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Shift in Indian summer monsoon onset during 1976/1977

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Abstract

The Indian summer monsoon rainfall (ISMR) contributes nearly 80% of the annual rainfall over India and has a significant influence on the country's gross domestic product through the agricultural sector. Onset of the ISMR displays substantial interannual variability and controls the crop calendar and hence the agricultural output. This variability is traditionally linked to sea surface temperature (SST) anomalies over the tropical Pacific Ocean. The tropical Pacific SST underwent a regime shift during 1976/77. We report a prominent delay in the Indian summer monsoon (ISM) onset following the regime shift. The onset dates are computed with the Hydrologic Onset and Withdrawal Index, based on vertically integrated moisture transport over the Arabian Sea (AS). The shift in onset is found to be due to the change in moisture availability over the AS. A delay in the development of easterly vertical shear reduces northward-propagating intraseasonal variability during May–June, limiting the moisture supply from the equatorial Indian Ocean (IO) to the AS. This, along with enhanced precipitation over the IO during the pre-monsoon, drives a reduction in moisture availability over the AS region from pre- to post-1976/77, delaying the ISM onset in recent decades. Our findings highlight the need for the re-assessment of the crop calendar in India, which is now based on the mean onset date computed from long-term data, without considering the regime shift or trends in onset.

1. Introduction

Indian summer monsoon rainfall (ISMR) contributes approximately 80% to the total annual precipitation over India (Jain and Kumar 2012). The southwest monsoon, with its variability in onset and withdrawal dates (Sabeerali *et al* 2012), total rainfall (Rupa Kumar *et al* 1992), extremes (Ghosh *et al* 2012) and intraseasonal oscillations (Singh *et al* 2014, Goswami and Ajayamohan 2001), has significant impacts on the country's agricultural output and hence on the gross domestic product (GDP) of the country (Gadgil and Gadgil 2006). The onset of the Indian summer monsoon (ISM) has significant influence on agriculture, specifically because the crop calendar for rain-fed agriculture largely depends on the onset dates (Rosenzweig and Binswanger 1992). The India Meteorological Department (IMD) defines the onset based on the starting date of rainfall at a few stations in Kerala on the western coast of India, along with

favourable wind and outgoing longwave radiation conditions (see supplementary information available at stacks.iop.org/ERL/10/054006/mmedia).

Even though the mean date of the ISM onset varies from May 30 to June 2, the earliest and the most delayed onset during the last century differ by 46 days (Joseph *et al* 1994). Information on the onset of the monsoon is thus critical for farmers in planning cropping strategies. This underscores the need for a reliable monsoon onset prediction, which requires comprehensive research and analysis on the phenomenon of onset and its variability. We report on one aspect of onset variability here, viz., a shift to a delayed onset coincident with the well-known regime shift of 1976/77.

Onset and withdrawal of ISM are modulated by the tropical Pacific sea surface temperature (SST), specifically by the El Nino–Southern Oscillation (ENSO) (Sabeerali *et al* 2012). The regime shift experienced by the tropical and north Pacific Oceans during 1976/77

resulted in extensive and abrupt changes in climatological, hydrological and biological variables across the globe (Trenberth 1990, Graham 1994, Zhang *et al* 1998). Significant changes in the global SST anomaly field were found in connection with the Northern Hemisphere regime shift (Yasunaka and Hanawa 2005). It was reported that there were changes in the tropical Atlantic thermocline also around the mid-1970s as a consequence of the Pacific shift (Murtugudde *et al* 2001), with a purported shift in the Indian Ocean as well (Annamalai and Murtugudde 2004). The Atlantic shift may induce similar decadal changes in the ISM characteristics, as the Atlantic SST anomalies and fluctuations of ISM rainfall are coherently linked (Zhang and Delworth 2006, Pottapinjara *et al* 2014). It has been reported that the western Indian Ocean (IO) SST variability at decadal timescales is modulated by the Pacific SST (Cole *et al* 2000). There is a coherent association between the tropical Pacific SST anomalies and variability of ISMR (Parthasarathy and Pant 1985, Kumar *et al* 2006). After the regime shift of 1976/77, changes have been reported in the relationship between the tropical Pacific SST and ISM variability (Kumar *et al* 1999). A tendency for early withdrawal and shortening of monsoon spells has been observed during the recent decades as a result of the change in the relationship between the ISM withdrawal date and the Indo-Pacific SST before and after the 1976/77 climate shift (Sabeerali *et al* 2012). However, with the tropospheric temperature gradient (difference of tropospheric temperature between two boxes, 5°N-35°N, 40°E–100°E and 5°N–15°S, 40°E–100°E) based analysis, ISM onset was not found to have a shift or a trend, unlike the monsoon withdrawal. Since the development of tropospheric temperature gradient is just one of the favourable conditions for ISM onset, that alone cannot explain the entire process of moisture dynamics associated with the onset. Here, we attempt to identify the response in onset dates of ISM across 1976/77, based on the Hydrological Onset and Withdrawal Index (HOWI) (Fasullo and Webster 2003). HOWI is derived by considering the dynamics of moisture flux through the computation of vertically integrated moisture transport (VIMT) over the Arabian Sea (AS). The data used and the methodology followed for the computation of HOWI are explained in the following section.

2. Method and data

Onset is associated with an increase in the precipitation, building up of vertically integrated humidity, strengthening of the low-level westerly wind over southwestern India and an increase in the kinetic energy (Krishnamurthi 1985). Since rainfall is poorly measured and modeled, an index identifying onset that is focused on the dynamics and not entirely on

rainfall will be more reliable. During the ISM onset, the horizontal flux convergence of heat and moisture is enhanced over the AS (Raju *et al* 2005). Considering the importance of this build-up of moisture over the AS, we employ HOWI, which is based on VIMT, to derive the onset dates (Fasullo and Webster 2003). VIMT is defined as

$$\mathrm{VIMT} = \int_{\mathrm{surface}}^{300\,\mathrm{mb}} q\,U\,dp, \qquad (1)$$
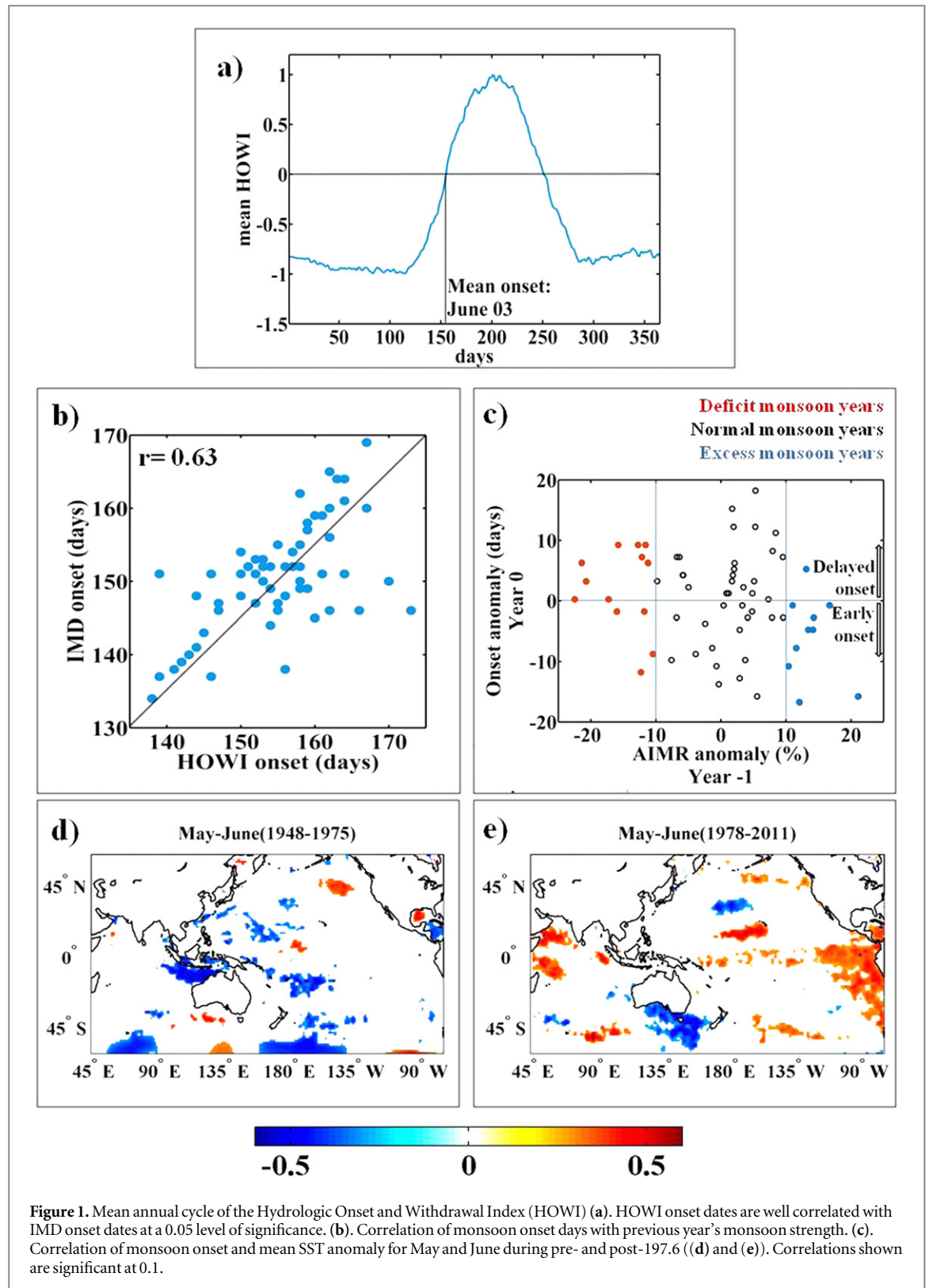
where q is specific humidity and U is wind vector. Unlike rainfall, VIMT is generally well estimated from observations and models and is indicative of the large-scale monsoon circulation. VIMT is estimated over the AS (5°N-20°N and 45°E-80°E), where its variability is substantial during the monsoon period. This VIMT averaged over the AS is normalized by the following transformation to get HOWI:

$$\bar{\chi} = 2 \times \left\{ \left[\chi - \min(\bar{X}) \right] \middle/ \left[\max(\bar{X}) - \min(\bar{X}) \right] \right\} - 1 \qquad (2)$$

where $\bar{X}$ is the mean annual cycle and $\bar{\chi}$ is the normalized time series, such that the climatological annual cycle ranges from –1 to 1. Pronounced variation of HOWI during the onset and withdrawal phase is observable from its mean annual cycle (figure 1(a)). Onset is defined as the day when HOWI turns positive. HOWI onsets show statistically significant correlation with the IMD onset dates at 99% confidence level (<0.01 significance) (figure 1(b)). Further, we test the strength of association between the VIMT over the AS (which is the basis of HOWI onset) during May and western coast rainfall during June, and we have found a similar correlation (0.63) with 99% statistical confidence (supplementary figure S1). The HOWI has the advantage that it captures the transition in the large-scale monsoon circulation rather than being highly sensitive to synoptic variability and the spatial complexity of the monsoon rainfall during the onset. Hence, it is robust to bogus monsoon onsets and reflective of the timing rather than the spatial character of the transition into the rainy season (Fasullo and Webster 2003).

It is important to note that there is an association between the HOWI onset date and total monsoon rainfall, which signifies the importance of onset and its variability. There is a statistically significant negative correlation (r = −0.32; significant at 0.01) between ISM onset dates and all India mansoon rainfall (supplementary figure S2 (a)). We find that none of the early-onset years is associated with a deficit monsoon (deviation from mean <−10%). Similarly, except one, no delayed-onset year is associated with a surplus monsoon (deviation from mean >+10%) (supplementary figure S2 (b)).

Here, we perform the analysis using the daily National Center for Environmental Predictions (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data, available at 2.5° × 2.5°

Figure 1. Mean annual cycle of the Hydrologic Onset and Withdrawal Index (HOWI) (**a**). HOWI onset dates are well correlated with IMD onset dates at a 0.05 level of significance. (**b**). Correlation of monsoon onset days with previous year's monsoon strength. (**c**). Correlation of monsoon onset and mean SST anomaly for May and June during pre- and post-197.6 ((**d**) and (**e**)). Correlations shown are significant at 0.1.

resolution (Kalnay *et al* 1996), for a 64-year period covering 1948 to 2011. NCEP/ NCAR data is preferred over other reanalyses data for its longer period of availability. However, in order to assess the sensitivity of the determined onset dates to the data used, we also computed the onset dates using European reanalysis (ERA) 40 data (1958 to 2001) (Uppala *et al* 2005), and the two sets of onset dates are found to have a

significant correlation of 0.76 (supplementary figure S3), though there is a bias between them for extreme early onsets. In this study, monsoon strength is determined from the monthly ISMR data provided by the Indian Institute of Tropical Meteorology (http://www.tropmet.res.in/). The SST data used here is a product developed by the Hadley Centre and served by the Asia-Pacific Data-Research Centre.
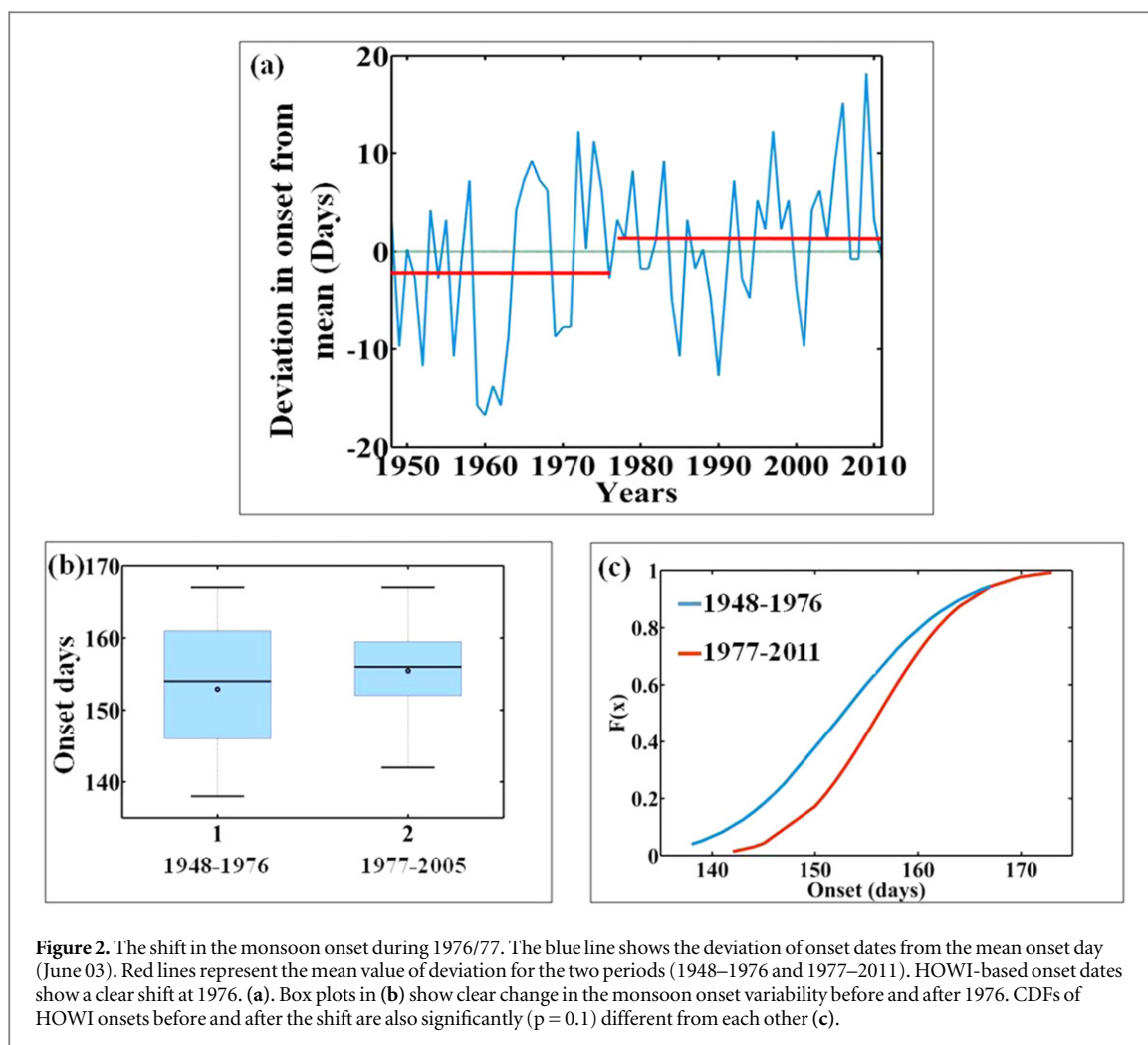
Figure 2. The shift in the monsoon onset during 1976/77. The blue line shows the deviation of onset dates from the mean onset day (June 03). Red lines represent the mean value of deviation for the two periods (1948–1976 and 1977–2011). HOWI-based onset dates show a clear shift at 1976. (**a**). Box plots in (**b**) show clear change in the monsoon onset variability before and after 1976. CDFs of HOWI onsets before and after the shift are also significantly (p = 0.1) different from each other (**c**).
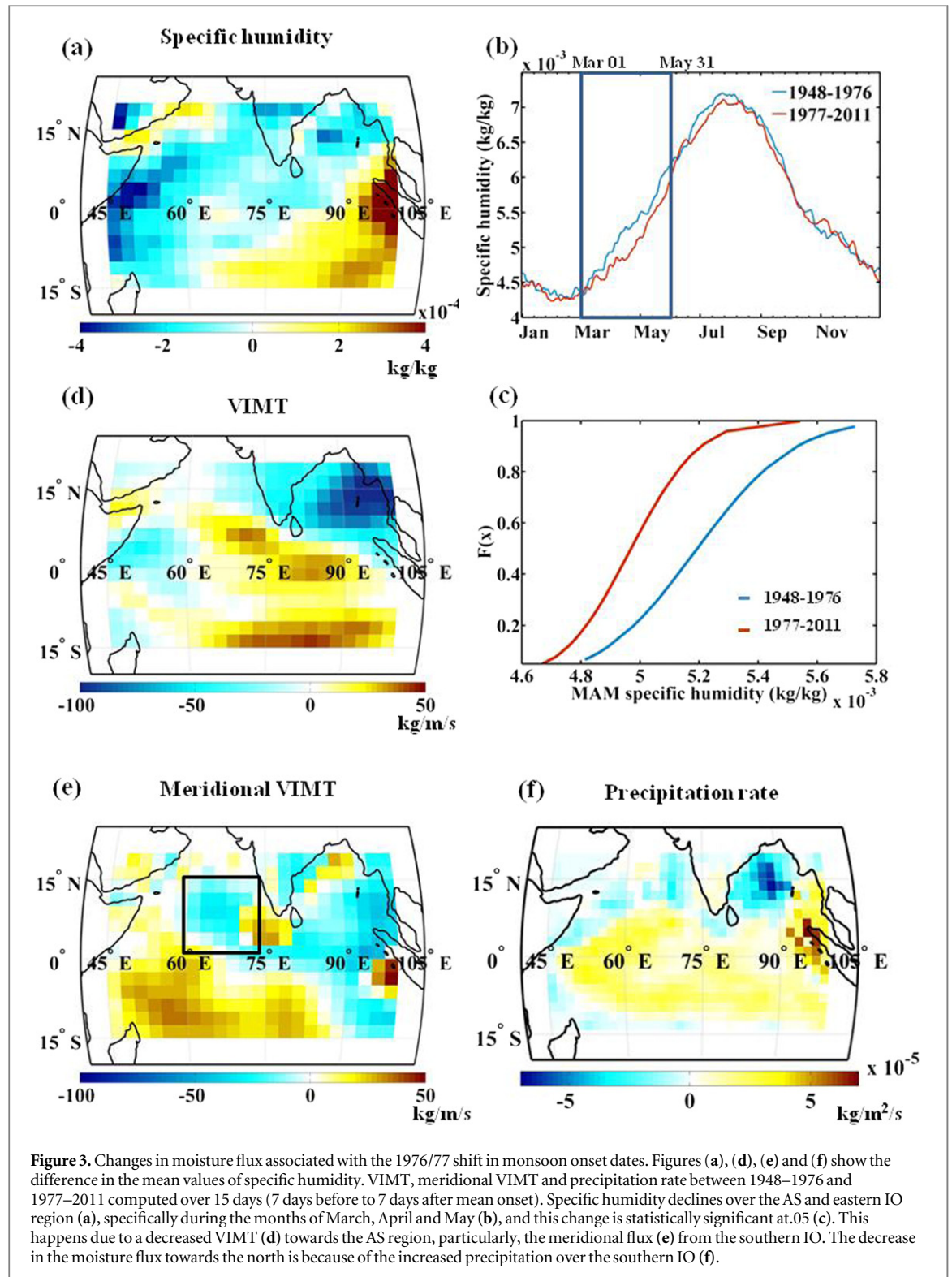
3. Results and discussion

It is well established that the ISM strength is affected by ENSO with a weaker (stronger) monsoon during warm (cold) ENSO. Our finding here is consistent, with stronger monsoons tending to lead to an earlier onset in the following year, which is in agreement with the speculation of Torrence and Webster (1999). However, figure 1(c) shows that a majority of the excess monsoon years (year −1) are followed by an early-onset (year 0), though the same is not always true for deficit monsoon years. There is a certain degree of teleconnection between ENSO and the ISM onset dates. To understand the change in the association between the ISM onset and Pacific SST, we plot the statistically significant correlation between them and observe strengthening of this relation during a recent period (figures 1(d)) and (e)). SST is considered during the onset period, i.e., May–June. The patterns of correlation between the onset and SST have not only changed for the Pacific Ocean, but also for the IO. This may be explained through the association between the SST of the Indian and Equatorial Pacific Oceans

(NINO 3.4) (Annamalai *et al* 2005; also see, Sabeerali *et al* 2012). The monsoon onset is positively correlated with the eastern Pacific SST anomaly for post-1976. The warming shift during 1976/77 in the eastern Pacific SST (supplementary figure S4) with strengthening of its association with the monsoon onset indicates the possibility of a shift to a delayed onset.

Hence, to investigate the probable shift in ISM onset in response to the Pacific regime shift, we first employ a change point analysis using the pruned exact linear time (PELT) method (supplementary Information).We observe a statistically significant change point during 1977. The same is also observed in the time series plot of onset for years 1948 to 2011. We find a shift causing a delay in onset during 1977 (figure 2(a)), which is also evident from the box plots of onset dates for the periods 1948–1976 and 1976–2005 (29 years each) (figure 2(b)).

The changes are not only observed in mean onset dates, but also in their interannual variability, which is weaker after 1976/77. The plots of cumulative distribution functions (CDFs) of onset dates for the two periods show distinct differences; the post-1976

Figure 3. Changes in moisture flux associated with the 1976/77 shift in monsoon onset dates. Figures (**a**), (**d**), (**e**) and (**f**) show the difference in the mean values of specific humidity. VIMT, meridional VIMT and precipitation rate between 1948–1976 and 1977–2011 computed over 15 days (7 days before to 7 days after mean onset). Specific humidity declines over the AS and eastern IO region (**a**), specifically during the months of March, April and May (**b**), and this change is statistically significant at .05 (**c**). This happens due to a decreased VIMT (**d**) towards the AS region, particularly, the meridional flux (**e**) from the southern IO. The decrease in the moisture flux towards the north is because of the increased precipitation over the southern IO (**f**).

period is associated with more delayed onsets and fewer early onsets (figure 2(c)).

We investigate the changes in moisture flux with specific humidity and wind velocity to understand the reason behind the shift of onset during 1976/77. Moisture flux is computed for 15 days comprising of a week before and a week after the mean HOWI onset (June, 3). The post-1976 period shows a decrease in specific humidity over much of the AS and western

equatorial IO (figure 3(a)) as compared to the pre-1976 period. From the mean annual cycles of specific humidity before and after 1976, it is evident that there is a drop in the specific humidity build-up over the AS during the pre-monsoon months of March, April and May (MAM) (figure 3(b)). Shifts in CDFs of the mean MAM specific humidity for the periods 1948–1976 and 1977–2011 are found to be statistically significant at 0.01 (figure 3(c)). This decline of the build-up of
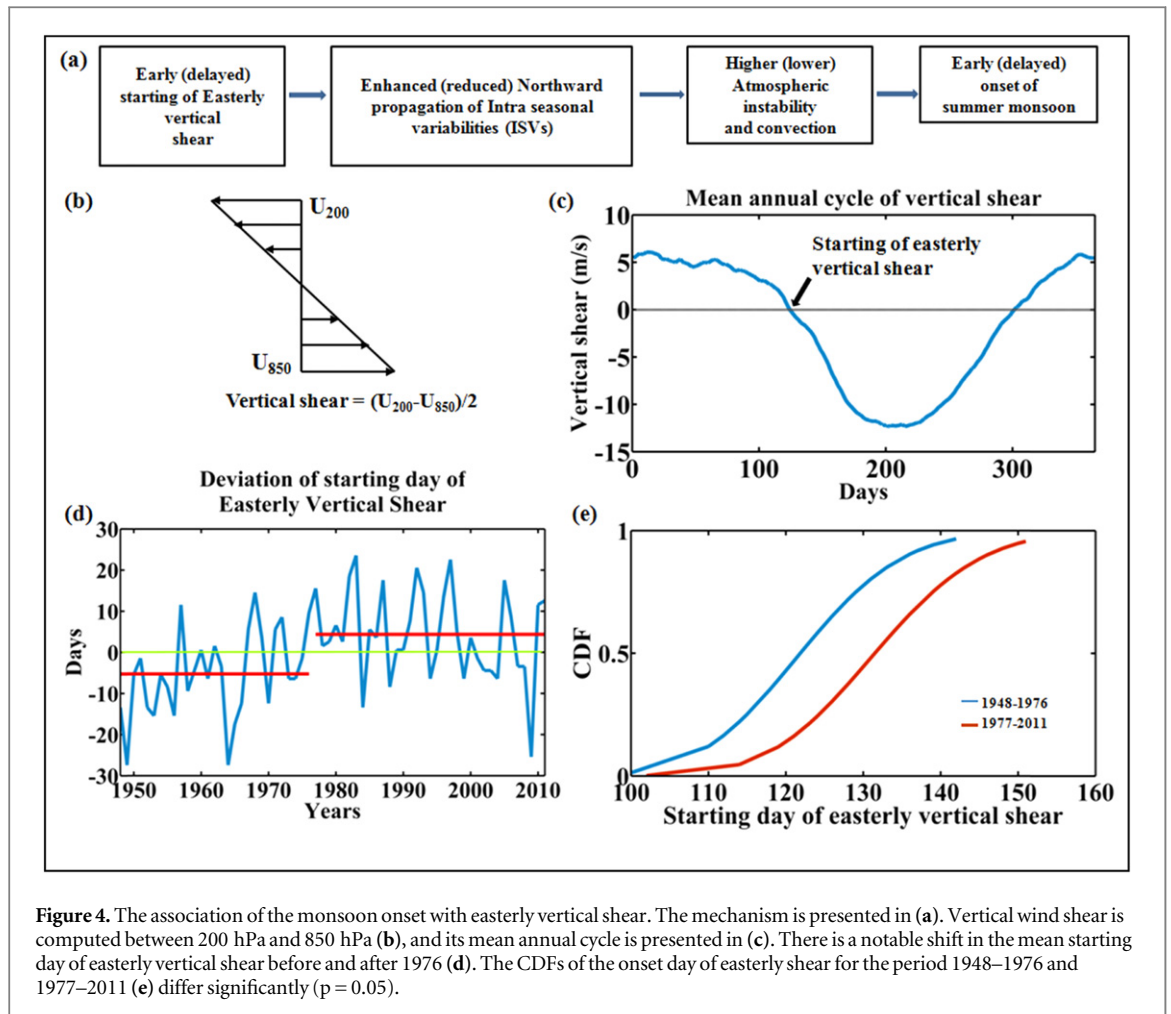
Figure 4. The association of the monsoon onset with easterly vertical shear. The mechanism is presented in (**a**). Vertical wind shear is computed between 200 hPa and 850 hPa (**b**), and its mean annual cycle is presented in (**c**). There is a notable shift in the mean starting day of easterly vertical shear before and after 1976 (**d**). The CDFs of the onset day of easterly shear for the period 1948–1976 and 1977–2011 (**e**) differ significantly (p = 0.05).

specific humidity is primarily due to the reduction in the net horizontal moisture flux (figure 3(d)); more specifically, the meridional VIMT from the IO (figure 3(e), marked with a box). It should be noted that though there is an increase in VIMT over the southern tropical IO, this moisture does not get transported to the AS or the Indian subcontinent. We argue that the observed increased precipitation over the IO in the southern hemisphere (figure 3(f)) is likely coming at the expense of the northward transport of moisture.

Strong northward-propagating intra-seasonal variabilities (ISVs) can favour an early onset since the northward transport of moisture and momentum leads to atmospheric instability and convection in the tropics (Zhou and Murtugudde 2014). Through the vertical shear mechanism, northward propagation of ISVs gets enhanced when the vertical shear turns easterly in the northern hemisphere (Jiang *et al* 2004). Hence, early (late) development of easterly vertical shear can lead to an early (late) onset of ISM (figure 4(a)). Wind shear between 200 hPa and 850 hPa over the AS (5°N-20°N and 45°E-80°E) is computed using NCEP/NCAR reanalysis data

(figure 4(b)). The starting day of easterly vertical shear is identified as the day when the vertical shear turns negative (figure 4(c)). We find that similar to the ISM onset, the starting days of easterly shear also have undergone a shift during 1976/77 (figure 4(d)). There is a statistically significant (0.05) shift in the cumulative distribution of easterly shear onsets between the pre- and post-1976 periods (figure 4(e)). We observe a higher probability of early development of easterly vertical wind shear during the pre-1976 period compared to the post-1976 period. Therefore, the shift in the HOWI onset of ISM during 1976 is induced by the changes in the northward propagation of monsoon ISVs. Similar results are also obtained for the analysis with easterly vertical shear carried out using ERA 40 reanalysis data, which establishes the robustness of the findings (supplementary figure S5). A change in the speed of propagation of the northward ISV was noted by Sabeerali et al (2014), but they did not relate it to the shift in the onset.

The tropical SST variation over the Pacific Ocean during the pre-monsoon month of May modulates the amount of subsidence over the AS region. A warmer (cooler) tropical Pacific SST leads to a stronger
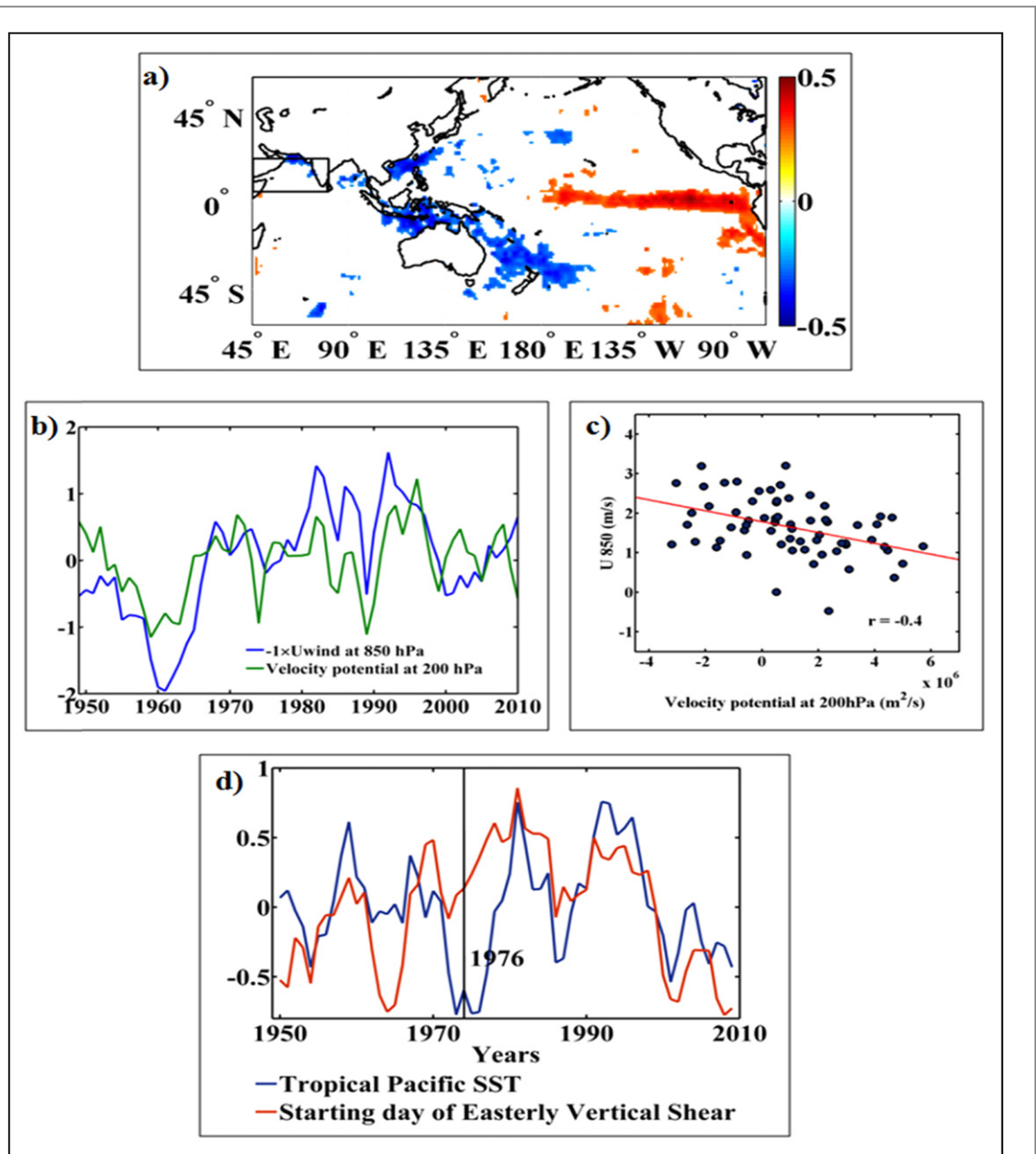
Figure 5. Association of tropical Pacific SST with the starting day of easterly vertical shear. (a) Correlation of the 200 hPa-velocity potential over the AS (enclosed in box) with SST. (b) Zonal wind at 850 hPa over the AS is modulated by the velocity potential over the region. (c) U850 and velocity potential are negatively associated with a statistically significant correlation of r = −0.4. (d) Development of easterly vertical shear prior to ISM is associated with the tropical Pacific SST changes.

subsidence (convection) over the IO region. Figure 5(a) shows that the velocity potential at 200 hPa, averaged over the AS region (enclosed in the box), is well correlated with the tropical Pacific SST during May. Velocity potential at 200 hPa is widely used as a surrogate for the Walker circulation. A positive (negative) velocity potential represents convergence (divergence) at 200 hPa and subsidence (convection) beneath.

The rise in the tropical Pacific SST across the regime shift resulted in an increased subsidence over the AS region during the pre-monsoon months, which is attributable to the eastward shift of the rising limb of the Walker circulation. This resulted in delayed strengthening of zonal wind at 850 hPa (figures 5(b) and (c)) and subsequent development of easterly vertical shear. The easterly vertical shear is a key player in the northward-propagating ISVs. Increased subsidence also reduces the convection over the AS region.

Here we find that the establishment of easterly vertical shear over the AS region is linked to the tropical Pacific SST averaged for the month of May (figure 5(d)). The starting day of easterly vertical shear is positively correlated with the mean-May tropical Pacific SST with a correlation coefficient of 0.45 (significance level of <0.01). Hence, the warming shift of 1976/77 in the Pacific SST resulted in a delay in the

development of easterly vertical shear (as shown in figure 4), which is also associated with the delayed onset of the monsoon (Zhou and Murtugudde 2014).

We find that the observed shift in the onset dates is in disagreement with the findings of Sabeerali *et al* (2012), where they found that the tropospheric temperature gradient (ΔTT) based monsoon-onset dates are devoid of any significant shift during 1976/77 (supplementary figure S6). This contradiction comes from the differences in the dynamics behind the two onset indices employed (ΔTT and HOWI). Tropospheric temperature gradient represents reasonably well the large-scale heating gradients driving the large-scale circulations (Xavier *et al* 2007). An enhanced TT gradient strengthens the monsoon circulation; but here, the observed variability in the onset dates is found to be due to the changes in the building up of moisture, specifically over the AS and the west coast of India, and hence it is better captured by the VIMT-based HOWI index.

Bollasina *et al* (2013) observed a trend towards earlier onset during 1950–99 when they considered April–May–June precipitation characteristics as indicators for the onset. They argued that the increasing trend of precipitation in northeast India during April and then the spreading of such a trend to central-northeast India during May and to central India during June are indications of an earlier ISM onset. This has been reported to be associated with aerosols. Here, we find that onset is not significantly correlated with the rainfall of northeast India during April, central-northeast India during May and central-western India during June (supplementary table 1). Hence, such rainfall characteristics are probably not resilient to bogus onsets. Bollasina *et al* (2013) employed the method by Wang and Ho 2002 for onset identification, which is merely based on rainfall; and rainfall-based onset indicators are not always reliable (Fasullo and Webster 2003). This is most likely the reason behind the disagreement of our conclusion with that of Bollasina *et al* (2013).

In the mid-1990s, an opposite climate shift was reported to the one that happened during 1976/77 and has had an influence on the Indian monsoon onset (Xiang and Wang 2013). We observe a reverse shift in the starting day of easterly vertical shear (supplementary figure S7) during the mid-1990s. However, such a shift is not very prominent in the HOWI onset derived from NCEP/NCAR reanalysis data. We have also analyzed the post-satellite (post-1979) reanalysis products for the same and could observe the reverse (early) shift of onset during the mid-1990s for ERA-interim and modern-era retrospective analysis for research and applications (MERRA) reanalysis (supplementary figure S8). This is an additional sample for the monsoon shift to support our previous analysis, based on HOWI, that there was indeed a shift in the onset during 1976/77.

4. Concluding remarks

The onset of ISM shows a significant interannual variability due to changes in the large-scale circulation driving the onset. Here we find that there is a statistically significant shift in the monsoon onset (identified using a moisture flux–based index) in connection with the 1976/77 regime shift. The observed shift in the monsoon onset is predominantly due to the changes in specific humidity over the AS and equatorial IO. The climatological mean of specific humidity before and after 1976 shows a clear shift to a slower build-up of moisture during the post-1976 period over the AS, which is modulated by the horizontal moisture flux from the IO. A net decrease in the moisture flux over the AS after 1976, despite increasing VIMT over the southern tropical IO, is probably due to the increase in precipitation over the equatorial IO.

The development of easterly vertical wind shear (between 200 and 850 hPa), which favours the northward propagation of ISVs and sets the stage for monsoon onset, shows a significant shift around 1976/77. The shift in the onset of easterly vertical shear and ISM onset are closely linked. The mean ISM onset date shifts from 1 June to 5 June after the climate shift because of the occurrence of more early onsets during 1948–1976. Prior to 1976, the probability of early establishment of easterly vertical shear is shown to be higher than during post-1976. We are further verifying our findings with model-driven hypothesis testing, where atmospheric general circulation models are being forced with Pacific Ocean SSTs at decadal time-scales. The results will be reported in a separate study. This analysis of the onset variability opens a window to the teleconnection of monsoon onset to other global phenomenon, like the intertropical convergence zone (ITCZ) and ENSO variability. Our findings highlight the need for the assessment of the crop calendar in India, which is based on mean onset date computed from long-term data without considering the regime shift or trends in onset.

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