Environmental Research Letters

LETTER

On the decreasing trend of the number of monsoon depressions in the Bay of Bengal

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Abstract

This study unravels the physical link between the weakening of the monsoon circulation and the decreasing trend in the frequency of monsoon depressions over the Bay of Bengal. Based on the analysis of the terms of Genesis Potential Index, an empirical index to quantify the relative contribution of large scale environmental variables responsible for the modulation of storms, it is shown here that the reduction in the mid-tropospheric relative humidity is the most important reason for the decrease in the number of monsoon depressions. The net reduction of relative humidity over the Bay of Bengal is primarily due to the decrease in the moisture flux convergence, which is attributed to the weakening of the low level jet, a characteristic feature of monsoon circulation. Further, the anomalous moisture convergence over the western equatorial Indian Ocean associated with the rapid warming of the sea surface, reduces the moisture advection into the Bay of Bengal and hence adversely affect the genesis/intensification of monsoon depressions. Hence, the reduction in the number of monsoon depression over the Bay of Bengal could be one of the manifestations of the differential rates in the observed warming trend of the Indian Ocean basin.

1. Introduction

India receives 70–90 percent of the annual rainfall during the four months of the summer monsoon season alone. Being a country having a large fraction of agriculture depend on the seasonal rains, variation in the monsoon rainfall affects the lives of billions of people and influence the economy of the country considerably (Gadgil and Gadgil 2006). There have been several studies on the interannual variation of the Indian summer monsoon (June–September) rainfall (ISMR), suggesting that there are teleconnections between the variation of ISMR and ocean-atmospheric processes happening elsewhere such as Pacific Ocean, Atlantic Ocean and Indian Ocean (Sikka 1980, Pant and Parthasarathy 1981, Gadgil et al 2004, Pottapinjara et al 2014, and references therein), and the nature of the links and the physical mechanisms of their interactions are still being explored. Similarly, the presence of long term trends in ISMR are also being

debated extensively (Wang et al 2013, Kitoh et al 2013, Guhathakurta and Rajeevan 2008, Goswami et al 2006). Differences in the conclusions are primarily due to the differences in the data sets used for these studies as pointed out by Wang et al (2013) as well as the analysis techniques. For example Guhathakurta and Rajeevan (2008) showed that even though there are no long term trends in the ISMR, there is a significant decreasing (increasing) trend in three (eight) meteorological subdivisions. Goswami et al (2006) argued that even though seasonal rainfall does not show any significant long term trend, the number of extreme (moderate) rainfall events within the season shows an increasing (decreasing) trend. In a recent study, using long term gridded rainfall data, Roxy et al (2015) reported that there is a significant decreasing trend in the rainfall over the central-eastern Indian region. They argued that this long term decreasing trend is primarily associated with the westward spread of the Indian Ocean warm pool. The

mechanism of this association put forth by them points to the reduced land-ocean thermal contrast and excessive atmospheric convergence to the western equatorial Indian Ocean which is responsible for the weakening of the monsoon circulation.

It is well known that the Indian summer monsoon is maintained by northward progression of the inter tropical convergence zone (ITCZ Sikka and Gadgil 1980) and the synoptic scale disturbances, commonly known as monsoon depressions (MDs), which generally form over the Bay of Bengal (BoB) or cross over to the BoB from south-China sea and propagate westward/northwestward to the mainland (Ding and Sikka 2006). It is not uncommon that MDs move north-westward along the monsoon trough and reach as far as northwestern India/Pakistan and produce large rainfall totals (some times up to 300–400 mm) along its track (Sikka 1977). As far as agriculture is concerned, MDs are very important, especially in central India as it could act as a main source of moisture (Sivakumar et al 2005). Some studies have reported a decreasing trend in the observed frequency of MDs in the recent decades (Patwardhan and Bhalme 2001, Kumar and Dash 2001, Mandke and Bhide 2003), while some other studies noted that along with the decreasing trend in MDs there is an increasing trend in the number of low pressure systems (Rajeevan et al 2000, Kumar and Dash 2001, Jadhav and Munot 2009). Nevertheless, understanding the reasons behind the decreasing trend in MDs is one of the most important science questions to be addressed.

High sea surface temperature (SST), presence of low level (850 hPa) cyclonic vorticity over the BoB, high mid-tropospheric humidity and weak vertical wind shear are considered to be the essential environmental conditions for the formation and intensification of MD (Sikka 1977). Interestingly, these are the same essential criteria for the genesis of tropical cyclones as suggested by Gray (1968). However, it may be noted that the vertical wind shear is very strong particularly over the Arabian Sea and the BoB during the monsoon season. This is a major factor that limits the synoptic scale disturbances from intensifying into tropical cyclones during this season, while in all other basins in the Northern Hemisphere, cyclone activity peaks in July-August (Gray 1968, 1979, Sikka 1977; and references therein). Recent studies of Rao et al (2004) and Rao et al (2008) suggested that the variation in the strength of upper tropospheric wind could modulate the frequency and intensity of the storms over northern Indian Ocean. It may be worth to note that the decadal variability of low-level vorticity and vertical and horizontal wind shear of zonal wind are in the unfavorable phase for the genesis and intensification of storms over the BoB after 1980 (Mandke and Bhide 2003). Rajeevan et al (2000) reported that SST in the BoB and frequency of MD had shown similar decadal variations till early 1980s, however the MD have been decreasing in-spite of increasing SST since mid-

1980s. Prajeesh et al (2013) suggested that the decreasing trend in the frequency of occurrence of MD could be associated with the declining trend in mid-tropospheric relative humidity.

Roxy et al (2015) observed that the decreasing trend in the rainfall activity over the central-eastern India is intriguing as this is the region which receives substantial amount of rainfall due to MDs/low pressure systems. This motivated us to explore whether there is any link between the decreasing trend in MDs and rainfall over the central-eastern Indian region and if so, whether the latter is also influenced by the changes in the monsoonal circulation as suggested by Roxy et al (2015). In fact, some of the studies on the long term variation of MD indicate that the changes in the 'large scale environmental parameters' are responsible for the decreasing trend in the frequency of MD over the BoB, which could be related to the changes in the circulation that Roxy et al (2015) refer to. Hence, in this paper, we try to address the links between the trends in the monsoon rainfall in India and the frequency of MD and derive the quantitative estimates of the relative contributions of each of the environmental variables responsible for the long term variation in the number of MD.

The Genesis potential index (GPI) formulated by Emanuel and Nolan (2004) is a useful tool to quantitatively describe the influence of large-scale environmental factors on the genesis of the tropical cyclones. GPI has been successfully used to analyze the seasonal, intra-seasonal and inter-annual modulation of tropical storm activity in various tropical basins (Camargo et al 2007, Camargo et al 2009, Yanase et al 2012, Li et al 2013, Girishkumar et al 2014). Given the fact that the environmental conditions responsible for the organization of the low pressure systems to depressions and cyclones are same (Sikka 1977), it is possible to use the GPI for estimating the relative contributions of different environmental conditions in the formation and development of MD.

2. Data and methodology

2.1. Data
The information on the number of days in which MD were present over the BoB or the Indian subcontinent is taken from the website of India Meteorological Department (IMD) (http://www.rmcchennaieatlas.tn.nic.in). Daily high resolution ($0.25° \times 0.25°$) gridded rainfall data (Pai et al 2014) for the period 1901–2010 is also used in this study. Monthly mean profiles of atmospheric temperature, horizontal wind, specific humidity, relative humidity, precipitation and evaporation (derived from latent heat flux) from National Centre for Environmental Prediction (NCEP) Reanalysis (Kalnay et al 1996) and monthly mean SST from the Hadley Centre Global Sea Ice and Sea Surface Temperature version2 (HadISST2)

(Rayner *et al* 2003) are used for the computation of GPI and moisture budget.

2.2. Methodology

2.2.1. Genesis potential index

Following Emanuel and Nolan (2004) and Li *et al* (2013), we have used the following expression in order to understand the relative contributions of the changes in individual environmental conditions in the changes of frequency of MDs

$$\delta \text{GPI} = \alpha 1 \times \delta \left(\frac{H}{50}\right)^3 + \alpha 2 \times \delta \, |10^5 \eta|^{\frac{3}{2}} + \alpha 3$$
$$\times \delta (1 + 0.1 V_{\text{shear}})^{-2} + \alpha 4 \times \delta \left(\frac{V_{\text{pot}}}{70}\right)^3. \tag{1}$$

where

$$\alpha 1 = \overline{|10^5 \eta|^{\frac{3}{2}}} \times \overline{(1 + 0.1 V_{\text{shear}})^{-2}} \times \overline{\left(\frac{V_{\text{pot}}}{70}\right)^3},$$

$$\alpha 2 = \overline{\left(\frac{H}{50}\right)^3} \times \overline{(1 + 0.1 V_{\text{shear}})^{-2}} \times \overline{\left(\frac{V_{\text{pot}}}{70}\right)^3},$$

$$\alpha 3 = \overline{\left(\frac{H}{50}\right)^3} \times \overline{|10^5 \eta|^{\frac{3}{2}}} \times \overline{\left(\frac{V_{\text{pot}}}{70}\right)^3},$$

and

$$\alpha 4 = \overline{\left(\frac{H}{50}\right)^3} \times \overline{|10^5 \eta|^{\frac{3}{2}}} \times \overline{(1 + 0.1 V_{\text{shear}})^{-2}},$$

where H is the relative humidity (%) at 600 hPa, is η the absolute vorticity at 850 hPa (s^{-1}), V_{shear} is the magnitude of the vertical wind shear (ms^{-1}) between 850 hPa and 200 hPa, and V_{pot} is the maximum tropical cyclone potential intensity (PI) (ms^{-1}) defined by Emanuel (1986, 1995, 1999) and modified by Bister and Emanuel (1998, 2002) to take into account of dissipative heating. The bar indicates seasonal (June–September) climatology and δ represents the difference between recent epoch (1981–2010) and earlier (1951–1980) epoch of individual parameter. As the GPI has a good skill in representing the parameters affecting the genesis potential of MDs over the BoB, as seen in the supplementary material, we use it for this study to address the changes in such environmental factors that affected the frequency in the occurrence of MDs over the BoB.

2.2.2. Moisture budget

Applying mass continuity equation and vertical integration to the water vapor budget proposed by Yanai *et al* (1973), Zangvil *et al* (2004) represented the traditional atmospheric moisture budget equation (MBE) as
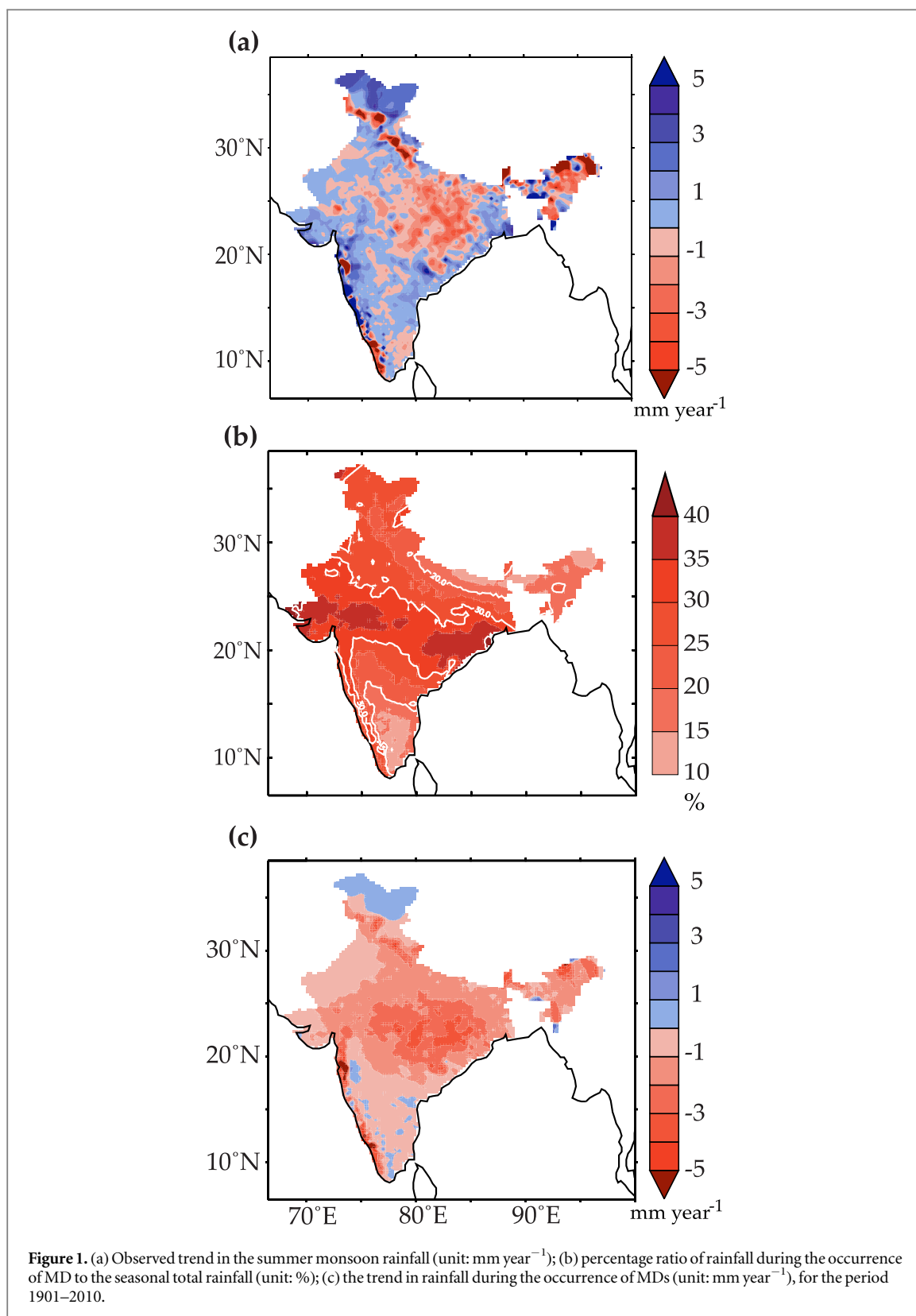
$$\frac{1}{g}\frac{\partial}{\partial t}\int_S^T q \, \mathrm{d}p + \frac{1}{g}\int_S^T \overrightarrow{V}.\nabla q \mathrm{d}p$$
$$+ \frac{1}{g}\int_S^T q \nabla.\overrightarrow{V} \mathrm{d}p = E - P \tag{2}$$

where, g is the acceleration due to gravity, S and T represents the surface and top level of atmosphere, and

E and P are the surface evaporation and precipitation rate, respectively. The first term in the left hand side of the equation (2) is the time change of atmospheric precipitable water, often called also 'storage term', which is negligible for large scale analysis (Jin *et al* 2011). The second and third terms are the horizontal water vapor advection and horizontal velocity divergence. The sum of second and third term is named as moisture flux divergence. Compared to the previous studies, moisture budget calculated by NCEP data shows appreciable match between left-hand side and right-hand side of MBE over the BoB (figure S4 in supplementary material).
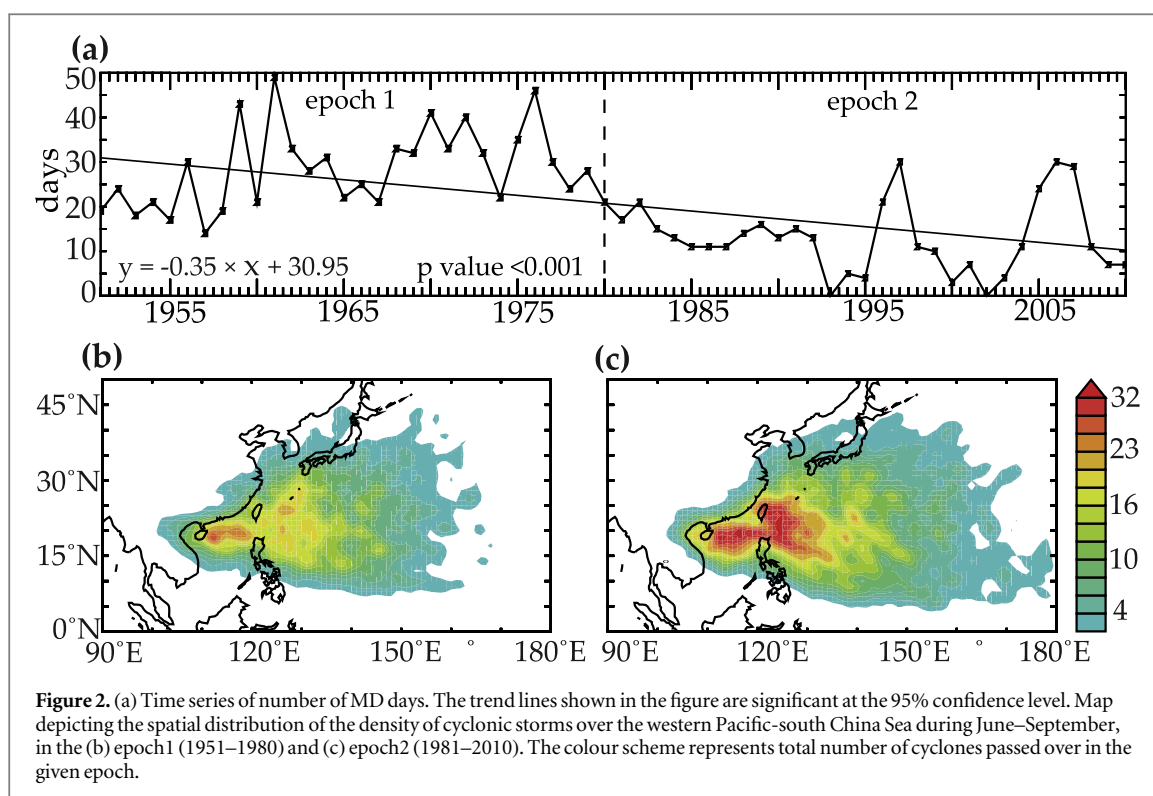
3. Results and discussions

Long term variation (1901–2010) of the monsoon rainfall over the Indian region shows decreasing trends in most parts of the country, with significant decrease observed in the central-eastern parts of the mainland as seen in figure 1(a). Recently, Roxy *et al* (2015) also had reported this decreasing trend in all India rainfall. In the Indian subcontinent, particularly in the core monsoon zone above which the monsoon trough lies, a large fraction of seasonal rainfall occur during the passage of MD. The ratio of rainfall in this region during the occurrence of MD to the seasonal mean rainfall varies in the range of 35–45%, which is quite substantial (figure 1(b)). It may be noted that even the west coast of India receives significant amount of rainfall during the occurrence of MD over the BoB. This is not surprising as it is well known that the orographic rainfall over the west coast of India has links to the large-scale convection over the BoB (Srinivasan and Nanjundiah 2002 Francis and Gadgil 2006). In this context, it is important to investigate whether the decrease in the rainfall over parts of the country has links to the decrease in the number of MDs. Figure 1(c) shows the spatial distribution of the long term trend in total rainfall received in association with MD in a given season. The rainfall of any day on which a MD is present over the BoB or the Indian subcontinent during summer monsoon season is considered as 'rain associated with MD'. It is interesting to note that the rainfall associated with MD shows a significant negative trend over the core monsoon region, particularly over the central-eastern India and the west coast of India. However, the rainfall in non-MD days has shown no significant trend except a prominent positive trend over the west coast of peninsular India (figure not shown). Essentially the decrease in rainfall is associated with a decrease in rainy days associated with the MDs, which could be either due to a decrease in the number of such systems or a reduction in their life span. Hence it is appropriate to assess the long term trend in number of MD days (days in which MDs were present) rather than the actual number of such systems. Figure 2(a) depicts the variation of number of MD days, which shows a clear

Figure 1. (a) Observed trend in the summer monsoon rainfall (unit: mm year^{-1}); (b) percentage ratio of rainfall during the occurrence of MD to the seasonal total rainfall (unit: %); (c) the trend in rainfall during the occurrence of MDs (unit: mm year^{-1}), for the period 1901–2010.

reduction in the number of such days after 1980. However, it may be noted that this decrease is essentially due to decrease in the number of MDs rather than changes in the life span of the systems (figure S1 in supplementary material).

Many studies reported that the majority of MDs over the BoB are attributed to re-genesis of westward-propagating residual lows of tropical storms, or of other tropical disturbances from western Pacific–South China Sea (WTP–SCS) region (Koteswaram and Bhaskara Rao [1963], Ramanna [1969], Mooley and Shukla [1989], Krishnamurti *et al* [1977]). It is interesting to note that the number of MDs over the BoB has shown a decreasing trend even though more cyclonic

Figure 2. (a) Time series of number of MD days. The trend lines shown in the figure are significant at the 95% confidence level. Map depicting the spatial distribution of the density of cyclonic storms over the western Pacific–south China Sea during June–September, in the (b) epoch1 (1951–1980) and (c) epoch2 (1981–2010). The colour scheme represents total number of cyclones passed over in the given epoch.

storms move westward from the WTP-SCS after 1980 compared to the earlier epoch (figures 2(b) and (c)). This suggests that either these systems are not reintensifying after they cross over to the BoB or there is considerable decrease in the number of MDs forming within the BoB basin. An important question which arises from these observations is essentially what changes in the environmental parameters which are responsible for the development and intensification of a MD have occurred in the recent epoch (1981–2010, epoch 2) compared to the previous one (1951–1980, epoch 1). In order to address this question, next we analyse the changes in each of the terms in the GPI equation.

3.1. Variation in the environmental factors responsible for the formation of MDs

The difference in the GPI between epoch 2 and epoch 1 clearly shows a decrease in the genesis potential over the head BoB (figure 3(a)) in epoch 2. The maximum epochal difference is about 1 (note that, GPI is a dimensionless quantity) where the climatological GPI is about 4.5 (which means that the reduction in GPI is approximately 22% of its mean value). A clear reduction in the GPI is observed in association with the decreasing trend in the frequency MDs (table 1). To assess the relative contribution of large-scale environmental parameters on the reduction in MD activity in different epochs, each of the terms in equation (1) is examined (figure 3) separately. Relative contributions (in percentage ratio) of the terms in the right-hand side of equation (1) to the reduction of GPI averaged over

the head BoB and central BoB are also presented in table 2. It may be noted that the key process responsible for the reduction in the GPI in the epoch 2 is the decrease in the mid-tropospheric relative humidity (figure 3(b)). The relative humidity term contributes around 62% and 72% of the total GPI reduction over the head BoB and the central BoB respectively (table 2). This is consistent with the results of Prajeesh *et al* (2013) which showed that the weakening trend in the mid-tropospheric relative humidity is a major factor in reducing the MD frequency. The strong spatial correspondence between the relative humidity term and net change in GPI (δGPI) clearly demonstrates the dominant contribution of mid-tropospheric relative humidity on the observed decrease in number of MDs.

The potential intensity term plays a secondary role in the decrease of GPI during epoch 2 (figure 3(e)). It contributes around 21% (25%) over the head BoB (central BoB) of the total GPI decrease. The vorticity term has a relatively lesser contribution to the reduction of GPI over the BoB during summer monsoon season (around 9% over the head BoB and 6% in the central BoB). It is interesting to note that the wind shear term has a positive (8%) contribution to the reduction of the GPI over the head BoB, while its contribution is almost negligible and negative (−3%) over the central BoB. We found that the GPI analysis using ERA-20C reanalysis data also yields similar results over the head BoB (figure S3 and table S1 in supplementary material). As it is clear that the decrease in the availability of the mid-tropospheric relative humidity plays the most important role in the
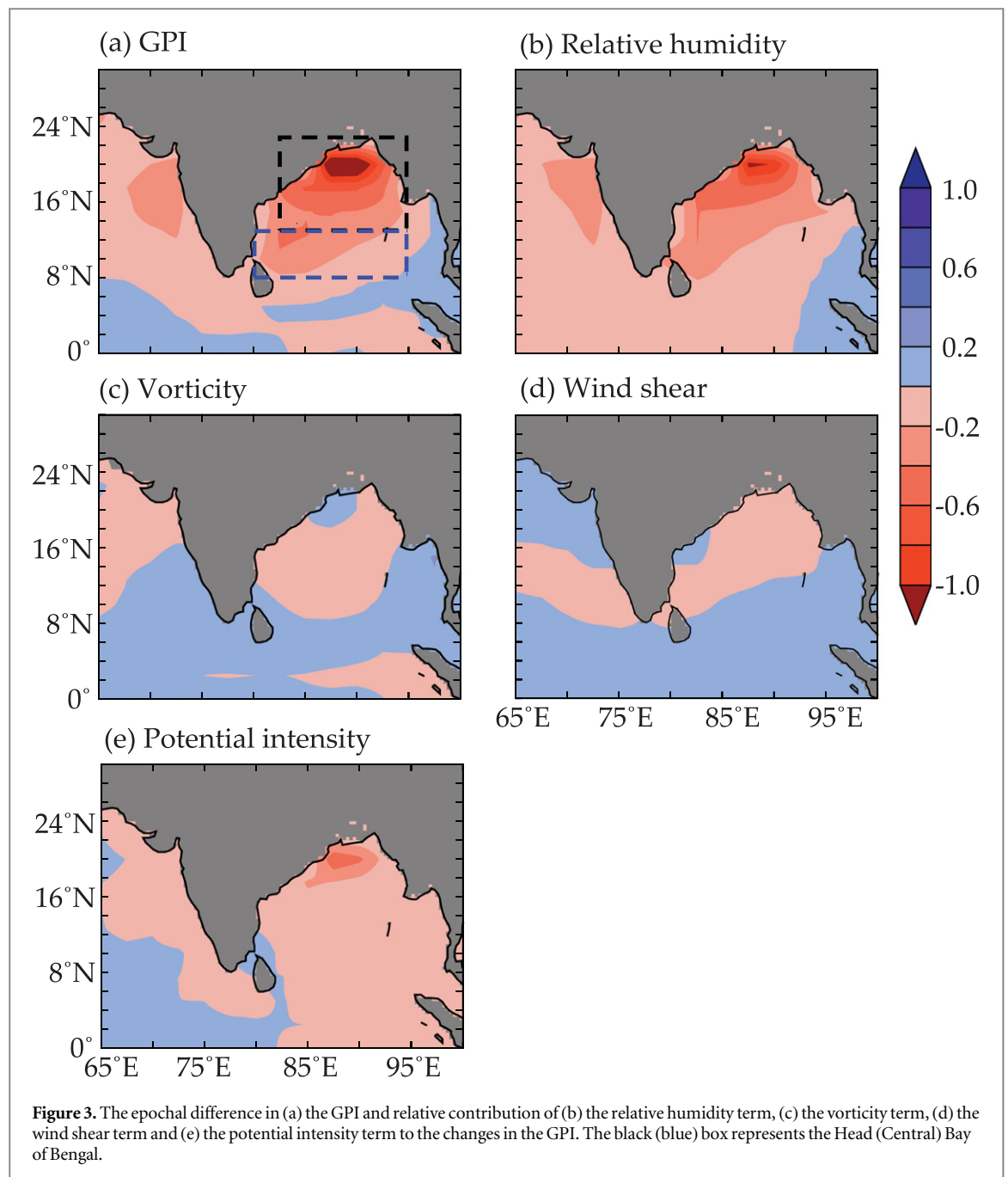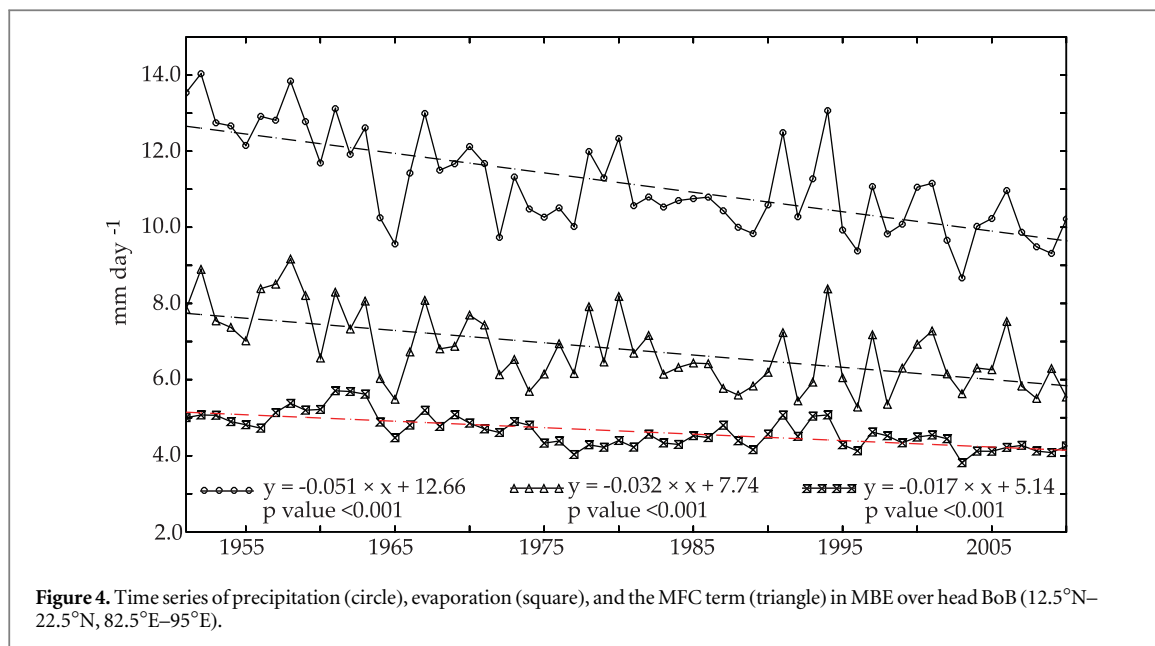
Figure 3. The epochal difference in (a) the GPI and relative contribution of (b) the relative humidity term, (c) the vorticity term, (d) the wind shear term and (e) the potential intensity term to the changes in the GPI. The black (blue) box represents the Head (Central) Bay of Bengal.

Table 1. Decadal mean frequency of monsoon depression (MD; wind speed 17–33 kt), cyclone (CS; wind speed 34–47 kt) and severe cyclone (SCS; wind speed 48–63 kt) formed in the BoB along with the mean GPI.

	Frequency of formation of			
Decades	MD	CS	SCS	GPI
1951–1960	5.90	0.80	0.10	1.88
1961–1970	5.50	0.70	0.10	1.41
1971–1980	4.70	1.10	0.70	1.51
1981–1990	3.00	0.70	0.20	1.08
1991–2000	2.00	0.30	0.00	1.06
2001–2010	2.50	0.60	0.10	1.14

Table 2. Seasonal estimate of relative contributions of the terms (in %), averaged over the head BoB (12.5° N–22.5°N, 82.5°E–95°E) and the central BoB (7.5°N–12.5°N, 80°E–95°E), on the right-hand side of equation (1) to the epochal difference in the GPI (δGPI) between recent (1981–2010) and earlier epoch (1951–1980).

GPI terms	Head BOB	Central BoB
Relative humidity	62.48	72.40
Vorticity	9.32	5.90
Wind shear	7.75	−2.89
Potential intensity	20.73	24.53

decreasing trend of MD, it is important to understand whether this reduction of relative humidity is due to changes in local evaporation or due to the changes in

Figure 4. Time series of precipitation (circle), evaporation (square), and the MFC term (triangle) in MBE over head BoB (12.5°N–22.5°N, 82.5°E–95°E).

the advection of moisture into the BoB. In order to answer this question, next we assess the relative roles of local and remote effects in the moisture budget over the BoB.

3.2. Moisture budget estimates

Moisture availability in a given atmospheric column is determined by the moisture advected and the local evaporation. The interannual variation of the seasonal moisture budget estimates over the head BoB (12.5° N–22.5°N, 82.5°E–95°E, where majority of the MD form) is depicted in figure 4. The contribution of moisture flux convergence (MFC), which is the negative of the moisture flux divergence in the MBE ($\sim$6.79 mm day^{-1}), to the net moisture content is significantly higher compared to the local evaporation ($\sim$4.64 mm day^{-1}) over the head BoB. Being a region with excess of precipitation compared to the local evaporation during the summer monsoon season (figure S5 in supplementary material), it is not surprising that there is substantial moisture convergence to the head BoB. It may be seen that both the local evaporation and MFC are decreasing at rates of 0.017 mm day^{-1} year^{-1} and 0.032 mm day^{-1} year^{-1} respectively over the head BoB (figure 4). The percentage contribution of the MFC term is higher (65%) than local evaporation (35%) to the decreasing trend in the total moisture flux also.

The decrease in the MFC should be either due to the decrease in the moisture advected into the region or due to the increase in the moisture advected out of the region or a combination of the both. Following Zangvil *et al* (2004), we quantitatively estimated the outflow and the inflow of the moisture of the head BoB

by modifying the MFD term in the MBE (equation (2)) as $\frac{OF}{A} - \frac{IF}{A}$ where as *OF*, *IF* and *A* represent the outflow, inflow and the surface area respectively. The estimates show that both the total inflow (TIF) and total outflow (TOF) over the head BoB are decreasing, with TIF decreasing at a higher rate (0.10 mm day^{-1} year^{-1}; *p* value <0.001) than the TOF (0.04 mm day^{-1} year^{-1}; *p* value 0.005) during the period 1951–2010. This suggests that the decrease of moisture advected into the head BoB is the major factor for the declining moisture over BoB.

All the terms of the MBE and the related parameters for the earlier (1951–1980) epoch and the recent epoch (1981–2010) and their differences are shown in table 3. In the recent epoch, all terms in the MBE show lower values compared to the earlier epoch. The advection terms (TIF and TOF) have higher epochal difference (-2.3 mm day^{-1} and -1.15 mm day^{-1}) compared to evaporation (-0.46 mm day^{-1}). In addition, the recycling ratio, the ratio of local evaporation to the total inflow, does not show any significant change (remains $\sim$0.15) for both epochs. This indicates that even though the net moisture content over the head BoB is decreasing, the percentage contribution of local evaporation and the TIF to the net moisture content remains same in both epochs. As the local evaporation contribute only 15% to the net moisture content, the variation in the TIF is the major factor for the increasing trend of dryness over the head BoB.

For the detailed investigation of TIF and TOF, we calculated the inflow and the outflow of moisture through all the boundaries of study area (head BoB; 12.5°N–22.5°N, 82.5°E–95°E). The inward moisture

Table 3. Moisture budget components calculated over the head BoB (12.5°N–22.5°N, 82.5°E–95°E) during recent (1951–1980) and earlier (1981–2010) epoch and their differences.

		1951–1980 (earlier)	1981–2010 (recent)	Difference (recent–earlier)
West	Inflow	15.240	14.280	−0.960
	Outflow	0.046	0.011	−0.035
East	Inflow	0.004	0.000	−0.004
	Outflow	12.230	10.810	−1.420
South	Inflow	12.010	10.350	−1.660
	Outflow	0.000	0.000	0.000
North	Inflow	0.413	0.745	0.332
	Outflow	7.388	7.690	0.302
Total Inflow (TIF)		27.670	25.370	−2.300
Total Outflow (TOF)		19.670	18.520	−1.150
TIF-TOF		8.001	6.854	−1.147
Avg Precipitation (P)		11.960	10.490	−1.470
Avg Evaporation (E)		4.879	4.418	−0.461
P−E		7.076	6.076	−1.000
Recycling ratio (R)		0.151	0.150	−0.001

transport over the head BoB is mostly through western (14.74 mm day^{-1}) and southern boundaries (11.18 mm day^{-1}), while the outward moisture transport is mainly through eastern (11.52 mm day^{-1}) and northern (5.54 mm day^{-1}) boundaries of the head BoB. The epochal difference shows a decrease in the moisture inflow through both western (0.96 mm day^{-1}) and southern (1.66 mm day^{-1}) boundaries (table 3). The moisture outflow through the eastern boundary also decreased in recent epoch (1.42 mm day^{-1}), while the outflow through the northern boundary increased (0.30 mm day^{-1}) (table 3). The decrease in the inflow of moisture through southern and western boundaries and increase in the outflow through northern boundary cause the observed decrease in the moisture content over the head BoB.

Interestingly, the epochal difference in vertically integrated moisture transport (VIMT) shows a decreasing trend into the head BoB (figure 5(a)). It may be noted that the changes in the lower level (700 hPa to 1000 hPa) moisture transport play a key role in the decreasing trend of VIMT. The epochal change in horizontal wind at 850 hPa, where the core of the low level jet (LLJ) present (Findlater 1969, Joseph and Raman 1966) and VIMT show strong spatial correspondence (figure 5(a) and (b)). The VIMT and LLJ have decreased in the recent epoch over the eastern Arabian Sea, the head BoB, and land over the east Asia, while it has increased over the northwest Pacific. Further, cross equatorial flow of moisture transport and the LLJ has weakened over the western Indian Ocean and strengthened over the western Pacific region. The strong spatial correspondence in the epochal changes in the LLJ and VIMT suggest that the weakening of LLJ is associated with the declining trend of moisture over the head BoB.
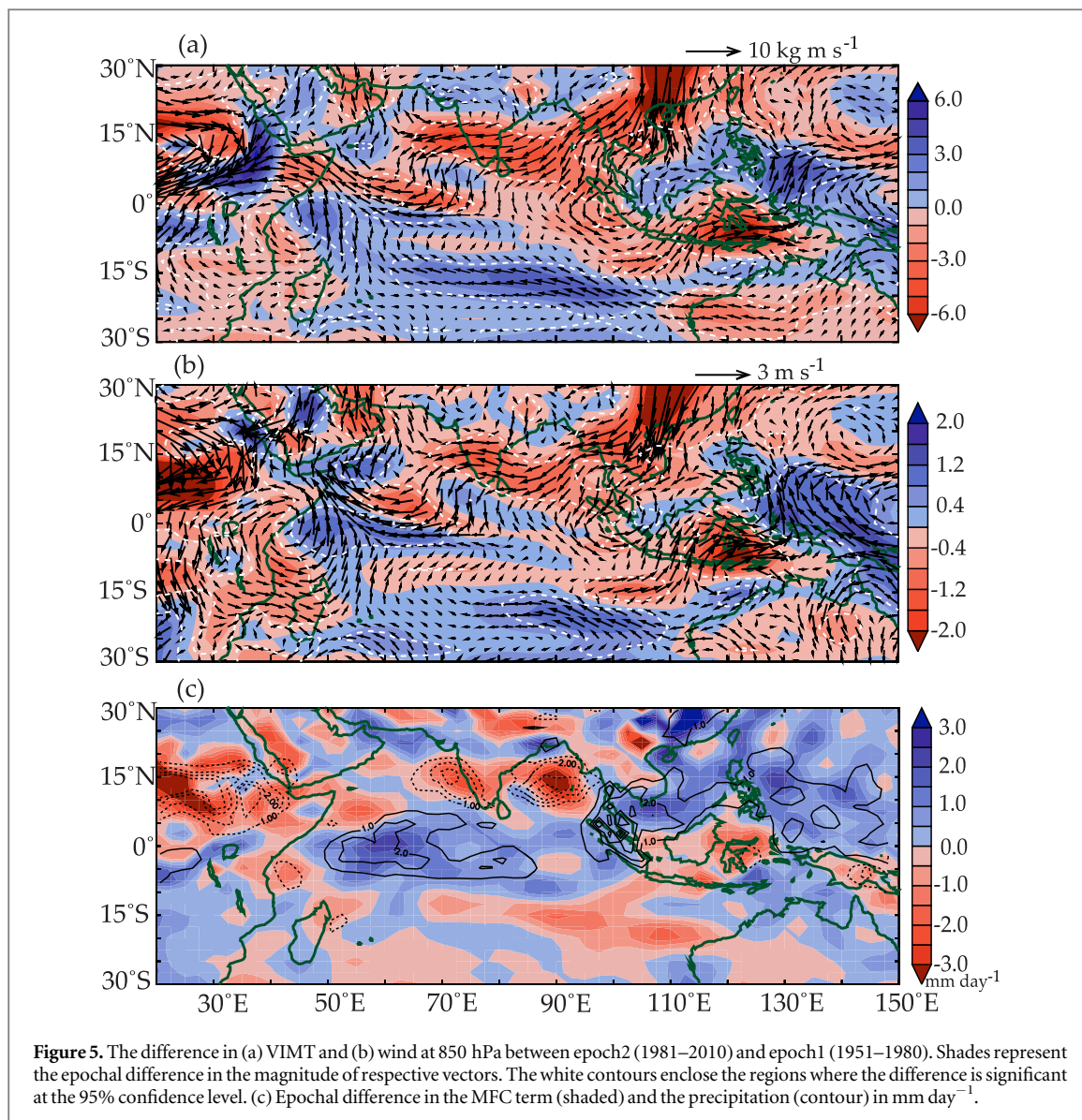
Anomalous convergence of VIMT seen over western equatorial Indian Ocean, leads to relatively higher accumulation of moisture over this region. It may be interesting to note that there is an increase in the rainfall over the western equatorial Indian Ocean in the recent epoch associated with an increased MFC (figure 5(c)). Hence, the observed weakening of the LLJ (which represents the strength of monsoon circulation Joseph and Simon 2005) in the recent decades might have reduced the moisture transport to the BoB, which can lead to a decrease in the moisture content over the BoB and hence cause reduction in the formation/intensification of MD.

4. Summary and conclusions

Rainfall over the central-eastern parts of India during the summer monsoon season is showing a decreasing trend (1.49 mm year^{-1}) in the recent years. In this paper we showed that this decreasing trend in rainfall is associated with the decreasing trend in the number of MD days (0.15 year^{-1}). We also showed that the reduction in the mid-tropospheric humidity is mainly responsible for the decrease in MD days. A moisture budget analysis suggested that compared to the changes in local evaporation, decrease in the moisture flux convergence (negative of moisture flux divergence) contributes significantly to the observed dryness over BoB in the recent years. It is also found that the observed weakening of moisture advection into the BoB has strong spatial correspondence with the variation in the intensity of the low level jet. Interestingly, there is an anomalous increase in the moisture convergence flux over the western equatorial Indian Ocean and enhanced precipitation over this region. The observed rapid warming of the western equatorial Indian Ocean could be reducing the meridional tropospheric temperature gradient, which leads to the weakening of summer monsoon circulation as suggested by Roxy *et al* (2015).

A study by Nieves *et al* (2015) reported that the observed decrease in the sea surface temperature in the Pacific Ocean during recent years is compensated by warming in subsurface of the Pacific Ocean and the Indian Ocean. Apart from this, the western equatorial Indian Ocean warming could be also associated with the asymmetry of ENSO teleconnection; El Niño events induce warming in Indian Ocean through Walker circulation and La Niña events failed to do the reverse (Roxy *et al* 2014). Further, increase in magnitude and frequency of El-nino events in recent decades may accelerate this warming (Roxy *et al* 2014).

Many studies using sensitivity experiments based on the numerical models have shown that the changes in the land-sea thermal contrast can modulate the monsoon circulation in the global warming scenario (Chou 2003, Wu *et al* 2012, Kamae *et al* 2014, Ma and Yu 2014). Increase in the aerosol concentration can enhance land surface cooling in the southern Asia

Figure 5. The difference in (a) VIMT and (b) wind at 850 hPa between epoch2 (1981–2010) and epoch1 (1951–1980). Shades represent the epochal difference in the magnitude of respective vectors. The white contours enclose the regions where the difference is significant at the 95% confidence level. (c) Epochal difference in the MFC term (shaded) and the precipitation (contour) in mm day^{-1}.

which could adversely affect the land-sea thermal contrast and hence weaken the monsoon circulation (Meehl *et al* 2008, Bollasina *et al* 2011, Dong *et al* 2014, Lau and Kim 2010, Sanap *et al* 2015). This might affect the transport of moisture into the BoB, which has a pivotal role in the genesis/intensification of monsoon depressions. Dong and Zhou (2014) used coupled climate model experiments to show that the long term changes in the surface latent heat and longwave fluxes favour basin wide warming of the Indian Ocean and the warming in the western Indian Ocean is particularly stronger to produce an equatorial dipole structure. Roxy *et al* (2015) also showed that the western equatorial Indian Ocean warming results in the weakening of monsoon circulation as seen as the weakening of Hadley circulation in the observation and model simulations. They suggested that the response of the Indian ocean to the global warming could lead to anomalous moisture convergence over the western equatorial Indian Ocean which could dampen the monsoon circulation. This observation is consistent

with our findings in this paper that the primary cause for the decrease in the number of MDs over the BoB is the reduction of moisture advected to the head BoB due to decrease in the strength of the low level jet. Hence, the decreasing trend in the number of MDs could be one of the manifestations of the response of Indian monsoon to the global warming.

Acknowledgments

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