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Moisture trend over the Arabian Sea and its influence on the Indian summer monsoon rainfall

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SUMMARY Indo-Pacific Ocean has been experiencing a basin wide warming since the 1950s but the large-scale summer monsoon rainfall over India is decreasing. At the same time the moisture over the Arabian Sea is also decreasing. In this study we intend to investigate how the decrease of moisture over the Arabian Sea is related with the Indo-Pacific Ocean warming and how this could affect the variability of the Indian summer monsoon rainfall. We performed the analysis for the period 1951-2012 based on the observed precipitation, sea surface temperature and atmospheric reanalysis products. The decreasing trend of the moisture over the Arabian Sea coincides with an increasing trend of moisture over the western Pacific region. This is accompanied by the strengthening (weakening) of the upward motion over the western Pacific (Arabian Sea/East Africa) that, consequently, contributes in strengthening the western Pacific-Indian Ocean Walker circulation. Associated with it, the low-level westerlies are weakening over the peninsular India, thus contributing to the reduction of moisture transport towards India. Therefore, rainfall has decreased over the Western Ghats and central-east India. In the very last decade of the analyzed time-series, moisture over the Arabian Sea started to increase accompanied by strengthening of vertical motion. At the same time, the SST over the western Pacific is cooling and causing the reduction of convection that in turn weakens the vertical motion compared to the decades before.

Keywords: Indian summer monsoon, Indo-Pacific ocean warming, Arabian Sea, low-level moisture, climate trends

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1. INTRODUCTION

Several studies have drawn attention on the fact that the Indo-Pacific Ocean has been experiencing a basin-wide warming since the 1950s (Levitus et al. 2000, 2005; Alory et al. 2007; Du and Xie 2008; Alory and Meyers 2009; Rao et al. 2012; Tokinaga et al. 2012; Hoell and Funk 2013). It has also been reported that the sea surface temperature warming is accompanied with a pronounced weakening of the large-scale summer monsoon circulation and a reduction of associated rainfall over India (Rao et al. 2004; Joseph and Simon 2005; Fan et al. 2010; Turner and Hannachi 2010; Luffman et al. 2010; Krishnan et al. 2012). Recently, it has been found that the SST trend over the tropical western Pacific played a major role in changing the atmospheric circulation and drying South Asian landmass (Kumar et al. 2004; Sanchez-Gomez et al. 2008; Zhou et al. 2009; Annamalai et al. 2013). The most intensive air-sea interaction takes place in the Indo-Pacific warm pool, corresponding to the largest area of warm water in the world with active convection (e.g. Saraswat et al. 2007), with the western Pacific warm pool being larger and warmer than the Indian Ocean warm pool (Vinayachandran and Shetye, 1991).

The Indian summer monsoon is characterized by a large cross-equatorial flow at low levels over the Indian Ocean with low level jet along the coast of east Africa (Findlater, 1969) and peninsular India (Joseph and Raman, 1966). The summer monsoon, which arrives at the southern tip of India by the last week of May or first week of June, brings a large influx of moist air into the Indian subcontinent through this low level jet. Numerous studies have pointed out the important roles of cross-equatorial moisture flux from the southern Indian Ocean and the evaporative flux from the Arabian Sea for the large increase of moisture during the summer monsoon. It was reported that water vapor from the portion of Indian Ocean south of the equator is the main source of the moisture for summer rainfall over India (Saha and Bavadekar, 1973; Cadet and Reverdin, 1981a; Cadet and Greco, 1987a). Some studies in the past tried to estimate the water vapor budgets in the Arabian Sea with available observed data and found that inter-hemispheric flux was larger than that from the Arabian Sea (Saha and Bavadekar, 1973; Cadet and Reverdin, 1981b; Cadet and Greco, 1987a, b). Pearce and Mohanty (1984) showed that a major part of the moisture necessary to provide the latent heat release over India is supplied by evaporation from the Indian Ocean south of the equator and off the horn of Africa and that this latent heat release, in turn, maintains the strong cross-equatorial flow. However, other studies concluded that the Arabian Sea is an important moisture source for Indian monsoon rainfall

(Pisharoty 1965; Ghosh et al. 1978; Murakami et al. 1984; Levine and Turner 2010).) The evaporation over the Arabian Sea constituted a key contribution to the moisture supply for the monsoon rains (Rao et al. 1981; Murakami et al. 1984; Sadhuram and Ramesh Kumar, 1988). Kishtawal et al (1993), using satellite data for three years, found that evaporation over the Arabian Sea is a variable quantity and forms a significant part of the net moisture budget over the Arabian Sea. Izumo et al (2008) have shown that the reduced ocean upwelling of cold water in the western Arabian Sea in late spring contributed to increase in moisture transport over the Arabian Sea and increase Indian monsoon rainfall over the Western Ghats.

Rapid warming of the Indo-Pacific basin has been observed in recent decades. As per the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2013), SST warming is projected to continue in the near term (Kirtman et al. 2013) and in the 21st century climate scenarios (Collins et al. 2013). Therefore, explaining the moisture changes in the Indian Ocean and its dependence on SST and other factors is important for understanding future climate projections of the Indian summer monsoon. Moisture availability and its advection by prevailing summer monsoonal winds is the principal aspect of the observed rainfall over the Indian subcontinent. In this study, we aim to demonstrate how the moisture over the Arabian Sea has changed during the last few decades and how it has influenced local atmospheric conditions and Indian monsoon rainfall. We have tried to understand the changes in the atmospheric processes that have occurred during the last six decades over the Indo-Pacific region using a linear trend approach. We have also carried out moisture flux analysis over the Arabian Sea to understand the precipitation changes over India.

The study is organized as follows: observed datasets and atmospheric re-analysis used in this study are described in Section 2. The main results are presented in Section 3 in terms of trends in the ocean and atmosphere above the Indo-Pacific region and related processes responsible for the changes. Finally, Section 4 collects the main conclusions of the study.

2. DATA AND METHODOLOGY

SST from the HadISST dataset (Rayner et al. 2003) covering 1951-2012 is used in the analysis. Long term precipitation for the period 1951-2012 is taken from the 0.5 degree Climate Research Unit (CRU) version 3.21 dataset (Harris et al. 2014), which is only available over the land. In the analysis of the recent period, we consider global precipitation from Global Precipitation Climatology Project (GPCP) version 2.2 dataset at horizontal resolution of 2.5x2.5 degree available over both land and ocean for the period 1979-2012 (Adler et al. 2003). The three dimensional specific humidity, winds, and vertical velocity (omega) are taken from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis for the period 1951–2012 (Kalnay et al. 1996) available at 2.5 degree resolution. For all the analysis in this study the June-July-August (JJA) mean, corresponding to the peak monsoon season over India, has been considered for the computation of the climatology, interannual variability and the linear trends for the period of analysis (i.e. 1951-2012). The temporal record of the analysis has been chosen as corresponding to the observed rapid SST warming over the Indo-Pacific region (Rao et al. 2012; Tokinaga et al. 2012; Hoell and Funk 2013).

To identify the spatial distribution of changes, the linear trend is computed at each grid point. Similarly, the interannual variability over specific regions is analyzed in terms of area-averaged time series, then corresponding linear trend has been calculated.

To understand the moisture variability, the time series of the fluxes across different sections of a rectangular box over the Arabian Sea (Fig. 1a) are computed. The box consists of eastern boundary: 0 – 16N (at 72E), southern boundary: 53E – 72E (at equator), western boundary: 0 – 16N (at 53E) and northern boundary: 53E – 72E (at 16N). The following equation is used to calculate the moisture transport across a wall.

$$F_v = \frac{1}{g}\int_{p_b}^{p_t}\int_0^L q v_n \, dp \, dl \tag{1}$$

where g is the acceleration due to gravity, p_t the pressure at the top of the layer (300 hPa), and p_b the pressure at the bottom of the layer (surface). L is the horizontal length of the section. q is the specific humidity and v_n is the wind component normal to the horizontal section (zonal or meridional). The top layer of the vertical integration is considered here at 300 hPa because above that level the specific humidity amounts are very low and therefore not included in the reanalysis (Kalnay et al. 1996). In fact, above 300 hPa the specific humidity in the tropics is at least two orders of magnitude smaller than that near the surface, and moisture transports are therefore of negligible influence to the calculation of vertical integrated moisture flux.

The evaporation (E) is computed from the bulk aerodynamic formula:

$$E = \rho C_d (q_s - q_a) V_a \qquad (2)$$

where q_s is the saturation specific humidity at the sea surface, q_a the specific humidity of air at 10m, V_a the wind speed at 10m, ρ the density of air, and C_d the transfer coefficient.

3. ANALYSIS OF THE INDO-PACIFIC REGION: TRENDS AND PROCESSES

3.1 SST AND PRECIPITATION

At first the observed trend and interannual variability of June-July-August (JJA) mean SST and precipitation is analyzed and presented in Figures 1 and 2, respectively. SST is consistently warming throughout the Indian Ocean and western Pacific Ocean during the period 1951-2012 (Fig.1). The maximum increase is observed over the equatorial central Indian Ocean (~1.5 C), northwest Arabian Sea, and the coast along the west of Australia (Fig 1a). At interannual time-scales SST averaged over the region 50-100 E and 10S-10N is increasing from 27.4C in 1951 to a summer climatology of 28.3C in 2012 (Fig 1b). Similar trend is also observed over the Arabian Sea (Fig. 1 c). SST is also increasing in the western Pacific Ocean but the rate of increase is lower (Fig. 1d) than that of the Indian Ocean. On the average, the SST warming over the central Indian Ocean, Arabian Sea, and the western Pacific is 0.93C, 0.87C, and 0.68C, respectively, during the 62 years period (1951-2012). Comparing the trends in the different areas, Fig.1d shows that after 1999 the SST increase over the western Pacific is much reduced and toward the end of the record, it actually started to reverse.

During the period 1951-2012, precipitation has been decreasing mostly over the Indian landmass, including the Western Ghats and central India, and slightly also over southeast Asia (Fig. 2a). On the other hand, it has increased over East Asia (Fig 2a). The area-averaged precipitation on interannual time scale over the Indian region (70-95E and 7-32N), central-east India (76-93E and 22-32N), and East Asia (105-125E and 20-35N) are shown in Figs 2b, c, d. The rate of precipitation changes for whole India, central-east India and East Asia are -14.45 mm, -33.42 mm and 14.92 mm respectively during the period 1951-2012 (Fig 2b, c, d). During the last decade of the time series precipitation is slightly increasing (or doesn't show any decreasing trend) over whole India and central east India compared to the previous decades. At the same time, it is slightly decreasing over East Asia compared to earlier decades (Fig. 2d). The changes occurring in the last decade are further discussed below in section 3.6.

3.2 MOISTURE CHANGES OVER THE ARABIAN SEA

The moisture over the Arabian Sea is important for the Indian summer monsoon rainfall as it is transported towards India subcontinent through the strong low-level winds during the monsoon season. In the summer climatology high values of moisture is observed over the north Indian Ocean and neighbouring Asian landmass both in the low-level and vertically integrated for the whole troposphere (Fig 3a and Fig 3d, respectively). The linear trend of specific humidity at 850 hPa level shows that the moisture is decreasing over the Arabian Sea/eastern Africa sectors and in the southern part of the Bay of Bengal, while it is increasing over the western Pacific and north-eastern parts of south Asian landmasses (Fig 3b). The decreasing moisture trend in the western part of the region and increasing to the east is more evident in the mass-weighted vertical integral (from 1000 hPa to 300 hPa) of the specific humidity (Fig 3e). The time series of moisture area averaged over the Arabian Sea for the 850 hPa level and the vertical integral, both shows a clear decreasing trend (Fig 3c and Fig 3f). As moisture over Arabian Sea is decreasing, it is likely that it will contribute to the decrease in precipitation over the Indian landmass. The low level moisture over the Arabian Sea is increasing from the surface up to the 925 hPa and decreasing above (not shown) it. Increased moisture in the very low portion of the troposphere reflects increased SST over the region. On the other hand, decreased moisture above 925 hPa is not directly related to the local SST changes. So, other factors have to be taken into account as discussed below.

3.3 UNDERSTANDING THE CAUSES FOR DECREASED MOISTURE OVER THE ARABIAN SEA

To understand the reason for the dryness over the Arabian Sea, we start considering the changes in the mean atmospheric processes over the region. Fig. 4 shows the summer climatology and the linear trend of vertical velocity at 500 hPa and its vertical integral in the troposphere (from 1000 hPa to 300 hPa) for the period 1951-2004. Here, we have considered the data series for the period 1951-2004 because the moisture over the Arabian Sea has decreased until 2004 and increased thereafter. So, the analysis for the period 1951-2004 would help us to understand the mechanism for the decreasing trend of moisture over the Arabian Sea.

The Arabian Sea, the Bay of Bengal, and the Asian landmasses are all regions of strong upward motion in summer associated with enhanced convection during the monsoon (Fig. 4a, 4c). In the summer climatology, the region of strong vertical motion over the eastern Arabian Sea and Bay of Bengal is associated with high values of moisture over the same regions, as shown before (Fig.3a, 3c). The strength of the upward motion has reduced over the eastern Africa, Arabian Sea, Bay of Bengal, and Indian landmass though it has enhanced over East Asia and western Pacific (Fig. 4b).

The cause of the moisture decrease and the weakening of upward motion over the Arabian Sea is explored by using the linear trend of the height-longitudinal cross section of specific humidity and vertical velocity (omega) averaged over the latitude 0-16N (Figure 5) for the period 1951-2004. The result indicates that there is a trend of rising motion over the western Pacific and corresponding trend of sinking motion over the Arabian Sea/East Africa and Indian landmass (Fig 5b). The trend of rising (sinking) motion is associated with the trend of increasing (decreasing) moisture over the western Pacific (Arabian Sea). The moisture decrease is observed throughout the atmosphere over the longitude band 0-60 E and 120W-180E (Fig. 5a). The trend of strong reduction of moisture over the 0-60E band coincides with the strong sinking motion (Fig. 5b). The intensity of moisture decrease is larger over the eastern Africa compared to other regions. It seems that the trend of sinking motion is linked to the western Pacific (Fig 5b). Increased rising motion over the western Pacific may be due to enhanced convection and associated SST warming trend over that region (Fig. 5c). Consequently, this contributes to the strengthening of the western Pacific-Indian Ocean Walker circulation with associated trends of rising motion over the western Pacific and the trend of sinking motion over the eastern Africa/Arabian Sea. Even though SST is warming across the Indo-Pacific Ocean basin, upward motion strengthens mostly over the western Pacific Ocean while the upward motion weakens over the Arabian Sea/East Africa. A trend of sinking motion is found over the central Pacific with an upward motion trend west and east of it, similarly to the La Niña Modoki pattern in the equatorial Pacific, as described by Ashok et al. 2007. Our hypothesis here is that the decreasing trend of moisture over the Arabian Sea is mostly related to the western Pacific and not directly to the warming of the Indian Ocean because the air mass that comes from the western Pacific sinks over the Arabian Sea. To see the relationship between the Arabian Sea and western Pacific further, the correlation coefficient of the low level moisture between the two regions is calculated and they shows significant negative correlation to each other (not shown).

In general, the region over 60-90E (110-140E) representative of north Indian Ocean (western Pacific) along the latitude band 0-20N shows more (less) upward motion associated with more (less) convection (Fig. 4a, c). It is worth to mention that the western Pacific SST reached 29.4C in the last decade (1995-2004) compared to the SST value of 28.9C during the period 1951-1960. Comparatively, in the period 1995-2004 the north Indian Ocean SST reached 28.6C from the value 28.0C in 1951-1960. Although, the rate of SST increase is almost equal over both the Indian Ocean and Western Pacific Ocean areas (0.57C and 0.54C respectively), the western Pacific has generated more upward motion in the recent decade likely due to the higher absolute temperature value. During summer, the atmosphere over the tropical western Pacific is more unstable than over the tropical Indian Ocean. Thus the rise in SST and accompanying moisture surplus in the lower troposphere can more readily destabilize the atmosphere and increase the vertical velocity anchoring convection in this region more than over the tropical Indian Ocean (Annamalai et al. 2013).

3.4 UNDERSTANDING THE CAUSES FOR CHANGES IN PRECIPITATION OVER THE INDIAN LANDMASS

We discussed in section 3.1 that precipitation shows decreasing trend over the Western Ghats, central and northeast India, and Myanmar region. To understand the mechanism for the decreasing trend of precipitation over Indian landmasses, we have computed the vertically integrated (1000-300 hPa) moisture divergence and its trend (Fig. 6a, e) over the Indo-Pacific region. The JJA climatology shows that the strong moisture convergence is observed over the Asian landmass region contributing to the summer monsoon rainfall. However, the linear trend pattern shows that the moisture convergence is weakening over the Indian landmass during the period 1951-2004, which is contributing to decreased precipitation over the region.

As described in the introduction, cross equatorial flow and the low level jet over the Arabian Sea transport moisture towards India. Those are important factors influencing the summer monsoon rainfall over India. To see their changing impact in the summer rainfall over India we have calculated the linear trend of the JJA mean zonal winds during the period 1951-2004. Westerlies are weakening over the Indian landmass, Bay of Bengal, and the surrounding countries Bangladesh and Myanmar (Fig. 6b, f). This weakening of the westerlies may be responsible for the reduction of moisture transport towards India and hence the decreasing precipitation, including that of orographic precipitation over the Western Ghats in India and Arakan mountains in Myanmar. Nevertheless, westerly is increasing just south of the Indian peninsula (along Sri Lanka). During weak monsoon conditions, the south-westerly moisture flow tends to weaken over the Arabian Sea, the Indian landmass and the Bay of Bengal and westerlies tend to be oriented along the equatorial Indian Ocean (Rodwell 1997; Joseph and Simon 2005; Krishnan et al. 2006). Joseph and Simon (2005) found that during spells of strong monsoon, the core of the low level jet (LLJ) passes through peninsular India between 12.5 and 17.5N latitudes. In weak monsoon spells, LLJ bypasses India and flows to its south through the latitude belt from 2.5 to 7.5N. To explain the reduced precipitation over the Myanmar region the contribution from the weakened westerlies is combined with the anomalous dry moisture flux coming from the colder north east region (not shown).

To see the vertical distribution of moisture transport that is entering India, the linear trend of height-latitude cross section of zonal moisture flux is analyzed along 75E (Fig. 7). It is observed that westerly moisture flux weakens along the belt 10-20N throughout the atmosphere, indicating the weakening of the moisture transport towards India. This is indicative of the weakening of moist flow towards India and hence decreased precipitation. Westerly moisture flux increases in the lower level (extending up to 800 hPa) from the equator to 9N (Fig. 7), indicating that moist flow bypasses India and turn towards south of the peninsular India at the time of decreasing precipitation trend over India. Westerly moisture flux is strengthening above 900 hPa in the latitude band 20-30N (Fig. 7), coinciding with slightly increasing precipitation trend over the northwest India (Fig. 2a).

The linear trend of the meridional winds shows that the southerly flow is getting stronger over the western Arabian Sea (Fig. 6g). At the same time southerly flow is weakening along the eastern Arabian Sea and over the Bay of Bengal. The increasing southerly wind over the western Arabian Sea along with the SST warming contributes to the increasing of evaporation over the western Arabian Sea (Fig. 6h). On the other hand, the weakening of southerly wind (Fig. 6g,h) is contributing to the reduction of evaporation over eastern Arabian Sea and Bay of Bengal. This weakening evaporation in turn leads to reduction of moisture availability that is required for the monsoon rainfall over India. The reduction of evaporation over the eastern Arabian Sea and Bay of Bengal is linked to the reduction of precipitation over the Western Ghats, central India, and the regions surrounding the Bay of Bengal. It was also verified that the precipitation over India has a positive (negative) correlation with the low level moisture over the Arabian Sea (western Pacific region) [not shown].

3.5 MOISTURE BUDGET ANALYSIS OVER THE ARABIAN SEA

To understand the variability and trend of the water vapor transport over the Arabian Sea during the monsoon season, the time series of vertical integrated moisture flux for the JJA season is analyzed over a box (Fig. 3b) for the period 1951-2012. It was observed that the mean climatology of fluxes along the eastern and western boundaries flows from west to east during the period 1951-2012. Similarly, the mean fluxes along the southern and northern boundaries flow from south to north.

Considering the moisture fluxes in the Arabian Sea (Fig. 8) during the monsoon season, there is an influx of water vapor across the southern and western boundary, while there is an outflux of water vapor along the eastern and northern boundary. In particular, the moisture flux transport along the eastern wall (eastern Arabian Sea) is large compared to that of the other three walls of the box (Fig. 8d). It indicates that a large amount of moisture is transported from the Arabian Sea to the Indian subcontinent, contributing to the summer rainfall. A large amount of moisture is also found entering through the western wall of the box (Fig. 8c). In this case, the flux across the western boundary is regarded as solely due to the deflected southern hemispheric trades (Ghosh et al. 1978). Also Murakami et al (1984) reported that the source for the westerly flux along the 45E is from the south of the equator. Considering the time-series from 1951 to 2012, in the Arabian Sea box the moisture flux decreased along the eastern boundary (Fig. 8d) and increased along the northern boundary (Fig. 8b). The decreasing trend of moisture flux along the eastern boundary coincides with weakening of the westerlies over this region. Similarly, the increasing moisture flux along the northern boundary is corresponding to the strengthening southerly wind along the line.

As the flux along the eastern wall is decreasing, this is contributing to the decreased precipitation over India. The moisture decrease along the eastern boundary is related to the moisture divergence towards south of the peninsular India and strengthening of westerlies over this region. Ghosh et al (1978) mentioned that the flux across the eastern boundary decreases considerably during weak monsoon. To understand the relation further, we have computed the correlation coefficient between the precipitation and the moisture fluxes along all the walls of the box over the Arabian Sea (Figure 9). The moisture flux along the eastern Arabian Sea (along 72E) has a positive correlation with the precipitation over India and Myanmar region (Fig 9d). The correlation is even stronger if we consider the eastern wall along the 8-22N latitude band (Fig. 9e), which lies just to the west of India. This is consistent with the discussion above about the declining of moisture flux along the eastern boundary that coincides with reduction of precipitation over the central-east India and Myanmar region (Fig. 2a). It indicates that once the westerly weakens over the eastern Arabian Sea, the moisture cannot reach India and Myanmar regions, hence precipitation there decreases. The moisture flux along the western boundary also has a positive relation with the precipitation over India (Fig 9b). The moisture flux that is entering through the western boundary is the component of cross equatorial flow along the western Arabian Sea. The flux along the southern boundary does not show any positive correlation (Fig. 9a) with the precipitation over India. This result is apparently in contrast with previous literature demonstrating that the moisture coming from the southern hemisphere strongly contributes to the monsoon rainfall over India. We explain this contrast in terms of the boundary chosen in our analysis, in fact we have considered the southern boundary along the equator from 53E to 72E while strong moisture transport should occur along the belt 45-53E, as a part of cross equatorial flow, that is not part of the Arabian Sea box considered here.

3.6 CHANGES IN THE VERY RECENT DECADE (2003-2012)

As shown in sections 3.1 and 3.2, the very last decade of our time series (i.e. 2003-2012) has experienced changes in moisture over the Arabian Sea, SST over the western Pacific and precipitation over both India and East Asian region which differ from the decades before. In fact, during this period moisture at 850 hPa increases, SST over the western Pacific decreases, and precipitation over India (East Asia) is slightly increasing (decreasing) compared to earlier decades. In the last decade, the moisture over the Arabian Sea started to increase, instead of the decrease seen up to 2004. Here we want to document how the changes in SST and atmospheric processes over the last decade are related with the changes in moisture trends over the Arabian Sea. So we consider here the last two decades of the time series (i.e. 1993 - 2012) dividing them into two equal parts for further analysis (i.e. 1993-2002 and 2003-2012). In the analysis that follows, the JJA mean of the period 1993-2002 is subtracted from that of the period 2003-2012.

Enhanced upward motion (Fig. 10b) is found over the Arabian Sea during 2003-2012 along with the enhanced moisture (Fig. 10a) compared to the decade before. The enhanced upward motion over the Arabian Sea is associated with weakening upward motion over the western Pacific. This weakening upward motion over the western Pacific is due to the cooling of the sea surface temperature during the period 2003-2012. This cooled SST caused weakening of the convection and hence weakening of upward motion. This is the reverse of what has occurred during the whole past decades and that was discussed in Section 3.3. Considering the whole period 1951-2012, upward motion is strengthening over the western Pacific and it is weakening over the Arabian Sea. This suggests that the local Walker circulation over the Arabian Sea and western Pacific changed in the very recent decade. However, in the recent decade the increased moisture over the Arabian Sea may also be attributed to more intense convection associated with the warming sea surface temperature in the recent decade (Fig. 10c). This enhanced upward motion must have helped to pump the moisture upward from the warm sea surface.

During 2003-2012, precipitation has increased over the northwest India compared to the decade before and this is associated with strengthened westerlies over the regions (Fig. 10d, e). The increased moisture along with increased westerlies contributed to transport more moisture toward northwest India and has caused more precipitation mostly in the western part of the subcontinent. At the same time the weakening of westerlies along the southern Arabian Sea reduced the moisture transport towards southern part of the western Ghats and reduced the precipitation there. The reduction of moisture transport along the Western Ghat must have also contributed to the reduced precipitation over the central-east and north-east India (as per the discussion in Fig. 9) as well.

4. CONCLUSIONS

Indo-Pacific Ocean has been experiencing a basin wide warming since the 1950s. SST warming is accompanied with weakening of the large-scale summer monsoon circulation and rainfall over the Indian sub continent. At the same time moisture has decreased over the Arabian Sea/eastern Africa regions and increased over the western Pacific/north-eastern South Asian landmasses. In this study we analyzed the linear trend of atmospheric variables over these regions to understand the relationship between the changes described.

The analysis of the trend of vertical velocity in the mid-troposphere indicates that upward motion weakened over the eastern Africa/Arabian Sea/Bay of Bengal while it strengthened over the western Pacific region. In terms of the local Walker circulation, we show that there is a trend of rising motion over the western Pacific and corresponding trend of sinking motion over the Arabian Sea/East Africa. The trend of rising (sinking) motion is associated with the trend of increasing (decreasing) moisture over the western Pacific (Arabian Sea/East Africa). Consequently, this contributes to the strengthening of the western Pacific-Indian Ocean Walker circulation wherein the trend of rising motion is observed over the western Pacific and that of sinking motion observed over the Arabian Sea/East Africa. Enhanced convection and associated SST warming trend in the western Pacific are mostly responsible for the intensified rising motion. The correlation coefficient of the low level moisture between the Arabian Sea and western Pacific shows significant negative correlation to each other. It was also verified that the precipitation over India has a positive (negative) correlation with the low level moisture over the Arabian Sea (western Pacific region).

Moisture is slightly increasing in the low level (1000-900 hPa) over the Arabian Sea and decreasing above, indicating that low level moisture trend is mainly influenced by local SST while upper level moisture is likely influenced by the western Pacific. The linear trend shows that the moisture convergence is weakening over the Indian landmass and this might be contributing to the precipitation decrease. Low level westerlies are also found to decrease during this period over the peninsular India contributing to reduce the transport of moisture over India, thus decreasing the associated rainfall. At the same time westerlies are increasing just south of the Indian peninsula.

Considering the water vapor transport over the Arabian Sea during the monsoon season, the largest influx to the volume occurs along the southern boundary, while the largest outflux along the eastern boundary. We show that in the period 1951-2012, the moisture flux along the eastern wall decreases, contributing to decreased precipitation over India. In fact, the moisture flux along the eastern Arabian Sea (i.e. 72 E) has a positive correlation with the precipitation over India and Myanmar region. This is in agreement with our conclusion that the declining of moisture flux along the eastern boundary coincides with the reduction of precipitation over the central-east India and the Myanmar region. It indicates that once the moisture flux weakens over the eastern Arabian Sea, the moisture cannot reach India and Myanmar region, thus precipitation there decreases.

We found that the very last decade in the time series shows changes in moisture, precipitation and SST different from the previous decades. In particular, during the period 2003-2012 the moisture at 850 hPa started to increase, while SST over the western Pacific started to decrease, showing a tendency opposite to the one of the previous decades. At the same time precipitation over India (East Asia) slightly increased (decreased). Enhanced upward motion is found over the Arabian Sea during 2003-2012 along with the enhanced moisture, if compared to the decade before (i.e. 1993-2002). The enhanced upward motion over the Arabian Sea is associated with a weakening of the upward motion over the western Pacific that is due to a cooling of the sea surface temperature there. This cooled SST caused weakening of the convection and hence weakening of upward motion. Increased moisture along with increased westerlies along the northern Arabian Sea contributes to transport more moisture toward northwest India and hence caused more precipitation there. At the same time the weakening of westerlies reduced the moisture transport towards southern part of the Western Ghats as well as local precipitation. As the moisture flux over the eastern Arabian Sea has a strong correlation with the precipitation over Indian region, the overall reduction of moisture transport towards the peninsular India contributed to the reduced precipitation over the central-east and north-east India.

In summary, it was observed that the moisture over the Arabian Sea and precipitation over India has strong correlation with the convection over the western Pacific. Weakening vertical motion over the Arabian Sea caused the reduction of moisture. Also, the weakening of westerlies over the Arabian Sea reduced moisture transport towards India and hence decreased precipitation over the Indian region. The reverse pattern was observed during the last one decade (2003-2012) compared to the moisture and precipitation trend during the long term period 1951-2004. It remains to be seen if this change continues in the future or returns to the earlier decade. This will be a good case for studying the decadal predictability of the system using coupled General Circulation Models (GCMs) including Coupled Model Intercomparison Project Phase 5 (CMIP5) model results.

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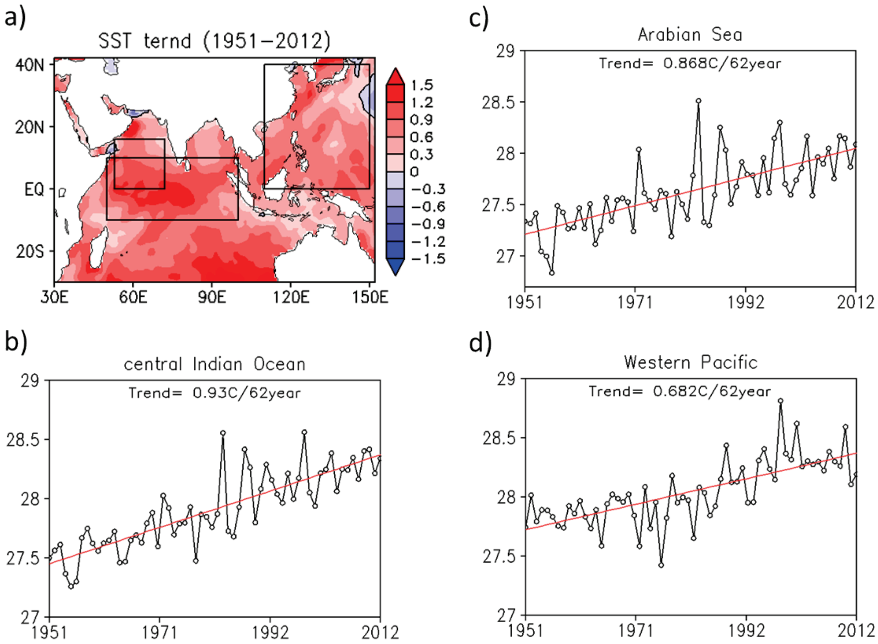

Figure 1: (a) The linear trend of JJA mean sea surface temperature (C/62 year) for the period 1951-2012. Interannual variability and linear trend of the JJA mean sea surface temperature averaged over (b) central Indian Ocean (50-100E; 10S-10N), (c) Arabian Sea (53-72E; 0-16N) and (c) western Pacific (110-150E; 0-40N).

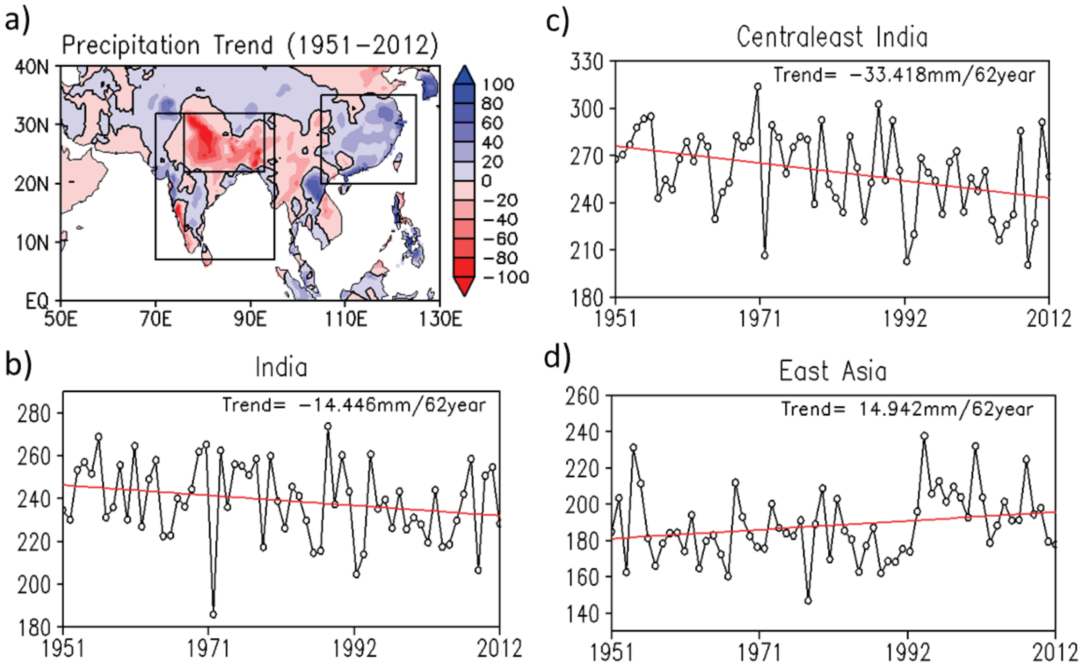

Figure 2: (a) The linear trend of the JJA mean precipitation (mm/54 year) for the period 1951-2012. Interannual variability and linear trend of the JJA mean precipitation averaged over (b) India (70-95E; 7-32N), (c) central-east India (76-93E; 22-32N) and (d) East Asia (105-125E; 20-35E).

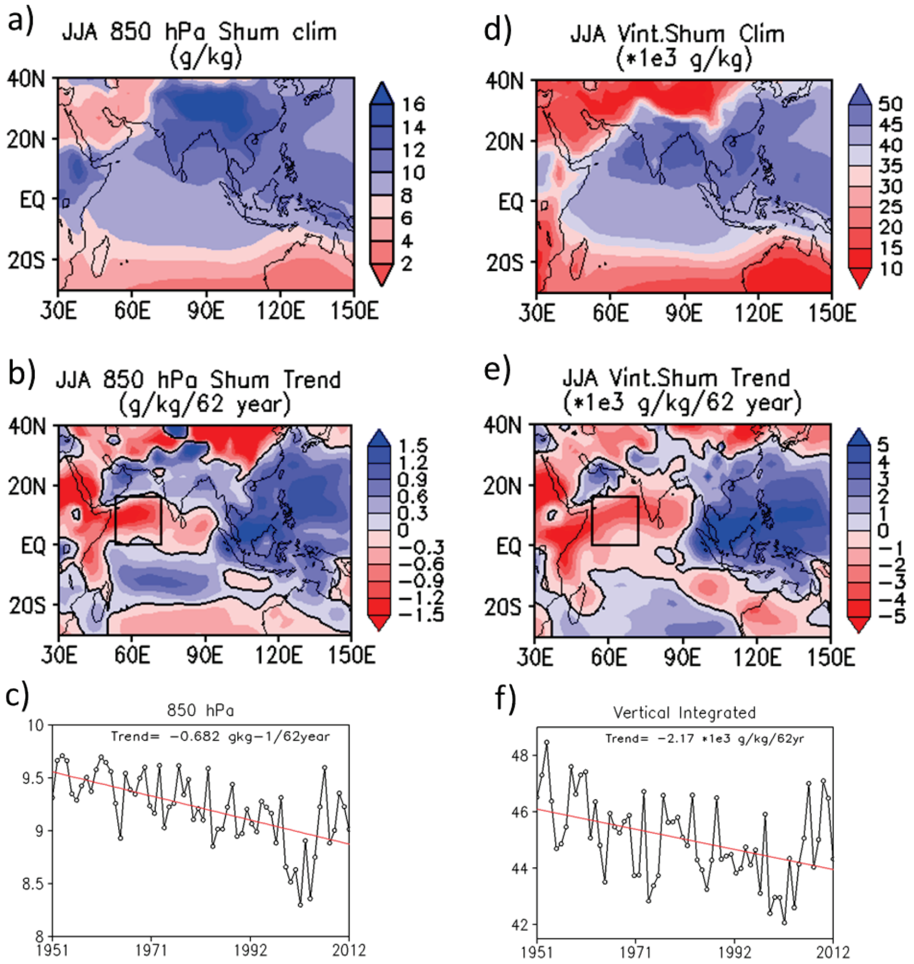

Figure 3: The JJA mean climatology of (a) 850 hPa specific humidity and (d) vertically integrated specific humidity (1000 hPa to 300 hPa) for the period 1951-2012. b and e, same as (a and d) but for linear trend. (c and f) Interannual variability of 850 hPa specific humidity and vertical integrated specific humidity averaged over the Arabian Sea region 53-72E and 0-16N (a box in the figure b and e).

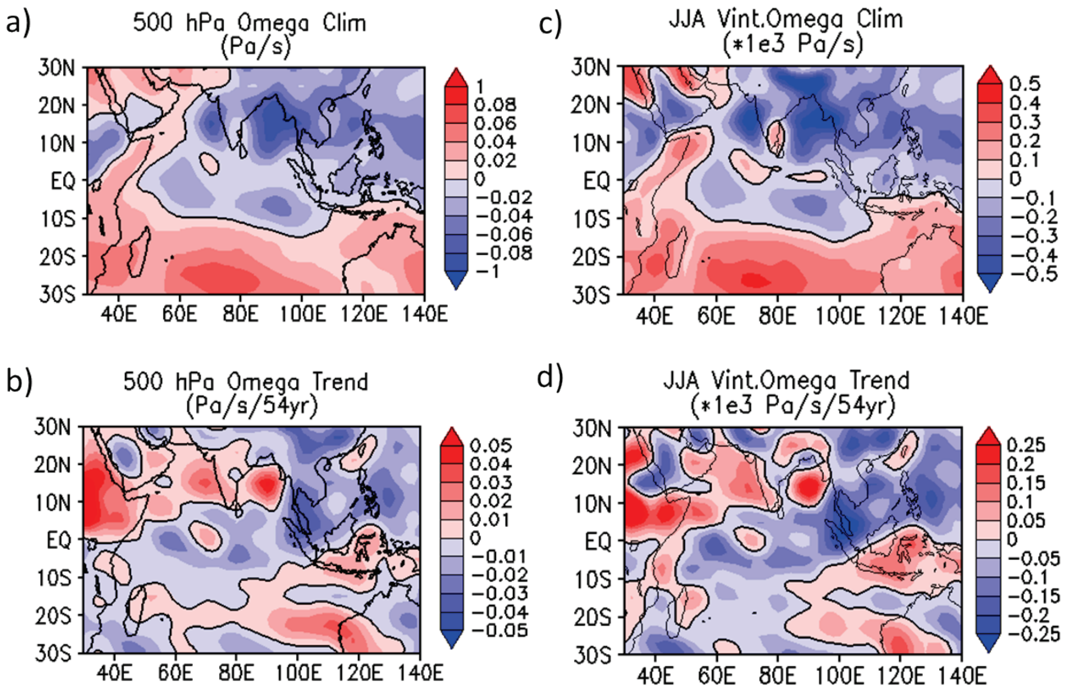

Figure 4: The JJA mean climatology of (a) 500 hPa Omega and (c) vertically integrated omega (1000 hPa to 100 hPa) for the period 1951-2004. b and d, same as (a and b) but for linear trend.

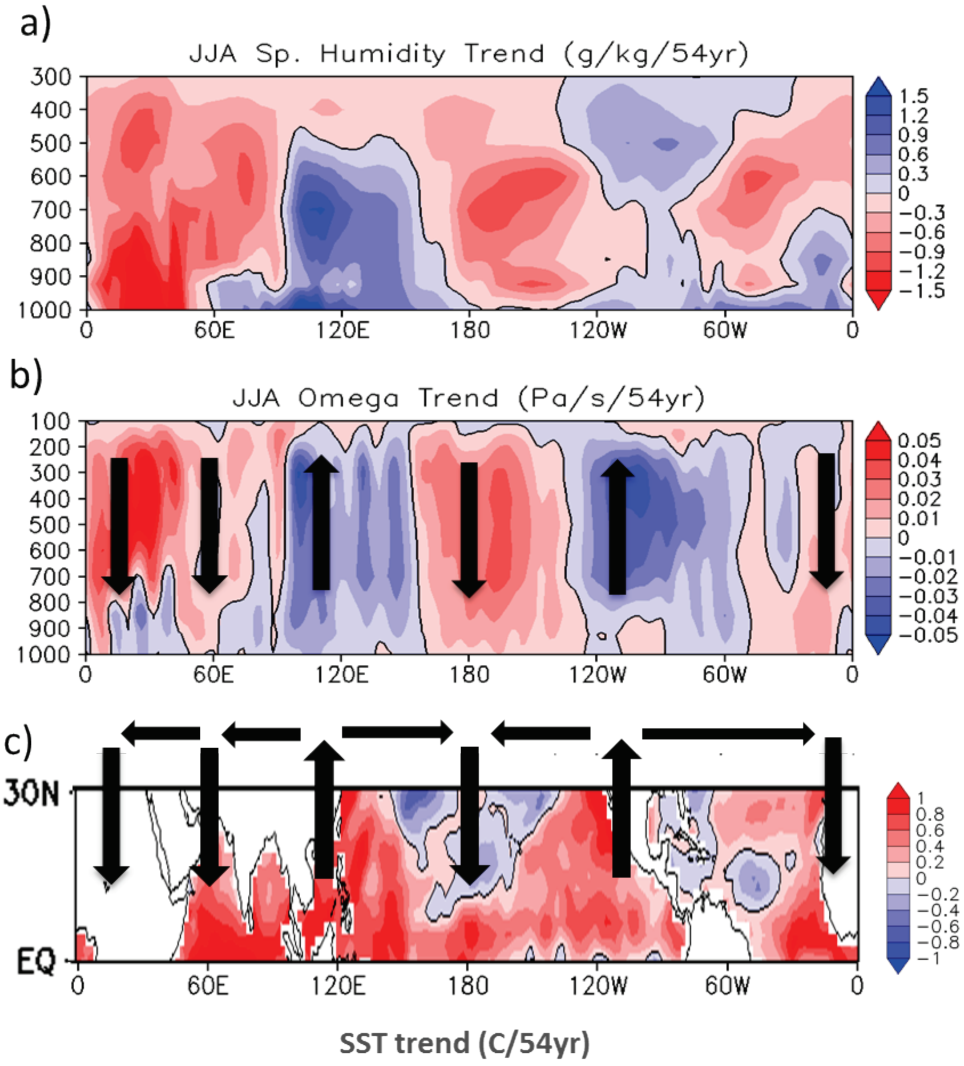

Figure 5: The linear trend of height-longitude cross-section (0-16 N) of JJA mean (a) specific humidity (g/kg) and (b) Omega (Pa/s) for the period 1951-2004. (c) The linear trend of JJA mean SST across the globe over 0-30 N (bottom).

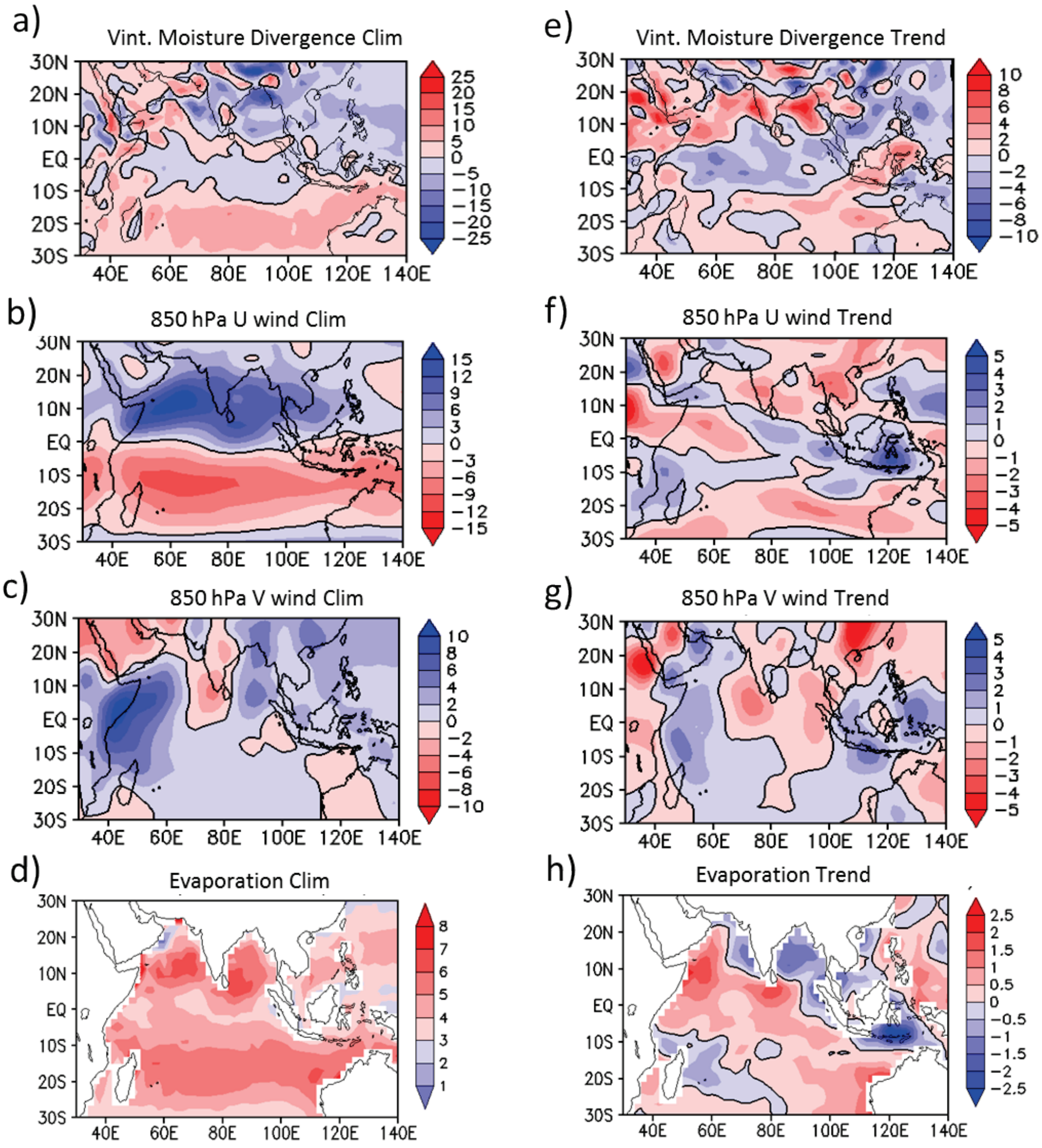

Figure 6: (a, e) The climatology and linear trend of JJA mean vertical integrated (1000-300 hPa) moisture divergence (/s and /s/54 year) for the period 1951-2004. (b, f) same as (a, e) but for 850 hPa zonal wind (m/s and m/s/54 year). (c, g) same as (a, e) but for 850 hPa meridional wind (m/s and m/s/54 year). (d, h) same as (a, e) but for evaporation (mm and mm/54 year).

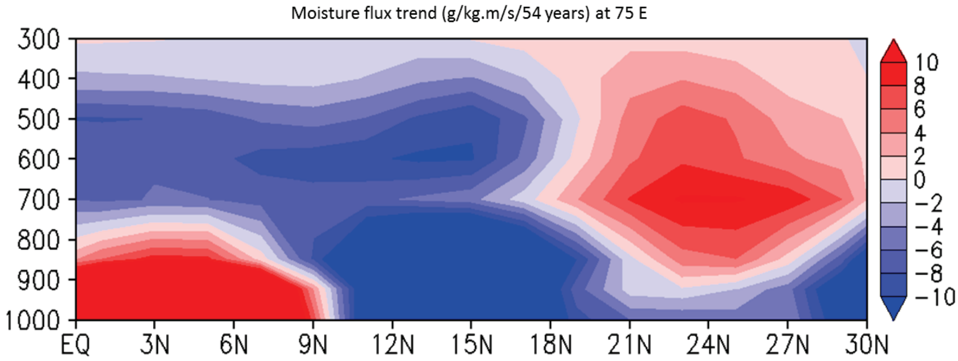

Figure 7: The linear trend of height-latitude cross section zonal moisture flux over the eastern Arabian Sea (at 75 E) for the period 1951-2004.

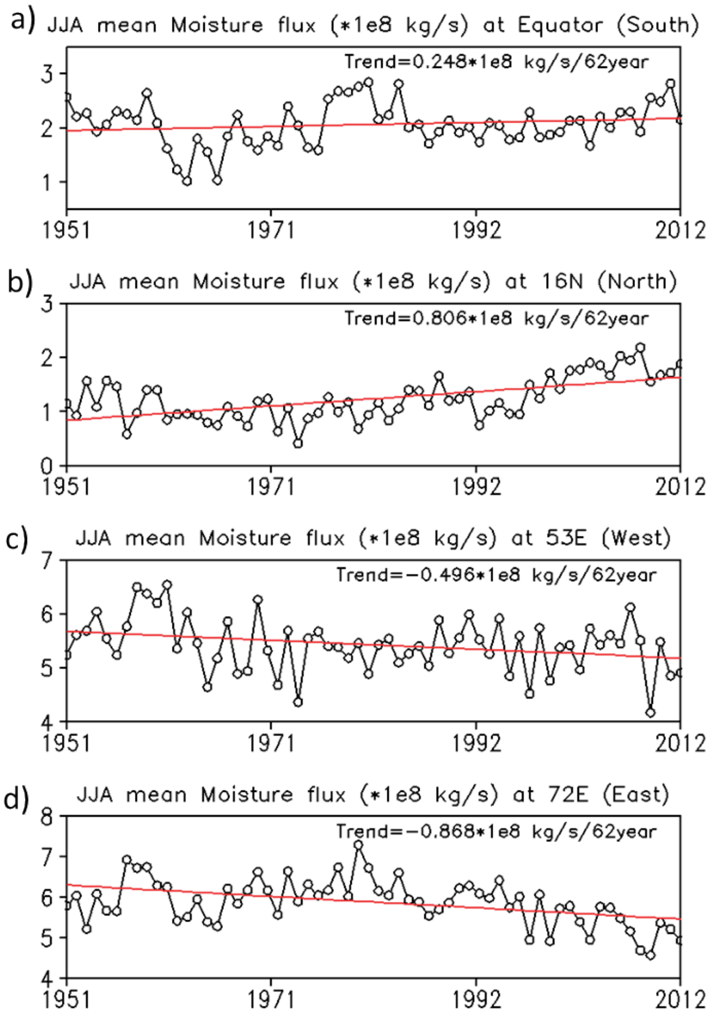

Figure 8: Moisture flux across the four walls (a) southern wall (b) northern wall (c) western wall (d) eastern wall of the box over the Arabian Sea (a box marked in Fig. 3 b) for the period 1951-2012.

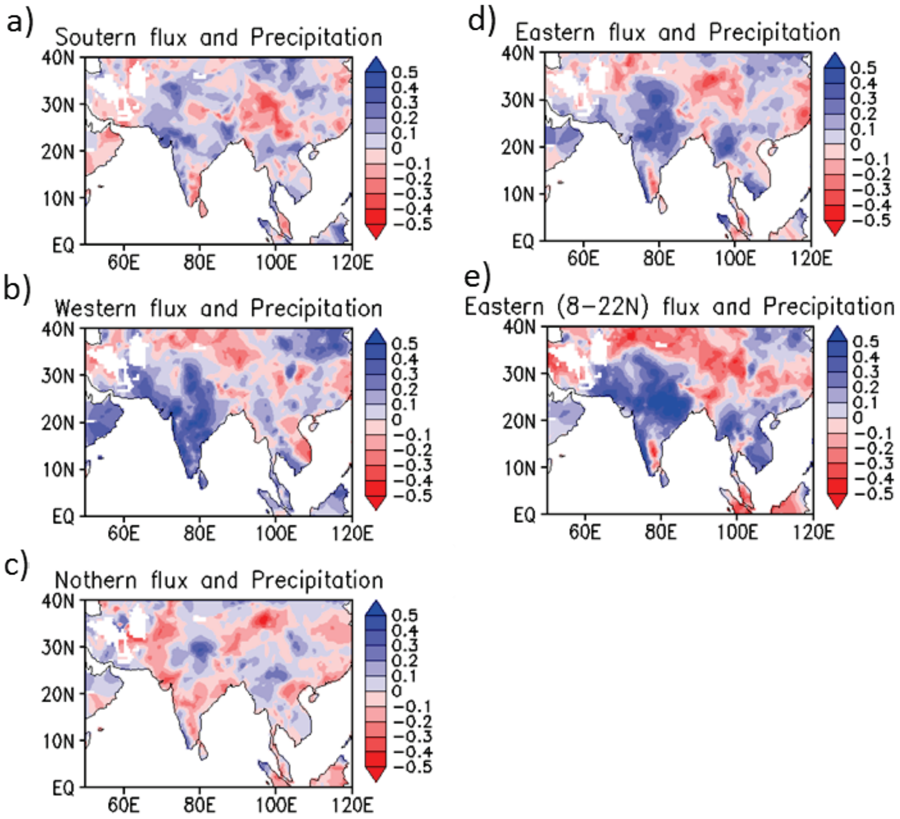

Figure 9: Correlation coefficient of precipitation with moisture flux along different wall of the box over the Arabian Sea (a) southern wall (b) western wall (c) northern wall (d) eastern wall and (e) eastern wall (8-22 N) for the period 1951-2012.

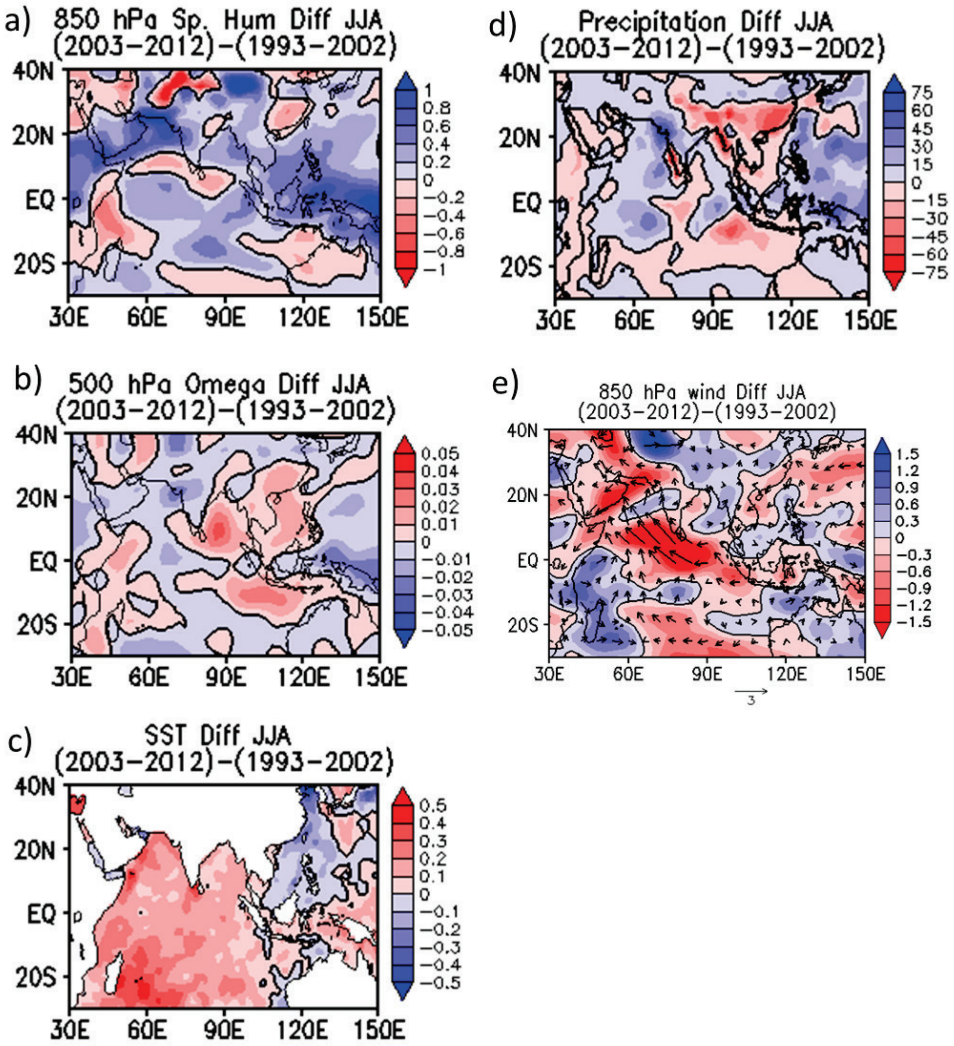

Figure 10: The differences of data for the JJA mean of 1993-2002 from JJA mean of 2003-2012. (a) 850 hPa specific humidity (g/kg), (b) 500 hPa omega (Pa/s), (c) sea surface temperature (C), precipitation (mm) and (e) and zonal wind overlies with wind vector (m/s).

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