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Role of changed Indo-Pacific atmospheric circulation in the recent disconnect between the Indian summer monsoon and ENSO

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Abstract

We explore the decadal variability of teleconnection from tropical Pacific to the Indian summer monsoon rainfall (ISMR) using various observational and Reanalysis datasets for the period 1958–2008. In confirmation with the earlier findings, we find that the interannual correlations between the various SST indices of ENSO and ISMR have continued to weaken. Interestingly, we find that even the robust lead correlations of the tropical pacific warm-water-volume with ISMR have weakened since late 1970s. Our analysis suggests that there is a relative intensification of the cross-equatorial flow from the southern hemisphere into the equatorial Indian Ocean associated with ISMR due to strenghtening of Mascarene High. Further, a shift in the surface wind circulation associated with monsoon over the northern pacific since late 1970s has resulted in a strenghtened cyclonic seasonal circulation south-east of Japan. These changed circulation features are a shift from the known circulation-signatures that efficiently teleconnect El Niño forcing to South Asia. These recent changes effectively weakened the teleconnection of the El Niño to ISMR.

Keywords ENSO · Indian summer monsoon · Pacific surface winds · Decadal variability · Warm water volume · Wind circulation

1 Introduction

No other tidings in the field of tropical climate science have caused as much commotion as the variability of ENSO-Monsoon Teleconnections did in the recent periods. ENSO is one of the strongest drivers of the Indian summer monsoons. The ENSO teleconnections to ISMR have been extensively studied (e.g. Walker and Bliss 1932; Sikka 1980; Keshavamurthy 1982; Rasmusson and Carpenter 1983; Kripalani and Kulkarni 1997a, b; Navarra et al. 1999; Lau and Nath 2000; Ashok et al. 2001, 2004; Ashok and Saji 2007) in parallel to those that addressed its existence, evolution, and variability, etc. (Zebiak and Cane 1987; Torrence and Webster 1999; Saravanan and Chang 2000; Krishnamurthy and Kirtman 2003; McPhaden et al. 2006; Ashok et al. 2007; Annamalai et al. 2007; Kripalani et al. 2007; Choi et al. 2012; Marathe et al. 2015). In addition to the well-known southern oscillation index, other ENSO indices derived from the Sea surface temperature (SST), based such as the NINO3 index have been used as a major predictor in the statistical forecast of the ISMR. Other indices like warm water volume (WWV) over entire Pacific basin are also available (Rajeevan and McPhaden 2004); the WWV has the highest (3–4 month) lead predictive skill.

Notably, the observed ENSO–ISMR link has weakened in the late twentieth century (Kumar et al.1999; Chang et al. 2001; Krishnamurthy and Kirtman 2003; Kawamura et al. 2005; Horii et al. 2012). Ashok et al. (2001, 2004), and Ashok and Saji (2007) suggest that this weakening is owing to the increased positive IOD events. Another study by Chang et al. (2001) suggests that the strengthening and pole ward shift of the jet stream over the North Atlantic might be the cause of this weakening. Sreejith et al. (2015) argue that the air-sea coupled interaction over tropical Indian ocean is the reason for weakening of the ENSO-ISMR links.

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Interestingly, the interannual manifestations of the tropical Pacific variability are also undergoing through significant changes over the recent period. Specifically, we see more and more of El Nino Modoki events, with anomalous warming along the central Pacific with anomalous cooling on both sides (Kug and Kang 2006; Ashok et al. 2007; Yeh et al. 2014) since late 1970s. On the other hand, the frequency of the canonical El Nino events, typified by anomalous warming (cooling) in the eastern (western) tropical has reduced substantially since then. The tropical Pacific also witnessed the hitherto unforeseen anomalous basin wide warming from May 2009 through April 2010 and then in 2014 (Ashok et al. 2012; Jadhav et al. 2015).

These conditions make it interesting to take a relook at the decadal variability of the teleconnections of the Pacific basin to the ISMR. It will be particularly worthwhile to see if there are any recent internal changes in the pacific atmosphere, which have a bearing for the monsoon teleconnections. This forms the main objective of this paper.

The remaining portion of the current manuscript is divided as follows. In the Sect. 2, we briefly discuss the Datasets and Methodology used in this study, followed by our results in Sect. 3. We provide our conclusions in Sect. 4.

2 Data and methodology

In the current study, we use the monthly-mean Indian summer monsoon rainfall data sets for homogenised area-averaged rainfall sets (Parthasarathy et al. 1994). We use the atmospheric circulation data and sea level pressure (SLP) from Derived National Centers for Environmental Prediction (NCEP) Reanalysis data, provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (Kalnay et al. 1996), and those from the first atmospheric reanalysis, (ERA-20C) from European Centre for Medium-Range Weather Forecasts (ECMWF).

We also use the Met Office Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) (Rayner et al. 2003) for the same period, along with the Simple Ocean Data Assimilation (SODA) Reanalysis 2.1.6 dataset (Carton and Giese 2008) for the 1958–2008 period for calculation of the WWV. Following Meinen and McPhaden (2000), we define the tropical pacific warm water volume, henceforth referred to as the WWV, as the integrated volume of water above the 20 °C isotherm between 5N–5S, 120E and 80W.

All the datasets have been de-trended for the 1958–2008 period in order to remove the linear trends and to emphasize only the interannual variability. Correlations have been calculated between ISMR and the SST indices, and those between ISMR and WWV, for three partially overlapping 30-year periods starting from 1958, specifically, 1958–1987, 1968–1997 and 1978–2007 for the monsoon season of June–September (JJAS) as well as the preceding seasons of February–May (FMAM); the importance of the statistically significant lead correlation between the tropical pacific WWV during the FMAM with the following Indian summer monsoon rainfall during JJAS for the 1958–2008 period (Rajeevan and McPhaden 2004).

Further, we also compute various correlations between tropical 1000 hPa winds and ISMR for the broad period of 1958–2008 and its various portions i.e., the periods 1958–1987, 1968–1997 and 1978–2007, in order to tease out any decadal variability. We also carry out a complementary regression analysis to attribute the relevance of any circulation changes in the pacific region for the changes in the tropical pacific teleconnections to the ISMR.

The significance of the correlation is calculated using the Student's two tailed test. The degrees of freedom have been ascertained as $N-2$, where N is the number of samples. As we take the interannual boreal summer values that are largely independent from 1 year to the other, this is a reasonable supposition. Therefore, the threshold of the significant correlation stands at 0.36 (0.28) for 30 (51) years at 95% confidence level.

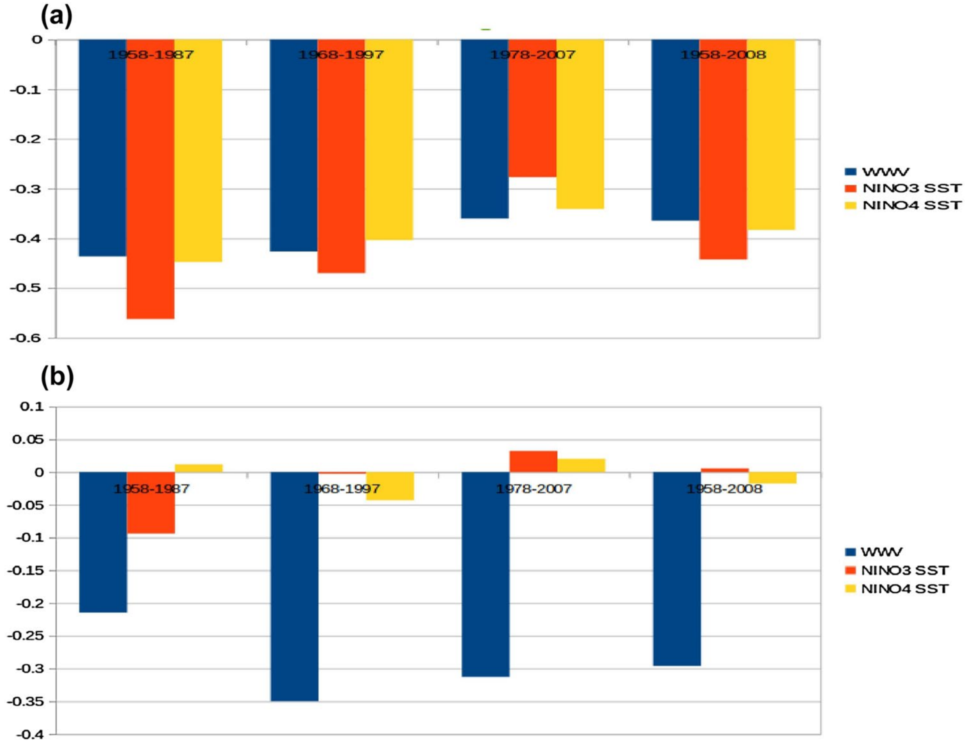
Further, we have ascertained the significance of the correlations between the ISMR and two NINO indices by a boot-strapping test (1000 simulations). For this, we used the bootstrapping subroutine "bootstrap_correl", from the NCAR Command Language (NCL) package. This routine takes, as inputs, two input timeseries for which the correlations need to be obtained (the ISMR and NINO3 SST, for example, in our case). Based on these input series, it generates 1000 time-series pairs randomly, and computes correlations between each pair. After that, the correlations are ordered as per magnitude. Once this is done, the 50th highest correlation among the 1000 correlations computed, for example, gives us the 0.05 significance level (i.e., 95% confidence level) for the correlations. In case of correlation differences between two time-series, the differences of correlations are ordered as per magnitude to identify the significant threshold values.

The results from the above bootstrapping test show that the correlations for recent period (1978–2008) differ from the total period (1958–2008) at 90% confidence level.

3 Results

Figure 1a shows the simultaneous correlations of the ISMR with the various ENSO indices, i.e., WWV, NINO3 and NINO4, for JJAS season for each 30-year overlapping periods (1958–1987, 1968–1997, 1978–2007) and total period (1958–2008). In accordance with the earlier findings (Kumar et al. 1999; Ashok et al. 2001; Rajeevan and McPhaden 2004), the results for this season show gradually weakening

Fig. 1 Correlation of Pacific Indices with ISMR during **a** JJAS and **b** FMAM



correlations of the ISMR with various Pacific SST indices over the time. The correlations with Nino3 index particularly show a very rapid decrease, with the correlations becoming insignificant during the recent period, i.e., 1978–2007. The Nino4 index, more relevant to the Indian summer monsoon rainfall owing to its relative proximity to the sub-continent (Kumar et al. 2006; Ashok et al. 2007), also shows gradually weakening association with the ISMR over the period, though the correlations are still significant at 95% confidence level even through the late 2000s. The multi-decadal correlation coefficient between the WWV and ISMR, also decreased from a high −0.44 in 1958–1987 to −0.36 in 1978–2007, though the recent correlations are still statistically significant at 95% confidence level.

Following Rajeevan and McPhaden (2004), we present the lead correlations of the various Pacific indices during the pre-monsoon season (FMAM) with the subsequent ISMR over different overlapping periods (Fig. 1b). Our results are in conformation with earlier findings in the sense that the lead correlations of the pre-monsoon WWV with the ISMR have been, all the while significant at 95% confidence level. However, just as the weakening simultaneous correlations, the magnitude of the lead correlation of the WWV with the ISMR has also steadily decreased. We also find that the lead correlation during FMAM has significant lead predictive skill, though it has weakened further and is insignificant for the recent period, 1978–2007.

For the 1958–2008 period as a whole, the seasonal correlations of ISMR with WWV show that these are maximum when computed simultaneously, just as that in case of the ISMR correlations with any simultaneous tropical pacific SST index. For ascertaining our results, we also use the WWV dataset from Tropical Atmosphere Ocean (TAO) project, (Auxiliary Figure 1).

Thus our analysis shows that weakening of ENSO-Monsoon correlation in the recent period can be attributed to changes associated with ENSO characteristics, or PDO. Having said that, one should be aware of the fact that such a weakening of correlation for the 1978–2008 period as compared to 1958–2008 period is potentially due to internal modulations in monsoon, and not necessarily related to any discernible external cause (E.g. Gershunov et al. 2001; Ashok et al. 2014; Wu et al. 2017), or in other words, just an issue of sampling (Delsole and Shukla 2012; Cash et al. 2017). From this context, it is pertinent to mention about our recent analysis of PMIP3 simulations for the last millenium (Tejavath et al. 2018), which show that, four of seven models simulate a statistically significantly weakened intra-annual ENSO-Monsoon correlations from Medieval Warm Period (1000–1199 AD) to Little Ice Age (1550–1749 AD) apparently during changes in ENSO characteristics.

3.1 Analysis of the surface winds over tropical Indo-pacific

We analyse the JJAS surface winds over the tropical Indian and Pacific Oceans. During the 51 year period, 1958–2008, the winds over the Tropical Indian Ocean (TIO) show a weakening correlation with ISMR (Figs. 2, 3). By intercomparing these correlations over various sub-periods (Figs. 2a–c, 3a–c), we find that, the surface winds during JJAS over tropical Indo-Pacific basin show the strongest links over the Pacific basin during 1958–1977 and over Indian subcontinent than anywhere else in the tropical region. Specifically the eastern tropical Pacific circulation exhibits rather weak links to ISMR during the recent period. Looking at the circulation patterns, the correlations show a shift in the circulation pattern during the recent period.

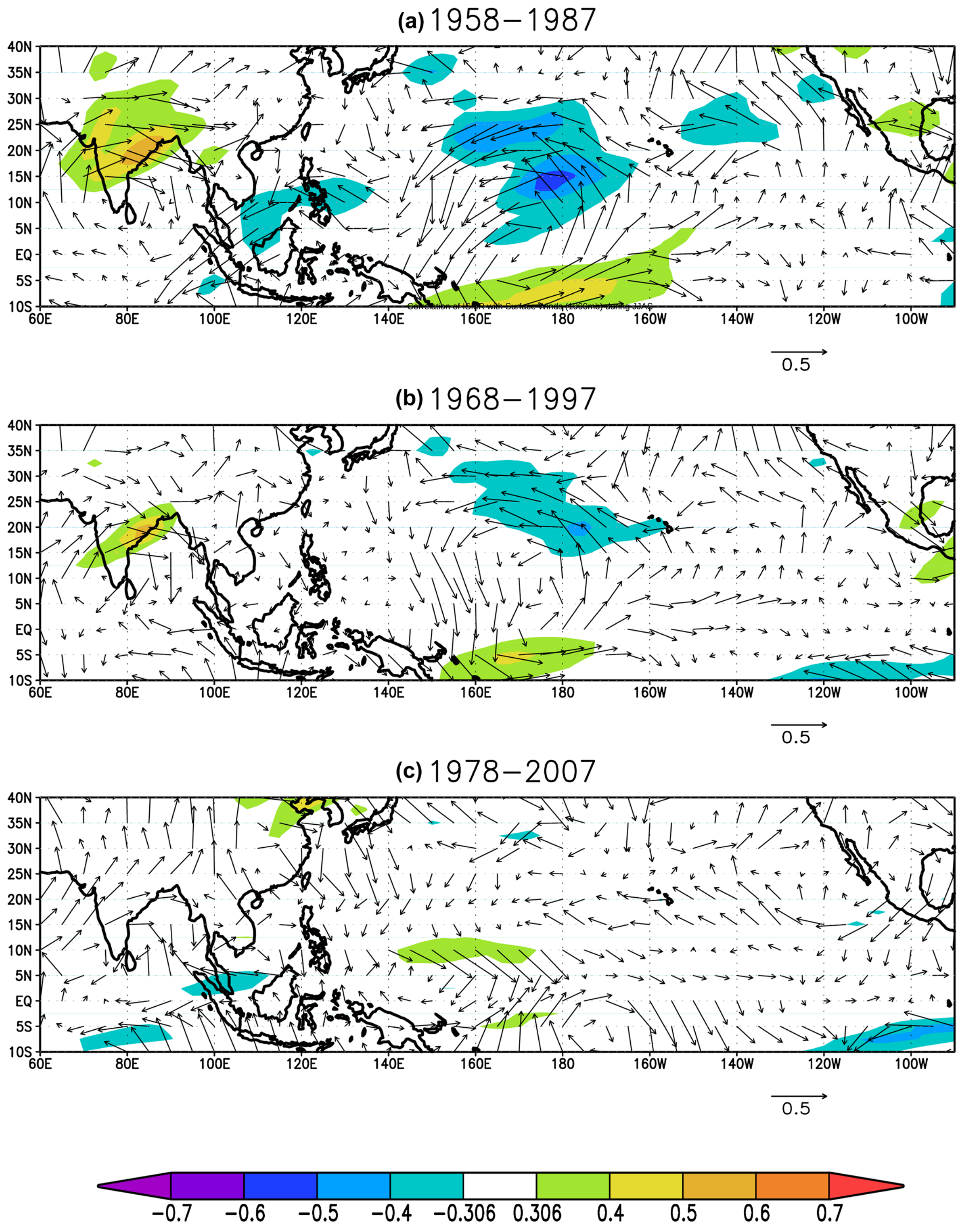


Fig. 2 Correlation of ISMR with surface winds (1000 mb) during JJAS (zonal correlations in colour)

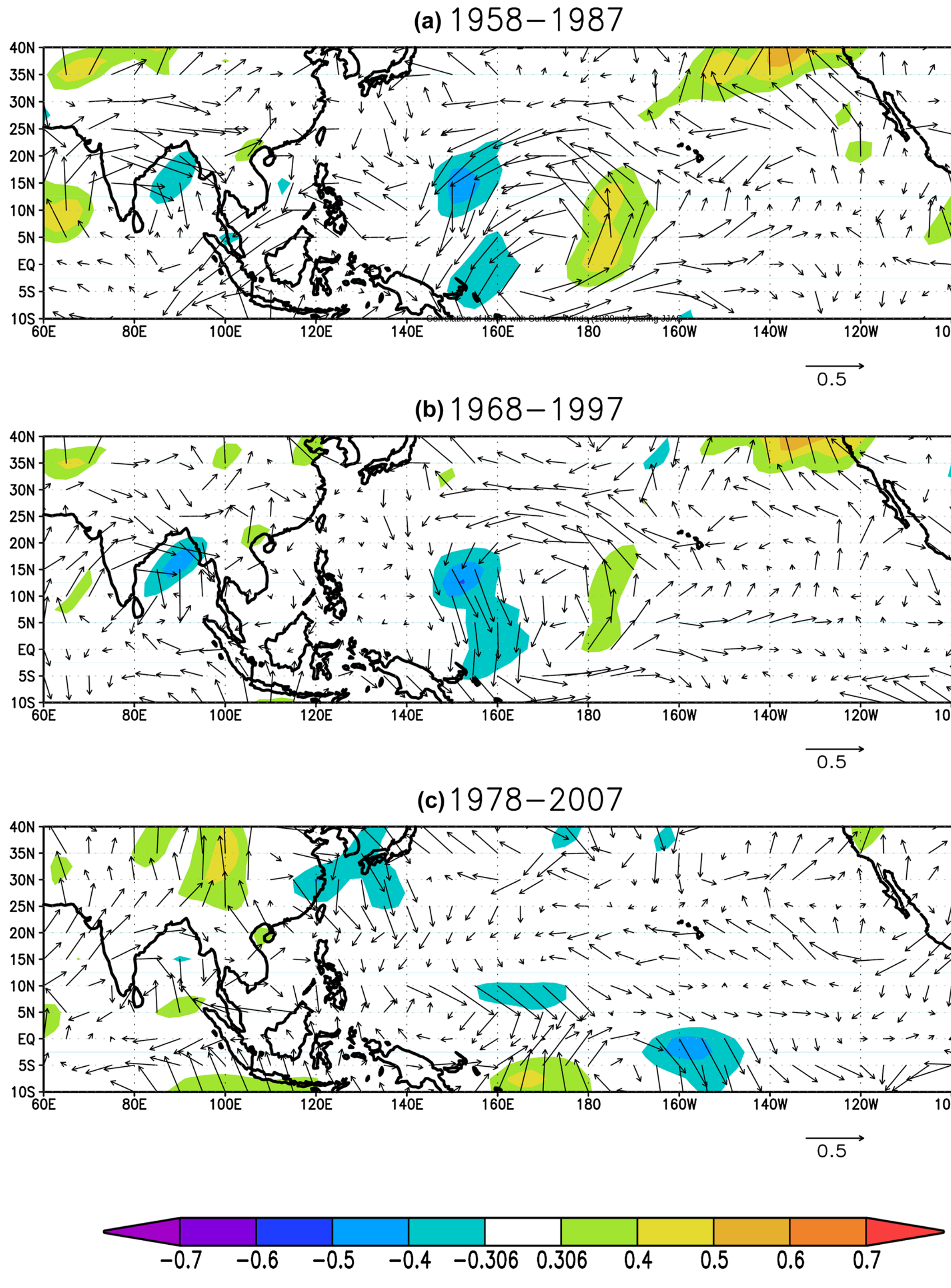


Fig. 3 Correlation of ISMR with surface winds (1000 mb) during JJAS (meridional correlations in colour)

There is a prominent weakening of the cyclonic circulation (observed in Figs. 2a, b, 3a, b) associated with ISMR over the tropical Pacific during the recent period (Figs. 2c, 3c). The corresponding correlations for the 1978–2007 period indicate a 'disconnect' in correlation vectors between the tropical Pacific and TIO. We believe that this is mainly due to a decadal change in the mean circulation over Indo-Pacific region.

A linear regression analysis (Figs. 4, 5) has been carried out to estimate and understand the apparent shift of dependence of ISMR. With the local zonal and meridional winds as independent variables and ISMR as the

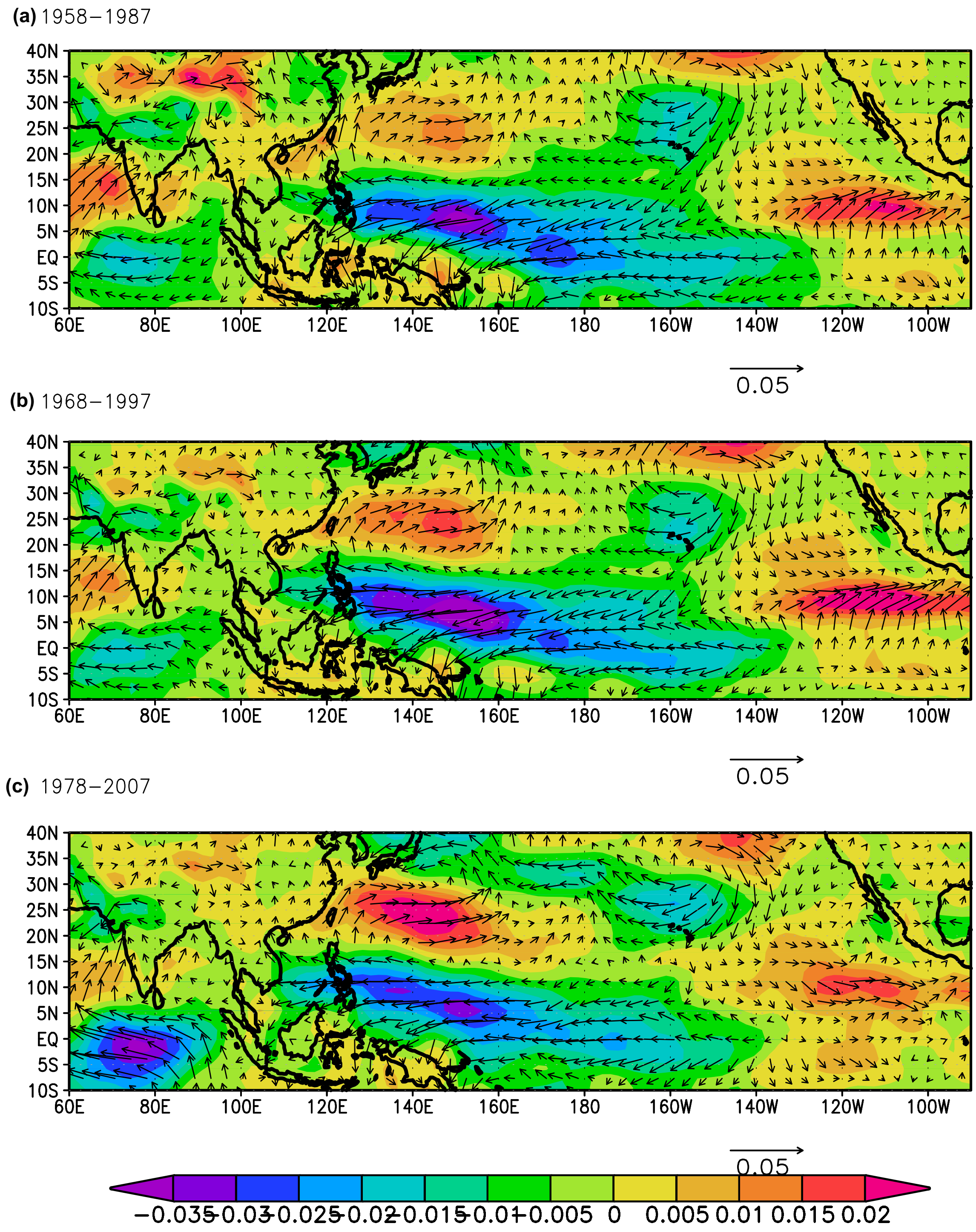


Fig. 4 Regression of ISMR with surface winds (1000 mb) during JJAS (zonal regression in colour)

dependent variable, the regression analysis show similar patterns, we find that this link over the whole period is mainly being contributed only from the early period. We notice a sudden increase of an apparent relevance of the circulation in TIO during 1978–2007 (Fig. 5c).

We also find strong regression vectors in western Pacific at 25^{o}N (Figs. 4c, 5c) (Krishnamurthy and Krishnamurthy 2017). Some studies show that there is a westward shift of subtropical high (Hu 1997; Gong and Ho 2002; Zhou et al. 2009; Mujumdar et al. 2012; Preethi et al. 2016), we believe

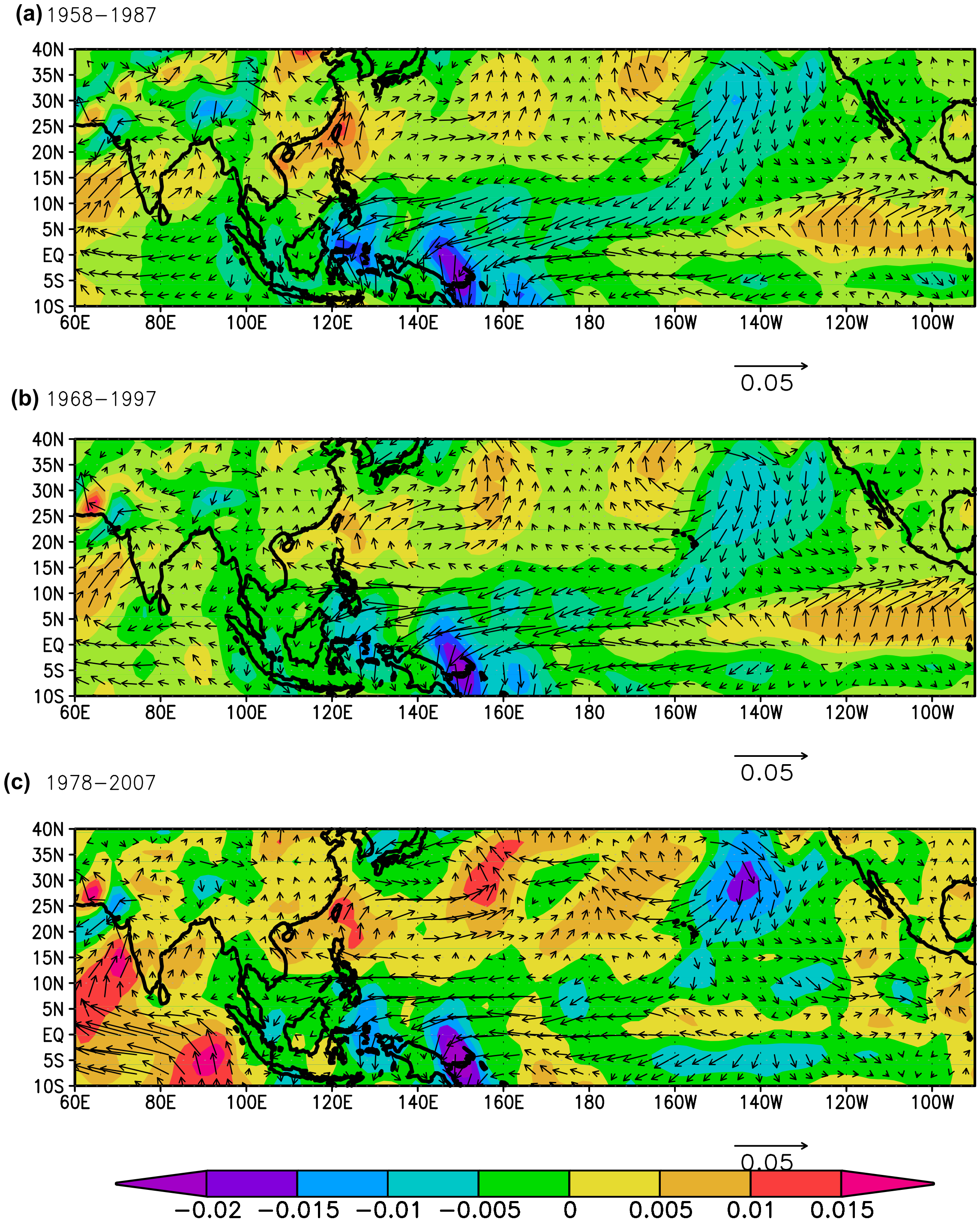


Fig. 5 Regression of ISMR with surface winds (1000 mb) during JJAS (meridional correlations in colour)

this shift might be arising mainly due to this westward intensification of subtropical high. This suggests a paramount relevance of the changes in the circulation over the western Pacific region for the weakening of the ENSO teleconnections to the ISMR. Indeed, a difference plot (Fig. 6) obtained by subtracting the regressions for the 1958–2008 from the recent decades of 1978–2008 indicate a strenghtening in the cyclonic correlation/regression vectors associated with ISMR south-east of Japan in the recent period. In this context, it is pertinent to recall the Figs. 7 and 8 of a seminal study by Lau and Nath (2000) figure which shows an anticyclone southeast of Japan and an anomalous cyclone

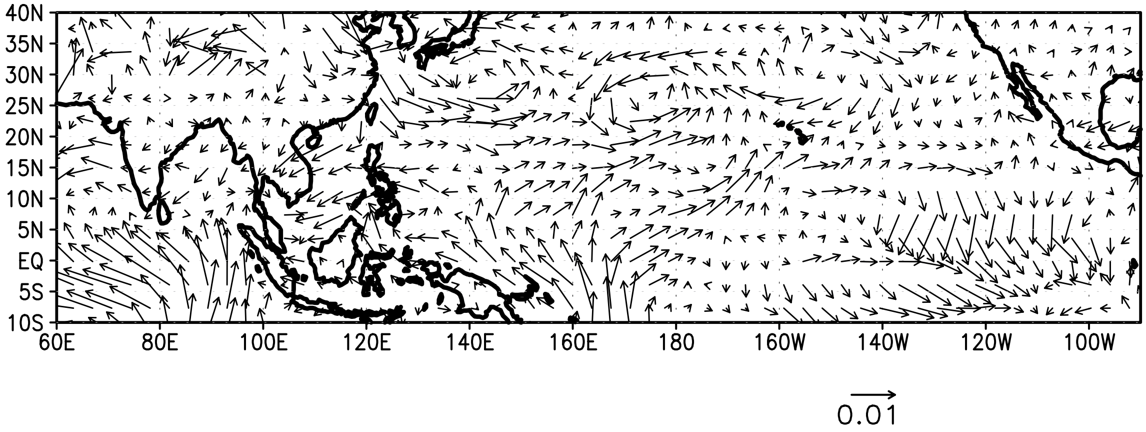


Fig. 6 Difference of regression of ISMR with surface winds (1000 mb) during 1978–2008 from 1958–2008 (51 years)

over the Bay of Bengal and the Indian region during boreal summer months in El Nino years. Evidently, the weakening of this anticyclonic circulation (or rather strengthening of the cyclonic circulation) associated with ISMR effectively weakened the ENSO-ISMR links.

Interestingly, the correlations shown in Figs. 2, 3, 4 and 5 also suggest a low level cross-equatorial strenghtening of the regression vectors over TIO. cross-equatorial circulation over the TIO and Bay of Bengal regions during 1978–2007 period as compared to the previous decades, along with the correspondingly strengthened cyclonic circulation south-east of Japan. The winds over TIO seem to have a north easterly directional shift post 1970s. The cross-equatorial flow which was limited to the west of the TIO has broadened eastwards, basin wide, along TIO. A further investigation into this shows that the variability of Mascarene High is relatively more relevant to the ISMR variability in the recent decades. The standard deviation of an SLP-based Mascarene high index (25°S:35°S; 40°E:90°E) for the 1978–2008 is 6.68% higher than that for the 1951–2008 period, suggesting that there is a decadal change in the Mascarene High strength, and consequently the associated circulation (Auxilliary Figs. 2 and 3). We believe that this has resulted in the observed relatively stronger association of monsoon rainfall with the cross-equatorial low level circulation in TIO in the recent decades. While further examination of this aspect is beyond the scope of the current study, it will be worth investigating a mechanism for this apparent decadal variability of Mascarene High.

4 Conclusion and discussion

Irrespective of the choice of the indices, the teleconnections of Pacific and ISMR seem to weaken, though WWV still has significance. WWV has a lead prediction skill during pre-monsoon season and the highest correlation was found to be during FMAM.

Our study shows that there is a shift in the mean state of winds in the recent period of 1978–2007 (Fig. 5). Particularly, the winds over north western Pacific show an cyclonic intensification during the same period. There is a weakening of an anticyclonic circulation correlation vectors south-east of Japan which connected ENSO to ISMR. A simultaneous strengthening of an cross-equatorial circulation in TIO as compared to the pre-1977 periods is also observed. An increased relevance of the cross-equatorial flow due to the decadal variability of Mascarene High. This is opposite to the circulation over Eastern TIO associating El Nino with ISMR. Such a change in the background state apparently disrupts the teleconnections of the ENSO impact which results in weakening of the ENSO connections. We have verified these apparent decadal changes by analysing the ERA-20C circulation datasets (figures not shown).

All this suggests that a shift in the ISMR associated surface wind circulation in recent decades over the Indo-Pacific region which weakens the El Niño transfer mechanism in recent decades. We also plan to reconfirm the results reported in the current work through analysis of various CMIP5 model outputs and by conducting some dynamical simulations.

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