Behaviour of Latent Heat Flux over the Bay of Bengal during Indian Summer Monsoon Deficit Period

Dhrubajyoti Samanta[1], Mihir K. Dash and P. C. Pandey
Centre for Oceans, Rivers, Atmosphere and Land Sciences, Indian Institute of Technology Kharagpur, India
[1]Present address: Asian School of the Environment, Nanyang Technological University, Singapore
Email: mihir@coral.iitkgp.ac.in

ABSTRACT

Variabilities of LHF and air-sea interaction processes over the Bay of Bengal (BoB) are studied on daily basis for the June-September (JJAS) period of 1998-2010. A new criterion for the Indian Summer Monsoon (ISM) break is considered using daily TRMM Microwave Imager (TMI) precipitation data over central India. An ISM break is defined if the standardized rainfall anomaly over central India is less than -0.5 mm for at least four consecutive days (following Samanta et al. 2016). The newly defined break periods match well with earlier studies. The most intriguing result of this study is to observe the antecedents of ISM break period in 10-90 days filtered latent heat flux (LHF) anomaly over the northern BoB. It is found that if intraseasonal LHF anomaly over the northern BoB is less than -5 Wm^{-2} and continued for four consecutive days then monsoon break occurs within next 10 days. In addition, the equatorward shift of the Inter-tropical Convergence Zone (ITCZ) few days prior to the break, is clearly observed consistent with the presence of negative outgoing longwave radiation (OLR) anomaly. The OLR shows a strong negative correlation with LHF over the northern BoB.

Keywords: *Latent heat flux, Indian summer monsoon break, ITCZ, TRMM and Outgoing longwave radiation.*

1. Introduction

It is well known that tropical Indian Ocean (IO) acts as the major source of heat and moisture in supplying the necessary energy to drive and maintain the large-scale summer monsoon circulation and associated rainfall over the Indian subcontinent. Therefore, understanding of the air-sea interaction processes over the tropical IO and its association with Indian Summer Monsoon (ISM) deficit is of importance. The knowledge of the heat loss from the ocean surface to the atmosphere, both in terms of Latent Heat Flux (LHF) and the Sensible Heat Flux (SHF) is of paramount importance for the study of air-sea energy exchange. The global mean of this energy transport is equivalent to 26% of the incoming solar energy at the top of the atmosphere. Incidentally, there is a lack of adequate observations over the Indian seas to estimate these fluxes. But, few observational studies are found in the literature based on the data collected during IIOE, ISMEX-72, MONSOON-77, MONEX-79, BOBMEX-99 experiments (Pisharoty, 1965; Mohanty et al. 1983; Mohanty and Mohan Kumar, 1990; Bhat, 2002). These studies have demonstrated the significance of the energy flux variabilities over the north IO and the summer monsoon activities over India during different epochs. In addition to the land-sea thermal contrast, the ISM rainfall is also affected by the total LHF, and its spatial distribution over the north Indian Ocean, the Arabian Sea (AS), and the Bay of Bengal (BoB). Webster (1972) found that both latent heat and the orography are important in forcing the mean circulation in the tropics and sub-tropics. The changes in the thermal conditions over the tropical IO are mainly contributed by changes in the LHF. During mid-May, the LHF over tropical IO drastically increases coinciding with the onset of Asian summer monsoon (Xu and Chan, 2001). Another study by Mohanty et al. (1996) showed a significant positive anomaly in LHF over the southwestern sector of the Arabian Sea off Somali coast during May. They attributed these variations to the intensity of Mascarene's high and the associated cross-equatorial wind.

The evaporation over the surrounding ocean suggests that one of the major sources of moisture during ISM rainfall over the Indian subcontinent is the BoB. The importance of air-sea fluxes and the summer monsoonal activity over India is well described by

Mohanty et al. (2002). A study based on Compressive Ocean Atmosphere Data Set (COADS) for a period of 1950–1979 showed higher LHF over the AS, BoB and western Equatorial Indian Ocean (EIO) during the excess monsoon years as compared to deficit years (Mohanty et al., 1996). In contrast, Ramesh Kumar and Schlüssel (1998) reported that the LHF over the AS has been found to be high during very weak monsoon (i.e. 1987) and relatively low during the active ones (i.e. 1988). They attributed this to the 850 hPa level wind flow over the AS, which was not conducive to advection of moisture to the subcontinent. It is well known that convective activity over BoB induces stronger wind over the AS and thereby increases moisture advection into the Indian subcontinent (Srinivasan and Nanjundiah, 2002). Ramesh Kumar et al. (2005) reported that the weaker moisture transport into the Indian subcontinent is due to the substantial decrease in convective activity over the BoB in July 2002 compared to July 2003 (normal monsoon month). Further, Joseph and Sijikumar (2004) showed that the convective heat source over BoB and the strength of the low zonal wind at 850 hPa over Indian peninsula have the maximum linear correlation at a lag of 2-3 days.

In the present study, the ISM break period is identified by standardized daily precipitation following Samanta et al., (2016). The behaviour of LHF over the BoB and the EIO is studied on daily basis for the same period. In addition, the behaviour of Inter Tropical Convergence Zone (ITCZ) is studied over the BoB and east equatorial Indian Ocean during the same period.

2. Data and Methodology

In this study, Tropical Rainfall Measurement Mission (TRMM) 3B42 daily data is used to calculate ISM break during the period of 1998–2010 following Samanta et al. 2016. The daily Objectively Analyzed (OA) flux (SHF and LHF), NOAA interpolated Outgoing Longwave Radiation (OLR) and NCEP–NCAR reanalysis wind data are used in this study. The LHF and OLR are filtered for 10–90 days using Butterworth band pass filter.

2.1 Tropical rainfall measurement mission 3B42 data

This study uses TRMM 3B42 version–6 of the daily data product. The aim of TRMM 3B42 algorithm is to develop merged Infrared (IR) precipitation and Root Mean Square (RMS) precipitation error estimates. The algorithm divided into two separate steps. The first part uses TRMM Visible and Infrared Radiometer System (VIRS) level–1 radiance product (1B01), TRMM Microwave Imager (TMI) level–2 rain profile product (2A12) and the monthly TMI Combined Instrument (TIC) calibration parameters (level 3 3B31) to prepare monthly parameters. These derived monthly IR calibration parameters are used in the second part to adjust the merged IR precipitation data. The merged IR data consists of Geostationary Meteorological Satellite (GMS), Geostationary Operational Environmental Satellites – East (GOES–E), Geostationary Operational Environmental Satellites – West (GOES–W), Meteosat–7, Meteosat–5, and NOAA–12 data. The final gridded, adjusted merged–IR precipitation (mm.hr^{-1}) and RMS precipitation–error estimates have a daily temporal resolution and with 0.25°×0.25° spatial resolution. Spatial coverage extends from 50°S to 50°N latitude. Details of TRMM data information are available at http://daac.gsfc.nasa.gov site.

2.2 Objectively analyzed heat flux data

The Objectively Analyzed (OA) Flux project is an ongoing research and development project for global air-sea fluxes. The project is planned to enhance global estimates of air-sea fluxes of heat, freshwater, and momentum, with a target of establishing a unique source for global ocean surface forcing datasets for various research. The major sources are marine surface weather reports from Voluntary Observing Ships (VOS), satellite remote sensing, numerical weather prediction analysis, and operational analysis outputs. This process reduces error in each input data source and produces an estimate that has the minimum error variance. The OA Flux project uses the objective analysis to get the optimal estimates of flux related surface meteorology and then calculates the global fluxes by using the advanced bulk flux parameterizations (Fairall et al., 1996, 2003; Bradley et al., 2000). The project currently provides global time series of ocean latent and sensible heat fluxes, ocean evaporation and flux related surface meteorology from 1958 to present. The flux datasets have the spatial resolution of 1°×1°. The LHF and SHF products were provided by the Woods Hole Oceanographic Institute (WHOI) OAFlux project (http://oaflux.whoi.edu) funded by the NOAA Climate Observations and Monitoring (COM) program.

2.3 Outgoing longwave radiation data and reanalysis datasets

The OLR data at the top of the atmosphere is observed from the Advanced Very High Resolution Radiometer (AVHRR) instrument on board the NOAA polar orbiting spacecraft. The mean monthly interpolated OLR data for the period 1975– 2009 is used in this study. Interpolated OLR and National Centre for Environmental Prediction (NCEP) reanalysis data are provided by the NOAA through their website at http://www.esrl.noaa.gov/psd. This OLR dataset is from the NOAA Climate Diagnostics Center (CDC), currently the Physical Sciences Division, the Earth System Research Laboratory (ESRL), with gaps filled with temporal and spatial interpolation (Liebmann and Smith, 1996). Areas with low OLR are associated with high cloud tops and hence deep convection. So OLR is considered as a proxy for convection (or rainfall) in the tropics. The OLR data is in 2.5°×2.5° spatial grid resolution. The horizontal wind fields used are obtained from National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996) for the same period as OLR.

3. Results and Discussion

3.1 Identification of monsoon break days from TRMM data

Dry spells for several days in peak monsoon period, i.e., June, July, August, and September (JJAS), is considered as monsoon break. Generally, monsoon break lasts for few days to two weeks. Meteorologists defined the break period in various ways. For example, the break is identified by Rao (1976) using low–level pressure and wind pattern. During break period it is noticed that monsoon trough is located close to the foothills of Himalayas, and easterly winds are absent in the lower troposphere over Indian region (Ramamurty 1969). Sikka and Gadgil (1978) proposed that the presence of anticyclonic vorticity above the boundary layer can be used to identify the monsoon break. Goswami and Ajaya Mohan (2001) used the strength of circulation present to the south of 15°N, 90°E at 850 hPa level to define the break. Krishnan et al. (2000) found that a monsoon break can occur when positive OLR anomaly exceeds 10 Wm^{-2} over the 18°N–28°N, 73°E–82°E. Similarly, Joseph et al. (2009) considered a monsoon break to occur if the standardized OLR anomaly over the above region is more than 0.9 for four consecutive days. Neena et al. (2011) took daily OLR and found that during break (active) phase of ISM daily OLR is more (less) than ±0.5 standard deviation. Rajeevan et al. (2010) analyzed daily gridded rainfall over India and found that if standardized rainfall anomaly over monsoon core zone is less than −1.0 then it will lead to a monsoon break. It is to be noted that in most of these studies the break is defined for the month of July and/or August. In the present study, high resolution (0.25°×0.25°) TRMM 3B42 version-6 of daily precipitation data over the Central India (CI) (averaged over 15°N–27°N and 72°E–84°E), is used to define the break period/dry spell during JJAS following Samanta et al., (2016). The monsoon break/dry spell is defined as the period during which standardized rainfall anomaly is less than −0.5 mm for at least four consecutive days (Samanta et al., 2016). In adopting this criterion, the broad pattern of observed rainfall departures during the break is kept in mind (Ramamurthy 1969). The newly defined break period matches well with several earlier studies (Krishnan et al., 2009; Rajeevan et al., 2010, 2013; Singh, 2013). The defined excess and deficit periods match well with IMD rain gauge observations also.

Figures 2(a), 3(a), 4(a) and 5(a) show the negative standardized rainfall anomaly for years 2003, 2007, 2002 and 2009 respectively. They clearly show the monsoon break in the above years.

3.2 Climatological heat fluxes over Bay of Bengal during ISM period

As mentioned earlier, the BoB plays the leading role in supplying moisture to the Indian landmass during ISM period. It is one of the active convective regions, which

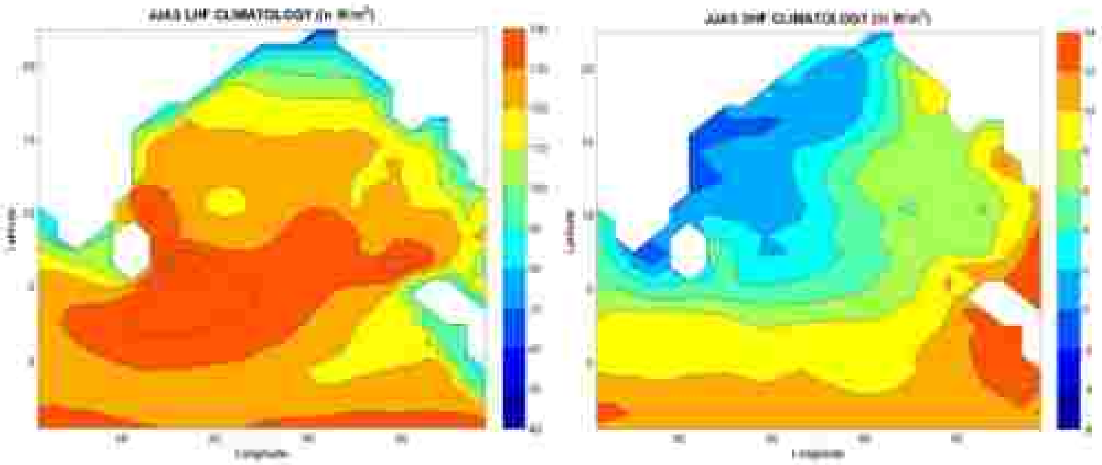

Figure 1: JJAS climatology of (a) Latent Heat Flux and (b) Sensible Heat Flux over the Bay of Bengal (in Wm^{-2}).

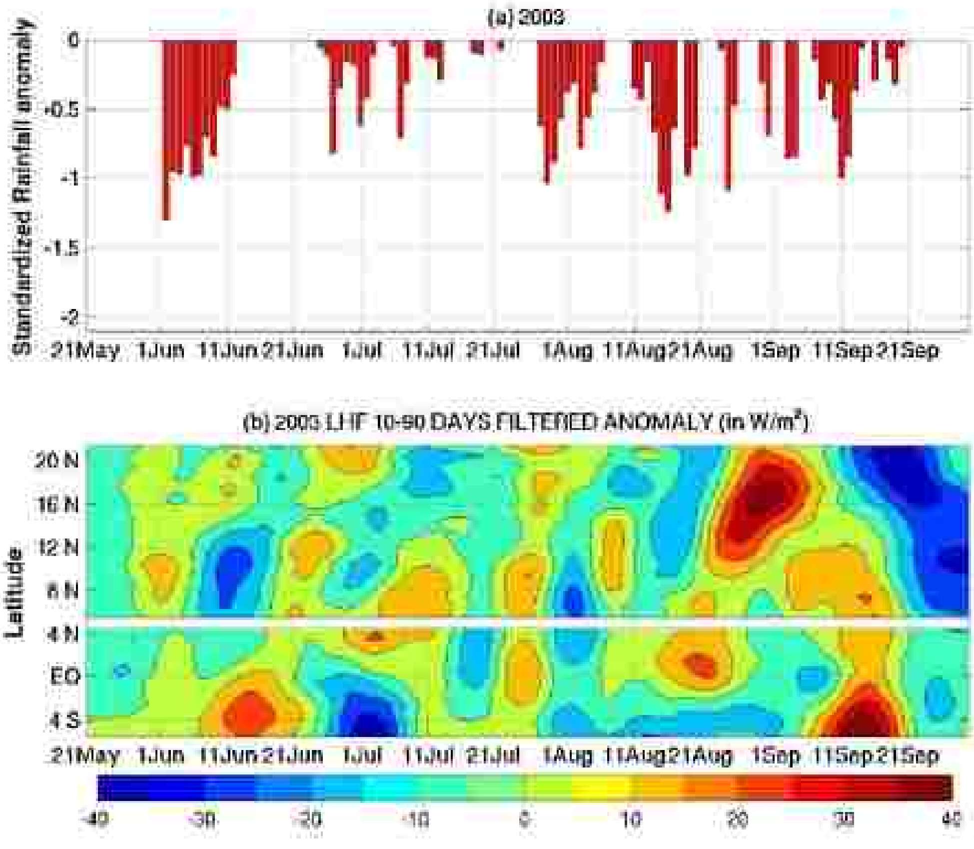

Figure 2: (a) Negative standardized rainfall anomaly for the year 2003 (red bar). (b) 10–90 days filtered LHF (in Wm^{-2}) averaged over the BoB (80°E–100°E) and the EIO (75°E–100°E) for the year 2003.

supplies moisture during ISM period. The key components of energy exchange between the ocean surface and the atmosphere are LHF and SHF. However, short and long wave fluxes have also a role in energy balance. However, in this study, the main concern is the heat fluxes, particularly LHF. Figure 1 shows the climatological condition of LHF and SHF over the BoB for ISM (JJAS) period. The LHF values vary from 40 to 140 Wm^{-2}. The latitudinal belt between the equator and 10°N shows the high LHF value (120–140 Wm^{-2}), signifying more convection over the region. On the other hand, SHF climatology varies from −6 to 14 Wm^{-2}. The LHF is of the order of 10 times than that of the SHF. It clearly indicates that the LHF contributes more to the energy balance than the SHF. The magnitude and variation of LHF over the BoB are much be the consequence of the presence of fresh water, discharged from rivers, over the region. The largest oceanic heat loss (LHF+SHF) occur nearer to the equatorial region and less along the east coast of India.

3.3 Northern Bay of Bengal Latent Heat Flux as an indicator of monsoon break

Generally, rainfall during extra–monsoon months is not associated with the LHF. The weekly SST variation shows that the northern BoB cooling precedes monsoon break by about one week (Vecchi and Harrison, 2002).

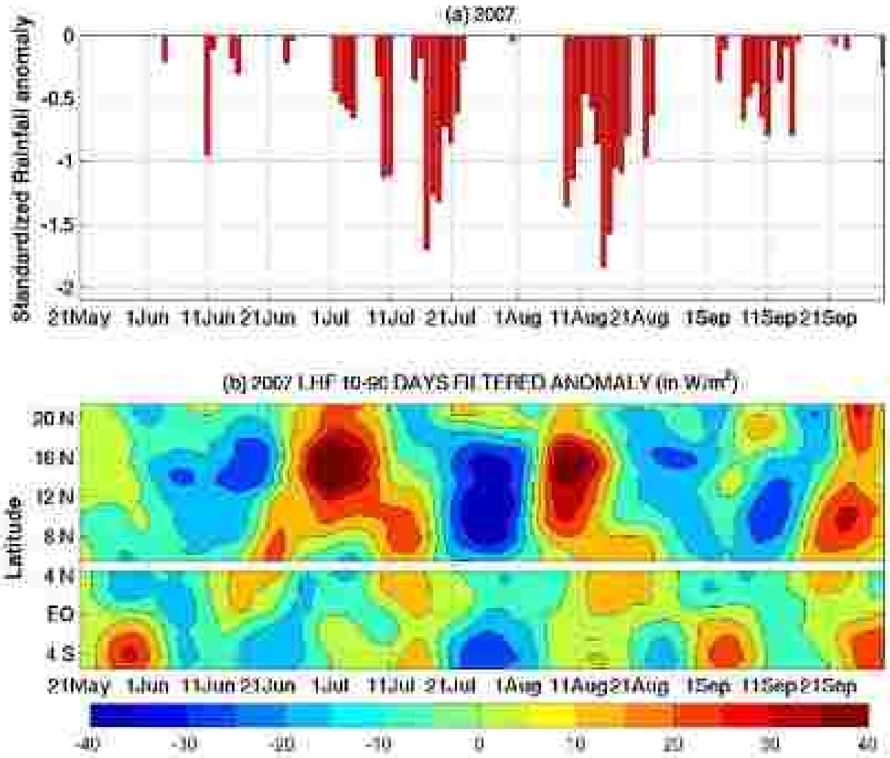

Figure 3: (a) Negative standardized rainfall anomaly for the year 2007 (red bar). (b) 10–90 days filtered LHF (in Wm^{-2}) averaged over the BoB (80°E–100°E) and the EIO (75°E–100°E) for the year 2007.

more than SHF. It triggers the logic of studying the LHF over the BoB in context to ISM failure. Figure 1 shows that during monsoon season the entire BOB shows higher LHF. Mohanty et al. (1996) also showed an increase of LHF in monsoon season in compared to pre– and post–monsoon period. The southern part of the BOB shows high latent heat flux (of the order of 130–140 Wm^{-2}). It may be due to the presence of higher SST over the region, which increases the sea surface air specific humidity difference, leading to greater LHF. It is interesting to note that the head bay region has low LHF that may

Hayes et al. (1991) found that intraseasonal SST anomalies generally lagged the reduced evaporation by about one–quarter cycle and thus concluded that LHF anomalies are primarily responsible for driving SST anomalies on the intraseasonal timescale. Thus, it is quite possible to study the active and break phase of monsoon by studying the LHF over the BoB. Earlier studies (Sengupta et al., 2001; Sengupta and Ravichandran, 2001) reported the coherent evolution of surface heat flux, SST, and convection in an intraseasonal scale. They also studied the variation of latent heat loss over the BoB

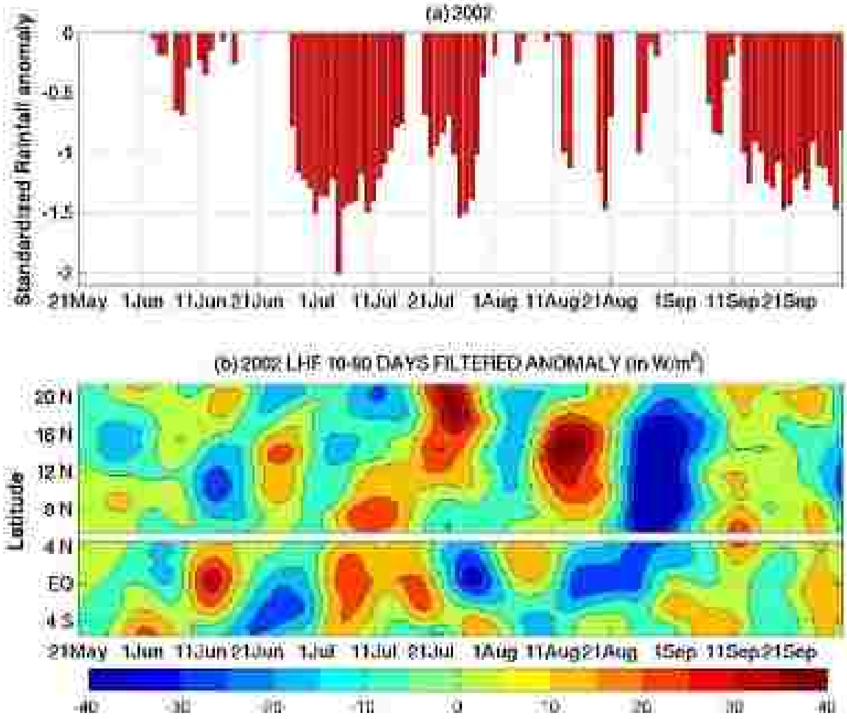

Figure 4: (a) Negative standardized rainfall anomaly for the year 2002 (red bar). (b) 10–90 days filtered LHF (in Wm^{-2}) averaged over the BoB (80°E–100°E) and the EIO (75°E–100°E) for the year 2002.

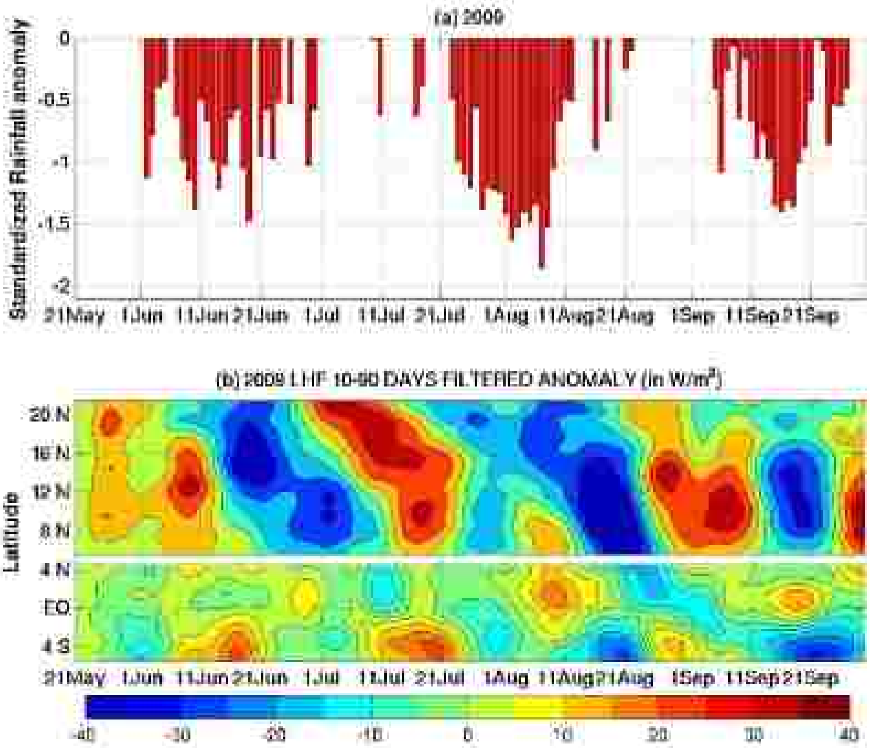

Figure 5: (a) Negative standardized rainfall anomaly for the year 2009 (red bar). (b) 10–90 days filtered LHF (in Wm^{-2}) averaged over the BoB (80°E–100°E) and the EIO (75°E–100°E) for the year 2009.

during active and break phases of the ISM ISO. Lin and Wang, (2012) analyzed OLR data during ISM period between 1979 and 2010, and reported the existence of two intraseasonal oscillations (ISO) active centres, one is over the EIO (5°S–5°N, 75°E– 100°E) and other over the BoB (10°N–25°N, 70°E–90°E). Therefore, it may be plausible to get signatures of monsoon break in the LHF over these convective regions. Two active convective regions over (i) the BoB (5.5°N–22.5°N) and (ii) the EIO (5.5°S–4.5°N) over the longitude range 75°E– 100°E are considered for the analysis. The ranges of these regions nearly match with that of Liu and Wang (2012). The daily LHF over the BoB during monsoon period for 1998–2010, is filtered using a second-order Butterworth bandpass filter with a 10–90 days period. (positive) and low (negative) phase over the ISM period. From figures, it is clear that the LHF also experiences prominent ISO over the BoB and the EIO (Figure 2b and 3b). In addition, an oscillation in LHF anomaly is found to be maintained between the EIO and the BoB. Similar oscillation in rainfall and SST is also observed during ISM ISO (Wang et al., 2005; Liu and Wang, 2012). Figure 2a and 3a show a negative standardized anomaly of daily rainfall over CI for the years 2003 and 2007. Before the occurrence of monsoon break, the presence of negative LHF anomaly over the BoB is clearly observed. The time–latitude variations of the filtered LHF

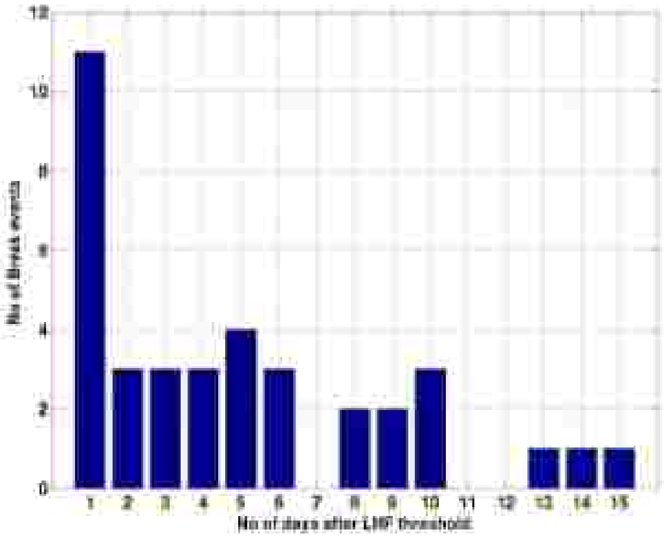

Figure 6: Frequency distribution of monsoon breaks during 1998–2010 at different time lags after the existence of below threshold (<–5 Wm^{-2}) LHF for four consecutive days over the BoB.

Daily filtered LHF anomaly is then spatially averaged over 75°E–100°E for each of the BOB and the EIO latitudes, considering only the ocean area. To investigate the variation of filtered LHF with respect to the monsoon break, two normal monsoon years (2003 and 2007) and two deficit years (2002 and 2009) (as per IMD) are selected. An interesting result by Roxy et al. (2013) showed that rainfall during ISM period lags SST by ~12 days. Keeping the lag time in mind, the examination of variation of LHF starts from 21 May of each year. Figures 2b and 3b show the latitude–time plot of the filtered LHF during the monsoon season of 2003 and 2007 respectively. Similar to active and break phase of monsoon, the LHF also maintains a high anomalies over the BoB and the EIO are plotted in Figure 4b and 5b for 2002 and 2009 ISM periods respectively. The ISO in LHF anomalies over the BoB and the EIO are more prominent during this period than that during normal monsoon years. Figure 4a shows a negative standardized anomaly of daily rainfall over CI for the year 2002. The monsoon break periods 24 June–16 July and 20–29 July are represented in Figure 4a as bars with standardized rainfall anomaly less than –0.5. Similarly, the bar plot in Figure 5a with standardized rainfall anomaly less than –0.5 represents the monsoon break for the year 2009. Figure 4 and 5 show the presence of negative LHF anomalies over the BoB before the occurrence of monsoon break. It can be inferred from the analysis that the presence of negative LHF anomaly over the BOB can be used as the antecedents for monsoon break. To investigate the relation between the LHF anomaly and the monsoon break, the averaged LHF over 15.5°N–21.5°N, 80°E–100°E region is studied. Comparing the monsoon break period and occurrences of LHF anomaly, it is found that monsoon break may occur within 10 days from the fourth date of the filtered LHF anomaly below the threshold value (–5 Wm^{-2}) for four or more consecutive days. The occurrence of monsoon break and the LHF anomaly below the threshold is studied for the entire thirteen years period. Figure 6 shows the frequency of occurrences of monsoon break at different time lags after the sustenance of LHF threshold (<– 5 Wm^{-2} for four consecutive days) over the northern BoB. From Figure 8, it is clear that a greater number of breaks starts after a day once the threshold is reached. The figure shows that there is also an occurrence of break beyond 10 days limit. However, it is found that, for 69.4% cases, there is a monsoon break after 1–10 days just after occurrence (after fourth consecutive day) of below threshold LHF anomaly over the northern BoB (15.5°N–21.5°N, 80°E–100°E). From this study, it may be inferred that LHF anomaly over the northern BoB can act as a precursor to the ISM break along with other meteorological parameters. However, the impact of the long existence of LHF anomaly below threshold value over the BoB on the length of monsoon break is not clear and needs further investigation.

To study the mechanism of the low LHF (compared to climatology) over the BoB before the monsoon break the surface wind speed derived from the TMI observations is analyzed. The left panel of Figure 7 represents the difference in the composite of TMI wind speed (i.e. the composite of wind speed during break period – the composite of wind speed for active period) for two typical normal monsoon years (2003 and 2007) and two deficit years (2002 and 2009). It is clearly found that during break period the wind speed reduces over the BoB and increases over the EIO nearer to the Indonesia coast. The decrease (increase) in wind speed might be the major factor to reduce (enhance) the LHF over the BoB (EIO) region. The right panel of Figure 7 represents the difference in the composite of horizontal wind vector (i.e. the composite of wind vector during break period – the composite of wind vector during active period) at 1000 hPa for normal and deficit monsoon year. The years 2003 and 2007 represent the normal ISM years; 2002 and 2009 represent the deficit ISM years. It is observed that during the break period, strong equatorward component dominates the flow. It suggests that the strength of the northwesterly wind field present over the BoB is reduced. The reduction in the wind field reduces the heat loss from the ocean surface and results in a decrease in LHF over the region. Additionally, the anomalous equatorward component of the wind flow suggests more moisture transport towards the equator. It is clearly observed that anomalous northeasterly wind persists over the BoB during the normal years, whereas, anomalous northwesterly flow persists over the Indian landmass during deficit years. During a normal year, a weak anticyclonic circulation developed over the head–bay region (Figures 7e–f). This circulation becomes strong and migrates towards the southern BoB and the equator during the deficit years (Figures 7g–h). The anomalous anticyclonic flow creates a clear sky condition over the region and is responsible for the release of more heat to the atmosphere from the ocean surface. Hence, it causes to increase of LHF in later stage over the region, thereby contributing to the active phase of ISM.

Therefore, the interaction between the atmosphere and the ocean thus maintains the active and break phase of ISM through air sea interaction. Figure 8 shows the composite of 850 hPa wind anomaly between break period and active periods of years 2003, 2007, 2002 and 2009. The composite of the wind anomaly shows almost similar structure as that of the 1000 hPa wind. The anomalous equatorward flow over the BoB is very clear in the 850 hPa level. It can be inferred from Figure 8 that of the low-level jet is weakened during the break period. This agrees with earlier studies (Rodwell, 1997; Joseph and Sijikumar, 2004), which showed that during the break period, southwesterly wind pattern after inhibited for northward motion, bents south–southwestward direction.

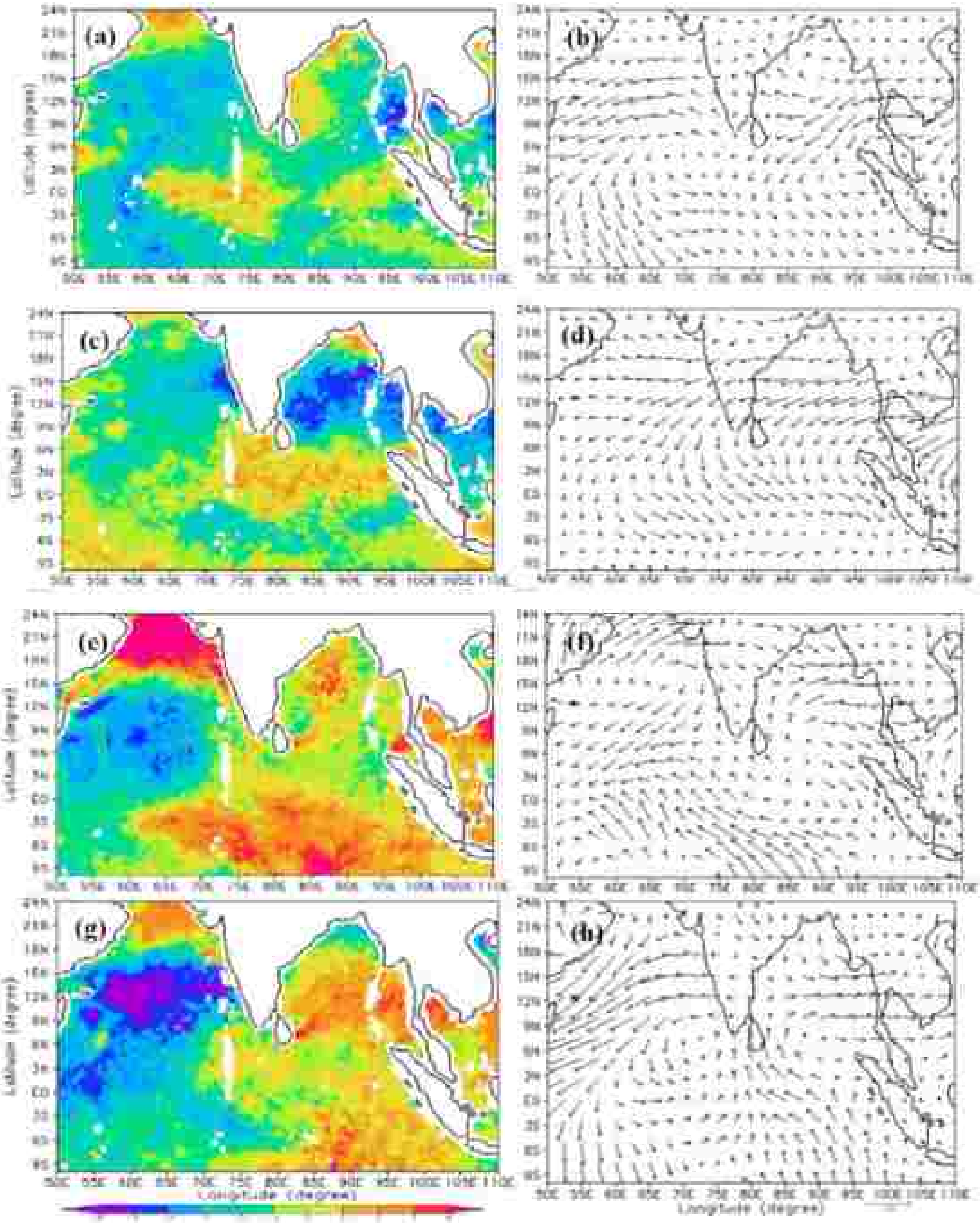

Figure 7: The left panel represents the difference in composite wind speed (break period – active period) in ms^{-1} over the North Indian Ocean for (a) 2003 (c) 2007 (e) 2002 and (g) 2009 from TMI observation. The right panel represents the composite surface wind (1000 hPa) anomaly (break period – active period) in ms^{-1} for (b) 2003 (d) 2007 (f) 2002 and (h) 2009.

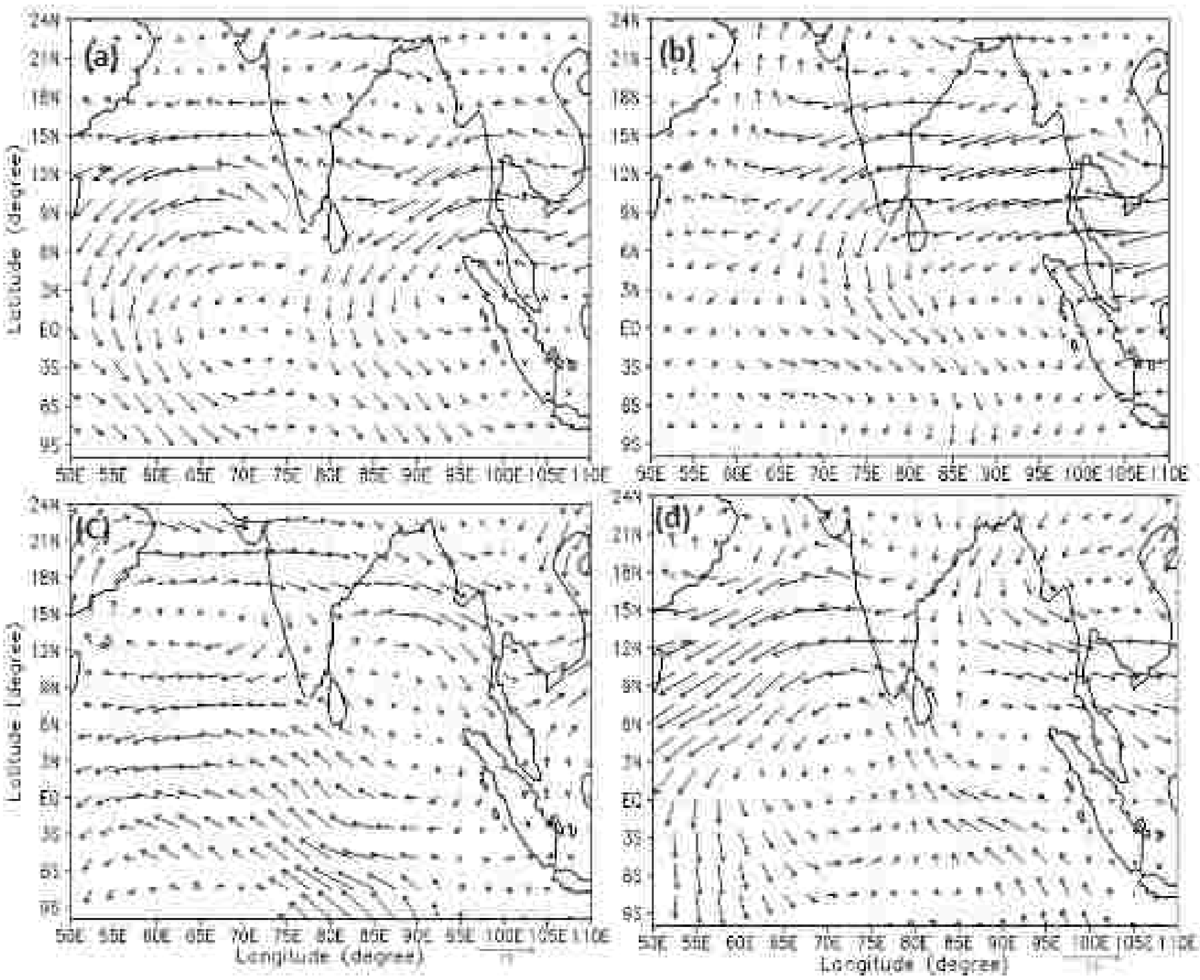

Figure 8: Composite anomaly (break period–active period) of 850 hPa wind field (in ms^{-1}) for (a) 2003 (b) 2007 (c) 2002 and (d) 2009.

3.4 Equatorward shifting of convective cloud band prior to monsoon break

The position and latitudinal movement of ITCZ is manifested by the position of convective cloud bands. The OLR is used as a proxy for convective activity and indicates the location of ITCZ. Figure 10 shows the climatological position of ITCZ in terms of OLR averaged over 75°E–100°E. During the ISM period, the main monsoonal convective region locates over the latitudinal belt of 10°N–20°N.

It is associated with low OLR (<200 Wm^{-2}) over the BoB (Figure 9). Previous studies (Sikka and Gadgil, 1980; Lawrence and Webster, 2001; Krishnamurthy and Shukla, 2007) showed that movement of ITCZ in north-south direction could affect the ISM break. To study the movement of ITCZ during the break period OLR anomalies for two normal ISM years 2003 and 2007 (Figure 10) and two deficit ISM years 2002 and 2009 (Figure 11) are analyzed. Shaded bands indicate the monsoon break periods for the corresponding year. The presence of convective cloud band is marked with the occurrences of negative OLR anomalies. It is clearly seen (Figures 10 and 11) that thick cloud band (negative OLR) is seen over the equatorial region during most of the break period. Only during August 2009 equatorial region shows less cloud cover, which is different from the other ISM breaks. It is to be noted that ISM deficit during August 2009 is created due to the ISO of the Pacific origin (Neena et al., 2011). Anomalous equatorward flow is noticed during ISM break period (Figures 7 and 8). The equatorward migration of cloud band (i.e. ITCZ) is clearly indicated by the presence of negative OLR anomaly before the occurrence of monsoon break (Figures 10 and 11). The equatorward movement of ITCZ marked the equatorward transport of moisture the (or equatorward shift in the convective region) from the BoB, which reduces the rainfall over the Indian landmass and results in monsoon break. Now the question arises, what are the relation between LHF over the northern BoB and equatorward movement of ITCZ prior to ISM break?

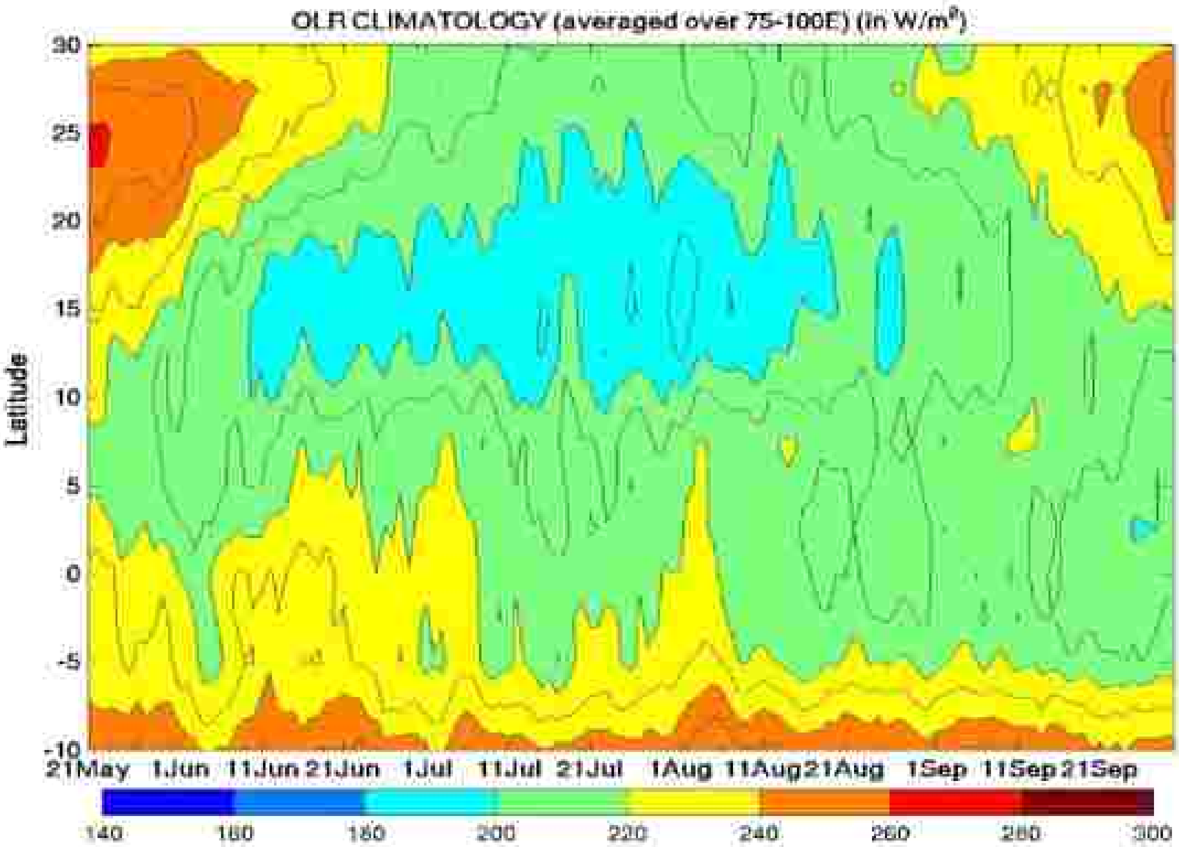

Figure 9: The climatological position of Inter Tropical Convergence Zone (ITCZ) in terms of Outgoing Longwave Radiation (OLR) averaged over 75°E–100°E during the monsoon period

From these results, we hypothesize that LHF over northern BoB plays a critical role in monsoonal convection.

It suggests that before 1–10 days of ISM break low LHF persists over the BoB. It is associated with the equatorward shift of the low-level jet. The anomalous equatorward flow during the break period (both normal year and deficit year) (Figure 8 and right panel of Figure 7) pumps moisture towards the equator and enhances the cloud formation, hence contributing to the decrease in OLR over the equatorial region

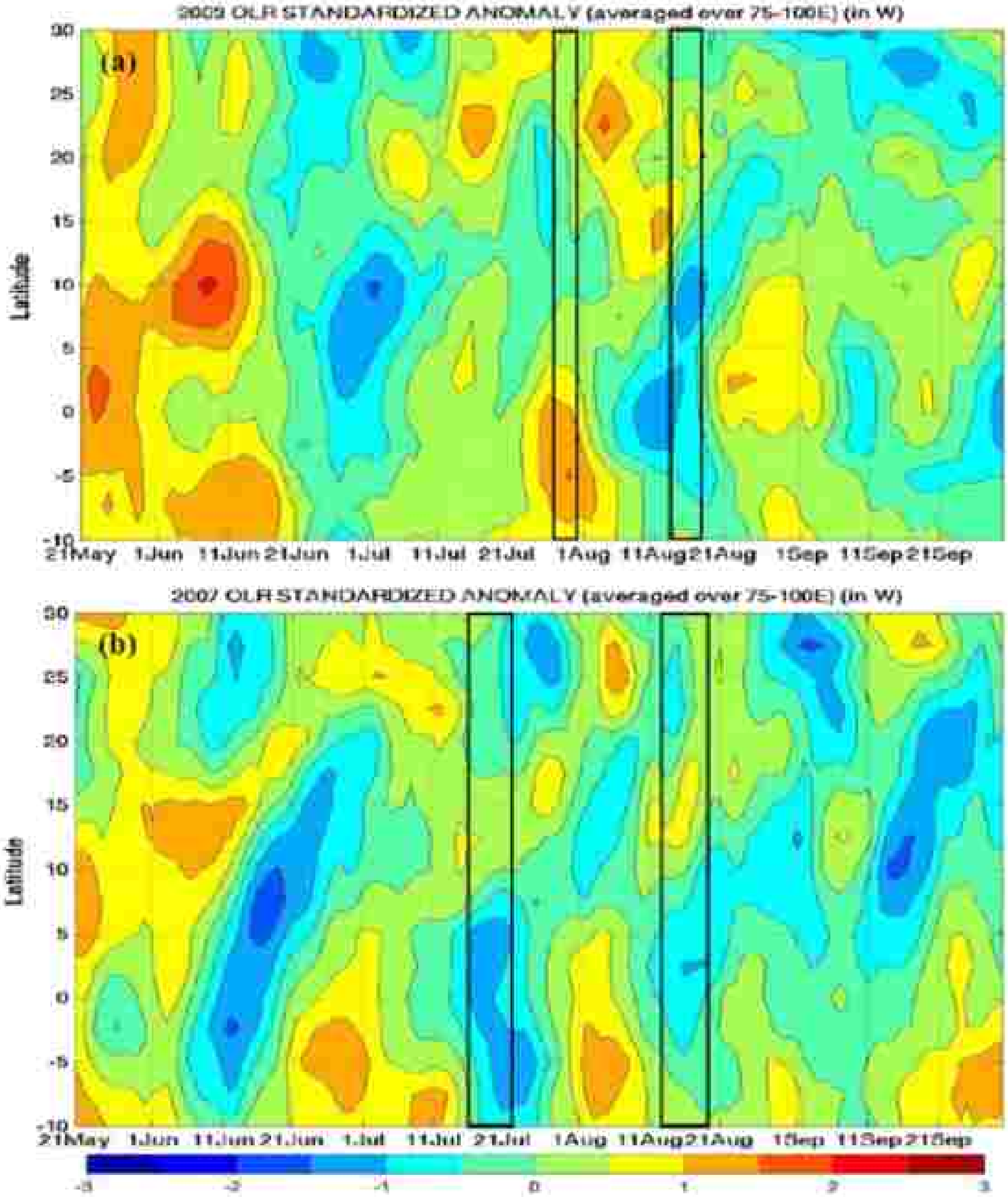

Figure 10: Standardized Outgoing Longwave Radiation (OLR) averaged over 75°E– 100°E during monsoon period of (a) 2003 and (b) 2007. The position of Inter Tropical Convergence Zone (ITCZ) is marked by negative OLR anomaly. The Box indicates the break period of the year.

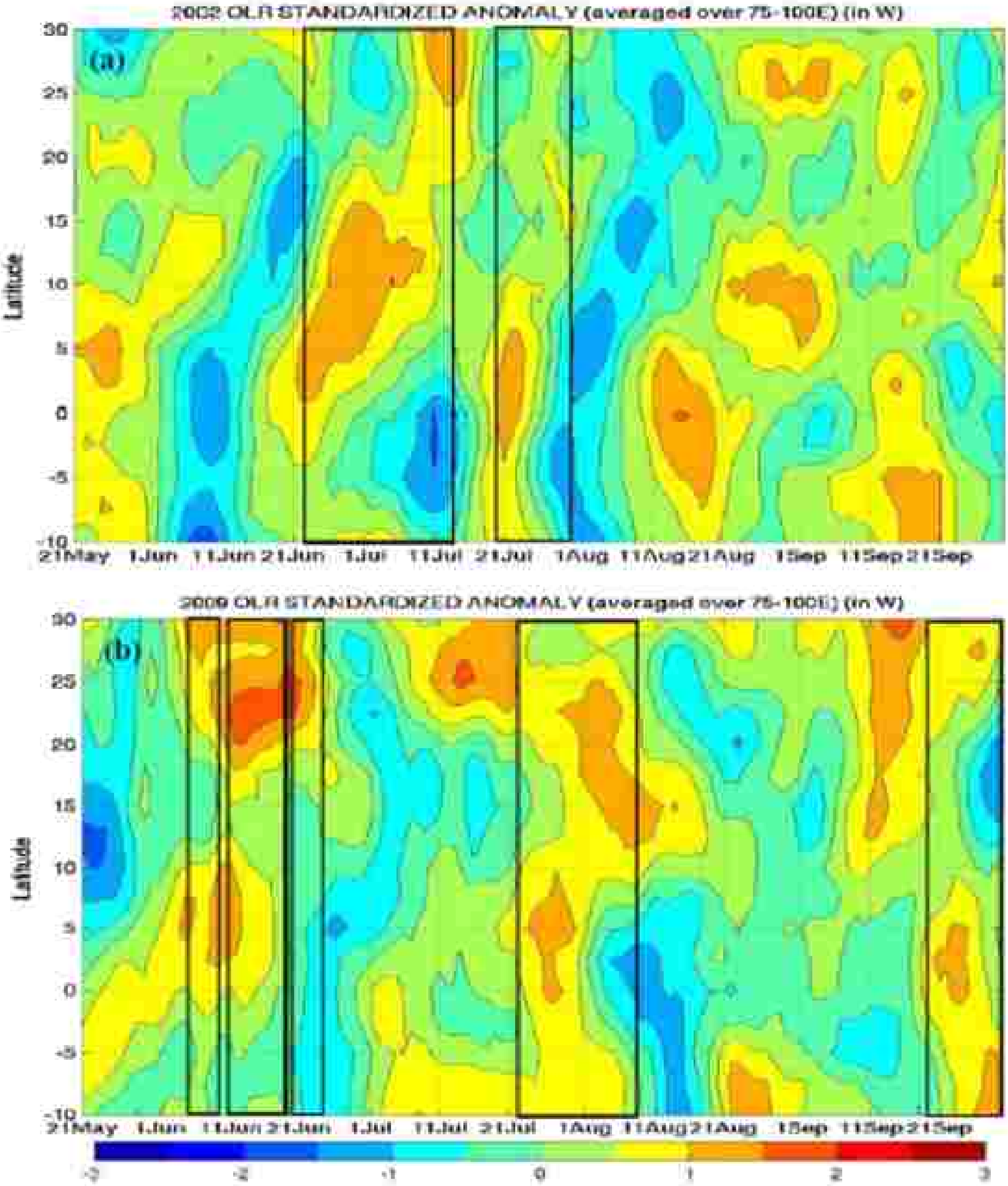

Figure 11: Standardized Outgoing Longwave Radiation (OLR) averaged over 75°E–100°E during monsoon period of (a) 2002 and (b) 2009. The position of Inter Tropical Convergence Zone (ITCZ) is marked by negative OLR anomaly. The Box indicates the break period of the year.

3.5 Meridional circulation during monsoon break period

It is well known that the position of ITCZ denotes the location of the ascending branch of Hadley circulation (Goswami and Ajaya Mohan, 2001). Figure 12a shows JJA climatological meridional circulation averaged over 75°E–100°E. The streamlines are plotted to get the shape of the different cells. The Hadley cell is represented by the presence of the descending branch extending from south of 15°S and the ascending branch north of 15°S.

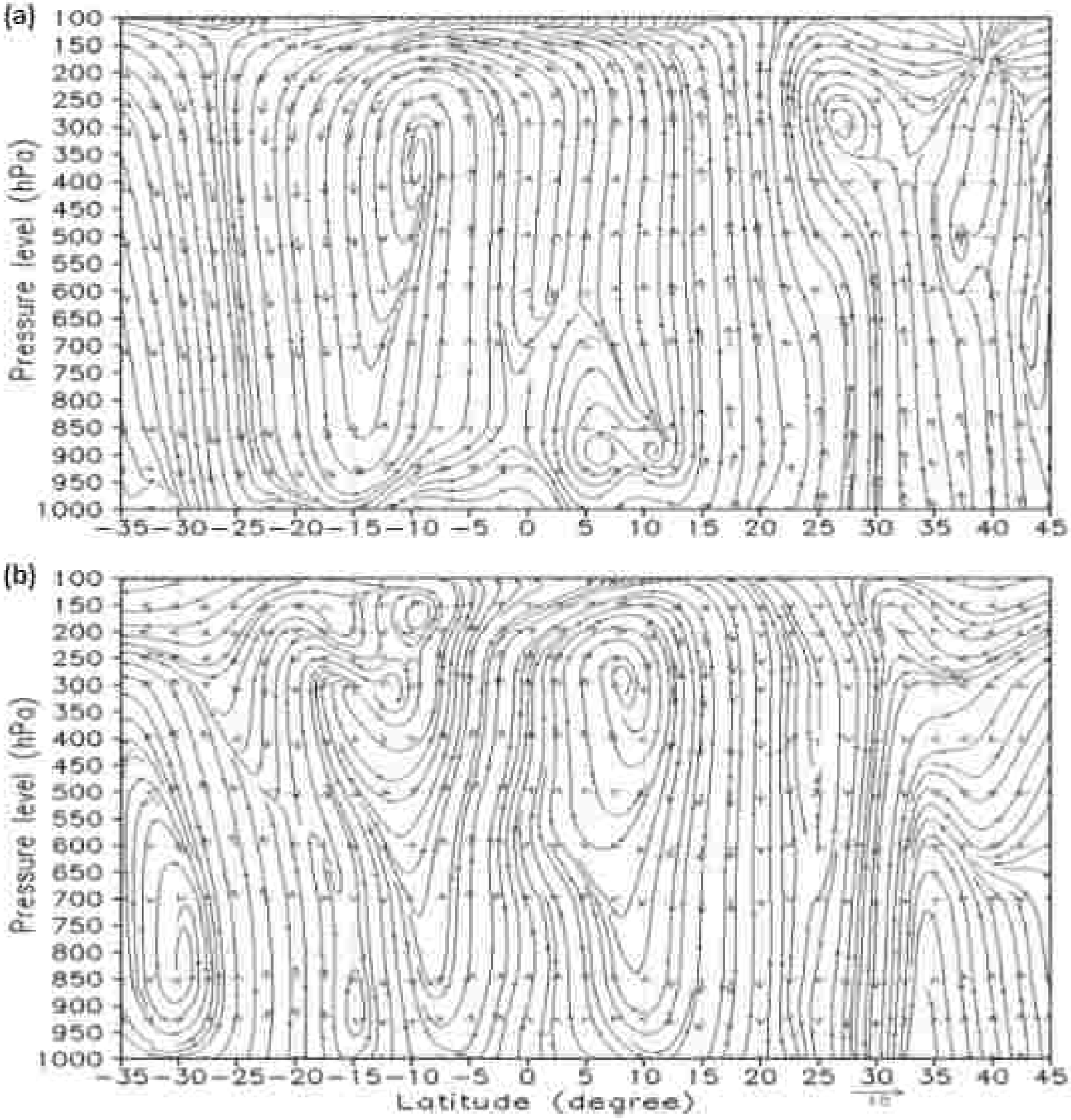

Figure 12: (a) JJA Climatology of meridional circulation averaged over 75°E–100°E (b) composite anomaly of meridional circulation during monsoon break in JJA during 1998–2010.

The Hadley cell circulation agrees with the previous studies. The signature of the low–level jet present during the ISM period is clearly seen by the vertical cell extending between the equator and 12.5°N. The vertical cell is extended up to 650 hPa level. It matches with that of Joseph and Sijikumar (2004). Figure 12b presents the composite anomaly of meridional circulation during ISM break for JJA for 1998–2010. Anomalous sinking (10°N–25°N) of air (i.e. reduction in convection) is observed in the ascending branch of the Hadley cell. In addition, anomalous rising (around 30°S–20°S) of air is observed in the descending branch of the Hadley cell. Moreover, the Hadley cell is squeezed to 10°S to 25°N. This results in a weak Hadley cell over the Indian region and results in suppression of convection over the BoB and the Indian subcontinent. The squeezing of the Hadley cell clearly indicates the equatorward movement of ITCZ. Moreover, during the break period, the normal meridional circulation cell is disturbed and resulted in inhibition of deep convection over the BoB and the Indian subcontinent. Hence monsoon break period persists.

4. Summary

Ocean can influence the atmosphere only through surface heat flux even if SST remains invariant. Therefore, the role of heat flux is more fundamental. Variability of LHF and air sea interaction processes over the BoB is studied on daily basis during JJAS period of 1998–2010. A new criterion for the ISM break is considered using daily TMI rainfall over the central India (Samanta et al., 2016). It is found that the break periods considered match well with earlier studies. The most intriguing result of this study is to observe the antecedents of ISM break period in 10–90 days filtered LHF over the northern BoB. It is found that low LHF persists over the BoB before 1–10 days of ISM break. It is associated with the equatorward shift of the low-level jet. Shifting of low-level jet pumps moisture towards the equator and enhances the cloud formation over the equatorial region. In addition, the equatorward shift of ITCZ observed consistent with the presence of negative OLR anomaly over the EIO. Weak regional Hadley cell during the ISM break period marks the shifting of ITCZ.

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