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ORIGINAL PAPER

Impact of Pacific Decadal Oscillation in relation to QBO on Indian summer monsoon rainfall

Rajeev Bhatla[1,2] · Sahil Sharma[1] · Shruti Verma[1] · Bimal Gyawali[1]

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Abstract

The relationship between Indian Summer Monsoon (ISM) rainfall (June to September) and Pacific Decadal Oscillation (PDO) Index for the concurrent and succeeding seasons over all India and its three specific regions, i.e., northeast, northwest, and peninsular region has been examined from the years 1953 to 2016. The information is shared for the full series as well as by grouping the seasonal rainfall of India and PDO data according to the different phases (westerly/easterly) of quasi-biennial oscillation (QBO) at the 50 hPa level. The results suggest that for full series, the concurrent season July–August–September (JAS) shows higher degree of association as compared with June–July–August (JJA). When the seasonal rainfall and the PDO index data are stratified according to the phase of QBO, correlation coefficient (CC) values are showing a strong inverse association during the easterly phase of QBO over all India and the northwest region of India while the CC value is reduced during the westerly phase. For the northeast Indian region, concurrent CC values are showing high (low) during the westerly (easterly) phase of QBO. In addition, the warm PDO events are persistent during the summer monsoon period in association of easterly (westerly) phase of QBO causes drought (flood) events over India. However, the cold phase of PDO follows the easterly and westerly phase of QBO where the indication of drought and flood events is not persistent.

Keywords Pacific Decadal Oscillation index · Quasi-biennial oscillation · Indian Summer Monsoon rainfall · Concurrent and succeeding seasons of monsoon

Introduction

The south-west (SW) monsoon season is one of the fundamental parts of the climate over tropical region. The Indian landmass receives about 75% of the annual rainfall during SW monsoon (Saha and Mooley 1978) which leads the income of approximately two third of the total population depends on agriculture (Krishna Kumar et al. 2004). Over 61% of the agricultural area in India is not in any form of irrigation and is completely dependent on Indian Summer Monsoon (ISM) rainfall. Half of the India's agricultural output comes from the summer crop which in turn depends on monsoon. Thus, the variability of summer monsoon rainfall has a profound impact on the Indian economy as well as on agriculture of India. Therefore, long range forecasting of ISM rainfall is highly important to balance the Indian economy and to feed the large population of India.

There are certain evidences, which are used in various studies, that show the variability of sea surface temperature (SST) anomaly over North Pacific (Davis 1976). The SST anomaly plays a major role in the inter-annual variability of tropical monsoon circulation. The inter-annual variability of rainfall is very complex and it depends on the global as well as regional circulation patterns. Several studies suggest that the inter-annual variation of ISM rainfall is significantly teleconnected with several global and regional climatic parameters, since the global boundary conditions have the potential to influence the monsoon circulation significantly (Charney and Shukla 1981). The tropical Pacific plays another major role in determining the inter-annual variability of ISM rainfall (Sikka 1980; Krishnamurthy and Kirtman 2009) through Walker circulation which is related with ENSO

Responsible Editor: Zhihua Zhang

✉ Rajeev Bhatla
rbhatla@bhu.ac.in

1 Department of Geophysics, Institute of Science, Banaras Hindu University, Varanasi 221005, India

2 DST-Mahamana Centre of Excellence in Climate Change Research, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India

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(Krishnamurthy and Goswami 2000). Pacific Decadal Oscillation (PDO) is important and recognized climate pattern in the extra-tropical region of Pacific Ocean (120°E-120°W, 20°N-60°S) in the Northern Hemisphere. This is an El-Nino like pattern with period around 60 years, oscillating between its warm and cold phases in every 20–30 years. In the climate system, PDO is considered as a dominant internal oscillation with phase shifts developing on decadal time scale. Several studies in the recent years have drawn attention to the inter-decadal variation over the tropical Pacific Ocean (Nitta and Yamada 1989; Zhang et al. 1997; Parker et al. 1994; Kachi and Nitta 1997). Generally, PDO is defined in terms of PDO index which is further defined as the leading principle component of North Pacific monthly SST variability and is the first principle component of Empirical Orthogonal Function (EOF) over the region (Trenberth 1990; Zhu and Yang 2003). As a dominant internal mode of the climate system, PDO affects the rainfall variations over many places around the globe (Goodrich and Walker 2011; Dong and Dai 2015; Newman et al. 2016; Zhang et al. 2018). Hadley and Walker circulation with tropical pacific suggests the PDO-monsoon relationship by playing an intermediary role between the North pacific and the Indian monsoon. Some studies have been done on the relationship between PDO and the ISM rainfall (Krishnan and Sugi 2003; Sen Roy 2011; Bhatla et al. 2013; Krishnamurthy and Krishnamurthy 2014; Newman et al. 2016; Krishnamurthy and Krishnamurthy 2017; Zhou et al. 2017). The strong relationship between year to year ISM rainfall and El-Nino Southern Oscillation (ENSO) has been acknowledged in the several studies in the past (Pant and Parthasarthy 1981; Shukla and Paolino 1983; Rasmusson and Carpenter 1983; Asrit et al. 2001; Chattopadhyay and Bhatla 2002; Kumar et al. 2006; Azad and Rajeevan 2016; Roy et al. 2019; Hrudya et al. 2020). In addition to anthropogenic external forcings (Bollasina et al. 2011; Li et al. 2015; Salzmann and Cherian 2015), the negative-to-positive phase transition of the decadal variability in the Pacific explains the total drying trend with similar magnitude to the anthropogenic aerosols over India from 1950 to 1999 (Salzmann and Cherian 2015). Krishnan and Sugi (2003) used the first principal component of the detrended and low-pass filtered SST to characterize the warm and cold composite of PDO and its relationship with precipitation variations over the different regions over India. The distribution of rainfall anomalies shows significant negative departures (below 10% of the normal) over several sub-divisions in the plains of northwest and north-central India. Another important oscillation in the tropics, i.e., tropical stratospheric quasi-biennial oscillation (QBO) and its relation with ISMR, has not been explored much in the past. The QBO in the mean zonal wind is the dominant feature of the tropical stratosphere in the height range of 18–50 km or 70–10-hPa pressure range (Baldwin et al. 2001). It consists of zonally symmetric regimes of easterly and westerly wind phases, which descend through the middle and lower stratosphere at a rate of about 1 km per month. According to the different phases (QBO), the grouping of data shows the usefulness and significant enhancement of correlation as compared with the full time series (Holton and Tan 1980; Labitzke and Van Loon 1990; Chattopadhyay and Bhatla 1993; Chattopadhyay and Bhatla 2002; Bhatla et al. 2013, 2016).

The present study is focused on the teleconnection between interannual variability of monsoon rainfall over all India and the different regions of India (i.e., northeast, northwest, and peninsular India) with PDO index. The intention of this paper is to describe the relation between PDO index and ISM rainfall using full series (1953–2016) as well as grouping of the different phases of QBO at 50 hPa level (Chattopadhyay and Bhatla 1993) for the concurrent and succeeding seasons from the year 1953–2016 over the different Indian regions. In addition, the relationship between the warm and cold phases of PDO with the flood and drought years over India along with the easterly and westerly phases of QBO has also been studied.

Data and methodology:

To study the teleconnection between ISM rainfall and PDO index, different datasets are used (ISM rainfall, POD index, phases of QBO). The PDO index data is available at JISAO, University of Washington, and it is considered for the time period 1953–2016. The different phase of QBO is obtained from Naujokat (1986) at 50 hPa during the different season of different years and is used to determine the phase of the QBO. The literature and the data of different phases of QBO are available at Atmospheric Dynamics group of Institute of Meteorology, Free University, Berlin. Since the QBO data is available only from 1953, the study has been done from the period 1953 to 2016. The ISM rainfall data sets over different Indian sub-division (northeast, northwest, peninsular, and all India) are obtained from the Indian Institute of Tropical Meteorology (IITM), Pune, India. The rainfall data of each year from 1953 to 2016 is expressed as a percentage departure from normal, i.e., rainfall anomaly. To study the inter-annual variability, one of the most appropriate parameters is the normalized ISM rainfall anomaly (Shukla 1987). The normalized ISM rainfall anomaly, when it exceeds the magnitude + 1 and − 1, shows that monsoon is above and below the normal, respectively. The major flood and drought years during the study period over Indian region are taken from the IITM homogenous Indian monthly rainfall data (www.tropmet.res.in). An area-weighted rainfall has been calculated for concurrent and succeeding seasons over all India and its three specific regions, i.e., northeast, northwest, and peninsular India. To identify the relation between ISM rainfall and PDO index, statistical method of correlation approach is used. The relation between two variables which are supposed to be related can be studied by calculating linear correlation coefficient (CC). The value of CC lies between − 1 and + 1. The CC values near − 1 and + 1 show that there is a strong relationship between two variables while the value near 0 indicates weak relation among them. Moreover, a correlation may be found accidentally when really no correlation is existing, so the use of Student's 't' test is considered at the significance levels of 0.05, 0.1, 0.5, 1, and 2.5 to approach the degrees of freedom (df) for various significance level readily found from any standard statistical table.

Results and discussions

Seasonal ISM rainfall and PDO index of concurrent and succeeding season

The correlation analysis of PDO index with ISM rainfall and three Indian regions, i.e., northeast, northwest, and peninsular India, is presented in Table 1. The CC is calculated for the full time series and grouping the dataset into westerly and easterly phases of QBO for concurrent and successive seasons. In this table, June–July–August (JJA (0)) and July–August–September (JAS (0)) represents concurrent seasons while September–October–November (SON (+)) and December–January–February (DJF (+)) represent succeeding autumn and winter season, respectively. The PDO index data of 64 years is divided into seasons by using QBO phase dataset. A very few of the years does not show a uniform pattern of the phase through 3-month seasons. In such cases, the phase, which persists for 2 months, has been taken as the QBO phase. The above correlation analysis is studied for different seasons and during different phases of QBO, while by doing so, the number of independent samples is reduced. The degree of association is calculated using statistical correlation technique and its significance was tested by the conventional t test using the suitable degree of freedom.

In full-time series, Table 1 shows a positive association between ISM rainfall with PDO index over northeast region of India. Two concurrent seasons (JJA and JAS) show the positive association with CC values 0.13 and 0.19, respectively. During the succeeding autumn and winter season, the CC values decrease to 0.04 and − 0.14, respectively. In addition, there is a negative association between PDO index and ISM rainfall over all India, northwest and peninsular region. It is interesting to note that, for any season, the highest value of CC (− 0.48) is obtained in the succeeding autumn month over all India. There is a progressive increase in the magnitude of CC values from concurrent JJA to autumn SON season (− 0.21 to − 0.48), after that magnitude of CC value falls to 0.30 in the succeeding winter month (DJF) over all India. But the CC values show a continued increase in the northeast (− 0.15 to − 0.38) and peninsular region (− 0.04 to − 0.33) for all seasons. The DJF season of all India, northwest and peninsular region shows significant negative CC values, i.e., − 0.30 (significant at level 1%), − 0.38 and − 0.33 (both significant at 0.5% level), respectively, while for northeast Indian region, the value is not so significant (− 0.14) as compared with other regions. The two seasons prior to JJA are not shown here in the table because the relationship is weak and insignificant for them. By analyzing the above table, it is seen that out of two concurrent seasons (JJA and JAS), the degree of association between the ISM rainfall and PDO index is stronger for the JAS season. When the data of full series is grouped according to the different phases of QBO (westerly and easterly), some interesting results are observed. From the table, it is noticed that the magnitude of CC values is remarkably increased from JJA to SON season over all India and northwest Indian region for the easterly phase of QBO. But for DJF, the increase in magnitude is seen during the westerly phase of QBO except for northeast Indian region where the magnitude increases during the easterly phase of QBO. The strongest enhancement occurs over the northwest Indian region for the concurrent season JAS where the CC value is enhanced to − 0.50 significant at 0.5% level but the full series has not shown any significant correlation (0.32). For JAS season, the CC value is −

Table 1 Correlation coefficient (CC) between PDO index and ISM rainfall over All India, Northeast, Northwest, Peninsular India for the full period, westerly phase, and easterly phase

Seasons	All India			Northeast India			Northwest India			Peninsular India		
	West	East	Full	West	East	Full	West	East	Full	West	East	Full
JJA (0)	− 0.19	− 0.23	− 0.21	0.23	− 0.03	0.13	− 0.14	− 0.18	− 0.15	− 0.02	− 0.09	− 0.04
JAS (0)	− 0.34*	− 0.44*	− 0.37%	0.25	0.12	0.19	− 0.21	− 0.50%	− 0.32@	− 0.18	− 0.13	− 0.16
SON (+)	− 0.47#	− 0.55*	− 0.48$	0.08	0.03	0.04	− 0.34*	− 0.47*	− 0.37%	− 0.33*	− 0.06	− 0.26*
DJF (+)	− 0.62$	− 0.14	− 0.30@	0.009	− 0.38	− 0.14	− 0.50$	0.03	− 0.38%	− 0.36*	− 0.23	− 0.33%

The superscripts $, #, %, @, * represent 0.05, 0.1, 0.5, 1.0, and 2.5% of significant levels, respectively. The 0 and + signs in the parenthesis represent the concurrent and succeeding seasons, respectively

0.44 (significant at 2.5% level) over all India while in the full series, the value is − 0.37 (significant at 0.5% level). For JAS season, the magnitude of CC values increases in the easterly phase, but for DJF, the increase in the values is seen during the westerly phase. Over all India and peninsular region, all seasons are showing an increase in magnitude of CC values from concurrent to succeeding months for westerly phase as compared with easterly phase.

The above analysis concluded that there is a positive association between the PDO index and ISM rainfall for the northeast region of India. This positive association is enhanced during the westerly phase of QBO for the concurrent seasons (JJA and JAS) while for the easterly phase, the CC value is high for DJF season. It is also noticed that for all India and northwest region, there is negative association between the PDO index and ISM rainfall. From JJA to SON seasons, the easterly phase of QBO shows strong negative association with a good CC values while the CC values are increased during the DJF season in the westerly phase of QBO. For the peninsular region, the westerly phase of QBO shows good negative association as compared with easterly phase for all seasons except JJA and a continuous increase value of CC is depicted from JJA to DJF for the westerly phase. The graphical representation of teleconnection between ISM rainfall anomaly and POD index anomaly for the concurrent season JAS over all India, northeast, and northwest Indian region is shown in Figs. 1, 2, and 3 for full series, west phase, and east phase of QBO, respectively. The degree of freedom reduced from 62 for full

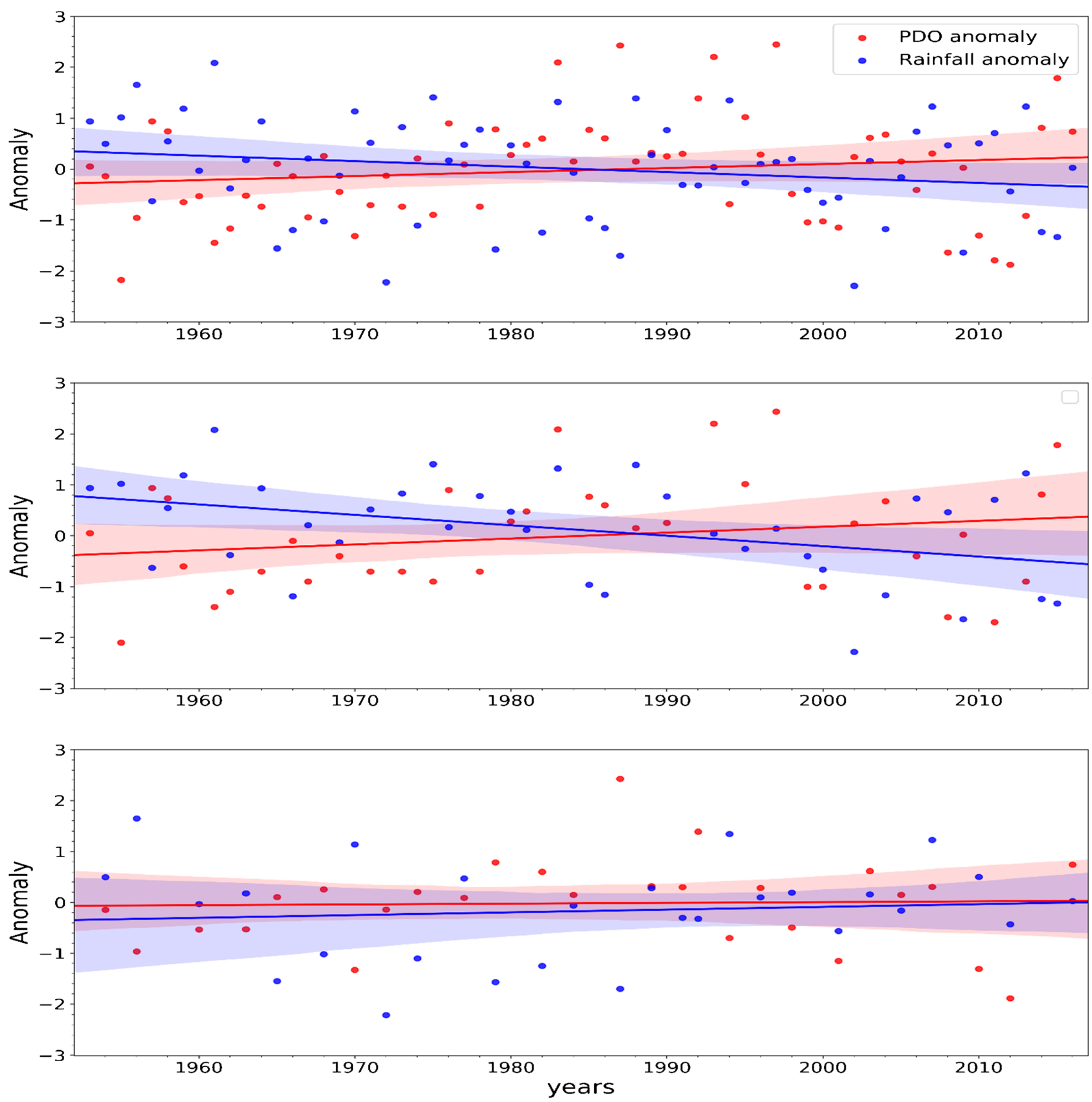

Fig. 1 The dots represent standardized ISM rainfall anomalies (blue dots) and PDO anomaly (red dots) over all India region during JAS season for the full series (top): $n = 62$, CC = − 0.37 (1953–2016). The west phase of QBO (middle): $n = 36$, CC = − 0.34 and the east phase of QBO (bottom): $n = 26$, CC = − 0.44. The lines represent the trend at 95% significant level

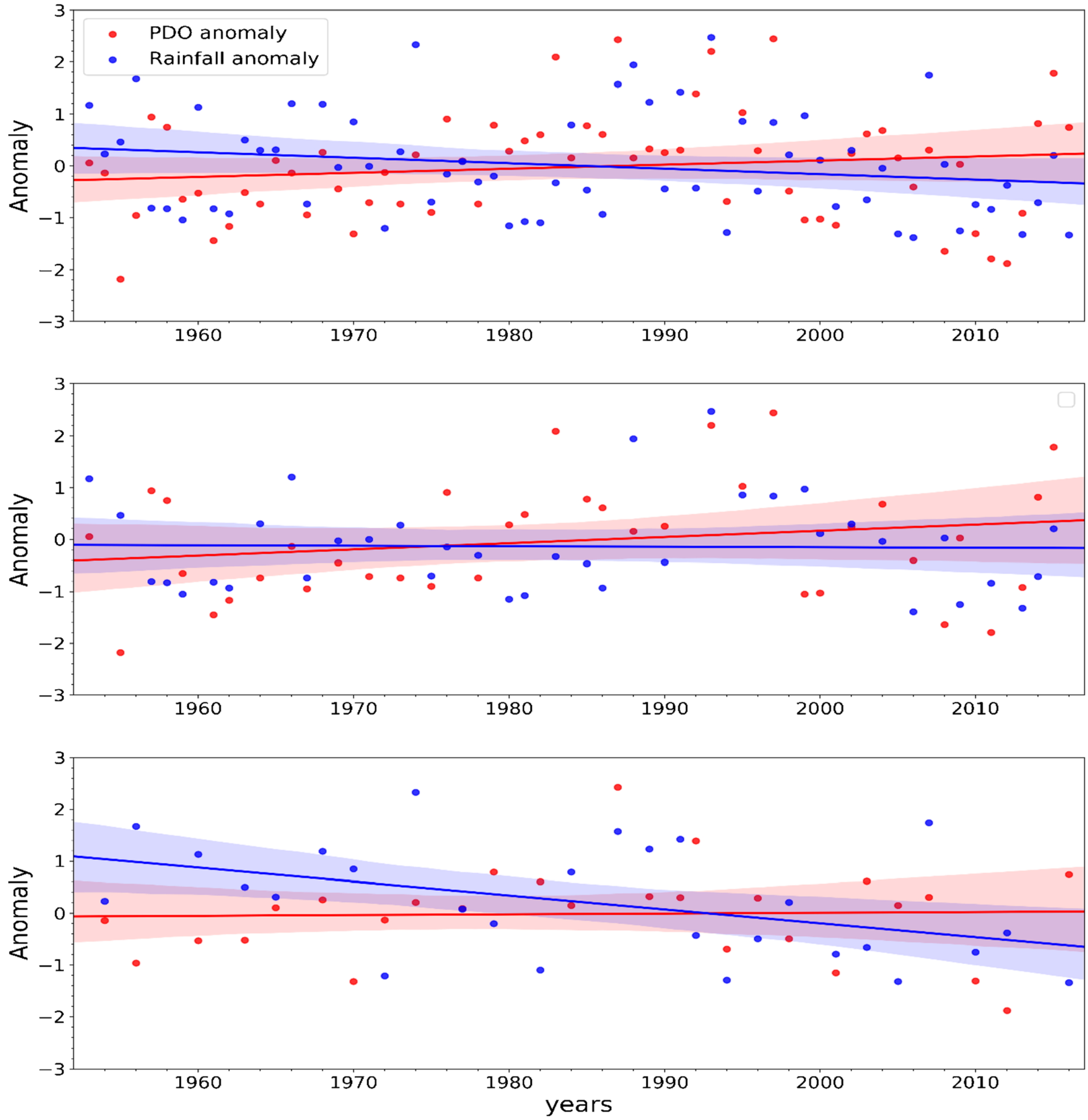

Fig. 2 The dots represent standardized ISM rainfall anomalies (blue dots) and PDO anomaly (red dots) over the northeast region during JAS season for the full series (top): $n = 62$, CC = 0.19 (1953–2016). The west phase of QBO (middle): $n = 36$, CC = 0.25 and the east phase of QBO (bottom): $n = 26$, CC = 0.12. The lines represent the trend at 95% significant level

series to 36 for westerly phase and 26 for easterly phase of QBO. From these graphical representations and analysis from the table, it is clear that over all India, there is a good inverse association between ISM rainfall and PDO index during the easterly phase of QBO for the concurrent season but the relation is weak for westerly phase (Fig. 1). It is also seen that the trend of PDO anomaly is increasing in both the phases of QBO as well as in full series but the trend in rainfall anomaly is decreased during the westerly phase while it increases during the easterly phase of QBO. For northeast (northwest) region, a positive (negative) association is seen during the westerly (easterly) phase of QBO for the concurrent season as compared with the easterly (westerly) phase (Figs. 2 and 3). Trend of rainfall anomaly for both northeast and northwest region behaves differently during the easterly phase of QBO. In northeast, the trend of rainfall anomaly is in decreasing, while in northwest, it is increasing during the easterly phase of QBO.

Different phase of QBO and PDO and its relation to drought/flood years

The PDO oscillates between its cold and warm phase about every 20–30 years. Table 2 represents two cold and one warm phase of PDO for period of 1953–2016. The cold phase of PDO regime is prevailed from 1953 to 1976 and again from 1998 to 2016 while warm phase of PDO regime from 1977 to 1997. According to Krishnamurthy and Kirtman (2009), the

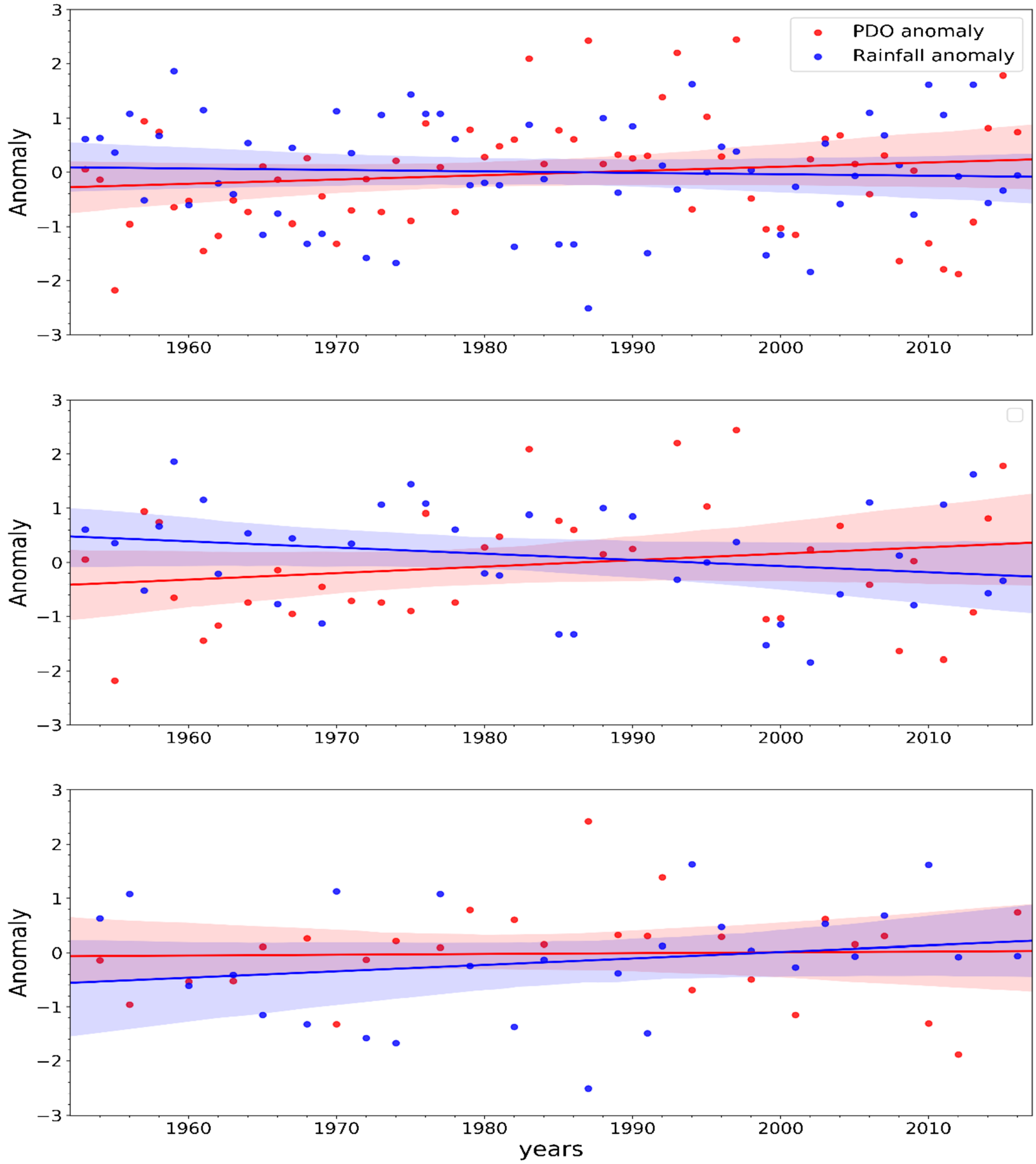

Fig. 3 The dots represent standardized ISM rainfall anomalies (blue dots) and PDO anomaly (red dots) over the northwest region during JAS season for the full series (top): n = 62, CC = − 0.32 (1953–2016). The west phase of QBO (middle): n = 36, CC = − 0.21 and the east phase of QBO (bottom): n = 26, CC = − 0.50. The lines represent the trend at 95% significant level

Table 2 Partitioning of years according to the cold and warm phase of PDO with major flood and drought years over India and its relation with the easterly and westerly phases of QBO

	Cold phase of PDO	Warm phase of PDO
PDO phase years	1953–1976, 1998–2014	1977–1997
Major flood years	1956 (E), 1959 (E), 1961 (W), 1975 (E)	1983 (W), 1988 (W), 1994 (W)
Drought years	1965 (E), 1966 (W), 1968 (E), 1972 (E), 1974 (E), 1979 (E), 2002 (W), 2004 (W), 2009 (W), 2014 (W)	1979 (E), 1982 (E), 1986 (W), 1987 (E), 1991 (E)

suppression or enhancement of the ISM rainfall depends upon the relative phases of the inter-annual and decadal PDO. The suppression (enhancement) of the ISM rainfall is related to the warm phase of PDO (cold phase of PDO). In this study, the relation between the different phases of PDO (cold and warm) is examined with the different phases of QBO (westerly and easterly) along with the major flood and drought year over India. It can be observed that all the major flood years occurred when the warm phase of PDO is in association with the westerly phase of QBO (warm phase of PDO-westerly phase of QBO-flood years) and when the cold phase of the PDO is in association with the easterly phase of QBO (cold phase of PDO-easterly phase of QBO-flood year) (Table 2). While the same is not observed for the cold phase of PDO and some of the years are in the westerly phase and some of the years are in the easterly phase that results in drought and flood over the Indian region (Table 2), it evidently shows that the warm phase of PDO ties well with the different phases of QBO for the flood and drought years as compared with the cold phase of PDO. Some recent studies suggested that the dry (wet) events are more likely over India when positive (negative) phase of ENSO coincides with the positive (negative) phase of PDO by weakening the walker and monsoon Hadley circulations induced by anomalous SST over the Pacific (Roy et al. 2003; Krishnamurthy and Krishnamurthy 2014). The anomalous Pacific SST are also substantially related to the frequency and intensity of the droughts over India in observations (Preethi et al. 2019).

Physical mechanism

The PDO and ENSO affect the SST, surface level pressure, and surface winds in much related way. The PDO and ENSO most apparently differ in the time scale. ENSO tend to persist in the order of at least 1 year whereas the PDO signature can last up to 30 years (Mantua and Hare 2002). A positive (negative) PDO index values indicate that the SST anomalies of the eastern extra part of tropical North Pacific are warmer (colder) than the western and central portions, which is the spatial pattern created by El Niño (La Nina) events. Thus, a positive or warm phase of PDO (negative or cold phase of PDO) produces climate and circulation pattern that are similar to El Nino (La Nina) (Gershunov and Barnett 1998). This does not mean that PDO physically controls ENSO, but somewhat, the subsequent climatic patterns interact with each other. On the other hand, the mechanism how the QBO influences the variability of ENSO and monsoon was hypothesized by Grey et al. (1992a, b). According to them, there are at least two different shear linked processes that may contribute to the modulation of ENSO by the QBO. First, the hydrostatic (thermal wind) effect in the Upper Troposphere and Lower Stratosphere (UTLS) region. At the equatorial zone, the convective activity may be modulated by the contrasting thermal regime attending the two phases of QBO due to hydrostatic effect in the UTLS region. Due to this effect, the east phase of QBO tends to favor the equatorial convection as compared with the west phase. Second, the vertical winds shear in the UTLS region (between approximately 200 and 50 hPa). The deep convection in the tropical area away from the equator may be promoted (reduced) by the west (east) phase of QBO. Any process which significantly alters the deep convective activity must also influence the local Walker and Hadley circulations and hence the Southern Oscillation and ENSO. During the easterly (westerly) shear phase of QBO, where the deep equatorial convection is enhanced (suppressed) while on the equator (off equator), monsoon convection is suppressed (enhanced). Thus, East (West) phase of QBO promotes the El Nino (La Nina) event. In a nutshell, it is interesting to say that during the warm phase of PDO which is similar to El Nino event, if the easterly (westerly) phase of QBO follows, there is a rising (sinking) motion and upper level divergence (convergence) in the central-eastern pacific, this is compensated by sinking (rising) motion and upper level convergence (divergence) in the maritime continent and Indian ocean and could lead to direct suppression (enhancement) of rainfall over India. However, during the cold phase of PDO which is similar to La Nina event, if the easterly (westerly) phase of the QBO follows, the signal is mixed and it is unlikely that severe drought and severe flood conditions occur over entire India.

Conclusions

The teleconnection between ISM rainfall over all India and its three different Indian regions (i.e., northeast, northwest, and peninsular region) with PDO index using the full series (1953–2016) as well as grouping of the data series according to the easterly and westerly phase of QBO was analyzed. From both concurrent seasons (JJA and JAS), the JAS shows stronger degree of association for ISM rainfall and PDO index over all India and northeast, northwest, and peninsular region. Further, northeast region shows the positive association between ISM rainfall and PDO index which generally enhanced for westerly phase of QBO during the concurrent seasons and a high CC values is obtained with 0.05% significant level in the succeeding winter season during the easterly phase of QBO. Moreover, the CC values for all India and northwest India is showing a strong negative association. For both concurrent and succeeding autumn season (SON), the CC values are increased during the easterly phase of QBO while for succeeding winter season (DJF), a remarkable increase is seen in CC value during the westerly phase of QBO with 0.05% significant level. The graphical representation shows the negative (positive) association between ISM rainfall anomaly and PDO index anomaly during the easterly (westerly) phases of

QBO for the concurrent season (JAS) over all India (northeast region). In addition, the warm phase of PDO is in association to easterly (westerly) phase of QBO which results to drought (flood) over India. However, the signal is mixed for both easterly and westerly phase of QBO for the cold phases of PDO.

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