



# Impact of Indian Ocean warming on increasing trend in pre-monsoon rainfall and Hadley circulation over Bay of Bengal

Devanil Choudhury<sup>1,2</sup> · Debashis Nath<sup>1</sup> · Wen Chen<sup>1</sup>

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## Abstract

In the present manuscript, we analyzed the pre-monsoon (March–April–May) rainfall over the Indian summer monsoon region using the Global Precipitation Climatology Project (GPCP) rainfall datasets during 1979–2015. It is found that the rainfall over the Bay of Bengal (BOB) has increased significantly and it is associated with the strengthening of local Hadley circulation over the BOB. The increasing Sea Surface Temperature (SST) over the Indian Ocean is playing an important role to the observed changes in convections and cloudiness over the BOB. In addition, the strengthening of the westerly enhances the wind speed and transports more moisture to the North Indian Ocean. In addition, warming of the SST and large-scale moisture convergence cause the rainfall to increase and the latent heat released in the process strengthens the divergent wind at 200 hPa. This strengthens the local Hadley circulation over the BOB, which may affect the monsoon strength over the Indian subcontinent, by influencing the onset of the Indian summer monsoon. This study will improve the understanding by monitoring the changes in the atmospheric processes over the BOB and the Indian subcontinent, which may result in better predictability of the Indian summer monsoon.

## 1 Introduction

Over the Indian Ocean, the inter-tropical convergence zone (ITCZ) is a semi-permanent feature, during moderate to active monsoon conditions. In the pre-monsoon season, i.e., March–April–May (MAM), the ITCZ shifted northward from the equator and after the onset of the monsoon it becomes the monsoon trough. The Indian summer monsoon trough can be considered as a large-scale cyclonic vorticity pattern extending from the Northern Bay of Bengal (BOB) to the western part of India (Rao 1976). This monsoon trough develops in May over the BOB, and the overall intensity of large-scale circulation and associated rainfall during the monsoon season depend on the strength of the monsoon trough. Usually, the pre-monsoon season is the hottest period of the year over most of the South Asian region, making it vulnerable to climate extremes, e.g., heat waves, thunderstorms, and dust storms, with serious societal impacts.

Ueda et al. (2015) showed that the projected increase in the summer monsoon rainfall over the Indian Ocean region and an increase in moisture convergence can be attributed to the basin-wide warming in the Indian Ocean during the past half-century. Prior to the monsoon onset, a continuous increase in sea surface temperature (SST) makes the central BOB region the warmest in the tropical Indian Ocean, which may enhance the convective activities by subduing the local systems (Jiang and Li 2011). Wu et al. (2012) reported that strong convective systems lead to the onset of vortices and the sensible heating induced by warm SST over the southeastern part of the BOB triggers the genesis of the vortices. In low latitudes, Hadley, Walker, and monsoon circulations play important roles in the tropical climatic variability. An expansion of the Indian Ocean warm pool can modify the strength of these large-scale circulations by modulating the land–sea thermal contrast. These atmospheric circulations are strongly associated with the occurrence of rainfall in the tropical and subtropical regions. Over the Indian subcontinent, a transition from hot and dry pre-monsoon season to wet monsoon season occurs due to changes in large-scale circulations. It is mainly driven by strong land–sea thermal contrast and brings significant moisture to the Indian landmasses. This seasonal transition from pre-monsoon to monsoon condition takes place rapidly with convective precipitation driven by intense surface heating in this period.

✉ Debashis Nath  
debashis@mail.iap.ac.cn

<sup>1</sup> Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, 40, Hua Yan Li, Chaoyang Dist., Beijing 100029, China

<sup>2</sup> University of Chinese Academy of Sciences, Beijing, China

Although there are previous studies, which investigate the long-term trend in the Indian summer monsoonal rainfall variability using 115 years of observation data (Goswami et al. 2006; Naidu et al. 2009); most of them did not find any significant trend in the rainfall amount (Thapliyal and Kulshrestha 1991; Rupakumar et al. 1992; Subbaramayya and Naidu 1992). Goswami et al. (2006) showed that, although seasonal mean monsoon rainfall remains stable, the frequency of extreme rainfall events has increased, whereas, the frequency of moderate rainfall events has decreased in the latter half of the twentieth century. Sathiyamoorthy et al. (2010) reported that rainfall has increased considerably over the pre-monsoon rainfall belts of the BOB and Southeast Arabian Sea (SEA) during May. They showed that rainfall rate has increased by 83.9% (94.5%) over the SEA and 54.6% (19.6%) over the BOB in the GPCP (CMAP) dataset during the study period. Moreover, the atmospheric temperature has increased over north/northwestern parts of the Indian summer monsoon region in May, which has possibly caused more rain by enhancing the meridional pressure gradient. Since the Indian summer monsoon first sets over the BOB in May, the BOB region receives considerable amount of rainfall during the pre-monsoon season. The rainfall in the pre-monsoon season mainly occurs due to the semi-permanent low-pressure zone over the northwestern parts of India and the eastern part of Pakistan (Chandrasekhar 2010). Using ECMWF reanalysis dataset, Shahi et al. (2015) reported an increase in precipitation over the Indian Ocean, maritime continent, west coast, and some parts of the Indian land point.

Under global warming scenario (IPCC 2007), an attempt has been made to investigate the long-term changes in (1979–2015) pre-monsoon rainfall over India and the surrounding oceanic regions, particularly in the BOB region. The present study is conducted to explore the impact of oceanic processes on the pattern of regional Hadley circulation over the South Asian region. Specifically, the aim is to investigate the physical mechanism and trend in different meteorological parameters over the BOB during the pre-monsoon season. Furthermore, we investigate the changes in regional Hadley circulation over the BOB and the role of Indian Ocean warming in it, which is not reported before in Sathiyamoorthy et al. (2010). The rest of the manuscript is organized as follows: the data and methodology for this study are described in Section 2. Results are presented in Section 3, and finally, the summary and conclusion are given in Section 5.

## 2 Data sources and methodology

Based on the availability of the observation and reanalysis dataset, we have chosen the post-satellite period, i.e., 1979 to 2015, for this study. The gridded monthly mean merged

(satellite and station data) precipitation analysis data from the Global Climatology Precipitation Project (GPCP-version 2.3, Adler et al. 2003) are used for the rainfall analysis. The data have a complete spatial coverage over most of the geographical regions, especially over the ocean, and are available at  $2.5^\circ$  latitude  $\times$   $2.5^\circ$  longitudes from 1979 onwards. The monthly mean NCEP/NCAR gridded ( $2.5^\circ \times 2.5^\circ$ ) reanalysis (Kalnay et al. 1996) data are used for temperature and wind fields. The monthly mean Hadley SST dataset (HadISST, Rayner et al. 2003) from the met office Hadley center is used for SST analysis, and the NOAA-interpolated outgoing long-wave radiation (OLR) observation data is used as a proxy of tropical convection. Based on availability and consistency between OLR and different meteorological parameters (temperature, wind, etc.), we have used the NCEP/NCAR reanalysis dataset for our analysis.

The inter-annual variability of different meteorological parameters is defined as an area-averaged time series over a specific region. Then, the linear trend is computed by regression analysis at each grid point and the significance is tested using the Student's  $t$  test. To understand the moisture variability, we computed the moisture budget by applying the mass continuity equation, and conservation of atmospheric water vapor content is estimated in pressure ( $p$ ) coordinates:

$$\frac{\partial q}{\partial t} + \nabla \cdot (qV_h) + \frac{\partial}{\partial p}(q\omega) = E - P \quad (1)$$

where,  $V_h = (u, v)$  represents the moisture budget for an air parcel, and the terms  $u, v, \omega, q, E,$  and  $P$  represent the zonal, meridional and vertical components of wind in pressure coordinate, specific humidity evaporation, and precipitation rates (source and sink terms), respectively. The horizontal moisture flux convergence (MFC), which is simply the negative horizontal moisture flux divergence, can be written as

$$\text{MFC} = -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - q \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \quad (2)$$

In Eq. (2), the first two terms are the *advection term* which represents the horizontal advection of specific humidity by zonal and meridional wind components and the last two terms are the *convergence term* which is the product of specific humidity and horizontal mass convergence. In order to find the changes in velocity potential, we have calculated the velocity potential using the horizontal wind vector  $V$  at the 200-hPa level following the definition by Krishnamurti (1971):

$$D = \nabla \cdot V = -\nabla^2 \chi \quad (3)$$

The divergence  $D$  is calculated in the spectral domain, i.e., spherical harmonic expansion of the wind vector.

### 3 Results

#### 3.1 Spatio-temporal changes of precipitation

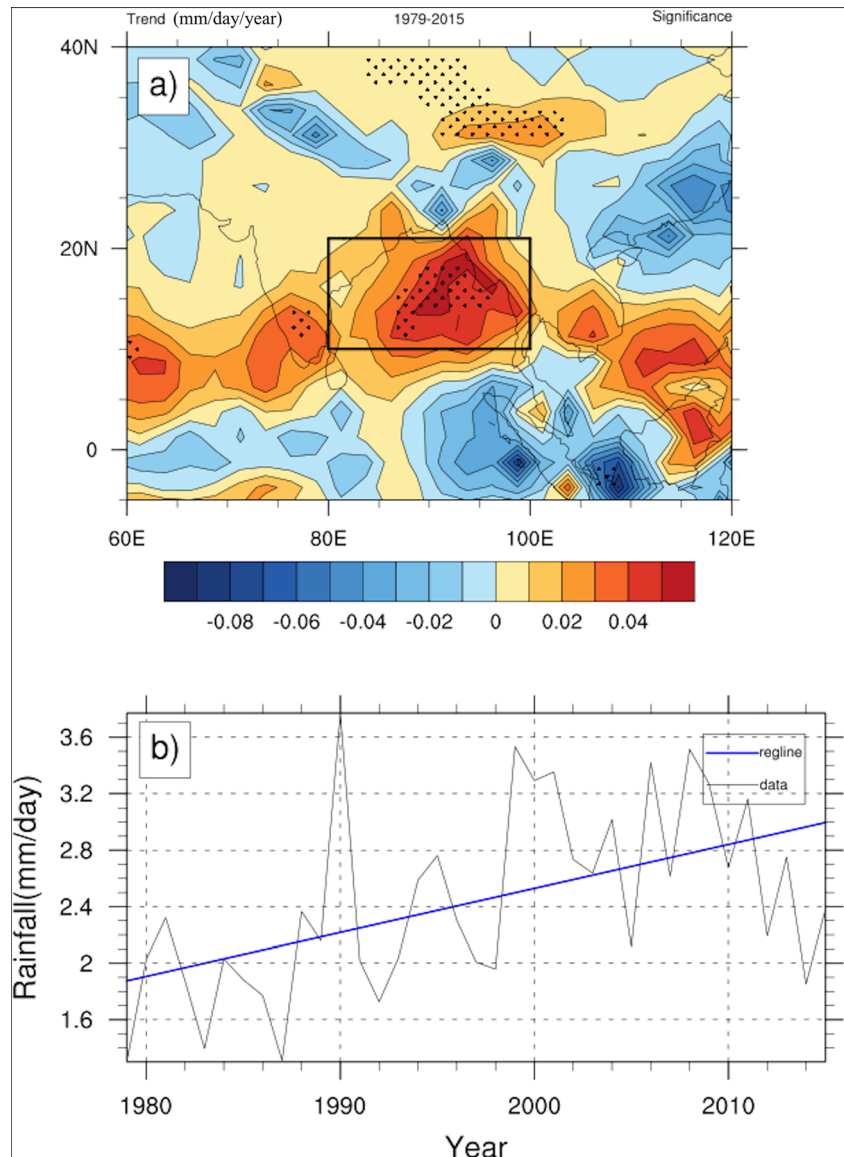
Figure 1a shows the linear trend in the pre-monsoon precipitation over South Asia from 1979 to 2015, using GPCP monthly mean dataset. A significant positive trend in precipitation is observed over the north-eastern and central BOB region, as well as in the southern part of the Western Ghat region. Using 31 years (1979–2009) of GPCP data, Sathiyamoorthy et al. (2010) also showed that the pre-monsoon rainfall in May has increased over the South Eastern part of the Arabian Sea (83.5%) and BOB (54.6%). The negative but non-significant trends are observed along the entire Gangetic–Brahmaputra–Meghna river basins, where agriculture is largely rain-fed. Figure 1b shows the inter-

annual variability in precipitation over the BOB region ( $11.25^{\circ}$ – $21.25^{\circ}$ N,  $81.25^{\circ}$ – $96.25^{\circ}$ E), and we can find some prominent positive peaks in rainfall above the 95% significant level, e.g., in 1990, 1998, and 2008. After 2008, precipitation over the BOB region decreases continuously; however, an overall increasing trend is observed throughout from 1979 onward.

#### 3.2 Variation of outgoing long-wave radiation

During the summer monsoon months, space–time variability of OLR provides an insight into the pattern of monsoonal rainfall and convective activities over the Indian sub-continent. OLR is often used as a proxy for tropical convective activities. In order to investigate the physical mechanism driving the enhanced precipitation

**Fig. 1** (a) Linear trend of seasonal (MAM) mean precipitation (mm/day/year) over South Asia during 1979–2015. The black box represents higher precipitation trend over the BOB. Dots represent 95% significance level based on Student's *t* test. (b) Area-averaged inter-annual time series of precipitation (mm/day/year) over Bay of Bengal ( $11.25^{\circ}$ N– $21.25^{\circ}$ N,  $81.25^{\circ}$ E– $96.25^{\circ}$ E); the blue line represents the linear trend

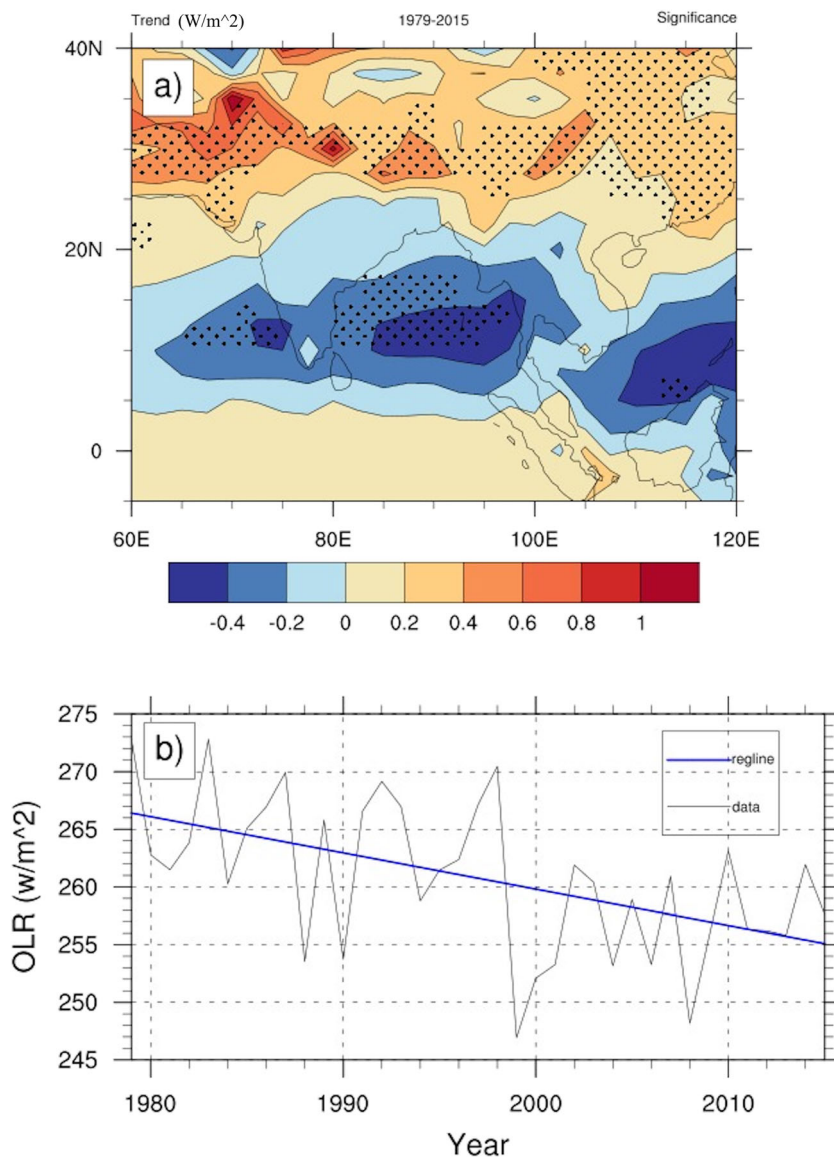


over the BOB, long-term OLR trend and time series are calculated here. In Fig. 2a, a significant negative trend in OLR can be seen in the central part of the BOB and parts of the Arabian Sea (AS) adjacent to the Western Ghats, which signifies an enhanced convection over there. Consequently, the area-averaged OLR (Fig. 2b) also exhibits a strong decreasing trend, which represents an increasing convective activity over the BOB (10–20°N, 80–95°E). Moreover, there are few cases when the seasonal mean (MAM) OLR is observed below 255 W/m<sup>2</sup>, particularly during 1999 and 2008. It is consistent with enhanced precipitation (Fig. 1b) in 1990, 1998, and 2008. These decreasing convective activities in the pre-monsoon season may affect the onset of the Indian summer monsoon, which normally arrives by the end of May over the BOB.

### 3.3 Warming of the Indian Ocean

Previous studies demonstrated a basin-wide Indian Ocean warming in the last half of the twentieth century (Rao et al. 2012; Swapna et al. 2014). Roxy et al. (2015) showed that for an extended period of 112 years, the West Indian Ocean (WIO, 50–65°E, 5°S–10°N) has experienced anomalous warming of 1.2 °C, which is 0.5 °C higher than the warming in the warm pool region. Vecchi and Harrison (2002) described the structure of sub-seasonal SST variability in the BOB during the southwest monsoon season, which reports a basin-scale strong (1–2 °C) warming due to large-scale changes in surface winds and convection. In the recent decades, a sustained Indian Ocean warming in the west extended further westward of the Indian Ocean warm pool region, which favors the supply of wind-driven moisture locally to the ocean. From

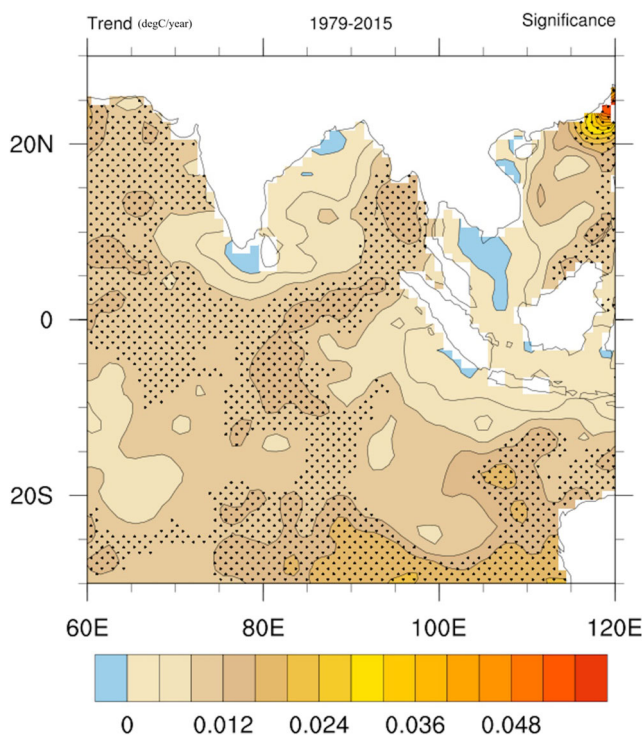
**Fig. 2** (a) Linear trend of seasonal (MAM) mean outgoing long-wave radiation (OLR; W/m<sup>2</sup>/year) over South Asia during 1979–2015. Dots represent 95% significance level based on Student's *t* test. (b) Area-averaged time series of OLR (W/m<sup>2</sup>) over Bay of Bengal (10°N–20°N, 80°E–95°E); the blue line represents the linear trend



our analysis using the Hadley SST monthly dataset, we found that the warming over the West Indian Ocean warming has extended significantly to the eastern part of the BOB (Fig. 3). This warm pool Indian Ocean warming can modify the land–sea thermal gradient, which modulates the strength of the monsoon circulation by strengthening the moisture-laden winds towards the subcontinent. Eventually, the warmer ocean also has a tendency to trigger more convection over the ocean. In addition, this sustained Indian Ocean warming increases the moisture supply to the southern peninsula and the ocean as well.

### 3.4 Strengthening of westerly wind speed

The South Asian summer monsoon is the important component of an annually reversing wind system over Asia (Ramage 1971; Rao 1976). It is well-known that the onset of the summer monsoon is accompanied with distinct changes in large-scale circulation and rainfall distribution over the Indian subcontinent and the adjacent oceans. It commences with the establishment of an upper tropospheric easterly jet stream (Koteswaram 1958) and lower tropospheric westerly Somali jet over the Arabian Sea (AS) (Findlater 1969). In Fig. 4a, b, we plotted the trend of zonal ( $u$ ) and meridional ( $v$ ) components of wind at 850 hPa, and area-averaged time series are presented in the MAM season. In Fig. 4a, an increasing trend in low-level westerly jet is noticed over the central and eastern parts of the BOB. Furthermore, to study the inter-annual



**Fig. 3** Linear trend of seasonal (MAM) mean sea surface temperature ( $^{\circ}\text{C}/\text{year}$ ) over the Indian Ocean

changes in wind speed, an area-averaged time series of wind speed over the BOB (10–20 N, 80–95 E) is presented in Fig. 4b. Noticeable peaks with wind speed more than 1.6 m/s are observed during 1990, 1999, 2010, and 2013. These higher wind speed enhances the westerlies and persists with enhanced precipitation (Fig. 1b), leading to an early summer monsoon onset. However, few years (1987, 1991, 1995, 1998, and 2005) with wind speed less than 0.8 m/s are also evident in Fig. 1b.

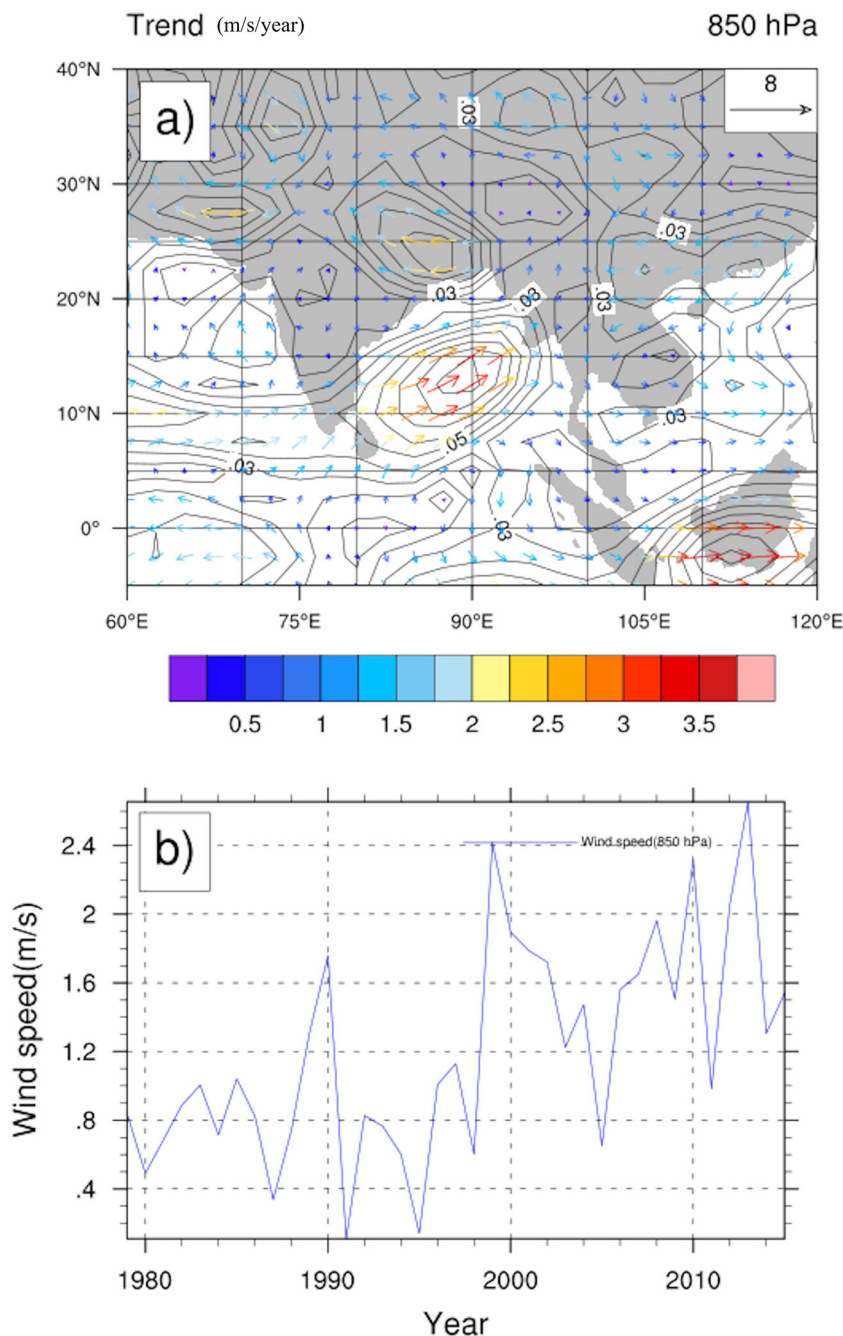
### 3.5 Increasing moisture flux convergence

The summer monsoon arrives over the BOB in the month of May and usually brings a large influx of moist air through low-level cross-equatorial jet. The cross-equatorial moisture flux over the Southern Indian Ocean and evaporative flux from the AS play important roles behind the convective activities over the BOB. It is well-known that water vapor from the Indian Ocean is the main source of moisture for summer monsoon rainfall over India (Saha and Bavadekar 1973; Cadet and Reverdin 1981; Cadet and Greco 1987). Wei et al. (2015) showed that the variation of MFC is more important than that of soil moisture for precipitation variability over the southern United States. They also showed that MFC affects precipitation directly through changing moisture inflow to the wet areas and indirectly by changing precipitation efficiency in the transitional zones, as well. Since the water vapor for precipitation comes from both local evapotranspiration (ET) and moisture transport, in Fig. 5, we plotted the linear trends in convergence and advection of horizontal MFC. In Fig. 5a, a significant increasing trend in moisture flux convergence is observed over the AS, the eastern part of the BOB, and along the Ganges–Brahmaputra–Meghna river plains. Like moisture flux convergence, the advection term exhibits an increasing and significant trend over the AS, north-western part of the BOB, and along the Ganges–Brahmaputra–Meghna river basins (Fig. 5b).

### 3.6 Spatial trend of latent heat

Latent heat is a form of thermal energy, released or absorbed by a body without changing its ambient temperature. Therefore, the latent heat can be understood as heat energy in the hidden form, which is supplied or extracted to change the state of a substance. Using linear trend analysis between 1979 and 2015, it can be seen (Fig. 6) that latent heat fluxes are increasing significant over the central to eastern BOB and in the south-central part of the peninsular India, the region that coincides with the increasing trend in precipitation. On the other hand, along the Western Ghat and some parts of the Gangetic plain, significant negative trend in OLR and precipitation are observed. Hence, it is clear that more diabatic heating over the BOB is resulting from deep convection,

**Fig. 4** Linear trend of seasonal (MAM) mean for (a) seasonal (March–May) mean linear trend (m/s/year) in UV wind trend at 850 hPa and (b) area-averaged time series of wind speed (m/s) over the BOB (10°N–20°N, 80°E–95°E)

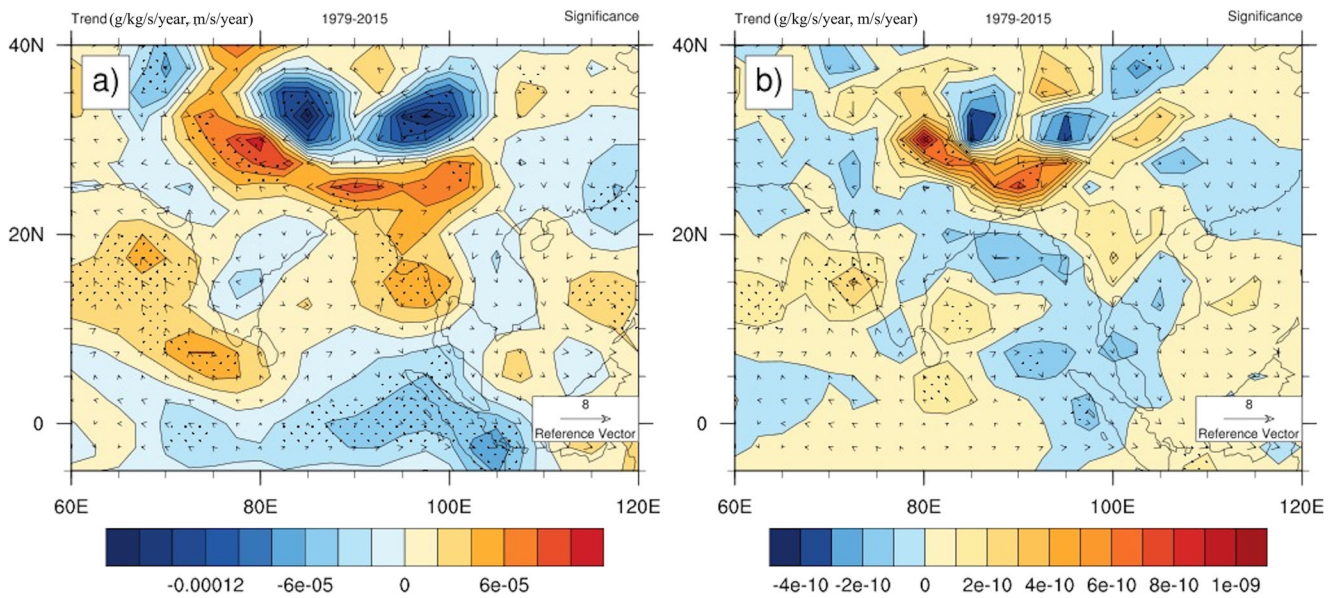


which is mainly due to the release of excess latent heat over this region. It is worth mentioning in this context that even though the SST warming is more over the AS compared to the BOB (Fig. 3), latent heat flux is strongly negative over the AS. Therefore, this strong positive trend in latent heat flux over the eastern BOB is probably due to intense oceanic mixing accompanied with stronger westerlies. The results are consistent with the previous studies which show that warm SST anomalies are accompanied with large variations in the lower and upper tropospheric latent heating, which has released from intense convection over the ocean (Danielsen 1993; Dai

et al. 2013; Su et al. 2003). These changes are also highly correlated with the strength of the Indian summer monsoon circulation (Xavier et al. 2007; Gadgil et al. 1984; Danielsen 1993; Dai et al. 2013).

### 3.7 Increasing land–sea thermal contrast

Land–sea thermal gradient has strong impact on the strength of the monsoon circulation. Previous studies demonstrate that in the northern hemisphere, the surface temperature over the land is increasing faster than that in the ocean due to enhanced

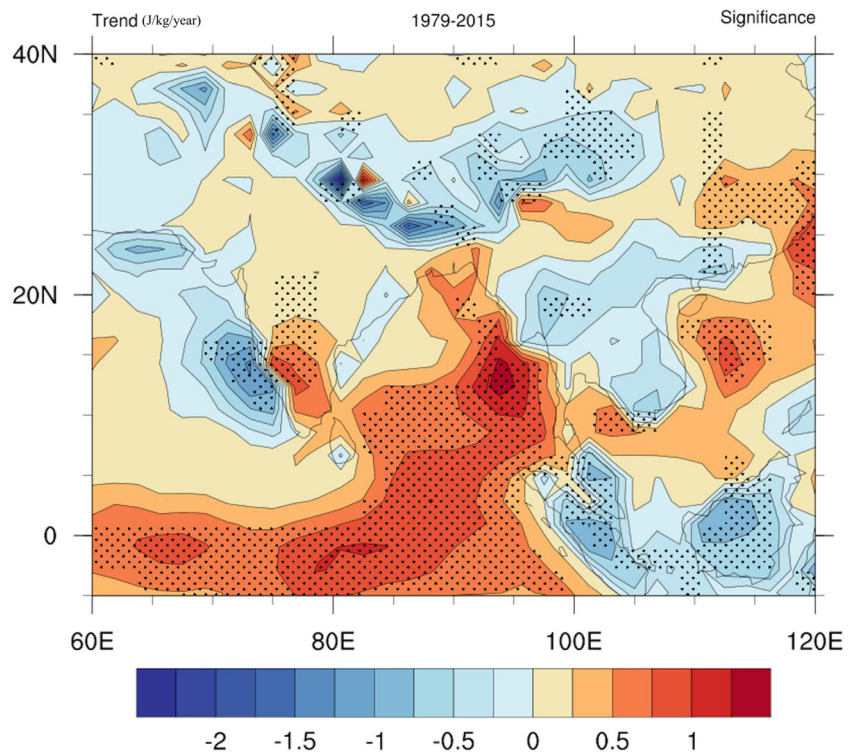


**Fig. 5** Linear trend of seasonal (MAM) mean horizontal moisture flux (MFC) terms and wind speed at 925 hPa; (a) moisture convergence term ( $\text{g/kg/s/year}$ ) and (b) moisture advection term ( $\text{g/kg/s/year}$ )

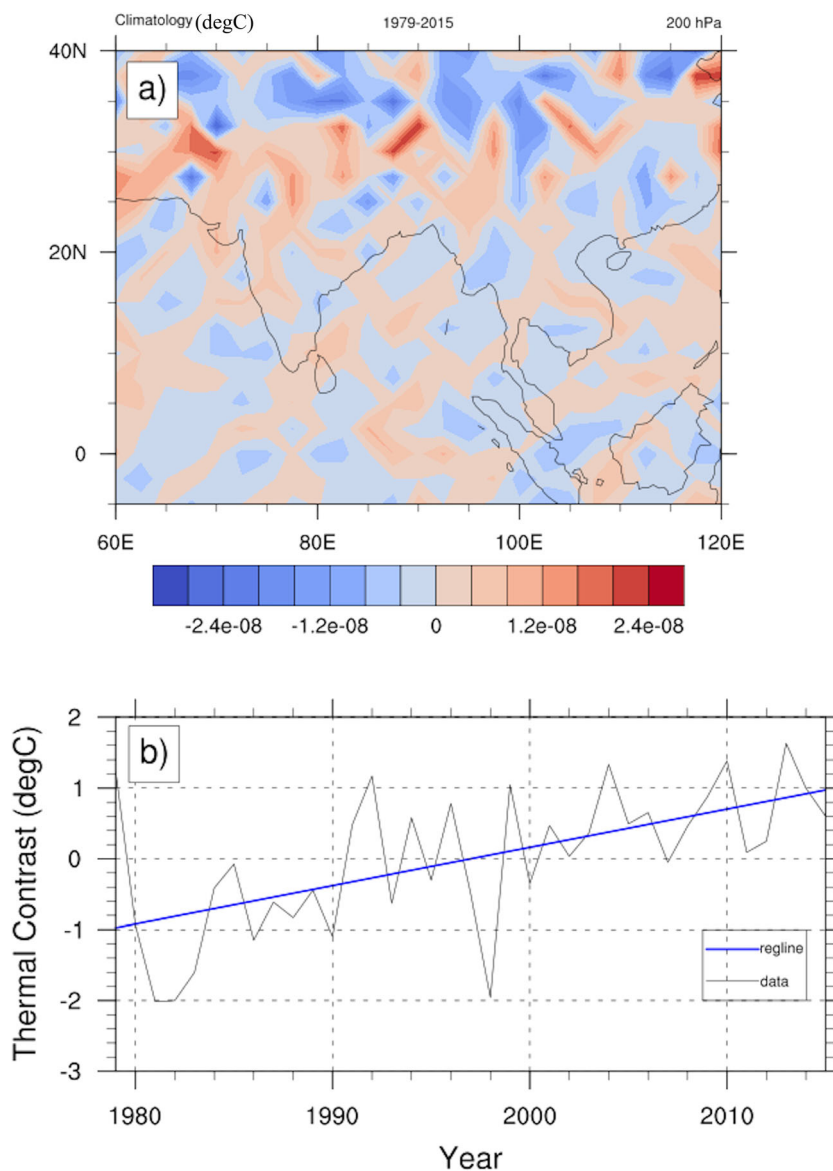
greenhouse gases (Kamae et al. 2014), which could enhance the strength of the monsoon. Since tropospheric temperature is a useful parameter for investigating the thermodynamic forcing related to monsoon (Xavier et al. 2007), we investigate the changes in land–sea thermal contrast and tropospheric mean temperature at 200 hPa during the pre-monsoon season. In Fig. 7a, seasonal (MAM) mean temperature anomalies at 200 hPa are shown and the positive anomalies are strongest

over the north western part of India. The land–sea thermal contrast is calculated based on the temperature (1000 hPa) difference between land (24–26 N, 80–100 E) and ocean over the BOB (10–20 N, 85–95 E) during March–May. Figure 7b shows the area-averaged differences in time series of land–sea thermal contrast, which exhibits strong positive trend over this region. During 1982 and 1998, the thermal gradient reaches to  $\sim 2^\circ\text{C}$ , representing a warmer sea compared to land, while,

**Fig. 6** Linear trend of seasonal (MAM) mean latent heat flux ( $\text{J/kg/year}$ )



**Fig. 7** (a) Seasonal (MAM) mean tropospheric mean temperature ( $^{\circ}\text{C}$ ) climatology (1979–2015) at 200 hPa. (b) Area-averaged time series of land–sea thermal contrast ( $[24^{\circ}\text{N}–26^{\circ}\text{N}, 80^{\circ}\text{E}–100^{\circ}\text{E}]–[10^{\circ}\text{N}–20^{\circ}\text{N}, 85^{\circ}\text{E}–95^{\circ}\text{E}]$ )



after 1998, an increasing trend in thermal gradient depicts a warmer landmass than the sea.

### 3.8 Impact on local Hadley circulation

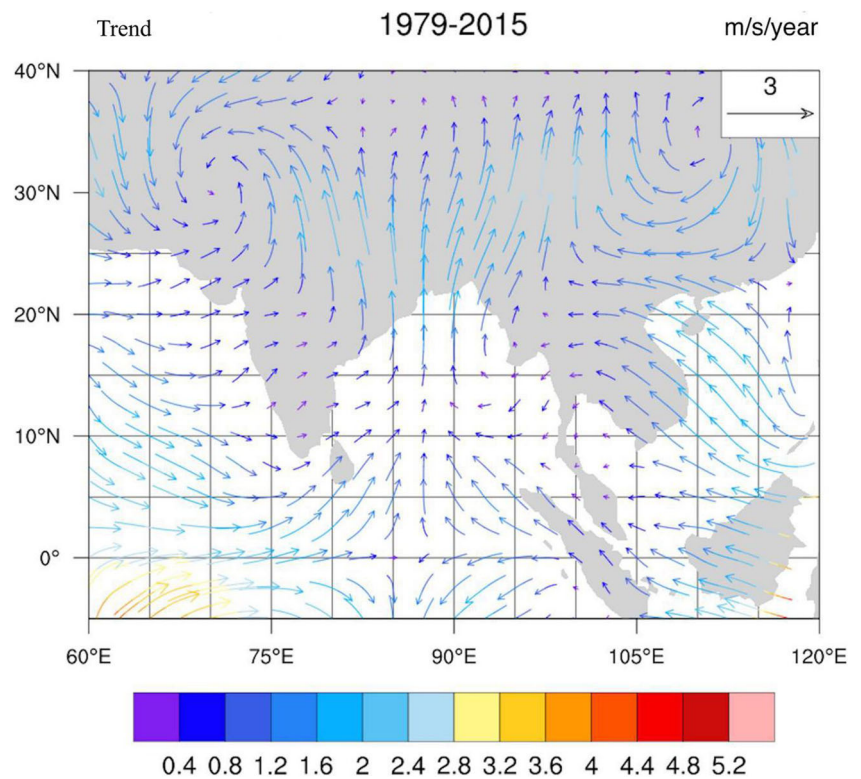
In general, the Hadley circulation is defined as a zonally averaged meridional circulation with an ascending motion over the ITCZ and descending motion to the subtropical high-pressure zone (Oort and Yienger 1996; Trenberth et al. 2000). The intensity of the Hadley circulation strongly controls the intensity of large-scale monsoon circulation as shown by Goswami et al. (1999). They proposed a monsoon Hadley circulation index defined by the difference in the meridional wind shear between 850 and 200 hPa and averaged over certain region. In the context of general circulation, the Hadley circulation is primarily driven by the differential heating due to the variation of solar insolation over the latitudes. Hence,

modification of land–sea thermal contrast affects the strength of the Hadley circulation and the monsoon circulation as well. The warming over the Indian Ocean enhances the convective activity, which strengthens the regional Hadley circulation over the Indian Ocean. Therefore, impact of the Hadley circulation on the monsoon is becoming more prominent in the recent decade. To investigate the impact on the Hadley circulation, we examine the changes in divergent wind and velocity potential at 200 hPa and vertical velocity ( $\omega$ ) over the South Asian region extending higher up to 200 hPa.

During the pre-monsoon season, the divergent wind trend at 200 hPa (Fig. 8) is strengthening over the BOB and the vectors are pointing towards the eastern part of the Indian landmasses. Vertical velocity or  $\omega$  is defined as the Lagrangian rate of change of pressure with time, and the negative values correspond to an ascending motion or warm advection. Therefore, an examination of the trends in  $\omega$



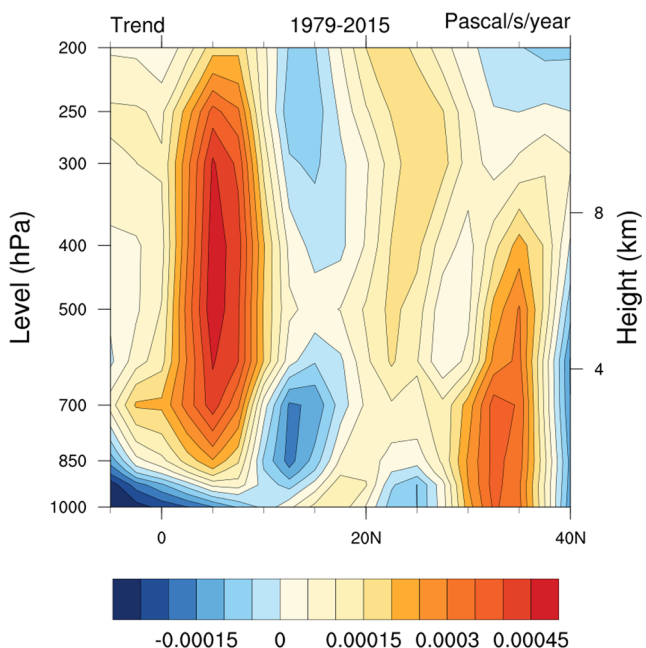
**Fig. 8** Linear trend of seasonal (MAM) mean divergent wind at 200 hPa (m/s/year)



during the analyzed period (1979–2015) reveals large-scale ascending motion (negative trend) over the central BOB (~ 9°–17°N) extending higher up to the upper troposphere, which strongly favors intense local convective activities (Fig. 9). This upward motion is compensated by subsidence

of air parcels over north India (~ 18°–38° N), which inhibits convection over north Indian landmasses.

The linear trends in seasonal mean velocity potential at 200 hPa are also analyzed over the South Asian region. In order to quantify the changes in atmospheric circulation, velocity potential ( $\chi$ ) at 200 hPa level is selected in this study as a variable suitable to reflect large-scale tropical meridional circulation. The velocity potential is then calculated through inverse spectral transform of weighted expansion coefficients. This velocity potential at 200 hPa reflects the intensity of the Hadley circulation. The seasonal mean trend of velocity potential over the South Asian region and during 1979–2015 is presented in Fig. 10. Positive trends are observed over the BOB, parts of north-east India, western Indian landmass, and southern Indian Ocean. Based on the above-mentioned results, the seasonal changes in the Hadley circulation are well-represented by omega and divergent wind trends, which suggests that a stronger Hadley circulation in the pre-monsoon season will have strong impact on the Indian summer monsoon rainfall.

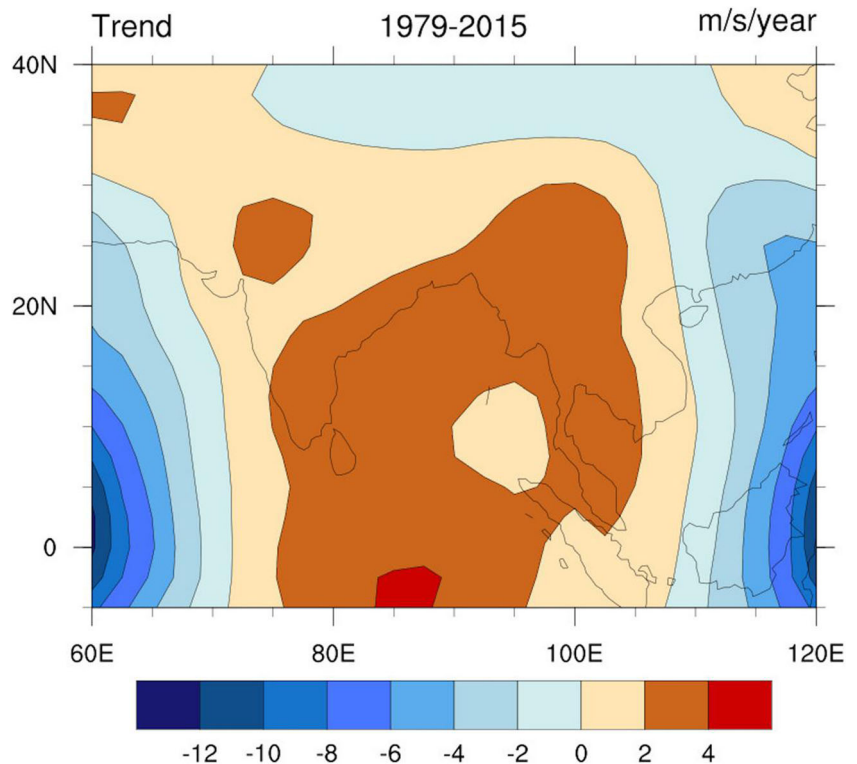


**Fig. 9** Seasonal (MAM) mean linear trend of longitudinally averaged of omega (Pascal/s/year), averaged over 60°E–120°E during 1979–2015

#### 4 Possible mechanisms

In order to explore the possible causes behind the increase in pre-monsoon rainfall over the BOB, all possible long-term changes are taken into account. The sub-seasonal SST changes are associated with the changes in surface winds and

**Fig. 10** Linear trend of seasonal (MAM) mean velocity potential (m/s/year) at 200 hPa

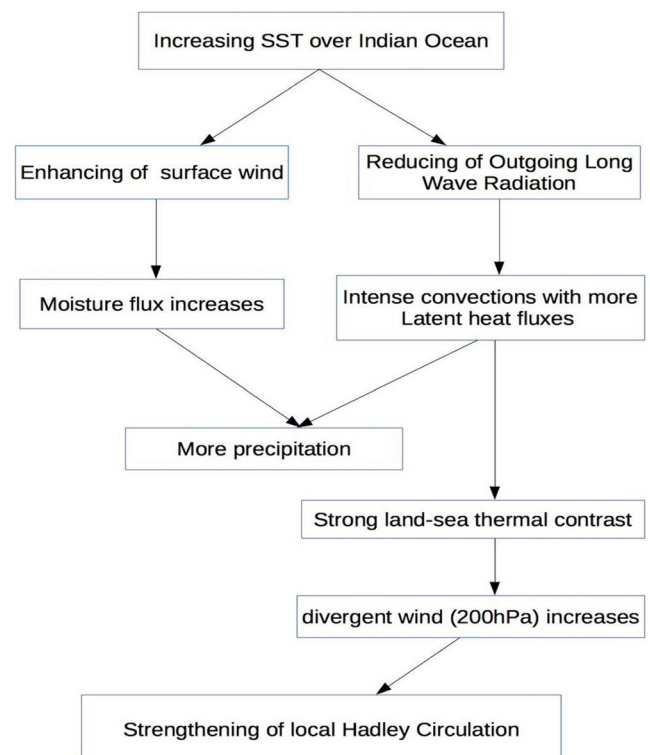


atmospheric convection over the BOB. The warming of the Indian Ocean may play an important role to the observed changes in wind speed, convective activities, rainfall, and moisture transport. An enhanced westerly wind will probably increase the air–sea interaction and vertical mixing in the ocean. In addition, decreasing OLR fluxes associated with increasing wind speed and moisture transport may increase the atmospheric convection and cloudiness. Furthermore, latent heat fluxes released in the process associated with intense convections and strong land–sea thermal gradient increase the divergent wind at 200 hPa. This strengthens the local Hadley circulation over the BOB, which may have significant impact on the Indian summer monsoon rainfall. The schematic diagram explaining the possible mechanism is shown in Fig. 11.

## 5 Summary and conclusions

In this paper, we have addressed the background meteorological changes in pre-monsoon season over the Indian summer monsoon region. The analysis of GPCP rainfall datasets, available for the last 37 years (1979–2015), suggested that pre-monsoon precipitation over the BOB has increased during the analyzed period and a significant (> 95%) positive trend in precipitation has been observed over the north-eastern part of the BOB region. To investigate the possible reason behind the increase of rainfall over the BOB and its impact on local circulation, SST, OLR, latent heat flux, winds, moisture

transport, tropospheric temperature, divergent winds, and velocity potential are analyzed during this period from 1979 to



**Fig. 11** The schematic diagram for the possible mechanism of the increasing trend of precipitation over the Bay of Bengal during the pre-monsoon season

2015. The significant warming over the western Indian Ocean and eastern BOB may act as a precondition for strengthening the sea surface wind speed over the BOB and more moisture to be transported to the north-eastern BOB region. The basin-wide warming over the Indian Ocean reduces the OLR which eventually triggers more convection and increases the rainfall. The latent heat released in this process over the eastern BOB strengthens the local Hadley circulation over the BOB during the pre-monsoon season. The Hadley circulation in this paper is defined as the zonally symmetric meridional circulation ascending over the mean ITCZ and descending over the subtropical high-pressure region. In order to analyze the large-scale characteristics of this thermally induced circulation, the upper tropospheric temperature, divergent wind, and velocity potential at 200 hPa are chosen as a suitable parameter to investigate the changes of Hadley circulation, which intensifies over the BOB. Sathiyamoorthy et al. (2010) reported that rainfall has increased considerably over the pre-monsoon rainfall belts of the BOB and Southeast Arabian Sea (SEA) during May. They showed that rainfall rate has increased by 83.9% (94.5%) over the SEA and 54.6% (19.6%) over the BOB in the GPCP (CMAP) dataset during the study period. However, they did not discuss the changes in the strength of the Hadley circulation during the pre-monsoon season due to the latent heat released from the precipitation. As the Hadley circulation is driven by the meridional differential heating, so the finding of the intensification of the local Hadley circulation is quite consistent with the outcome of Sathiyamoorthy et al. (2010), where they argue that the increased atmospheric temperature by 0.8 °C in the northern India enhances the meridional temperature gradient. This intensification of the Hadley circulation over the BOB in the pre-monsoon season due to latent heat fluxes released in the process associated is a key scientific finding in the manuscript, which may have strong impact on the Indian summer monsoon onset.

This is well-known that summer monsoon onsets by the end of April over the southeast BOB prior to the onset over the Indian landmass (Ananthakrishnan et al. 1981). This onset is associated with a low-level vortex known as the onset vortex (Krishnamurti et al. 1981), which usually forms around 10°N in the BOB and east of AS (Ananthakrishnan et al. 1968). As the onset vortex is influenced by the boundary condition associated with the local SST (Joseph 1990), convection in the tropics is highly modulated by the SST. Therefore, these intense convective activities over the southeastern BOB probably influence the onset of the South Asian summer monsoon. As suggested by Ju and Slingo (1995) and Chandrasekar and Kitoh (1998), at an inter-annual timescale, relatively moderate changes in the SST can have large impacts on atmospheric circulation in the Indian Ocean. So, the changes in the Hadley circulation forced by the changes in the SST probably affect the monsoon strength over the Indian subcontinent.

An improved understanding and monitoring of oceanic variability in the BOB may result in an improved predictability of monsoon variabilities. Therefore, the dynamic mechanism related to the formation of convections over the BOB is an important topic that requires further investigation. In this regard, a high-resolution and coupled modeling study would be very useful to reveal more details of the convective developments.

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## Compliance with ethical standards

**Competing interest** The authors declare that they have no competing interest.

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