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The Unified Response of the Atlantic Multidecadal Oscillation and Quasi-Biennial Oscillation on Indian Summer Monsoon Rainfall

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Abstract—This study investigates the relationship between Indian summer monsoon (ISM) rainfall and the Atlantic Multidecadal Oscillation (AMO) on a monthly and seasonal basis with respect to the quasi-biennial oscillation (QBO) during the period 1953–2016. The analysis is performed for full time series of monthly and seasonal ISM rainfall and AMO index data as well by regrouping according to the westerly and easterly phase of the QBO (at 50 hPa). A direct positive association is observed between ISM rainfall and the AMO for the full time series during the pre-monsoon (March–April–May) and winter (January–February) seasons via the Rossby wave train from the North Atlantic across South Asia, thus resulting in an increase in the temperature gradient between the Indian Ocean (IO) and Eurasia which strengthened the ISM. The strongest association was found during the pre-monsoon season and especially during April. The variability in ISM rainfall was more prominently modulated by the pre-monsoon warm phase of the AMO along with the westerly phase of the QBO as compared with the easterly phase. The elevated ISM rainfall during the warm AMO phase and westerly phase of the QBO ultimately triggered low IO sea surface temperature and salinity during September–October.

Keywords: Atlantic Multidecadal Oscillation, quasi-biennial oscillation, Indian summer monsoon, sea surface temperature, sea surface salinity, Indian Ocean.

1. Introduction

The Indian summer monsoon (ISM) is an active and most efficient branch of the South Asian monsoon system covering most of the tropics. The intraseasonal and interannual variability in monsoon precipitation and circulation have significant economic and social consequences for the people of India (Gadgil et al., 2004; Gadgil & Gadgil 2006). The geographical features of the Indian subcontinent and its associated atmospheric and oceanic factors affect the understanding and predictability of complicated meteorological phenomena (Charney & Shukla, 1981; Palmer, 1994). Agriculture is a very important part of the Indian economy, and the agricultural activity of India, which provides a living to more than 80% of the total population of the country and accounts for about 22% of the total Indian gross domestic product (GDP), is dependent on the southwest monsoon (Bhatla et al., 2019; Gadgil & Gadgil 2006; Prasanna, 2014). Therefore, understanding the ISM along with climate factors affecting the monsoon becomes very important. Climate scientists have always been concerned with understanding a climate feature located far from the area of interest, which is known as teleconnection. The ISM is affected by many such remotely located climatic parameters at different spatial and temporal scales. For example, Bhatla et al. (2016) studied the influence of the North Atlantic Oscillation (NAO) on ISM rainfall. The ISM has been observed to have multidecadal variability (Ding et al., 2013; Krishnamurthy & Krishnamurthy 2014; Shi et al., 2014), and according to these studies, less rainfall was observed during the periods of 1901–1930 and 1961–1990, and more rainfall was observed during 1871–1900 and 1931–1960.

The sea surface temperature (SST) in the Atlantic exhibits an oscillation with a period of 65–80 years on a multidecadal timescale and amplitude of 0.4 °C (Enfield et al., 2001; Schlesinger & Ramankutty, 1994), a phenomenon termed Atlantic Multidecadal

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Oscillation (AMO). Many studies have reported the association between the AMO and the Atlantic Meridional Overturning Circulation (AMOC) (Delworth & Mann, 2000; Knight et al., 2006; McCarthy et al., 2015). The two phases (positive and negative) of the AMO have different consequences. In the positive phase of the AMO, the northern Atlantic experiences warmer temperatures than average and cooler SST in the South Atlantic, and vice versa for the negative phase (Enfield et al., 2001; Knight et al., 2006; Zhang et al., 2016). The effects of such decadal to multidecadal oscillations on the ISM have been studied in various ways (Goswami et al., 2006; Li et al., 2008; Zhang & Delworth, 2006). Malik et al. (2017) investigated the effect of the AMO and Pacific Decadal Oscillation (PDO) on the ISM on decadal to multidecadal timescales; this research also revealed that most of the dry decades occur during a negative phase of the AMO and a concurrent positive phase of PDO. Moreover, on a global scale, the positive AMO phase can contribute to heavy rainfall in the African Sahel, wetter summer in northern Europe, efficient droughts in northeast Brazil, loss of sea ice in the Arctic, and a wetter ISM (Alexander et al., 2014). Warm AMO phases also favor drier conditions in North America and are found to contribute to the dust bowl drought across American and Canadian prairies during the 1930s (Knight et al., 2006). The warm AMO strengthens the ISM due to a positive anomaly of tropospheric temperature in late summer/autumn that delays the withdrawal of the monsoon, which indicates a direct relation between the ISM and AMO (Goswami et al. 2006). The effects of the negative AMO phase are often the opposite of what is observed in a positive phase, including drought conditions in the South Asian regions (Zhang et. al., 2016). Evidence from tree rings suggests that the AMO has existed for many centuries. In recent history, a warm phase of the AMO was observed during 1925–1965 followed by cool phase from 1965 to 1995, and the AMO has been positive from 1995 onwards (Enfield et al., 2001; Trenberth and Zhang 2017). Observations suggest that the warm AMO period is longer than the cold AMO period (Trenberth & Zhang 2017). Since the AMO is predictable, the relation between the ISM and AMO can be helpful for climate prediction and agricultural policies of India (Griffies & Bryan, 1997).

The lower stratospheric winds at 50 hPa affect the wind divergence at the upper troposphere to enhance cloud formation and dispersion (Yamazaki et al., 2020). Holton and Tan (1980) described how equatorial stratospheric winds at 50 hPa affect the global circulation, and as the ISM is a cross-equatorial phenomenon covering the Indian Ocean (IO) and the South Asian subcontinent, this study motivated the authors to investigate the effects of the quasi-biennial oscillation (QBO) on the ISM teleconnection. The study by Labitzke and Van Loon (1995) reported a significant relation between atmospheric elements and solar variability after the data were divided into the different phases of the QBO. The idea of grouping the data according to the phases of the QBO was explored by Holton and Tan (1980), Singh (1988), Chattopadhyay and Bhatla (1993a, 1993b, 1994, 2002), and Bhatla et al. (2013). The influence of the QBO on ISM rainfall describes how the teleconnection of the PDO and North Atlantic Oscillation (NAO) is significantly increased when data are divided into two groups, one for the QBO westerly phase and the second for the QBO easterly phase (Bhatla et. al., 2016). The study of the probable link between the PDO and ISM in regard to the QBO by Bhatla et al. (2020) explains how the statistical correlation between the PDO and ISM improves when the full time-series data are regrouped into westerly and easterly phases of the QBO. Therefore, the primary goal of this study is to investigate the relation between the ISM and AMO in the context of regrouped westerly/easterly phases of the QBO. The experiment was also carried out with the subsequent AMO indices to the corresponding monsoon season to see whether the variability in rainfall had any effect on the further evolution of the AMO. The Indian monsoon is a major weather phenomenon and it also affects the sea surface indices of the IO (Venugopal et al., 2018; Vinayachandran et al., 2009, 2015). Therefore, a good or poor ISM rainfall might be interlinked with IO sea surface indices, since QBO westerly and easterly phases are interlinked with ISM (Bhatla et al., 2020). Therefore, in this paper, the association of ISMR-AMO in the westerly and easterly phases of the QBO is investigated with its possible link between SST and sea surface salinity (SSS) anomalies of the IO with the ISM during different phases of the QBO.

2. Data and Methodology

The teleconnection of the ISM and AMO is studied in accordance with the QBO phases for the period 1953–2016. To identify the relationship between AMO and ISM series, the Pearson product-moment correlation approach is used (Obilor & Amadi, 2018). The AMO index is calculated by taking the annual mean Kaplan SST anomaly when excluding the North Atlantic (0°–70° N, 75°–7.5° W) and subtracting it from the annual mean SST anomaly averaged over the North Atlantic only. The AMO index is taken from the NOAA PSD (https://www.esrl.noaa.gov/psd/data/). The all-India summer monsoon rainfall data are obtained from the Indian Institute of Tropical Meteorology (IITM), Pune www.tropmet.res.in. Rainfall anomaly is used to determine the correlation coefficient (CC) and is computed by subtracting the difference from the long-term mean. In this study, the difference is taken from the mean rainfall during the period 1953–2016. The different phases of the QBO at 50 hPa are taken from the Institute of Meteorology, Free University Berlin http://strat-www.met.fu-berlin.de/products/cdrom/data/QBO/. The QBO phases only represent whether the wind direction at 50 hPa in the tropical region was easterly or westerly during most of a month, as these winds affect the wind divergence at the upper troposphere to enhance cloud formation and dispersion (Yamazaki et al., 2020). Further, the IO SST and SSS data are taken from the Ocean Reanalysis System 4 (ORAS4) (http://apdrc.soest.hawaii.edu/datadoc/ecmwf_oras4.php). The ORAS4 data used in this analysis are the latest ocean reanalysis product issued by the European Centre for Medium-Range Weather Forecasts (ECMWF) and use a sophisticated data assimilation methodology with model bias correction. It has 1° resolution output with 42 vertical levels for ocean interior presentation with 5-m depth on the surface. Again, the CC, SST, and SSS anomalies are calculated by taking the mean from the 1953–2016 data and differentiating with the time-series data. However, sometimes when there is no correlation, accidentally some correlation may be found, and to overcome this, Student's *t*-test is used, which uses several steps to give a significance level in percentage. In this process, the correlation coefficient of the two time-series data is calculated and the null hypothesis and the alternative hypothesis are expressed as CC = 0 and CC $\neq$ 0. In the next step, the test statistic is calculated using the formula

$$t = \frac{CC \times \sqrt{N-2}}{\sqrt{1-CC^2}}$$

where CC is the correlation coefficient and N is the number of degrees of freedom (Obilor & Amadi, 2018).

To analyze the effects of changes in the pattern of warm and cold phases of the AMO, global precipitation and temperature 2 m above ground are used. NCEP reanalysis data for the climatology period 1953–2016 are used for this analysis (https://www.esrl.noaa.gov/psd/data/). The mean surface temperature anomaly of the previous winter and pre-monsoon season (January-May) along with the mean precipitation anomaly is used to analyze the overall impact of the warm and cold phases of the AMO.

3. Results and Discussion

To examine the effect of the AMO on the ISM, a thorough analysis of the association of the AMO anomaly with the ISM anomaly is performed on a monthly, bimonthly, and seasonal basis from 1953 to 2016 (64 years). The statistical correlation technique is used to calculate the degree of association, and its significance is determined/tested using the *t*-test with suitable degrees of freedom. In this correlation analysis, the values of the AMO index are considered for each separate month, for a pair of 2 months (mean of 2 months), and for each season (mean of 3 months) for all the years separately, while the anomaly of the ISM for the months of June–September is used. In this study, the correlation between the AMO index anomaly and standardized ISM rainfall time-series anomaly is extremely weak, with a low confidence level (not significant), from May to December, so these months are not considered in the overall

Table 1

Correlation coefficient between AMO and ISM rainfall anomaly over all of India (for the full time series and during westerly and easterly phases of the QBO)

Month/Season	Westerly			Easterly			Full phase		
	T	CL (%)	CC	T	CL (%)	CC	T	CL (%)	CC
Jan(−)	2.74	99	0.41	−0.43	00	−0.09	1.64	80	0.20
Feb(−)	2.68	98	0.40	−0.70	50	−0.15	1.45	80	0.18
Mar(−)	2.06	95	0.31	0.13	00	0.03	1.69	90	0.21
Apr(−)	2.37	95	0.35	0.33	00	0.07	2.12	95	0.26
May(−)	2.32	95	0.35	−0.09	00	−0.02	1.83	90	0.23
JF(−)	2.79	99	0.41	−0.66	00	−0.14	1.57	80	0.20
FM(−)	2.12	95	0.32	−0.12	00	−0.03	1.61	80	0.20
MA(−)	2.30	95	0.35	0.34	00	0.07	1.94	90	0.24
AM(−)	2.31	95	0.37	0.10	00	0.03	2.03	95	0.25
DJF(−)	2.39	95	0.36	−0.66	00	−0.14	1.26	70	0.16
JFM(−)	2.77	99	0.41	−0.58	00	−0.12	1.67	90	0.21
FMA(−)	2.28	95	0.33	0.12	00	0.03	1.83	90	0.23
MAM(−)	2.04	95	0.31	0.25	0.00	0.06	1.96	90	0.24

T t-statistic, *CL* confidence level, *CC* correlation coefficient, *Full phase* for all time-series data, *Easterly* data of QBO easterly phase, *Westerly* data of QBO westerly phase and (-) denotes the previous month/season

analysis to study the link between ISM rainfall and AMO, and only the months of January–May separately and their combinations are considered for correlation analysis of the AMO and ISM rainfall of the respective year and also for the QBO (westerly/easterly) phases separately.

3.1. Association of ISM with AMO in the Context of Regrouped QBO Phases

In the first part of our investigation, the correlation between the AMO index of each year and the ISM rainfall time-series anomaly of the same year for the aforesaid time period is investigated separately on a monthly, bimonthly, and seasonal basis. Further, to investigate the influence of different phases of the QBO on AMO and ISM rainfall variability, 64 years of AMO data are divided into two groups as the easterly and westerly phases of the QBO, and correlation analysis is performed separately between standardized ISM rainfall time-series anomaly and AMO indices for the easterly and westerly phases of the QBO on monthly, bimonthly, and seasonal scales. It may be noted that to find the phases of the seasons (3 months), the phases of the QBO of each individual month were accounted for, but a few years showed no uniform phase throughout the 3 months of the season. In such cases, the phase which persisted for 2 months was taken as the QBO phase (e.g., if the QBO westerly phase was dominant during 2 months of a 3-month season and the easterly phase was dominant in the third month, then the whole 3-month season was considered in the QBO westerly phase). The outcome of the correlation analysis for the ISM rainfall with the AMO and for the easterly and westerly phases of the QBO separately is summarized in Table 1 along with the significance level of the CC.

On looking at the monthly correlation analysis, Table 1 shows a positive correlation between ISM rainfall and the AMO anomaly for full phases of the AMO, with a confidence level of 80% during January and February, 90% during March and May, and 95% for April with the highest correlation value of 0.26 (positive). This shows that AMO in the month of April is significantly correlated with ISM. These results also show that a positive AMO in the month of April can strengthen the ISM more rapidly than the AMO of the other months. However, it is interesting to note that when the AMO data are divided into groups of the QBO easterly and westerly phases, the positive magnitude of the CC is enhanced for the westerly phase compared to the easterly phase, with values of 0.41 for January (99% significance), 0.40 for February (98% significance), and 0.31, 0.35, and 0.35 for March, April, and May, respectively (each 95% significance). On the other hand, the CC magnitude is decreased for the easterly phases, and is even negative for January (−0.10) and February (−0.15), with a very low confidence level, while a very weak and insignificant correlation is identified for March, April, and May. The above discussion shows that the westerly phase of the QBO has a significant impact on the relation of AMO with ISM rainfall in each month, with the greatest impact in January, which can enhance the ISM rainfall strength, while the easterly phase of the QBO has an almost insignificant impact on the relation between the AMO and ISM rainfall. A graphical depiction has been created to further explain the previous discussion concerning the link between the ISM rainfall anomaly and AMO index, as well as the influence of the easterly and westerly phases of the QBO. For this purpose, the AMO index and rainfall anomaly for the easterly and westerly phases of the QBO in

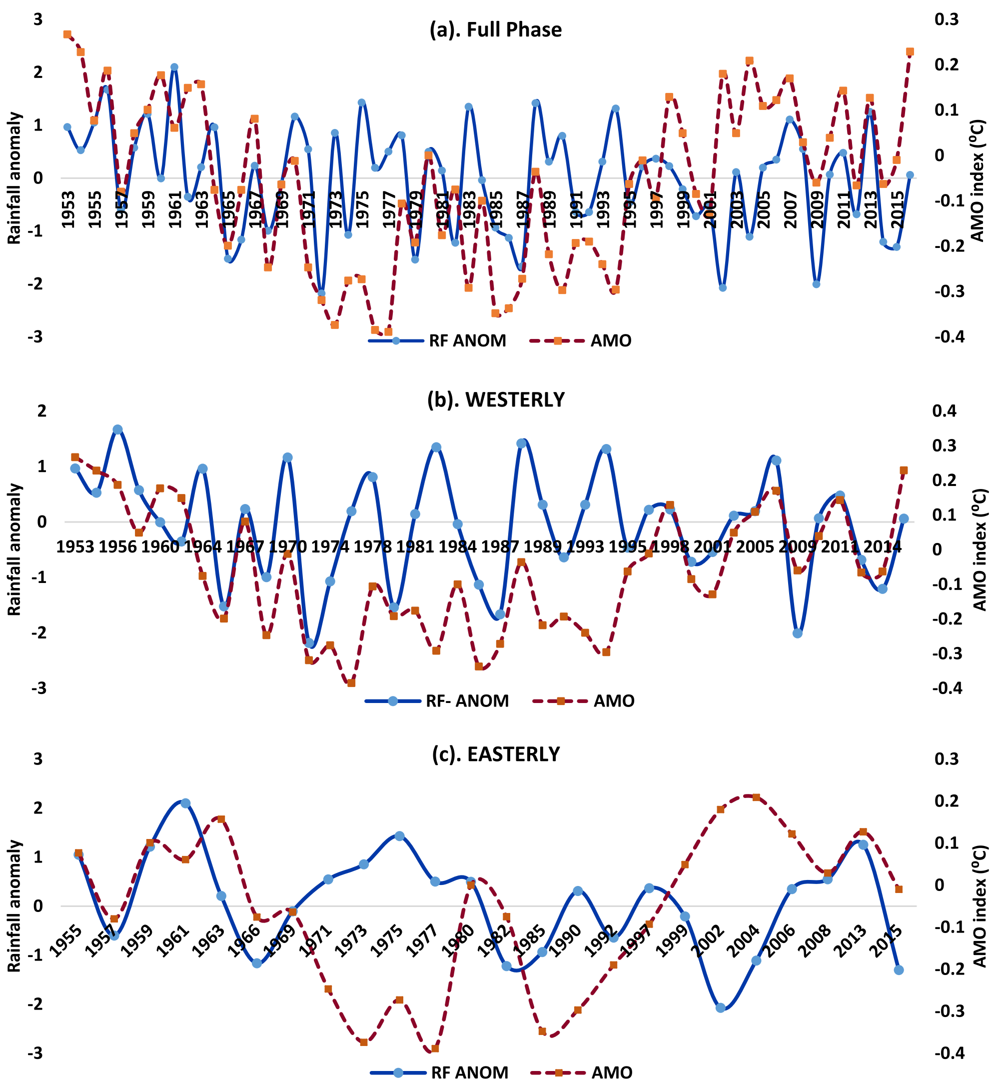

Figure 1
Time series of the standardized all-India summer monsoon rainfall anomalies (blue line) and AMO anomalies (orange line) during January for the period 1953–2016: **a** full time series, **b** QBO westerly phase, and **c** QBO easterly phase

January are chosen (highest CC between ISM rainfall and AMO for the QBO westerly phase with 99% and 98% confidence level). The interannual variation in the ISM rainfall anomaly with the AMO index, and year-wise easterly and westerly phases of the QBO for the month of January, is shown in Fig. 1. Figure 1a presents the interannual variation in the ISM rainfall anomaly with the AMO index for the month of January for all 64 years (1953–2016). It is clear that for most of the years, the AMO index of January is coherent with the ISM rainfall anomaly of the respective years, for example, onwards from 1953 to 1959, 1965 to 1971, 1987 to 1990, and 2003 to 2016. The corresponding results indicate that the AMO during most of January is directly proportional to ISM rainfall of the different years, which leads to a positive CC (0.20) that can enhance the ISM rainfall strength for a positive AMO phase. Figure 1b shows the interannual variation in the ISM with the westerly phase of the QBO for January. For this, only those years are chosen in which the QBO is in the westerly phase. It is shown from this graph that for most of the years of the westerly phase of the QBO for January, the AMO index is coherent with the ISM of the same year except for a few years. This indicates that the westerly phase of the QBO in January can positively strengthen all ISM, which is interesting to note. On the other hand, Fig. 1c shows the interannual variation in the ISM rainfall anomaly along with the AMO index during the easterly phase of the QBO years and indicates that there is a weak relation between them, with no coherence between these two variables. A similar analysis was performed (interannual variation in ISM with AMO for the QBO westerly/easterly phase) separately for the months of February, March, April, and May (not shown graphically), and it was observed that the westerly QBO phase of these months is positively associated with the ISM interannual variability, whereas the easterly QBO phase has no such relationship. The above analysis indicates that the AMO index (when the QBO is in the westerly phase) in pre-monsoon months separately can directly influence the ISM variability and its strength of the same year.

To further see the variability in ISM rainfall with the AMO and QBO (westerly/easterly) phase on a bimonthly scale [January–February (JF), February–March (FM), March–April (MA), and April–May (AM)], the CC between the ISM rainfall anomaly is calculated for the full time series of the AMO and grouping the dataset into the westerly and easterly phases of the QBO for the concurrent 2-month combination. This correlation analysis is performed for different bimonthly sets and for a different phase of the QBO, while by doing so the number of independent samples is reduced. In full time series, Table 1 shows a positive association of the ISM rainfall anomaly with the AMO index for every 2-month combination. Two concurrent combinations of 2 months, JF and FM, show a positive association with CC 0.20 and 0.20. During the months of MA and AM, CC values increase to 0.24 and 0.25, respectively (increased association), with a significant level of confidence. It is interesting to note a small progressive increase in CC values from concurrent JF to AM. These results suggest that when 2 months of AMO are chosen together, the degree of correlation between ISM and AMO is positive. After May, the combination of two concurrent months is not shown in Table 1 since the association between AMO and ISM is significantly weaker and insignificant. When the data of the AMO full time series are grouped according to the different phases of the QBO (westerly and easterly), some interesting results are obtained. It can be seen from Table 1 that for JF, FM, MA, and AM, the CC is markedly increased for the westerly phase of the QBO, with CC values of 0.41, 0.32, 0.35, and 0.37, respectively. The strongest enhancement occurs for the concurrent months of JF. Interestingly, it is noted that for the easterly phase of the QBO, the CC is negative and weak (insignificant) for JF and FM (−0.14 and −0.08), whereas for MA and AM the CC is increasing and positive (0.07 and 0.03) but still very small and insignificant. The overall results indicate that there is a positive association between ISM and the AMO when data are grouped for the westerly phase of the QBO on a concurrent bimonthly scale, but no significant relation is obtained for the easterly phase of the QBO; however, the association is strong and highly significant for the westerly phase of the QBO.

In line with the investigation of the relationship of the ISM rainfall anomaly with the AMO index and QBO westerly/easterly phase separately on a seasonal basis, correlation analysis is performed and the corresponding values are seen in Table 1. For this purpose, the concurrent seasons December–January–February (DJF) (December of the previous year), January–February–March (JFM), February–March–April (FMA), and March–April–May (MAM) have been chosen. It is noted that for the full phase of the AMO, the correlation between the AMO index and ISM rainfall anomaly during the antecedent winter season, i.e. DJF, is weak, with a CC of 0.16 at a 70% confidence level compared to the other seasons, JFM, FMA, MAM, where CC values are 0.21, 0.21, and 0.24 at a 90% confidence level with positive values. It is interesting to note that the correlation continues to strengthen even after removing December from DJF and with the inclusion of March as the season JFM, with an increasing confidence level from 70 to 90%. The peak correlation between the AMO and ISM rainfall anomaly is found for the season MAM, which shows that the AMO of MAM has a greater effect on enhancing the ISM during the aforesaid period. Furthermore, by separating the AMO and rainfall data for each phase, the correlation coefficient is calculated for the ISM rainfall anomaly with the AMO index for the easterly and westerly phases of the QBO. It is noted from Table 1 that for the QBO easterly phase there is a very weak correlation between the AMO and the ISM rainfall anomaly for each concurrent season, with a low level of confidence, which shows an insignificant relation of ISM with the QBO easterly phase in all chosen seasons. It is also interesting to note from Table 1 that the AMO index is highly correlated (high significant level) with the ISM rainfall anomaly in each concurrent season, with increasing values of CC for the QBO westerly phase. During the westerly phase of the QBO of JFM, AMO is positively and strongly associated with the ISM rainfall anomaly, with CC of 0.41 and a 99% confidence level, which is higher than any other season. The above analysis shows that grouping of data in the QBO westerly phase of each season can enhance and strengthen the ISM and AMO relationship, with the highest effect for JFM, whereas the easterly phase of the QBO of each season has no role in modifying the relationship with the ISM. To investigate the seasonal association between ISM and AMO and the QBO westerly/easterly phase, temporal plots of the ISM rainfall anomaly with AMO index, for the QBO westerly and easterly phases for DJF and JFM are shown in Fig. 2a–c and Fig. 3a–c, respectively. From Fig. 2a it is clearly seen that the association of the ISM rainfall anomaly with the AMO anomaly time series for DJF is consistent year to year except for the years 1962–1963, 1973–1975, 1982, 1994, and 2002. Also, it is interesting to note that for positive AMO phase years, the peak of the maximum ISM rainfall anomaly is overlain with the AMO index. To further see the variability in the ISM rainfall anomaly with the AMO index for the QBO westerly phase (Fig. 2b), only those years are chosen in which the QBO is in the westerly phase during DJF. It is interesting to note that for most years, the ISM rainfall anomaly is highly consistent in phase with the QBO westerly anomaly for DJF, except for a few years in which they are opposite in phase. Interestingly, it is noted from Fig. 2c (for the years of the QBO easterly phase) that for the years 1969–1980 and 1997–2013, the ISM rainfall anomaly variation with the QBO easterly phase for DJF is strongly opposite in nature. These results show a strong positive association of ISM rainfall anomaly with the AMO index for the westerly phase of the QBO in DJF; however, the easterly phase of the QBO has no such effect. A positive association also exists for the AMO full phase with the ISM for DJF but it is weak.

As there was a strong correlation (highly significant) between the ISM and AMO and the westerly QBO for JFM (Table 1), the year-wise variation in the ISM rainfall anomaly with AMO was also analyzed from Figs. 3a (full phase), b, and c (for the QBO westerly and easterly phases) for JFM. It is clear from Fig. 3a that for most of the year, the ISM rainfall anomaly follows the nature of the AMO index time series. These results suggest that the seasonal JFM AMO is proportional to the ISM. It is also interesting to note that for most of the years, the AMO full phase of JFM is strongly associated with the ISM compared to other years. Similarly, in Fig. 3b it is clear that onwards after the year 1964–2015 the AMO index of season JFM is nearly in the same phase as the ISM rainfall anomaly, which indicates that for the westerly phase QBO of JFM, the AMO is strongly associated with the ISM. Thus, Figs. 2 and 3 indicate that a positive link between

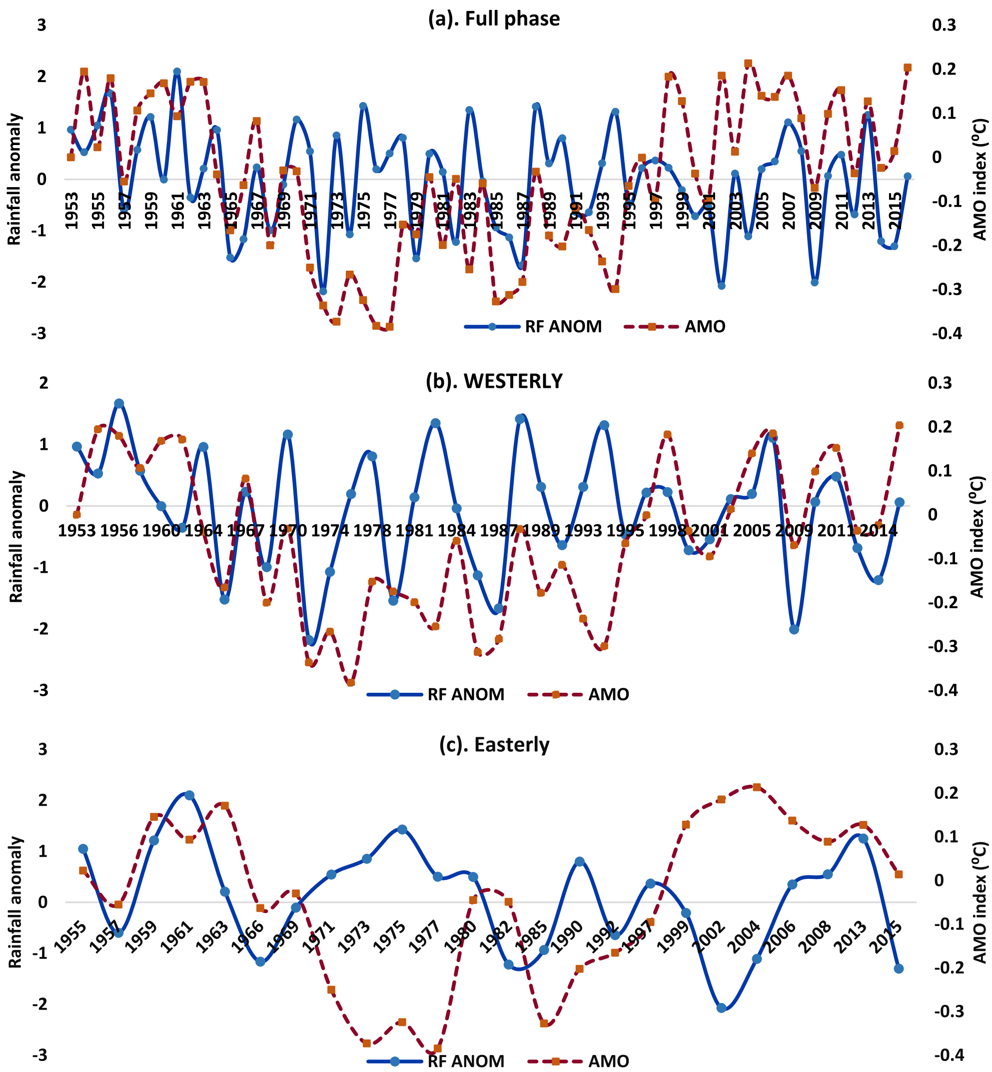

Figure 2

Time series of the standardized all-India summer monsoon rainfall anomalies (blue line) and AMO anomalies (orange line) during DJF (−) for the period 1953–2016: **a** full time series, **b** QBO westerly phase, and **c** QBO easterly phase

AMO and ISM rainfall anomaly occurs for the whole time series and strengthens for the QBO westerly phase on the seasonal scale, but no such relationship exists for the QBO easterly phase. Therefore, these results also indicatge that the CC during all four seasons, as well as the significance level of the correlation field, is increased after classifying the data according to the phases of the QBO, despite the reduction in the degree of freedom. The above analysis of the relationship of ISM with AMO and QBO for concurrent monthly, bimonthly, and seasonal scale indicates that the AMO has a positive association with ISM rainfall and the QBO westerly phase has a prominent role in enhancing the ISM.

As previously demonstrated, the ISM has a significant positive relationship with the AMO index during the QBO westerly phase rather than the AMO index during the QBO easterly phase. Because the nature of the link of ISM with AMO differs during the easterly and westerly phases of the QBO, the geographical distribution of the ISM rainfall anomaly is examined separately for the easterly and westerly

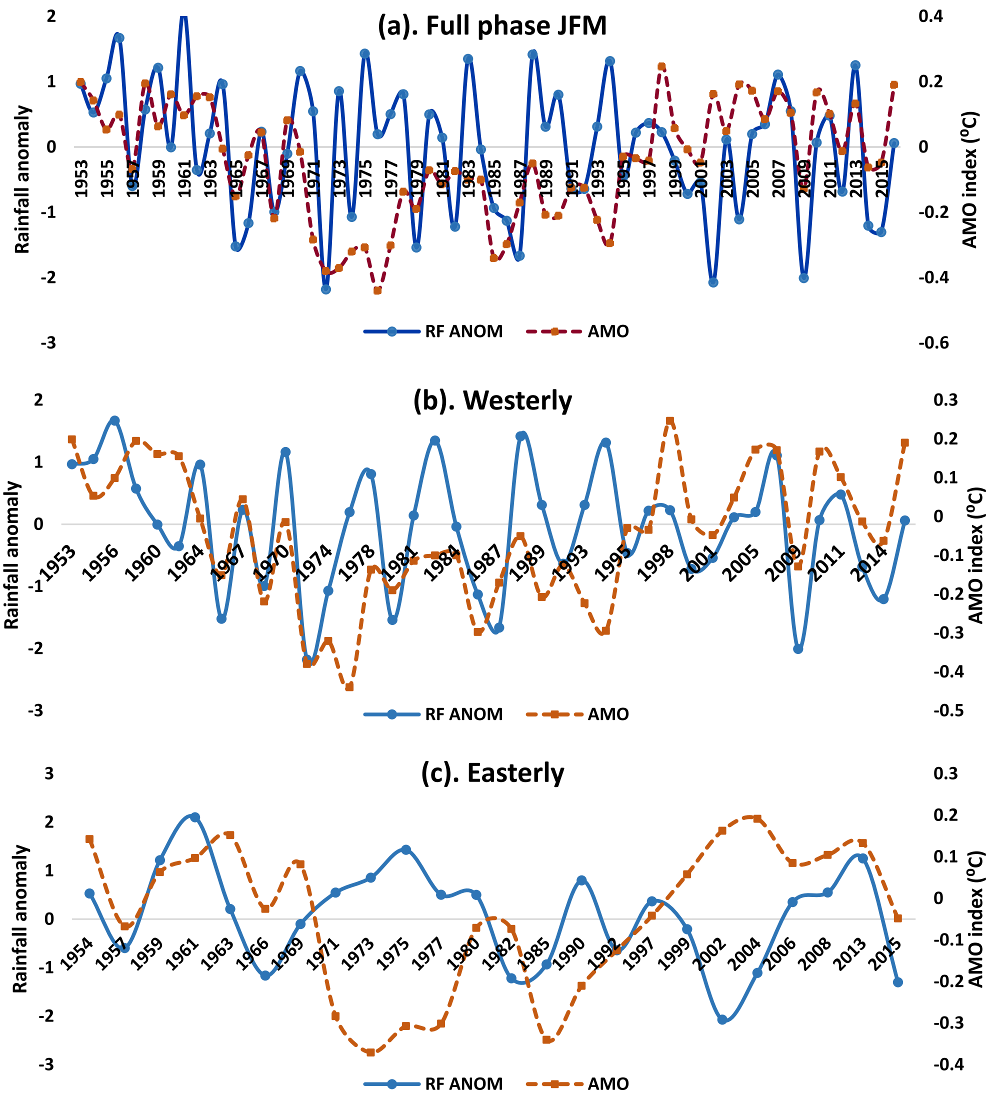

Figure 3

Time series of the standardized all-India summer monsoon rainfall anomalies (blue line) and AMO anomalies (orange line) during JFM for the period 1953–2016: **a** full time series, **b** QBO westerly phase, and **c** QBO easterly phase

phases of the QBO during one of the years of positive and negative AMO. Figure 4 presents the mean ISM rainfall anomaly spatial distribution for the two consecutive years 1956–1957 and 2002–2003 (AMO was in a positive cycle) when the QBO of JFM of these years was in easterly and westerly phases, respectively. From Fig. 4a (when the QBO of JFM was in the easterly phase for the year 1957 while AMO was in the positive phase), normal to below normal rainfall is seen in the states of northern, central, and eastern India (Madhya Pradesh, Uttar Pradesh, Bihar, Jharkhand, Chhattisgarh, Odisha). In the previous year, 1956, when the QBO was in its westerly phase during JFM (AMO in positive mode), from Fig. 4b positive anomalies of rainfall are seen over the northern, eastern, central, and western states (Madhya Pradesh, Uttar Pradesh, Bihar, Jharkhand, Chhattisgarh, Odisha, Gujrat, Rajasthan). Similar results were observed for the ISM rainfall anomaly (Fig. 4c, d) for the two consecutive years 2002 and

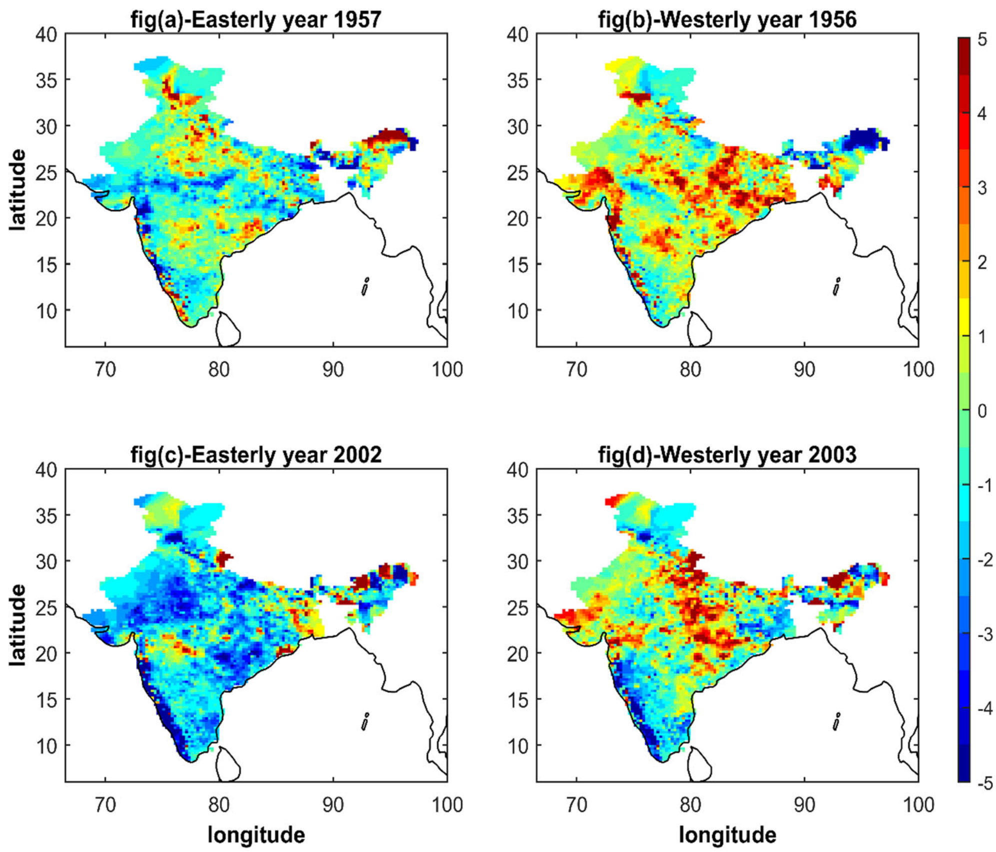

Figure 4
Spatial plot of mean JJAS rainfall anomaly for westerly years 1956 and 2003 (**b**, **d**) and easterly years 1957 and 2002 (**a**, **c**) of JFM during the positive cycle of the AMO

2003 when the QBO was in easterly and westerly phases, respectively. Further, it is noted that for the year 2003 when JFM was in the westerly phase, the ISM rainfall anomaly over Uttarakhand, Delhi, and Arunachala Pradesh was positively affected. Similarly, the spatial distribution of the ISM rainfall anomaly for the consecutive years 1979–1980 and 1989–1990 (AMO was in a negative cycle) was examined while the QBO of JFM in these years was in easterly and westerly phases, respectively. Figure 5a, c presents the ISM rainfall anomaly for the easterly phase of the QBO in JFM during the negative phase of the AMO. It is clear from these figures that the northern, eastern, central, and some parts of western states of India have a positive rainfall anomaly. Looking at the ISM rainfall anomaly (Fig. 5b, d) during the westerly phase of the QBO in JFM during the negative phase of the AMO, a negative rainfall anomaly is seen in northern, eastern, and central India. The high negative anomaly is seen for the year 1979 from Jammu to West Bengal and Uttar Pradesh to Chhattisgarh. We obtain similar results for other years and other seasons (not shown). The above study clearly shows that during the positive phase of the AMO, higher/lower rainfall is observed along the Western Ghats, central India, and the eastern and western peninsula in the westerly/easterly phase of the QBO, and inverse results are noted during the negative phase of the AMO. This suggests that the obtained results are unlikely to occur by chance, but rather there is a solid scientific reason behind this, indicating that the QBO at 50 hPa has a significant association with ISM rainfall, which is not only regionally different but also seasonally

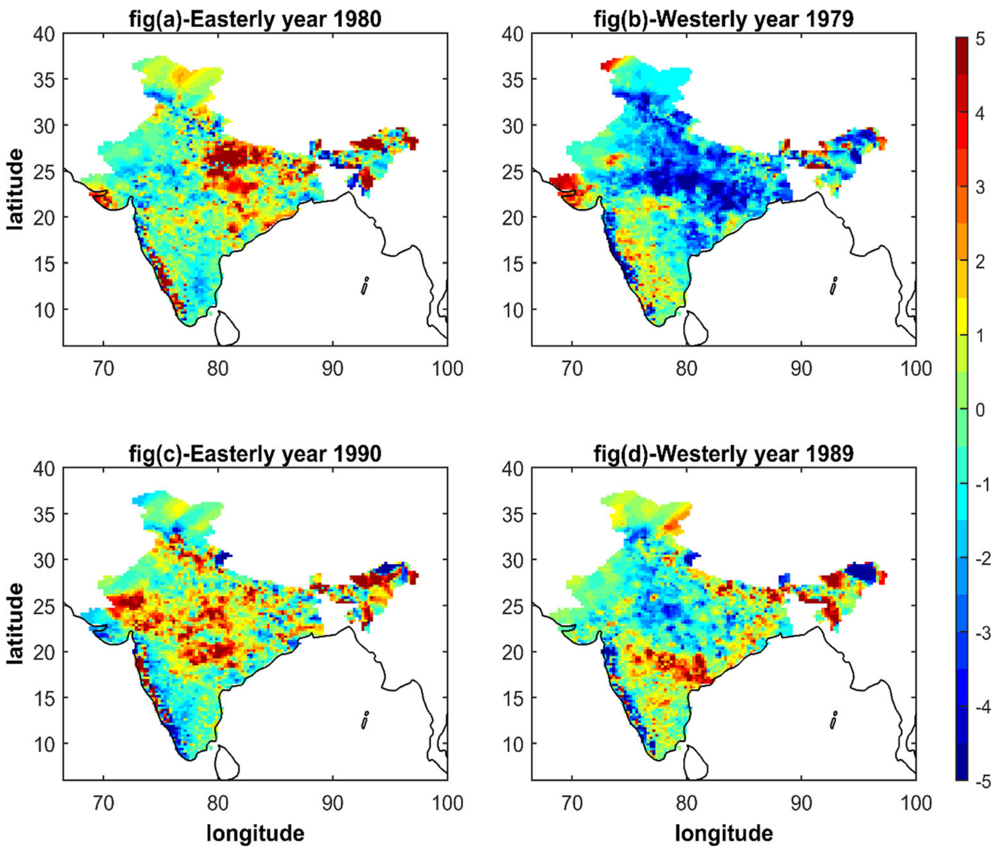

Figure 5
Spatial plot of mean JJAS rainfall anomaly for westerly years 1979 and 1989 (**b**, **d**) and easterly years 1980 and 1990 (**a**, **c**) of JFM during the negative cycle of the AMO

different. This shows the influence of the stratospheric circulation on tropospheric wind anomalies with a different interaction.

3.2. Analyzing the Correlation Between ISM Rainfall and IO Indices for the Full Phase and by Regrouping Data in the QBO Westerly and Easterly Phases

The above discussion illustrates the significant association of the ISM with the AMO full time series. The AMO in the westerly phase of the QBO shows a stronger and more significant relation with ISM compared to the full phase, whereas the easterly phase shows no significant relation during concurrent previous months and seasons. Many studies show that the ISM has a prominent effect on surface ocean variables of the IO and vice versa (Clark et al., 2000; Huang, 2001; Krishnamurthy & Goswami, 2000; Rao & Goswami, 1988; Terray et al., 2003, 2005). Because the ISM is influenced by the AMO (during distinct phases of the QBO), this study explored the relationship of surface ocean variables of the IO (SST and SSS) with ISM rainfall during different phases (westerly/easterly) of the QBO at 50 hPa and analyzed it for warm and cold periods of the AMO. Since the AMO affects the ISM, analyzing the relationship of IO indices and ISM and relating the results with the AMO-ISM relationship can reveal the effects of the AMO on IO sea surface indices. For this purpose, correlation analysis is performed between the SST and SSS of the IO with the ISM anomaly for full time series and for the easterly and westerly phases of the QBO for the period of 1958–2016. The corresponding

Table 2

Correlation coefficient between SSS anomaly and ISM rainfall anomaly over all of India (for the full time series and during westerly and easterly phases of QBO)

Month/Season	Full phase			Westerly			Easterly		
	CC	T	CL (%)	CC	T	CL (%)	CC	T	CL (%)
Jul	−0.18	−1.42	80	−0.30	−1.82	92	−0.04	−0.18	00
Aug	−0.19	−1.52	80	−0.36	−2.33	96	0.08	0.40	60
Sep	−0.28	−2.29	96	−0.45	−3.29	99	0.00	0.01	00
Oct	−0.21	−1.64	80	−0.36	−2.48	98	0.13	0.56	00
Nov	−0.14	−1.09	60	−0.31	−1.94	94	0.19	0.95	60
Dec	−0.15	−1.13	60	−0.25	−1.55	80	0.09	0.40	00
JAS	−0.22	−1.76	92	−0.41	−2.76	99	0.05	0.25	00
ASO	−0.23	−1.86	92	−0.40	−2.77	99	0.02	0.09	00
SON	−0.22	−1.75	92	−0.38	−2.73	99	0.17	0.76	00
OND	−0.17	−1.33	80	−0.32	−2.07	95	0.13	0.62	00

T t-statistic, *CL* confidence level, *CC* correlation coefficient, *Full phase* for all time-series data, *Easterly* data of QBO easterly phase, *Westerly* data of QBO westerly phase

CC values between the SSS anomaly and ISM rainfall anomaly for the easterly and westerly phases of the QBO are shown in Table 2 separately**.** For this purpose, the SSS was evaluated from July to December (post-monsoon months) of concurrent years, because the correlation of ISM rainfall with SSS from January to June is very weak and insignificant; therefore, these months are not included. This study revealed a negative association between SSS anomaly data and ISM rainfall for all months and seasons, demonstrating a reduction in salinity with higher positive rainfall anomaly and vice versa. The highest negative correlation is found for the month of September (−0.28), significant up to a 96% confidence level. This result shows that during the ending month of the summer monsoon (September), the SSS of the IO will lead to lower rainfall than in all other months. This study further investigates the correlation between the ISM and SSS for different phases of the QBO (easterly/westerly), and the CC values are given in Table 2. It is clear that there is no significant correlation between ISM rainfall and SSS for the easterly phase during any month/season, while for the westerly phase the negative correlation is enhanced with higher significant levels in each month and season. Again, it is noted that for the westerly phase of the QBO, the highest negative correlation between SSS and ISM rainfall is found for the month of September (−0.45) and the concurrent seasons (JAS, ASO, and SON) which include September with the highest confidence levels. The aforementioned study reveals a negative link between SSS and ISM for all of the selected months/seasons, and this negative relationship is amplified during the westerly phase of the QBO for the concurrent months and seasons; however, no relationship was observed between SSS and ISM rainfall on a monthly and concurrent seasonal scale during the easterly phase of the QBO. For the month of September, the association of SSS with the ISM is highly negative, so the graphical representation of the teleconnection between the ISM rainfall anomaly and SSS anomaly for the full time series and for the years of the westerly and easterly phases of the QBO are shown in Fig. 6a–c for the month of September of concurrent years. The number of data values reduces from 59 for the full time series to 35 for the westerly and 24 for the easterly phase of the QBO. Figure 6a, b show an inverse relationship between ISM rainfall and SSS anomaly for all time-series data and during the westerly phase of the QBO for the concurrent September months. It is also noted from Fig. 6b that this inverse association is very strong for the westerly phase. Overall, the above observations indicate that the SSS of the IO decreases during the end of the monsoon and post-monsoon with a positive rainfall

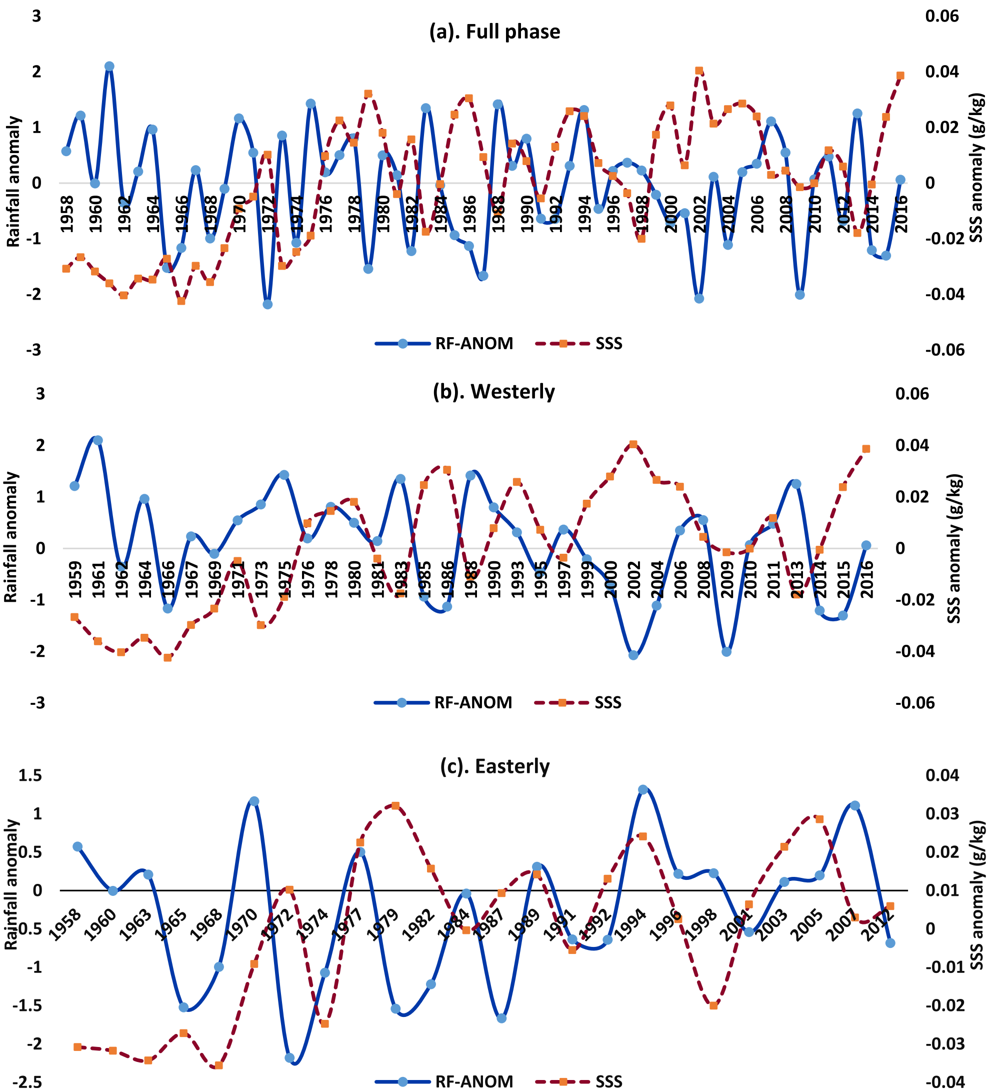

Figure 6

Time series of SSS anomalies (blue line) and all-India summer monsoon rainfall anomalies (orange line) during the month of September: **a** full time series, **b** QBO westerly phase, and **c** QBO easterly phase

anomaly during the summer months (inverse association with ISM and vice versa for a negative ISM rainfall anomaly year). It should be kept in mind that for the QBO westerly phase, even after a decrease in the number of degrees of freedom, the correlation and corresponding calculated *t*-values increase, and hence the confidence level increases.

The correlation analysis between IO SST and ISM rainfall is performed for the full time series as well as the QBO westerly and easterly phases and analysed for the warm and cold periods of AMO. For this purpose, the SST data have been taken for the 59-year full time series (1958–2016) and by dividing the data for the easterly and westerly phases of the QBO separately. Table 3 represents the calculated values of the CC by the method described in the above section between the SST anomaly and ISM rainfall anomaly. In the correlation analysis for the IO SST and ISM rainfall, the months with significant results are shown in Table 3. It is clear that for the full time-series data,

Table 3

Correlation coefficient between SST anomaly and all-India ISM rainfall anomaly for the full, westerly and easterly phases of the QBO during 1958–2016

Month/Season	Full phase			Westerly			Easterly		
	CC	T	CL (%)	CC	T	CL (%)	CC	T	CL (%)
Jan	0.06	0.43	00	0.26	1.63	90	−0.33	−1.68	90
Feb	0.10	0.75	00	0.26	1.65	90	−0.22	−1.02	60
DJF(−)	0.10	0.76	00	0.30	1.91	94	−0.28	−1.36	60
Aug	−0.14	−1.10	60	−0.35	−2.24	96	0.15	0.72	00
Sep	−0.17	−1.32	80	−0.32	−2.01	95	0.03	0.13	00
Oct	−0.21	−1.65	90	−0.40	−2.82	99	0.20	0.82	00
Nov	−0.18	−1.43	80	−0.38	−2.58	98	0.14	0.69	00
Dec	−0.31	−2.56	98	−0.46	−3.36	98	0.01	0.05	00
ASO	−0.18	−1.37	80	−0.34	−2.25	96	0.04	0.21	00
SON	−0.19	−1.51	80	−0.39	−2.80	99	0.29	1.32	60
OND	−0.24	−1.93	94	−0.43	−3.04	99	0.10	0.45	00

T t-statistic, *CL* confidence level, *CC* correlation coefficient, *Full phase* for all time-series data, *Easterly* data of QBO easterly phase, *Westerly* data of QBO westerly phase, *DJF(−)* previous winter

the correlation is very weak between the SST anomaly and ISM rainfall anomaly and insignificant for the months of January, February, and August of the concurrent years, while from September to December the correlation is negatively increasing, with the highest negative for the month of December (−0.31) with a 98% confidence level. For the full time series, the data analysis correlation is positive but statistically insignificant during the pre-monsoon months, whereas the correlation is negative for the post-monsoon months as well as for winter months. This may indicate that a higher IO SST during the pre-monsoon period can be an indicator of a good ISM, and a good ISM can be an indicator of warm SST. Further, it is seen that for the concurrent seasonal scale, the highest negative correlation (−0.24) between ISM rainfall and SST is seen for OND. Furthermore, when the SST data were separated according to the easterly and westerly phases of the QBO, a highly negative association was found between ISM rainfall and SST in the westerly phase during the months of August–December, as well as the corresponding season of concurrent years. A large negative correlation with a significant confidence level was found in the months of October (−0.40), November (−0.38), and December (−0.46). A strong negative correlation between SST and ISM rainfall was also found for all the seasons with maximum negative CC in the season OND (−0.43) for the westerly phase. During the easterly phase of the QBO, there is a very weak positive/negative correlation with no significance level between ISM and SST in nearly all months and seasons of concurrent years but only for the month of January is the CC somewhat negative with a 90% confidence level. The calculated CC values in Table 3 clearly show that the association of SST with ISM rainfall is strongly opposite from the months of August to December and for all chosen seasons during the full time-series data, while this inverse association is very strong in the westerly phase of the QBO. It is also noted that this inverse association is positive and weak for January and February during the westerly QBO phase. For the QBO easterly phase, this association has no significant relation. To further investigate the variability of the SST anomaly with the ISM rainfall anomaly, temporal variation is shown in Fig. 7a–c for the month of October for the full time series and for the westerly and easterly phases of the QBO, respectively. Figure 7a clearly shows mostly an inverse relation between ISM rainfall and the SST anomaly, whereas for a few years the relation between them is in the same phase with a weak approaching nature. Interestingly, it is noted from Fig. 7b that during the years of the westerly phase of the QBO, the inverse relation between the SST anomaly of October and

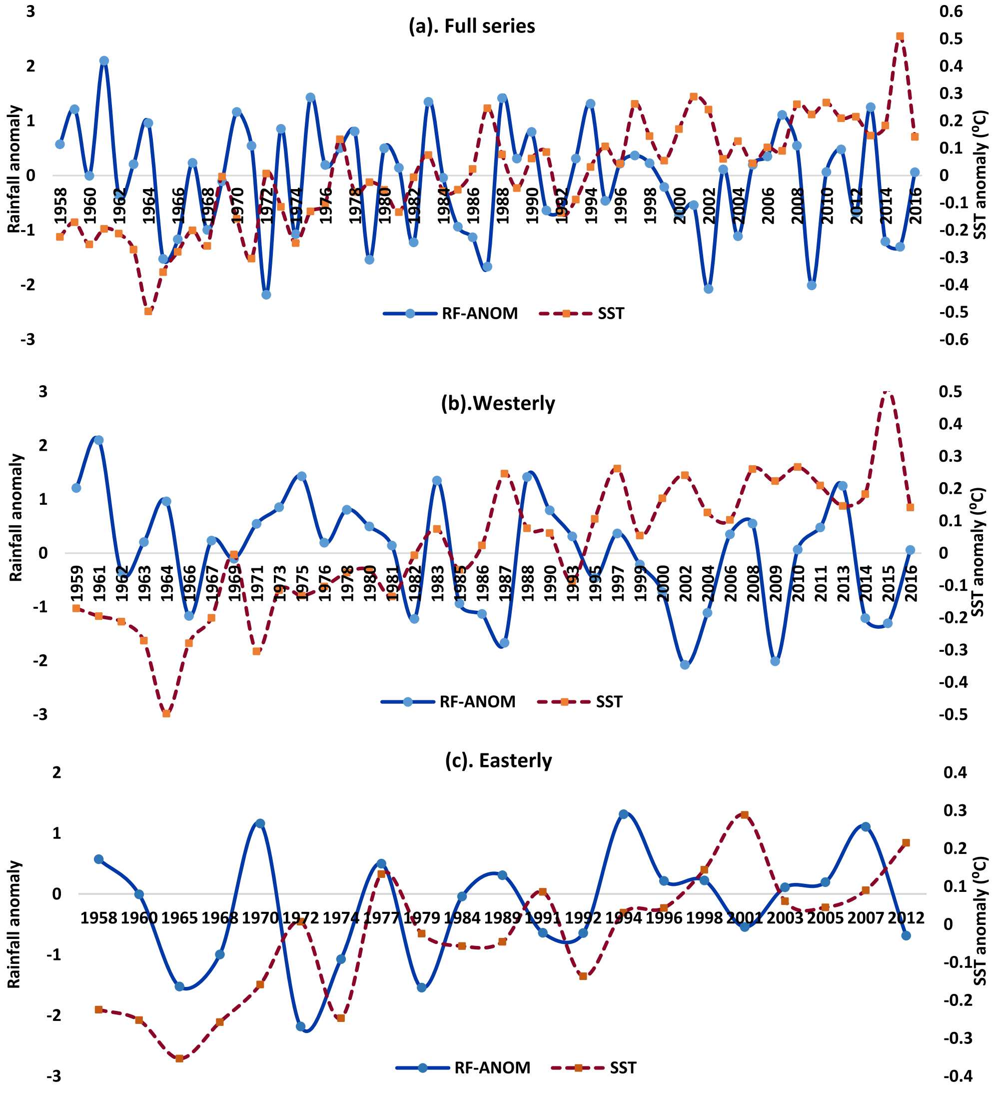

Figure 7
Time series of SST anomalies (blue line) and all-India summer monsoon rainfall anomalies (orange line) during the month of October: **a** full time series, **b** QBO westerly phase, and **c** QBO easterly phase

ISM rainfall anomaly exists for the whole time period. It is also noted that this inverse relation is very steady and strong compared to the full time-series data. The above discussion shows that the SST of the IO decreases with an increase in ISM rainfall (inverse association with ISM) during the full time-series data and during the westerly phase of the QBO; more importantly, the degree of inverse association is very strong for the westerly phase of the QBO. Overall, the above results show that there is a clear and significant effect of the QBO westerly phase on the ISM-AMO relationship and also on the ISM-SST/SSS relationship, implying that stratospheric oscillations can also have an impact on ocean surface indices.

As discussed above, the ISM has a negative and significant relationship with the SST and SSS of the IO during the full time-series data and the westerly phase of the QBO versus the easterly phase in post-monsoon months/seasons. Because the association of the ISM with SST and SSS differs in nature during the post-monsoon season during different phases of

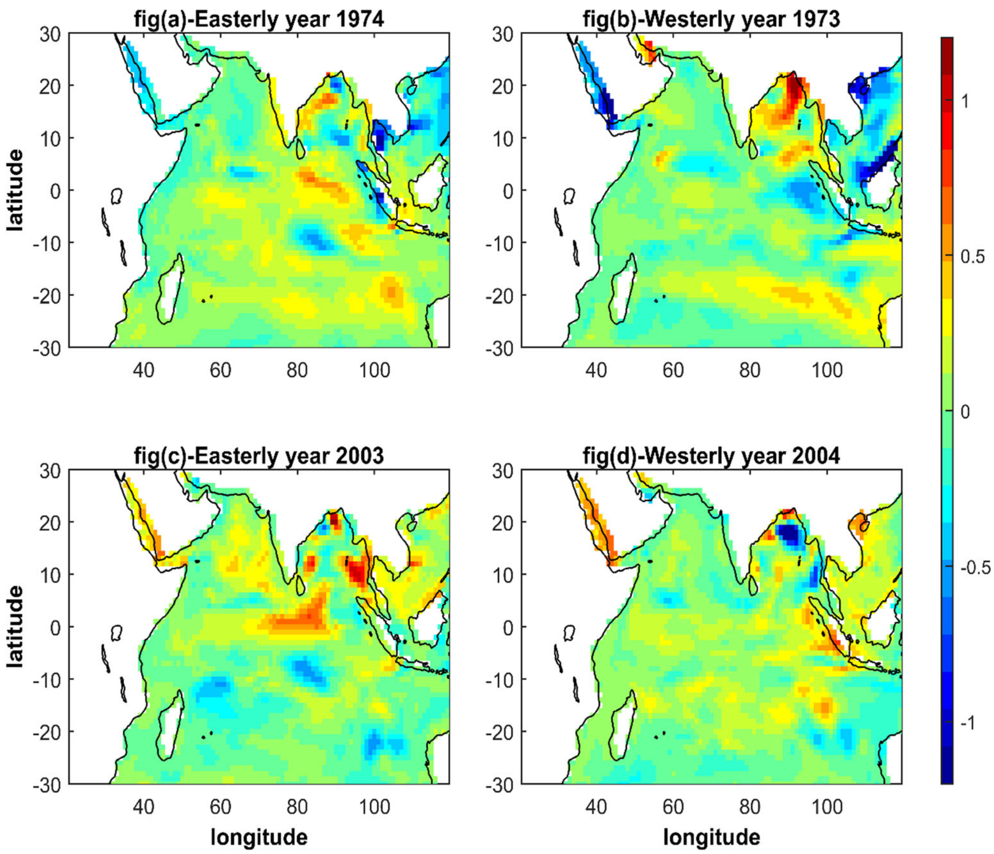

Figure 8
Spatial plot of mean September SSS anomaly for easterly years **a** 1974, **c** 2003, and westerly years **b** 1973, **d** 2004 during negative AMO cycles

the QBO, the spatial distribution of the SSS and SST anomaly were plotted separately for the QBO easterly and westerly phases during one of the years of positive and negative modes of AMO. Figure 8 presents the spatial distribution of the SSS anomaly for the month of September for two consecutive years, 1973 and 1974 (AMO was in negative phase), and 2003 and 2004 (AMO was in positive phase) when the QBO was in the easterly and westerly phases in different years. From the first row of Fig. 8 (AMO is in negative phase), it is seen that during the westerly QBO phase of 1973 and easterly QBO phase of 1974, the SSS anomaly variation is very weak and nearly the same in most of the study domain; however, it is interesting to note that the SSS anomaly is very strong in the Bay of Bengal (BoB) during the westerly QBO phase compared to the easterly QBO phase. Interestingly, from the second row of Fig. 8, when the AMO is in a positive phase, the SSS anomaly is relatively weak in the BoB during the westerly phase of the QBO in 2004, but this anomaly variation is strong in the BoB during the easterly phase of the QBO. It is also noted that the Arabian Sea (AS) and equatorial IO SSS anomaly is slightly stronger in the easterly phase of the QBO (2003) than in the westerly phase of the QBO (2004), but this difference is very small. This analysis shows that there is an inverse relation between the SSS and ISM as clearly depicted from the above discussion. The positive phase of the AMO shows high rainfall (dominant in the westerly phase of the QBO) and hence less surface salinity and vice versa in the AMO negative phase. The dominant effect is shown in the eastern part of the southern IO and BoB (highest)

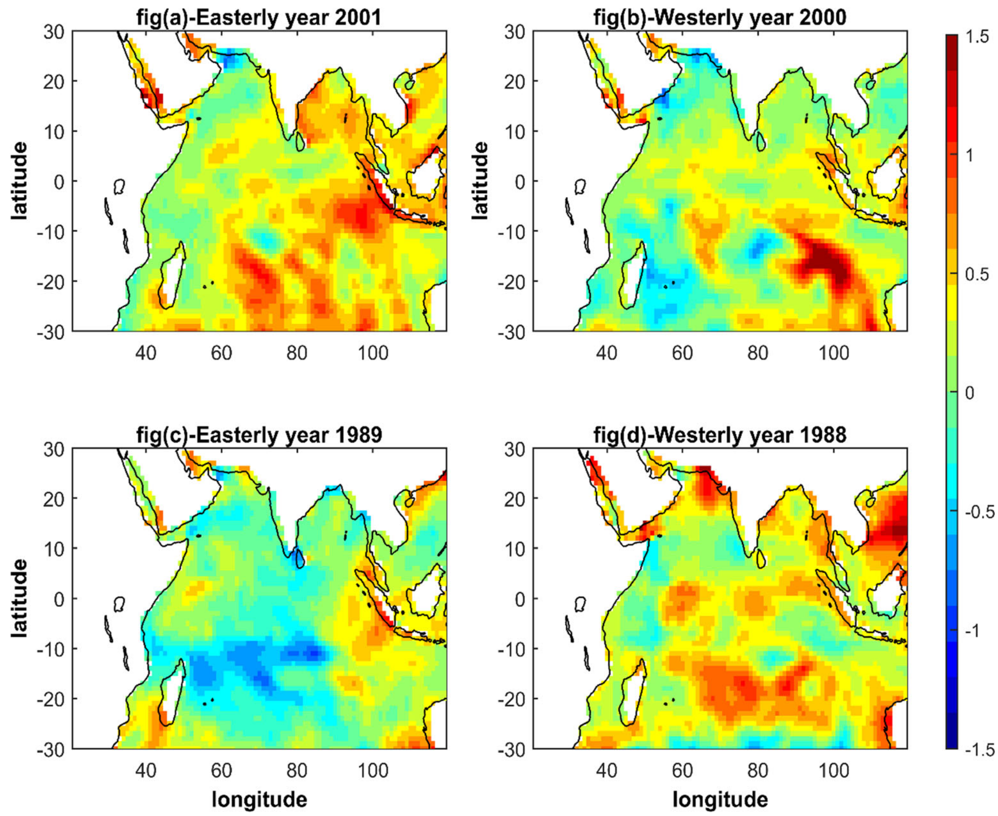

Figure 9
Spatial plot of mean October SST anomaly for westerly years 2000 and 1988 (**b**, **d**) and easterly years 2001 and 1989 (**a**, **c**) during AMO positive (first row) and negative (second row) cycles

Table 4

Correlation of pre-monsoon AMO with post-monsoon IO SSS for the period 1958–2016

AMO	JAS			ASO			SON			OND		
Month/Season	CC	T	CL	CC	T	CL	CC	T	CL	CC	T	CL
Jan	−0.08	−0.64	0	−0.08	−0.58	0	−0.13	−0.98	60	−0.21	−1.69	90
Feb	−0.17	−1.35	80	−0.17	−1.31	80	−0.21	−1.68	90	−0.29	−2.36	95
Mar	−0.16	−1.28	70	−0.17	−1.34	80	−0.20	−1.59	80	−0.25	−2.00	95
Apr	−0.11	−0.86	50	−0.15	−1.14	70	−0.21	−1.66	90	−0.27	−2.24	95
May	0.03	0.20	0	−0.01	−0.05	0	−0.06	−0.44	0	−0.12	−0.92	60
JFM	−0.15	−1.14	70	−0.15	−1.13	70	−0.19	−1.48	80	−0.26	−2.12	95
FMA	−0.15	−1.19	70	−0.17	−1.30	80	−0.22	−1.70	90	−0.28	−2.28	95
MAM	−0.08	−0.63	0	−0.11	−0.84	0	−0.16	−1.24	70	−0.22	−1.75	90

T t-statistic, *CL* confidence level, *CC* correlation coefficient

region compared to AS and other domains. Furthermore, Fig. 9 depicts the spatial distribution of the SST anomaly (October) over the IO during successive years of warm AMO (2000 and 2001) and cold AMO (1988 and 1989) periods at a distinct phase of the QBO. From row 1 of Fig. 9, it is seen

Table 5

Correlation of pre-monsoon AMO with post-monsoon IO SST for the period 1958–2016

AMO	JAS			ASO			SON			OND		
Month/Season	CC	T	CL	CC	T	CL	CC	T	CL	CC	T	CL
Jan	−0.20	−1.61	80	−0.19	−1.46	80	−0.17	−1.32	80	−0.15	−1.13	70
Feb	−0.23	−1.82	90	−0.21	−1.63	80	−0.18	−1.37	80	−0.15	−1.12	70
Mar	−0.28	−2.31	95	−0.26	−2.09	95	−0.21	−1.67	90	−0.16	−1.24	70
Apr	−0.34	−2.88	99	−0.32	−2.69	99	−0.29	−2.38	95	−0.25	−2.02	95
May	−0.43	−3.93	99	−0.40	−3.59	99	−0.35	−3.04	99	−0.30	−2.47	98
JFM	−0.25	−2.02	95	−0.23	−1.82	90	−0.20	−1.53	80	−0.16	−1.22	70
FMA	−0.29	−2.44	98	−0.27	−2.22	95	−0.24	−1.88	90	−0.19	−1.52	80
MAM	−0.36	−3.17	99	−0.34	−2.90	99	−0.30	−2.46	99	−0.25	−1.99	90

T t-statistic, *CL* confidence level, *CC* correlation coefficient

that during the positive phase of the AMO, the SST of the IO is much higher during the easterly phase of the QBO (2001) than the westerly phase in the entire domain. The highest positive SST anomaly is seen in the BoB and southern IO during the easterly QBO phase, which is absent in the westerly phase of the QBO. The AS also shows a strong SST anomaly during the easterly phase of the QBO. Similarly, row 2 of Fig. 9 demonstrates that during the cold phase of the AMO (years 1988 and 1989), the SST of the whole IO is much higher in the westerly phase (1988) than in the easterly phase of the QBO (1989). The highest change is seen with the BoB, AS, and southern IO basin. The effect of the QBO westerly phase mainly appears in the eastern equatorial IO, southeastern IO, and the BoB, and this might be because of higher precipitation during westerly years, causing more fresh water and higher river runoff in the region. The overall results show that the eastern equatorial, BoB, and the southern IO are mostly affected in different phases of the QBO. Since the QBO is a tropical phenomenon, the BoB and the eastern equatorial IO can have a direct effect through it, but the effects on the southern part must be due to some indirect influence of some other atmospheric or oceanic phenomenon.

SSS and SST in the IO decreases due to enhanced precipitation across the Indian subcontinent during the warm phase of the AMO, as described in the earlier segment (Tables 2 and 3). The correlation study of AMO with the IO indices displayed in Tables 4 and 5 yields similar results. Tables 4 and 5 provide CC values and the associated calculated value of t-statistics. The confidence level for the *t*-values with a certain degree of freedom have been provided from the Student's *t*-table. Table 4 describes the negative correlation between AMO (January–May) and the seasonal mean SSS of IO from July to December, whereas Table 5 depicts the negative relationship between AMO and SST. The correlation of AMO and SSS of IO shows significant results for pre-monsoon AMO and post monsoon SSS of IO. Also, the late monsoon to early post-monsoon SST of IO shows a significant relationship with the pre-monsoon AMO.

3.3. *Possible Physical Mechanism for the Association of ISM Rainfall with AMO and QBO*

The CC (Table 1) showed a strong in-phase relation between AMO and ISM rainfall for the westerly QBO phase. The study by Zhou et al. (2015) concluded that a positive AMO phase enhances the warm SST response in the Indo-Pacific, and so the easterlies in the equatorial western Pacific are strengthened, which leads to the intensification of the ISM. Similarly, the studies by Li et al. (2008) and Wang et al. (2009) conclude that the tropospheric warming over western Asia and Europe during the positive AMO phase increases the meridional temperature gradient between the IO and Eurasia, which

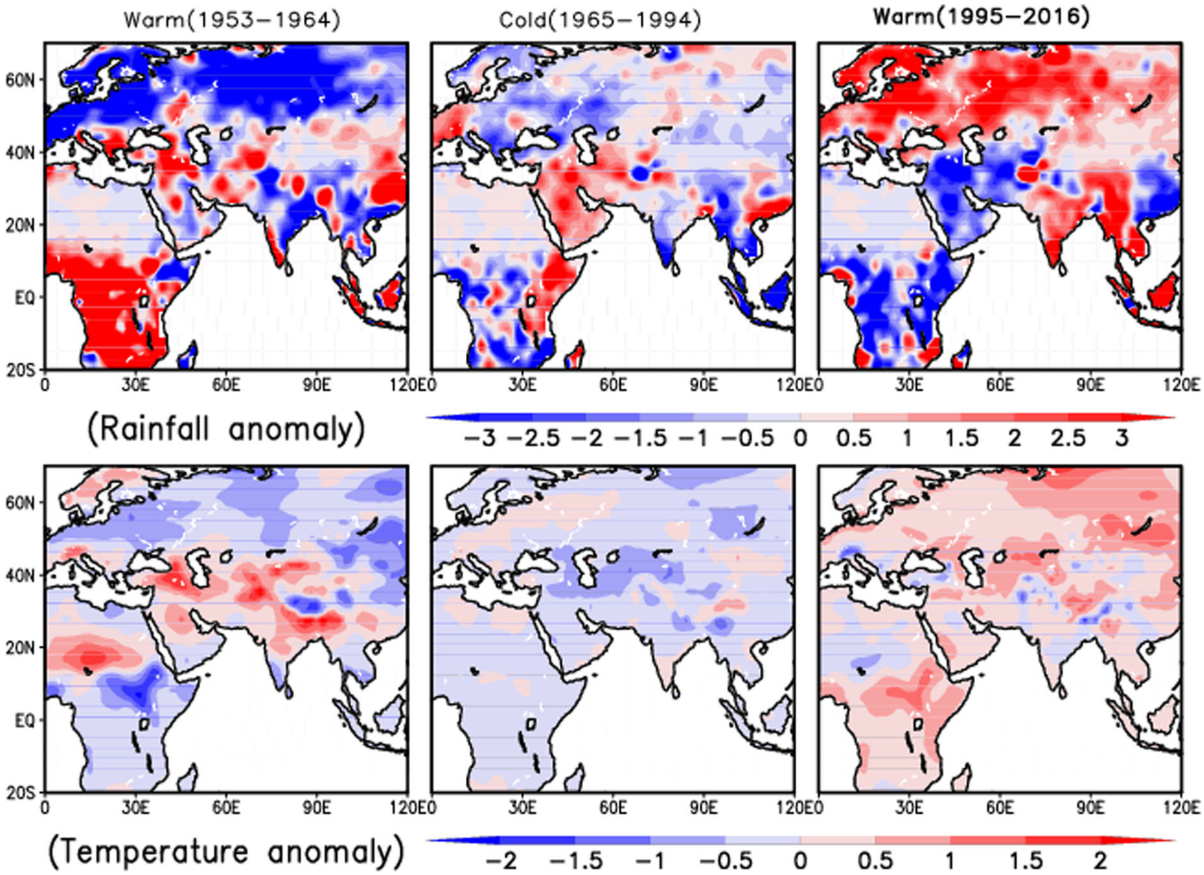

Figure 10

Mean precipitation and mean temperature 2 m above the surface for the pre-monsoon season for warm phases 1953–1964 and 1995–2016 (left and right panels) and cold phase 1965–1994 (center panels)

intensifies the ISM. The phenomenal response of the AMO phases on ISMR were explained with the help of anomalous global precipitation and 2-m surface temperature patterns during the previous winter (January–February) and pre-monsoon season (March–April-May) during 1953–2016 (Fig. 10). The higher surface air temperature anomaly over the Eurasian region is dominant during both warm AMO phases, i.e. 1953–1964 (+1.5 °C) and 1995–2016 (+1 °C to +1.5 °C), causing warming prior to the south-west monsoon. In the recent warm phase, the anomalous surface warming dominated and covered the entire tropic and subtropic zones. As the pressure gradient is the key to the monsoon dynamics, and this warming of the Eurasian region provides a steeper pressure gradient during the warm AMO phase, which strengthens the ISM. Further, warming over the Tibetan plateau during the warm AMO phase also causes enhanced cross-equatorial flow and analogous strengthening of the Somali jet and westerly winds that bring moisture to southern India (Rajagopalan & Molnar, 2013). Rainfall anomaly plots also depict the increased precipitation over the subcontinent during the warm phase of AMO, particularly over the Western Ghats region, and the current warm phase of the AMO also has a huge impact. During the cold AMO phase, the temperature anomaly is substantially lower over Eurasian and Tibetan regions, resulting in less rainfall across the subcontinent. During the negative phase of AMO, the ITCZ shifted southward over the Pacific and Atlantic. This shifting of the ITCZ weakens the surface trend winds over the Pacific and results in a weakening in the ISM. Another simulation study by Luo et al. (2011) showed that during the positive AMO phase, Rossby wave trains from the North Atlantic cross South Asia, which increases the temperature gradient between the IO and Eurasia, strengthening the ISM. The mechanism of how the QBO influences the El Niño-Southern Oscillation (ENSO) variability and the monsoon was hypothesized by Gray et al. (1992a, 1992b). They reported that the QBO appears to be a significant factor in altering intense deep convective activity throughout the tropical Pacific warm pool in the western Pacific. The major convective processes through which the QBO promotes the convection activity include the contrasting westerly phase versus easterly phase wind shear between the lower (20 hPa) and upper troposphere (50 hPa). This deep convection activity influences the Hadley and Walker circulations which affect ENSO and the Southern Oscillation, and hence the ISM. In a study by Callimore et al. (2003), the mechanisms interlinking the deep convection and higher ISM rainfall with the QBO westerly phase were discussed, and according to this study, the QBO affects divergence in the lower stratosphere to upper troposphere and modulates the tropopause height by strong zonal shear allowing higher convection and hence more deeper cloud growth during some years. Apart from this, the QBO modulation of upper-tropospheric relative vorticity may relax dynamic constraints on cloud-top outflow and thus allow more convection and cloud growth in some years compared to other years. Also, earlier studies on teleconnections reported that the association between ISM rainfall and various atmospheric and oceanic oscillations is enhanced during the westerly phase of the QBO if the ISM is directly correlated with these oscillations, while the association is enhanced during the easterly phase if they are inversely correlated (Chattopadhyay & Bhatla, 1993a, 1993b, 2002; Bhatla et al., 2013; 2020). In other words, the westerly phase of the QBO is always linked with enhanced convection and higher ISM rainfall, whereas the easterly phase causes less convergence and hence reduced rainfall.

4. Conclusions

The teleconnection between ISM with AMO and IO surface indices (SST and SSS) using the full time series as well as grouping the data according to easterly and westerly phases of the QBO at 50 hPa is analyzed separately. The time interval chosen for this purpose is 1953–2016 (64 years) to investigate the relationship between ISM rainfall and AMO in the context of regrouped QBO phases, and 1958–2016 (59 years) for the ISM correlation with the IO SST and SSS.

The pre-monsoon concurrent months/seasons demonstrate a positive association between ISM rainfall and AMO during the full time series. The maximum CC (highest association) is found during the months of April and May. Further, after dividing the ISM rainfall and AMO index according to different phases of the QBO (easterly/westerly), the positive association increases during the westerly phase of the QBO for pre-monsoon months and seasons, while no significant relationship is found for the easterly phase. It is also found that during the positive phase of the AMO, ISM rainfall over the northern, eastern, central, and western states of India increases/decreases when the QBO is in the westerly/easterly phase and vice versa for the negative phase of the AMO. These results further confirm our findings that the westerly phase of the QBO has a prominent effect on the relation between ISM rainfall and the AMO. Analysis reveals an inverse relation between the SST/SSS of the IO and ISM rainfall for post-monsoon. The study clearly shows that the SST and SSS of the IO decrease post-monsoon with increases in ISM rainfall for the full time-series data and during the westerly phase of the QBO, while for the easterly phase no relationship exists. This study also concludes that the SST and SSS of the eastern equatorial IO, southeastern IO, and the BoB decreases in the post-monsoon months/seasons with increasing ISM rainfall. Since the ISM positive/negative anomaly is associated with the AMO positive/negative index, a positive/negative AMO phase can indicate lower/higher values of SST and SSS, which shows a clear and significant effect of the QBO westerly phase on the ISM rainfall-SST/SSS relationship, implying that stratospheric oscillations such as the QBO can also have an impact on ocean surface indices. Therefore, the AMO index of pre-monsoon months can be used as a good predictor for ISM, and good prediction of ISM rainfall can lead to a better understanding of the post-monsoon SST and SSS.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of interests The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

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