrement in pulses in these years is terribly low as compared to the previous years. Four out of 7 combined El Nino and drought years are positively associated with the pulse production. Pulses production requires somewhat dry conditions. Two out of 3 combined El Nino and flood years are positively associated with the pulse production. One out of 7 combined La Nina flood years is negatively associated with the pulse production whereas 2 out of 4 combined La Nina drought years are negatively associated with pulse. Seven out of 18 neutral years are negatively associated with the pulse production. Three years out of 6 positive IOD years which happens to be El Nino years as well and are negatively associated with the production of the crop as compared to positive IOD (Table 10). Only 1 year out of 7 negative IOD years is affecting the pulse crop production. Gujarat hills and plains region representing the semi-arid areas and some arid regions of Gujarat, i.e. over GPHR, only 1 El Nino year is associated with the increase in the production of pulses. Only 1 out of 7 El Nino drought years is positively associated with pulses production. All the 4 combined El Nino flood years are negatively associated with the pulse production. There are 7 La Nina years that are associated with the decrement in pulses production. All the 5 combined La Nina drought years are negatively associated with the pulse production. Moreover, all the 6 La Nina flood years are positively associated with the pulse production. There are total of 4 neutral years out of 18 neutral years have a negative association with the pulses production. Four (4/6) out of 6 positive IOD years are associated with a decrement in pulse production. All the 4 years are combined El Nino-positive IOD years. The reason may be El Nino is affecting the production as compared to positive IOD (Table 10). There are 2 negative IOD years which are associated with the decrement in the pulse production out of 7 years.

Pulses are the majorly grown crops in WDR, i.e. Western dry region. Here, the other crop production is extremely small. So, here, only the pulse production is considered. Six out of 12 El Nino years is associated with the increment in pulse production as compared to the previous year. There are 8 El Nino and drought combined years out of which two are positively associated with the pulses production. On the other hand, 6 out of 15 La Nina years are associated with a decrement in the pulse production as compared to the previous year. Only 2 out of 6 La Nina and flood combined years are negatively associated with the pulses production. Ten out of 18 neutral years are resulting into a decrease in the pulse production over this zone. All the 3 El Nino flood years

Table 9 Rates of increment/decrement of crop production (in kT/year) over the years 1966–2011 (maximum increasing trend is shown in red)

Crops	Zone1	Zone2	Zone 3	Zone 4
Rice	13.60	5.94	25.27	−0.001
Maize	32.21	48.73	11.07	−0.02
Pulses	58.08	52.31	10.27	17.34
Sugarcane	1.86	121.84	40.84	−0.007

Table 10 Correlation of rainfall with ONI and DMI for combined El Nino-positive IOD years from 1966–2011 (*significant up to 90% confidence level)

Zones	Rainfall and ONI	Rainfall and DMI
01	−0.59	0.10
02	−0.80*	−0.52
03	−0.44	−0.13
04	−0.46	−0.26

are positively associated with the pulses production. Three (1971, 1974 and 1999) La Nina drought years out of 4 are decreasing pulse production. There are 4 drought years out of 17 are associated with an increase in pulses production. Four out of 15 flood years are associated with a decrement in the pulse production. In positive IOD years, there is only 1 year which is also an El Nino year that is associated with the decrement in the pulse production. On the other hand, 4 out of 7 negative IOD years are associated with the decrement in the pulse production. Out of them, two are pure negative IOD years and have negative rainfall anomalies associated with it in the zone [Ashok et al. (2004)]. Two others are combined La Nina negative IOD years.

Figure 4d represents the impacts of the climate modes mentioned above on sugarcane production. Over CPHR, i.e. Central plateau and hills region, out of 12 El Nino years, 9 years have a positive association with the sugarcane production where 6 years are even drought years in the region. Although, the increment in these El Nino years is small, i.e. 4 years have below 10 K tonnes increment w.r.t previous year. In these, in 4 drought El Nino years, an increment of sugarcane production is seen but is a very small increase as compared to the previous year. There are 3 El Nino flood years that are positively associated with the sugarcane production as the correlation of sugarcane production with rainfall is 0.26 (although insignificant) during El Nino years. El Nino years generally give less than normal monsoon rainfall and sugarcane production requires sufficient rainfall. The contrasting results may be due to better irrigation techniques and the varieties of sugarcane grown in these areas. For example, a variety of sugarcane which is CoPant 90,223 identified in the year 2000 is tolerant to several diseases and tolerant to drought (Shukla et al. 2018). Six out of 15 La Nina years are negatively

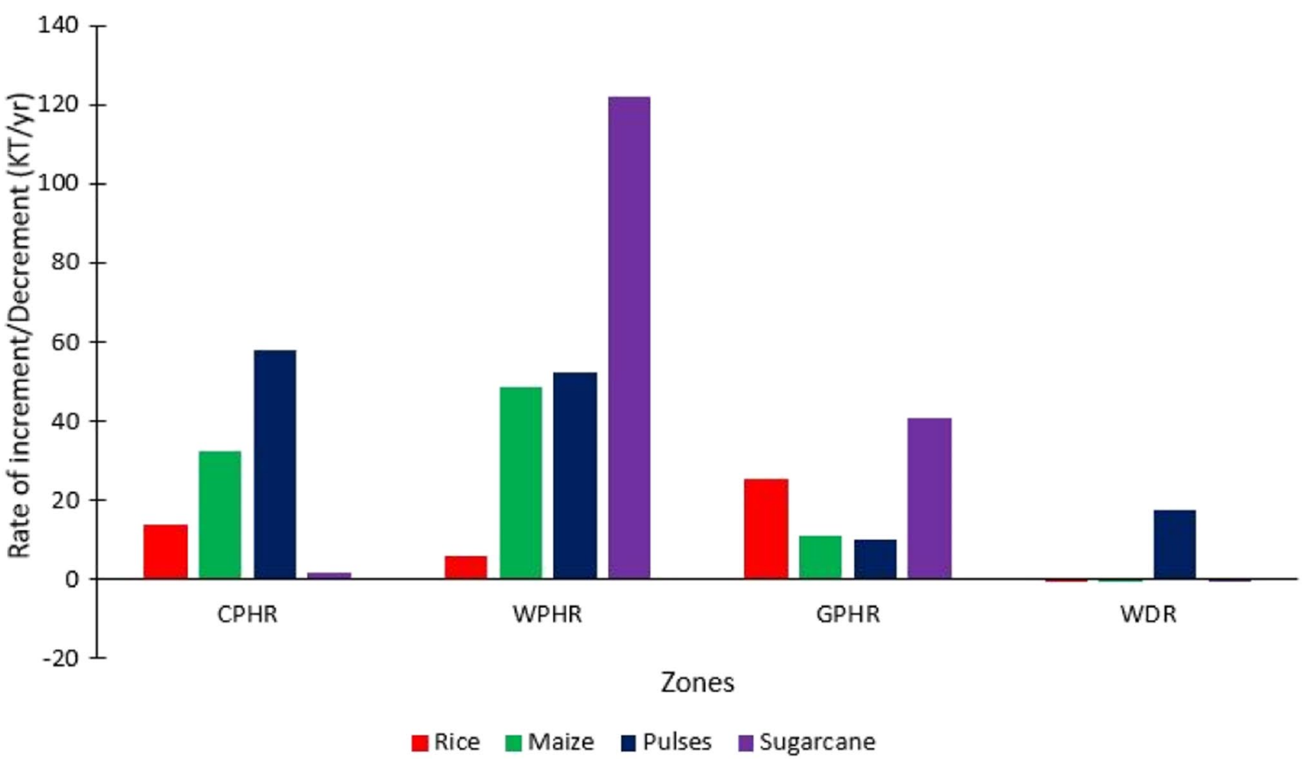


Fig. 5 Bar plot of the rate of increment/decrement of crop productions over the entire period of study over four zones

associated with sugarcane production. Only 2 out of 6 La Nina flood years are negatively associated with the sugarcane production. Out of 4 combined La Nina drought years in this zone, 2 years are positively associated with the sugarcane production. Eleven out of 18 neutral years are negatively associated with the sugarcane production. It is observed therefore that neutral years are not very suitable to grow sugarcane. Four out of 6 positive IOD years are positively associated with the sugarcane production. One of these is a pure positive IOD year which is associated with positive rainfall anomaly over the zone (Ashok et al. 2004). Three out of 7 negative IOD years are negatively associated with the sugarcane production. All are pure negative IOD years which usually have negative rainfall anomalies over certain parts of the zone (Ashok et al. 2004). Sugarcane production shows the strongest increasing trend over the years 1966–2011, i.e. 121.84 kT/year (Table 9, Fig. 5) at WPHR, i.e. Western plateau and hills region. Out of 12 El Nino years, 8 are there where there is a good production of sugarcane. Sugarcane production requires 2 to 3 seasons of rainfall and then a drought or low rainfall period. Irrigation is required in almost all phases of its growth (Srivastava and Rai 2012). Irrigations along with short rainfall in El Nino years may be giving good production and providing a minor impact on the crop. Only 4 out of 15 La Nina years are associated with a decrement in sugarcane production as compared to previous years. Four out of 7 combined El Nino drought years are positively associated with sugarcane whereas 3 combined El Nino flood years are positively associated with sugarcane production. All 7 combined La Nina flood years are positively associated with the sugarcane production. Two out of 4 La Nina drought years are negatively associated with sugarcane. Ten out of 18 neutral years are negatively associated with the sugarcane production. Only 2 years out of 6 positive IOD years are there in which the sugarcane production has shown decrement. Only 1 year out of seven negative IOD years is negatively affecting the sugarcane production.

At GPHR, i.e. Gujarat hills and plains region, out of 12 El Nino years, 7 years are associated with the increment in sugarcane production. The reason for a minor impact of sugarcane in El Nino years may be due to better irrigation technique that provides sufficient water. Drought conditions are also required after 2 to 3 good spells of rainfall. El Nino years provides the same condition. Even if the rainfall is little, irrigation if done properly at each stages of development can lead to good production (Srivastava and Rai 2012). On the other hand, 5 out of 7 combined El Nino and drought years are positively associated with sugarcane production. Two out of 4 combined El Nino flood years are positively associated with the sugarcane production. There are 7 La Nina years out of 15 years where the sugarcane production has decreased from its just previous year. Three out of 6 combined La Nina and flood years are associated with negative sugarcane production. Three out of 5 combined La Nina drought years are negatively associated with sugarcane production. There are 7 neutral years out of 18 years when the sugarcane production has decreased. Here, neutral years are suitable for good sugarcane productions. Three out of 6 positive IOD years are associated with a decrease in sugarcane production. All are combined El Nino IOD years. Only 2 negative IOD years out of 7 years are associated with a decrement in sugarcane production. Seven out of 15 drought years are negatively associated with the sugarcane production. Seven flood years out of 15 years are negatively associated with sugarcane production. Sugarcane are hardly grown over the WDR, i.e. the Western dry region.

4 Conclusions

Here, the effect of El Nino, La Nina as well as IOD on the four agro-climatic zones of western India are studied by considering four kharif season crops namely rice, maize, pulses and sugarcane from 1966 to 2011. There are many factors on which the crop production over a zone depends upon such as maximum and minimum temperature, relative humidity, rainfall and sunshine hours. Here, mostly based on monsoon rainfall, the study has been done. Based on the observations of the productions of these crops and monsoon rainfall in El Nino/La Nina (ENSO) and IOD years, the following conclusions are made.

Over all zones, El Nino years seem to affect the rice production especially the drought years. Hot and humid climates are very suitable for rice production. El Nino years particularly drought years give less than normal rainfall. The scarcity of soil moisture reduces the production of rice. La Nina years are very good to produce rice over all the zones of our study. Pulses are the dominant crop in two zones namely CPHR and WDR. Pulses are mostly affected in the El Nino years most specifically the drought years associated with El Nino in both zones. Even La Nina years also negatively affect the pulse production but not as much as in El Nino years. Neutral years are seen to be best suited to produce pulses in any agro-climatic zones considered in our study. Sugarcane is the dominant crop in WPHR and GPHR. In almost all the zones, El Nino and La Nina years are associated with good sugarcane production. El Nino particularly has a minor impact on sugarcane production may be due to good irrigation techniques used over WPHR or due to the use of drought and disease-resistant variety of sugarcane. On the other hand, in GPHR, sugarcane are grown well in the neutral years and in La Nina years. Some four-five El Nino and La Nina years seem to affect the production of sugarcane in CPHR and WPHR. Neutral years have affected sugarcane productions over these zones. For sugarcane productions, La Nina years are suitable. Maize crop, although not a dominant crop in any zone but when the observations are analysed, it is seen that El Nino years are severely affecting the maize production specially the drought years associated with El Nino. La Nina years as well as neutral years are suitable for maize production in any of the mentioned zones. Positive IOD years are affecting the rice production in the mentioned zones negatively as almost all positive IOD years happen to be El Nino years. It has been seen that the rice production gets terribly affected in El Nino years. On the other hand, negative IOD years show a better result in terms of rice production over all zones of our study. Mostly all the crops considered in our study zones shows better result in terms of their production in the negative IOD years as compared to that in positive IOD years. But, there is an exception, pulses in WDR show slightly better productions in positive IOD years than negative IOD year.

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Author contribution R.B. helps in the conceptualisation of the study. S.B. and S.V. have analysed the data and provide methodology. R.K.M. and R.S.S. have guided in the agriculture section, review and editing of the manuscript. S.G., S.V. and R.B. completed the writing of original manuscript of the paper.

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Data availability All data generated or analysed during this study are included in this published article.

Code availability Not required.

Declarations

Ethics approval For this type of study, formal approval is not required.

Consent to participate For this type of study, formal consent is not required.

Consent for publication For this type of study, consent for publication is not required.

Conflict of interest The authors declare no competing interests.

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