Theoretical and Applied Climatology (2019) 137:1895–1907
https://doi.org/10.1007/s00704-018-2709-9

ORIGINAL PAPER

Bay of Bengal branch of Indian summer monsoon and its association with spatial distribution of rainfall patterns over India

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Received: 5 July 2018 / Accepted: 5 November 2018 / Published online: 21 November 2018

Abstract

Indian summer monsoon rainfall is characterized by a considerable variability on the spatial and temporal scale, though the standard deviation of rainfall on the temporal scale is much smaller (ca. 10% of annual long-term mean) compared with that of the spatial scale. It is known that the seasonal rainfall amplitude over India as well as the statistical properties of the subseasonal variability is strongly linked to the Pacific teleconnection on interannual timescales, such as El Niño-Southern Oscillation (ENSO) and La Niña, and the teleconnection is primarily arising from central and eastern Pacific Ocean. But, the west Pacific controls on the southwest monsoonal flow, and in turn, the modulation of rainfall variability in the subseasonal scale by this low-frequency seasonal to interannual background over India is poorly understood. Here, we examine the moisture pathways by which the spatial pattern of rainfall variability in the subseasonal scale is envisaged to be arising due to the interplay between the Bay of Bengal (BoB) summer monsoon circulation and the South China Sea (SCS) moisture dynamics under different background conditions provided by ENSO or the subseasonal movement of the Inter Tropical Convergence Zone (ITCZ). We observe that the south BoB branch of the summer monsoon could occasionally extend up to 120° E in the SCS and reverse back to Indian mainland. We propose a mechanism by which the south BoB branch interacts with the SCS (viz. western Pacific) atmospheric system, thereby facilitating a pathway of the west Pacific moisture intrusion into the Indian subcontinent. The study concludes that the changes in surface temperature/pressure spatial pattern between India and SCS region play an important role in the distribution of the rainfall. In this study, for the first time, the life cycle of south Bay monsoon flow and its interaction with the SCS are discussed, likely to warrant special attention for modelers trying to understand the spatial distribution of rainfall over India.

1 Introduction

Indian summer monsoon (ISM) circulation originates in the southern Indian Ocean. After crossing the equator, it broadly bifurcates into two branches, commonly known as the Arabian Sea (AS) branch and the Bay of Bengal (BoB) branch of the ISM system (Das 1968). They contribute more than 75% of annual rainfall over the Indian subcontinent. It is known that the moisture fractions originated from the AS and the BoB, as well as the spatial pattern of rainfall, are intrinsically linked to the dynamics and physics of southwesterly (SW) flow of the ISM. Several researchers have investigated the rainfall variability at the regional scale and the change in spatial features on an intraseasonal scale. Some of these are active and break phases of monsoon (Krishnamurthy and Shukla 2000; Rajeevan et al. 2010), dynamics of the monsoon trough (Koteswaram and Rao 1963), low-pressure systems (Goswami 1987), stratosphere-troposphere interaction (Fadnavis and Chattopadhyay 2017), etc.

Goswami (2012) demonstrated that the monsoon intraseasonal variability manifested in the form of active and break phases plays an important role in the spatial distribution of rainfall. Besides, the most important semi-permanent system which prevails over the Indian subcontinent during the summer monsoon period is the monsoon trough. This elongated low-pressure zone extends from northwest India up to the BoB. The eastern edge of this trough dips into the Head Bay creating a cyclonic vorticity conducive for moisture

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00704-018-2709-9) contains supplementary material, which is available to authorized users.

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transport from the BoB toward inland. Also, the distribution of the summer monsoon (Jun–Sept) rainfall over the Indian region is linked to the variation of the convection over the BoB (Gadgil 2000). Previous studies highlighted the BoB branch controls on monsoon intensification, which drives the spatial variation of rainfall on the intraseasonal timescale (Rao 1976; Gadgil 2000; Bhat et al. 2001). The BoB branch propagates northwards into central BoB and the north BoB branch reaches eastern India and subsequently deflected by southern barrier of Himalaya and progresses westwards (Das 1968; Pai and Rajeevan 2009). This may be referred as the *internal modulation* of monsoon rainfall variability.

Furthermore, monsoon is also modulated by *external teleconnections*. The Indian monsoon system is known to be intricately related to global-scale circulation patterns (Rasmusson and Carpenter 1982; Meehl 1987; Kutzbach 1987; Webster and Yang 1992; Yasunari and Seki 1992; Ju and Slingo 1995; Kawamura 1998). Previous studies suggest that the Hadley and the large-scale Walker circulation and their intraseasonal variations are interconnected with the monsoon circulation (Goswami et al. 1999; Trenberth et al. 2000). That is, the indirect effect of ENSO modulates the tropical Indian Ocean sea surface temperature (SST) (Kawamura et al. 2001; Wu and Kirtman 2004; Achuthavarier et al. 2012; Krishnan et al. 2006) and the meridional temperature gradient over South Asia (Yang and Lau 1998; Goswami and Xavier 2005). Thus, the ENSO forcing on Hadley cell, in turn, circulation changes over the Indo-western Pacific (e.g., Webster and Yang 1992; Krishna Kumar et al. 2005, 2006; Chattopadhyay et al. 2016) mostly explained the changes in spatial pattern of the Indian rainfall. The tropical Indo-Pacific SST exhibits pronounced intraseasonal variations as described in earlier studies (Hendon and Glick 1997; Shinoda and Hendon 1998). Some studies have also explored the role of disturbances over the western Pacific on synoptic-scale systems of the BoB, in turn, the revival of the ISM (Sikka and Dixit 1972; Sikka and Gadgil 1980). Mujumdar et al. (2017) provided evidence of moisture inclusion originated from the west Pacific cyclonic events to the BoB on the subseasonal timescale. It is also known that monsoon is significantly modulated by the tropical and extra-tropical teleconnections (Chattopadhyay et al. 2015).

Studies suggest that the *external teleconnections* as well as *internal modulations* control the Indian summer monsoon variability in the subseasonal scale (Goswami 1997; Goswami and Xavier 2005; Goswami and Ajay Mohan 2001; Neena et al. 2011) thereby modulating the seasonal quantum as well as spatial distribution of rainfall. In this context, however, the dynamical control mechanism of the western Pacific on the distribution of rainfall in the subseasonal scale mostly remained elusive. It is possible that the South China Sea (SCS) can be an important source of monsoon variability through background modulation such that (a) it favors the *internal modulation* and/or (b) it can act independently as a modulator of monsoon via monsoon Hadley cell control in some way similar to the ENSO-monsoon teleconnection that modulates the subseasonal rainfall distribution (e.g., Joseph et al. 2011; Gill et al. 2015). It may be noted that this definition of two mechanisms, i.e., *internal modulation* and *external teleconnection* are only for description purpose in the remaining part of the text. They will highlight two distinct roles played by the SCS/West Pacific in modulating the monsoon subseasonal variability in Section 3.

It has been reported that the intraseasonal SST variability is also observed in the SCS (Zhou et al. 1995; Gao et al. 2000). However, to the best of our knowledge, no information has been provided about the linkage between the intraseasonal SST variations over the SCS and the ISM rainfall. This study explores this SCS–monsoon link with the hypothesis that (a) the western Pacific can provide a necessary background feedback which can control the rainfall and moisture associated with the BoB branch (*internal modulation*) and/or (b), the ENSO type low-frequency variability provides a low-frequency background that modulates the subseasonal variability of monsoon through modulation of monsoon circulation (*external teleconnection*) acting as a low-frequency moisture source or sink.

In a recent study, Chakraborty et al. (2016) demonstrated how the isotopic proxies could be used to better understand the rainfall variability and moisture dynamics over the BoB. Further study by Sinha et al. (2018) revealed that the isotopic variation in the southern BoB region was temporally dependent with the average rainfall over central India. The results of these authors indicated a retrograde motion of the BoB circulations, occasionally driving the south BoB moisture either directly or through a reverse flow reaching the Indian landmass. However, Sinha et al. (2018) neither demonstrated the south BoB moisture flow nor present any mechanism explaining its *reversal* toward India. Furthermore, the intraseasonal features of the reversal of BoB moisture to the Indian region and its role in modulating the spatial pattern of rainfall to our knowledge are not investigated earlier. Therefore, the present study establishes the reversal of south BoB branch and provides evidence of reversal around the SCS region for several years during the ISM.

The study also examines the contribution of the south BoB moisture associated with *internal modulations* as well as *external teleconnections* to the spatial distribution of ISM rainfall. The focus of the present study will be on the relationship of intraseasonal variation of winds over the Indian region (up to the western Pacific) with variability in the surface meteorological parameters over the SCS. We propose a possible mechanism occurring in SCS based on an observation of *reversal* of moisture of the BoB branch from this region, and in turn, propose that the SCS responsible for reversal of the south BoB branch thereby actively taking part in modulation of monsoon circulation.

2 Data used

In this study, a period of 1980–2015 and an extended region consisting of the northern Indian Ocean and its adjoining areas (0° N–35° N and 50° E–130° E) have been considered. The data diagnostic include horizontal winds, surface temperature/pressure, specific humidity, and rainfall (Table 1). We characterize the ISM years into normal years, El Niño and La Niña years based on the Oceanic Niño Index (ONI), to investigate the rainfall spatial variability and wind circulations over India (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). We examined all the strong El Niño years between 1980 and 2015 (ONI ≥ + 0.8, JJA) such as 1982, 1987, 2002, 1997, and 2015 and hence, to compare we have chosen only six normal (− 0.2 < ONI < + 0.2, JJA) monsoon years (1983, 1990, 1993, 2003, 2006, 2012). Throughout the summer monsoon season (2012–2015), daily rain samples were collected for isotopic analysis (^{18}O and ^{2}H) from the Port Blair site. Chakraborty et al. (2016) reported the methodology and the initial results (the year 2012–2013) and the subsequent data have been presented in Sinha et al. (2018). As per the results from Sinha et al. (2018), we have also considered the year 2014 for our investigations.

3 Results and discussion

3.1 Circulation pattern of the south BoB branch during ISM

Prior to re-examining the circulation patterns over the study region, the pathway of the south BoB moisture during the ISM has been investigated. An alternative way to delineate the atmospheric moisture pathways from their initial location is to compute the wind trajectories. We use the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al. 2015) to trace the moisture originated from the south BoB. Toward this, Port Blair (11.66° N, 92.73° E) in the Andaman Islands has been considered as a moisture source location, situated in the south BoB. Normal trajectory type and reanalysis data (global, 1948–present) are chosen, and the model was run on the daily timescale for the post and pre-240 to 300 hours (i.e., forward and backward trajectory analysis, ~ 10–12 days). Started with the recent years (2012, 2014, and 2015) as in Sinha et al. (2018), we further investigated the moisture trajectories for the period between 1982 and 2015 for the ISM months. We have chosen several dates between June and September to demonstrate the moisture dynamics of the south BoB region. Detailed trajectory analysis of the moisture flow pathway depicts that the air-mass containing moisture from the south BoB transported toward the SCS under the influence of SW flow and also rises to about 700–600 hPa. Afterward, the moisture transports to the northwestern part of the Pacific (hereinafter, normal flow); but in certain circumstances, a fraction of moisture gets reversed at around SCS and advances toward the Indian mainland (hereinafter, reverse flow). It has been observed that there are only a few years for which the reversal of the south BoB moisture occurs within the summer season. We found up to ten events of reversal within a month (i.e., > 35%), particularly during the mid summer (July/August). Although, the daily trajectory analysis reveals that the reverse flow may not persist for the whole month, however, its effect is expected to be perceptible in the mean monthly wind patterns (discussed later).

It is not feasible to illustrate the entire calculated trajectory; therefore, a few of them are shown in Fig. 1 to distinguish the two distinct pathways of the south BoB moisture. The individual trajectory plot has two segments; the upper segment depicts the moisture trajectory while the lower segment shows the corresponding pressure levels (in hPa). Some examples of normal flow using forward trajectories represent the moistures originated from Port Blair reaching the northwest Pacific via Southeast Asian region (Fig. 1, left panel (a–f)). On the other hand, a few examples of reverse flow, which show the moisture flow gets reversed at around the SCS (100° E–120° E) at pressure levels between 700 and 600 hPa (Fig. 1(1(a), 2(a), 3(a))). In the case of reverse flow, the trajectories show that the reversed moisture reaches to central India at around 500 hPa in 10–12 days between the latitudinal ranges of 20° N–30° N. Considering the results of the forward trajectory, we have

Table 1 Datasets used in the study for the period of 1980 to 2015

Datasets	Atmosphere grid resolution	Parameter(s)	Main reference
National Center for Environmental Prediction (NCEP)	2.5° × 2.5°	Wind (u, v), surface pressure, surface temperature	Kalnay et al. (1996)
European Centre for Medium Range Weather Forecasts interim (Era-Interim)	0.5° × 0.5°	Wind (u, v), surface pressure, surface temperature, specific humidity	Dee et al. (2011)
Japanese 25-year reanalysis (JRA 25)	1.125° × 2.5°	Wind (u, v)	Onogi et al. (2007)
Hadley Centre sea level pressure (HadSLP2)	5° × 5°	Surface pressure	Allan and Ansell (2006)
Hadley Centre temperature anomaly (HadCRUT4)	5° × 5°	Surface temperature	Morice et al. (2012)
Global Precipitation Climatology Project (GPCP)	2.5° × 2.5°	Rainfall	Adler et al. (2003)

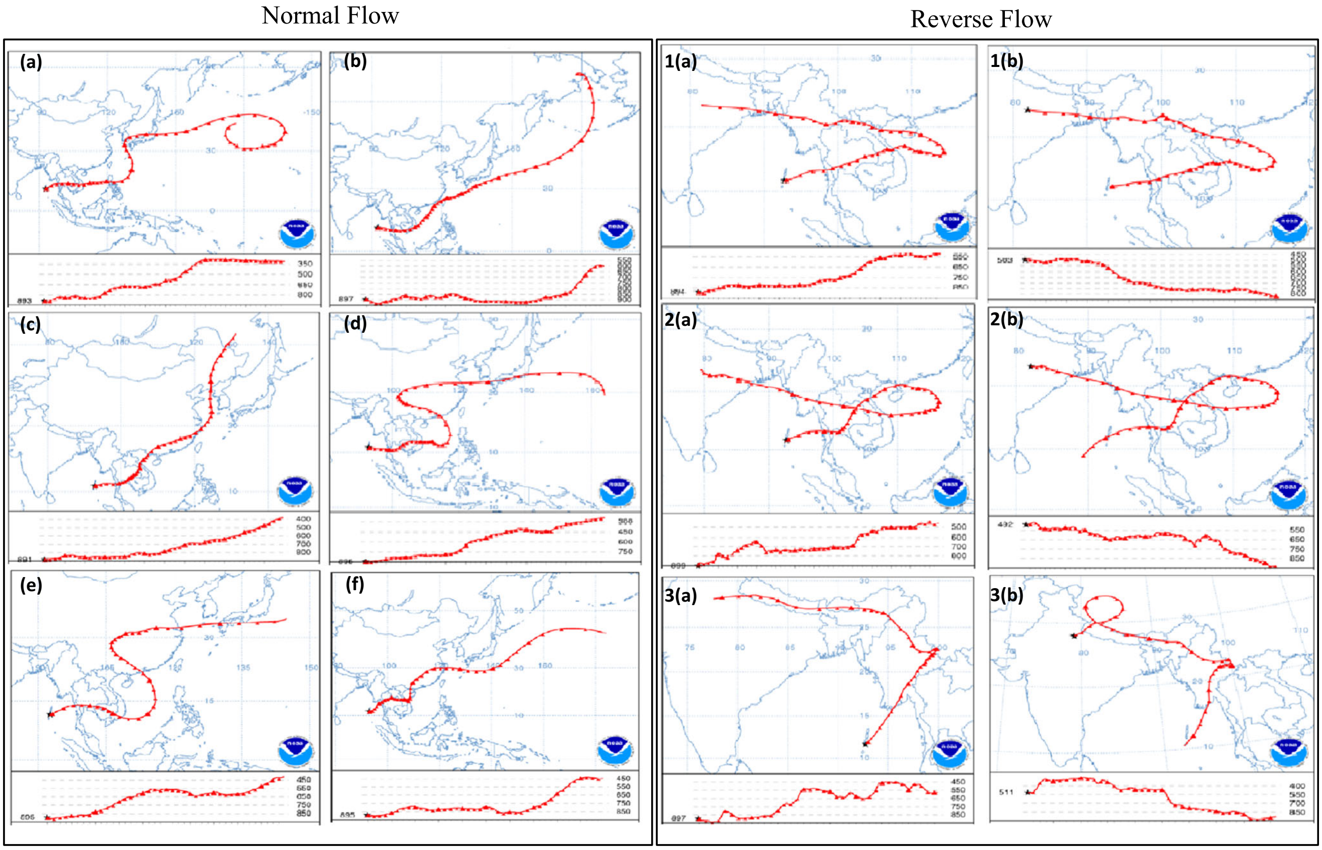

Fig. 1 Left panel showing forward trajectories ((a) to (f)) as some examples of normal flow during the Indian summer monsoon (ISM) and the right panel showing the forward (1(a), 2(a), 3(a)) and corresponding backward (1(b), 2(b), 3(b)) trajectories during ISM as some examples of reverse flow. Star (*) is the source (for forward) and end (for backward) point, Port Blair (11.66° N, 92.73° E, 1000 m, 10–12 days) for forward trajectory chosen as the source and in the case of backward trajectories, the source (5500 m, 10–12 days) was chosen to endpoint (± 0.5°) of corresponding forward trajectory

chosen a few locations over central India to perform the back trajectory analysis (Fig. 1(1(b), 2(b), 3(b))). The star denotes the selected location at 500 hPa and model was run for pre-10–12 days to obtain the moisture source region (i.e., backward trajectory). It is interesting to note that the back trajectory almost identically retracing the moisture pathway which was obtained by the respective forward trajectories. An analogous pathway for forward and backward trajectories for the reversal events support that the moisture originated from south BoB suffers inversion at around the SCS and subsequently reached the Indian landmass. Thereby, the mid-atmospheric level over the central Indian region could have one of the moisture sources from the south BoB through the reversed branch.

As discussed above, if the reversals of the south BoB moisture occur in a month, it should be reflected on mean monthly wind circulation. It may also help to indentify the summer months comprising of the reverse flow, instead of performing the labor-intensive daily calculation of wind trajectories. With the reference of trajectory analysis results, we investigated the monthly wind circulation at various pressure levels (1000–500 hPa). The mean monthly wind plots also reveal two types of circulation patterns of the south BoB branch during ISM, which needs to be investigated in detail. Firstly, wind flows from the south BoB to the western Pacific (e.g., Fig. 2(a), Fig. S1.1 (a)); this is a component of the general circulation flow of the south BoB branch for the ISM season (i.e., normal flow). On the other hand, one part of the south BoB branch gets reversed toward the Indian landmass, i.e., reverse flow (e.g., Fig. 2(b), Fig. S1.1 (b)). We have shown the circulation patterns at 500 hPa, because the reversal event appears to be the strongest at this level. Additionally, during the active period of ISM, wind vector anomalies at 500 hPa bear close resemblance with those at 850 hPa (Goswami and Ajay Mohan 2001), though the reversal is not visibly manifested at the surface level due to the strong influence of SW circulation. It is observed that the low-pressure system developed at the surface level over the north BoB progressively strengthened and extended up to the SCS. For instance, circulation patterns shown at different levels for the month of August 1982, area marked at mid-levels with the rectangular box in Fig. S1. This feature indicates an additional pathway of mid-level moisture intrusion through the negative zonal wind (Fig. 2(b), shaded) toward the Indian region. We have also examined monthly moisture flux associated with the distinct wind circulation

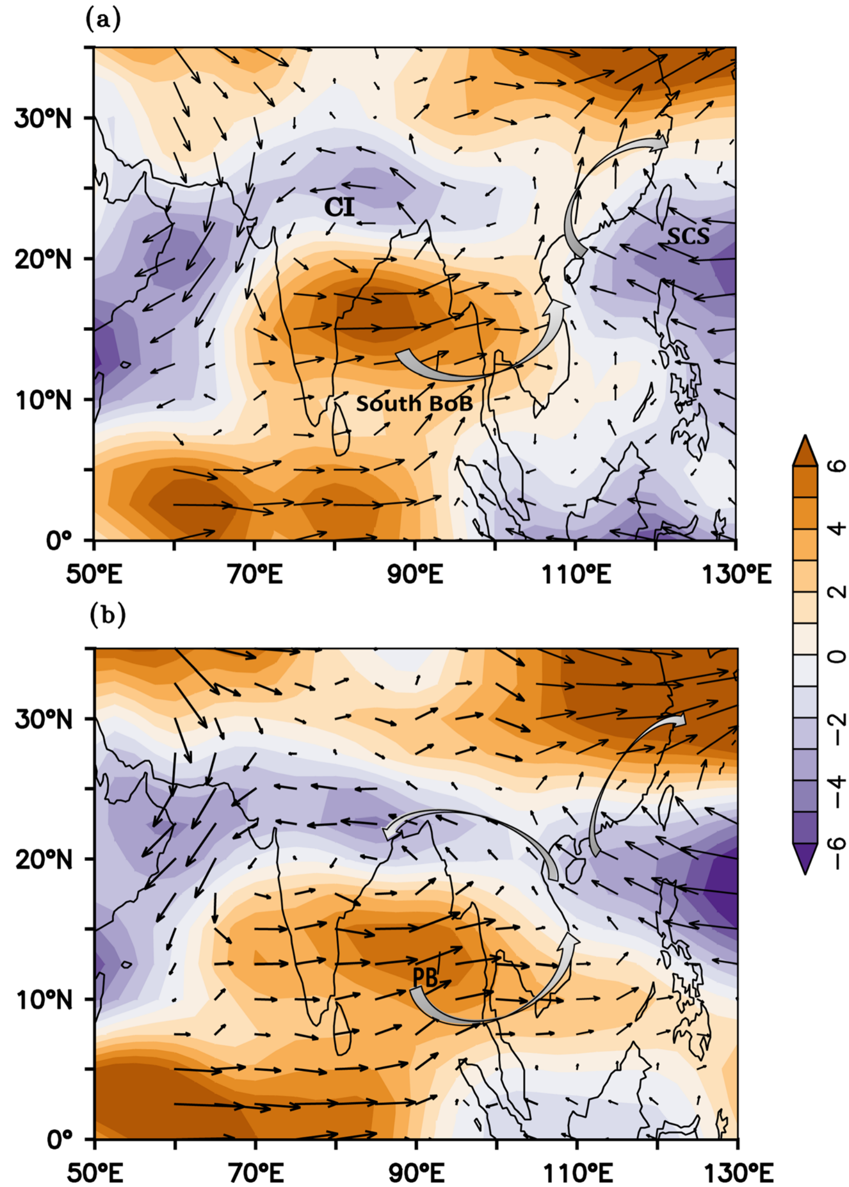

Fig. 2 (a) and (b) July zonal wind (shaded, m/s) and wind direction (vector) for two distinct wind patterns at 500 hPa, one with normal flow and other with reverse flow of the south BoB branch respectively. Where, CI - Central India, South BoB - South Bay of Bengal, SCS - South China Sea, PB - Port Blair

patterns. An example for the month of July 1990 and 1982 respectively reveals the difference in circulation and associated moisture convergence for the normal and reverse flow (Fig. S2). The year 1982 shows a moisture contribution associated with the wind circulation within the latitudinal (longitudinal) range of 20° N–30° N (100° E–110° E). Until now, we have established that the south BoB branch of ISM is characterized by two distinct circulation patterns. We observed that the chosen six normal monsoon years show normal flow of south BoB branch throughout the ISM season (refer to as case I, Table 2). On the other hand, out of the examined strong El Niño years (1982, 1987, 2002, 1997, and 2015) and 2014, only four years (refer to as case II, Table 2) have shown the reverse flow during the ISM months. Other two strong El Niño years (1987 and 1997) during the study period have not been manifested by any reversal events during the summer months (discussed later).

3.2 Evidence of reversal and re-entrance of south BoB moisture to the Indian region

3.2.1 Power spectrum of zonal wind

Based on observed wind circulation and the reversal pathway, a large variance of the zonal wind over the SCS due to the reverse

Table 2 Case I—years with normal flow of the south BoB branch and case II—years those comprise reverse flow of the south BoB branch, during the Indian summer monsoon (Jun–Sept)

	Years
Case I	1983, 1990, 1993, 2003, 2006, 2012
Case II	1982, 2002, 2014, 2015

flow is envisaged. FFT of the average mid-level zonal wind was calculated to determine the variance over a selected area = 10° N–30° N, 110° E–130° E. Two datasets have been used for the FFT analysis; one is a daily composite of Jun–Sept of the case I years, and another with the years those comprise reversal events (i.e., case II years). The harmonic signal components in the composite time series of the two datasets are shown in Fig. 3(a, b) respectively. They clearly show the difference between composites of daily wind circulations over the SCS. On the one hand, the composite of ISM months of years belonging to case I shows a well-constrained peak of around 14 days. On the other hand, a quasi-periodic broad spectrum of 5–15-day timescales is apparent for the composite of ISM months of case II years, which comprise the reversal events. The extension and shifting of the low-pressure region toward east through the reversed south BoB branch (Fig. S1) on intraseasonal timescale could be accountable for the observed variances over the SCS.

3.2.2 Study of stable isotopes in rain samples

Isotopic analysis of rainwater is considered as a reliable means of obtaining observational evidence of moisture source-related information (Pfahl and Wernli 2009; Kumar et al. 2010; Gimeno et al. 2012). Analysis of daily rain during the summer monsoon helped to understand the isotope-rainfall relationship on spatial as well as temporal scales. For example, Chakraborty et al. (2016) demonstrated that rain isotopes appear to be linked with the monsoon intraseasonal variability in addition to synoptic-scale fluctuations. Sinha et al. (2018) proposed that dual-site (source and receiver) analysis of rain isotopes provides a direct evidence of subseasonal moisture transport from the BoB to the Indian continent during the ISM. These authors have found that the isotopic signatures of the rain samples at the source (i.e., Andaman Island) and the receiving sites (mainland India) showed synchronous variation in isotopic ratios, when the travel time of moisture between the source and receiver had been suitably adjusted.

A brief description of the isotopic study of rainfall is presented here. The rain-isotope data for the summer monsoon months of the year 2012, 2014, and 2015 have been used to reveal their correlation with the spatial rainfall amount on a daily timescale. We calculated the correlation between the rain oxygen isotope ratio ($\delta^{18}O$) and amount of rainfall with time lead regression of 3–12 days in the rain. In Fig. 4, negative correlation between the rainfall amount and rain-$\delta^{18}O$ over the Port Blair region (11.66° N, 92.73° E) at lead 0 validates the inverse relationship, as expected from the *amount effect* consideration (Dansgaard 1964). Interestingly, on the one hand, we observed positive correlation pattern for the year 2012 at lead 0 over central India and no significant changes with lead time in the rain was observed in the spatial patterns (Fig. 4(a)). On the other hand, observed positive correlation patterns over the monsoon zone (red box) at lead 0 moving northward/westward and the pattern turns substantially negative in 10–12 days for the years 2014 and 2015 (lower central region), see in Fig. 4(b, c) respectively. It implies rainfall variations over central India appear to be associated with the rain over the Port Blair region on a timescale of 10–12 days. The correlation turning negative reveals a strong indication that a fraction of the south BoB moisture eventually traveled to the central Indian region for the years 2014 and 2015 during the summer months. Nonetheless, the correlations are not very strong

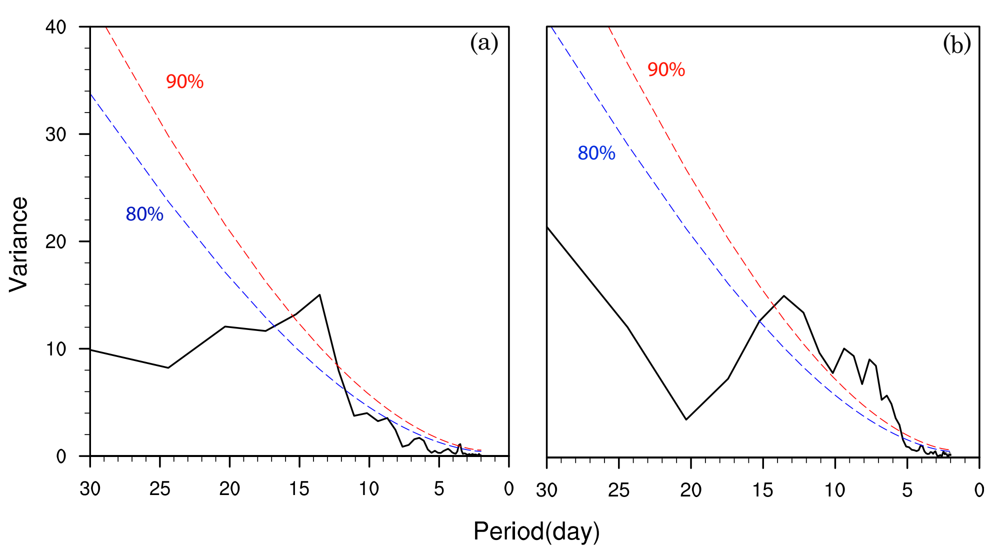

Fig. 3 Power spectrum of daily zonal wind (m/s) at 500 hPa averaged over the box (10–30° N, 110–130°E) for the years reported in Table 2 as case I and case II for (a) variance for the ISM with normal flow and (b) variance for the ISM comprises reverse flow respectively

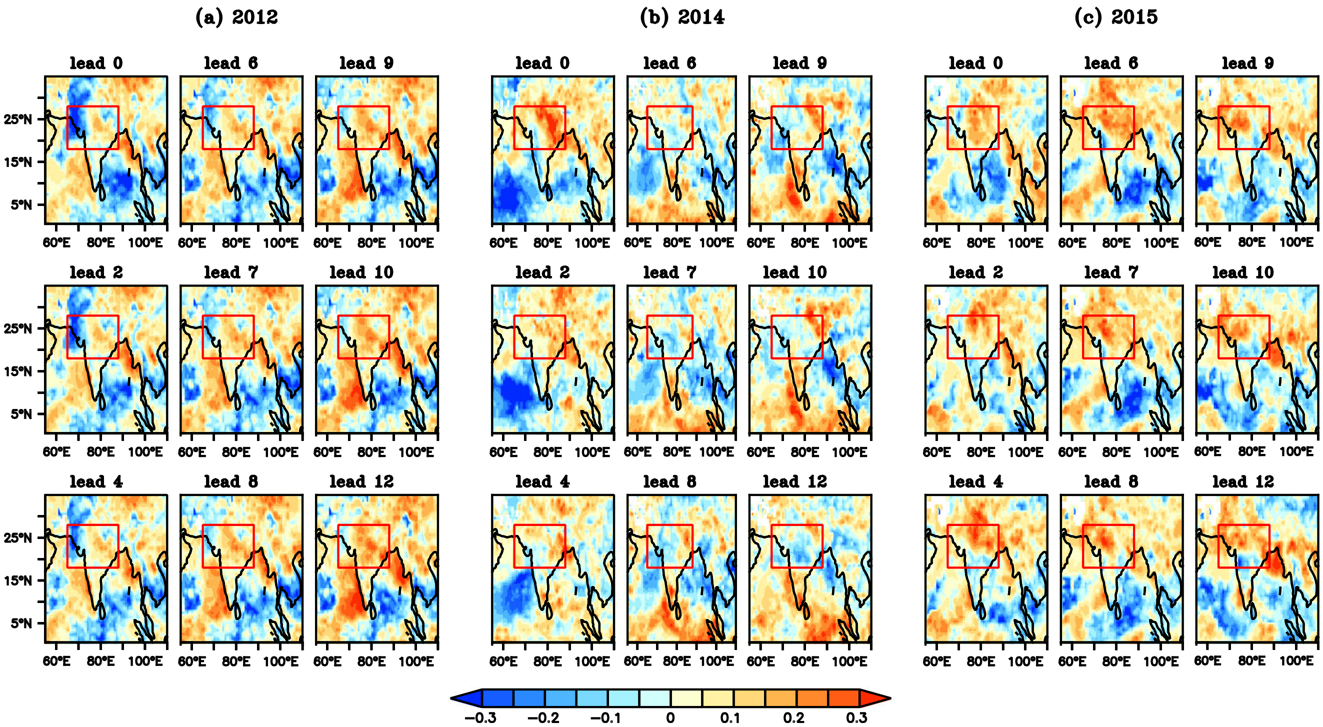

Fig. 4 Plots represent the spatial correlation between Port Blair rain $\delta^{18}O$ (‰) and the gridded rainfall (mm) amount over the Indian region during ISM. The core monsoon zone shown as a rectangular area (red) has been specifically studied. (a) Spatial variation in correlation patterns with lead time in the rain for the year 2012 and (b) same for 2014 and (c) same for 2015. The correlation patterns over the core monsoon zone (CMZ, red rectangle) for the normal flow are found to be not significantly varying with a lead time (2012). On the other hand, observed positive correlation patterns over CMZ at lead 0 moving northward/westward and the pattern turns substantially negative in 10–12 days for the years (2014 and 2015) comprise reverse flow

($-0.3 \leq r \leq 0.3$) as the isotopic fractionation and local moisture intrusion during air-mass transport may have altered the source signature (Sodemann et al. 2008) and, in turn, weakened the correlation. Thus, the investigation with the available data (2012–15) of isotopic ratio in the rainwater samples also provides an evidence that the moisture from the south BoB contributing to the ISM rainfall through the south BoB branch.

3.3 South BoB moisture contribution (internal modulations)

We aimed to gain insight into the changes in moisture content or rainfall spatial patterns, if any, due to the distinct flow of the south BoB branch. Firstly, we examined the vertical moisture variations in the normal and reverse flow. Toward this, we calculated the longitudinally averaged specific humidity and plotted between the latitudes 5° N–35° N (Fig. 5). The plot shows the vertically integrated (1000–300 hPa) latitudinal variations of seasonal (Jul–Aug) mean moisture content over the Indian region for the years belonging to the two cases (Table 2), as well as two exception years (1987 and 1997). The vertical moisture content (Fig. 5, red curves) for the years that comprise reverse flow are found comparably equivalent to years with normal flow of the south BoB branch (Fig. 5, black curves). Although, corresponding years of case I and case II have had normal and poor summer monsoonal rainfall respectively. Furthermore, all the years that have shown the events of reversal of the south BoB branch are El Niño years and/or rainfall was below normal considering India as a whole. However, the convergence of the red curves between the latitudes 20° N–30° N shows that there is an additional moisture source over central India. It can be interpreted that the reversal of the south BoB branch during these years could be the source of moisture, thereby weakening the effect of El Niño induced teleconnection, which is known to suppress the seasonal rainfall over the Indian landmass. The years have shown no reversal during the ISM, such as 1987 and 1997 coinciding with conditions of drought and below normal rainfall over central Indian region respectively (ftp://www.tropmet.res.in/pub/data/rain/iitm-regionrf.txt). The low seasonal moisture content over central India (Fig. 5, green curve) indicates a relatively weak summer monsoon.

Further on spatial scale, the distribution of rainfall during ISM (Jun–Sept) over the Indian subcontinent has been shown for the respective case I and case II composite years in Fig. 6. Rainfall patterns in latitudinal belt 20° N–30° N over central India in both the cases are found to be similar particularly during the mid months (Jul and Aug) of the ISM. However, deviation in rainfall patterns and shifting in rain bands toward central and northeast Indian region manifested for the

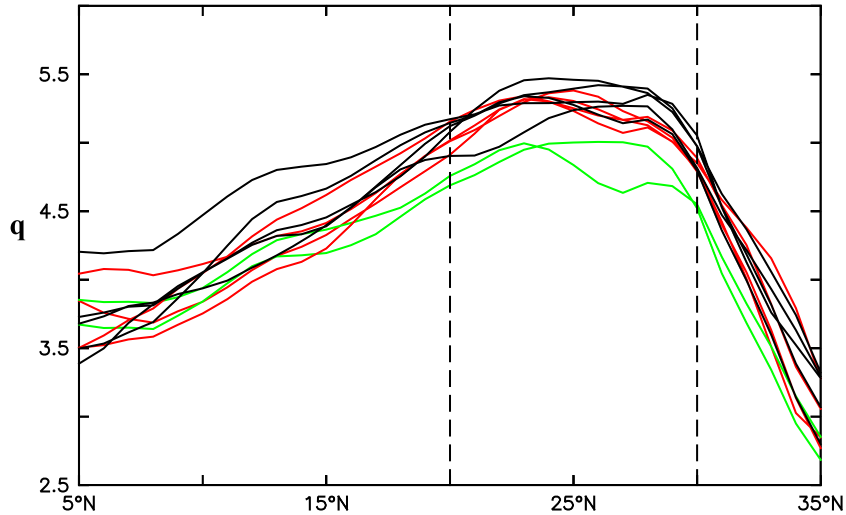

Fig. 5 Vertically integrated specific humidity (q, kg/kg) averaged over longitudes 75° E–85° E and plotted along the latitude between 5° N and 35° N. Dashed straight lines are representing central India (20° E and 30° E). Black and red curves showing the variation in moisture content for the years (Table 2) with normal flow and reverse flow during ISM respectively, the green curves are for the two El Niño years without reverse flow (1987 and 1997)

composites of the case II years. Consistent with the reported rainfall variability (Guhathakurta and Rajeevan 2007), calculated coefficient of variability for composites of ISM mid months of case I and case II years show low variance (< 0.3) particularly over the central/northeast India as compared to the other regions (Fig. S3). The results from our investigation of the rainfall patterns during ISM mid months for case I and case II show similar rainfall distribution and coefficient of variability over the Indian region. However, there were changes in rainfall patterns and slight shifting of depression center toward east of India for case II. The observed changes in the ISM circulation patterns for the case II years over the region could explain the corresponding changes in the rainfall distribution. That is the synoptic systems like low-pressure area extension through the reversed branch of the south BoB (internal modulations) and centered depression over the BoB is responsible for the rainfall distribution over central north and northeast India and adjacent area of the north BoB (Fig. 6(b)).

3.4 Large-scale controls on ISM (external teleconnections)

As known from the earlier studies, the changes in the spatial pattern of Indian rainfall have been mostly explained through

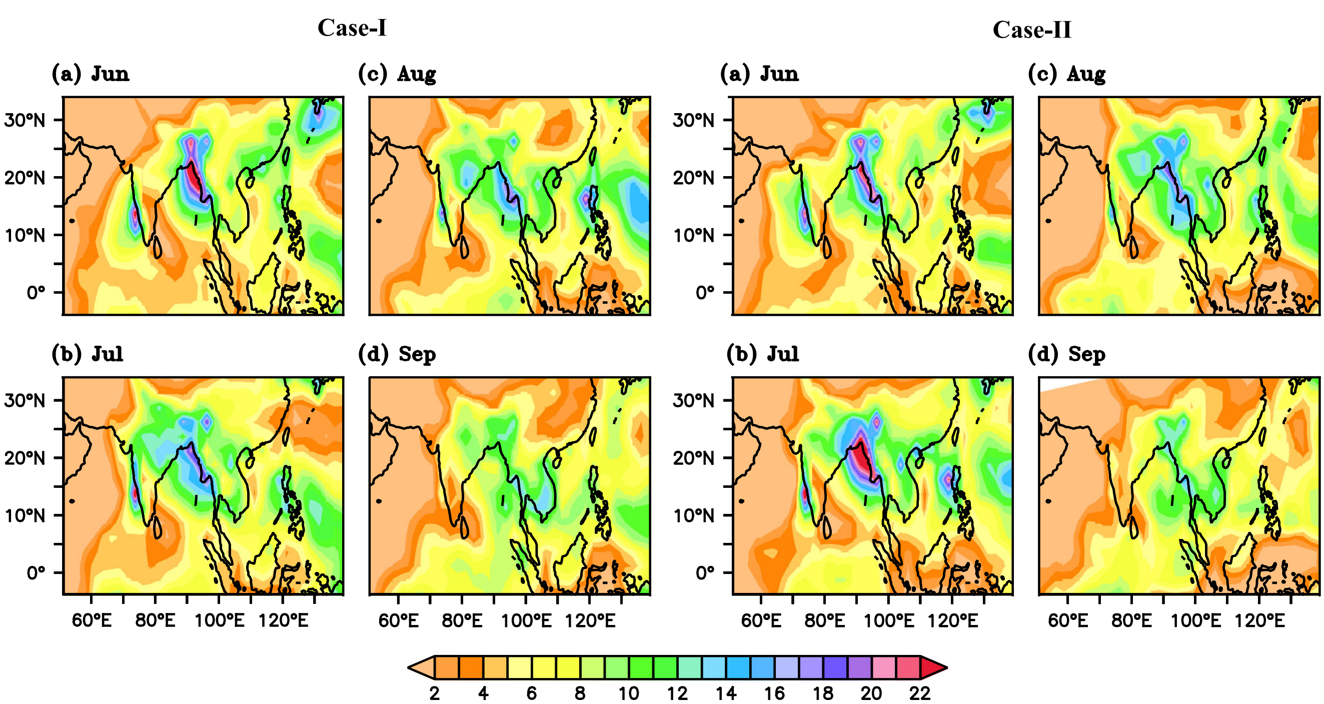

Fig. 6 Composite of rainfall amount (mm) during ISM months to compare the change in rainfall patterns for the years (case I) with normal flow and the years (case II) comprises reverse flow of the south BoB branch

the indirect effect of El Niño event on large-scale circulations (e.g., Krishna Kumar et al. 2006; Chattopadhyay et al. 2016). Further, Goswami (1994) proposed that the Indian monsoon circulation evolves as an interacting system between a regional-scale Hadley circulation and large-scale Walker circulation. However, on a larger scale, the effect of Pacific teleconnection and variability of Hadley or Walker circulation on the spatial distribution of ISM rainfall remains dynamic within a season (Gill et al. 2015) with strong evidence of year wise influences on monsoon (Krishnan and Sugi 2003).

It is reasonably well known that the ISM rainfall spatial variation is modulated by the surface synoptic-scale disturbances over the BoB (Gadgil 2000). We propose that moisture from the south BoB and in several events associated with moisture reversal near the SCS may play a critical role in the redistribution of the rainfall patterns thereby acting as a source of external teleconnection. It is known that El Niño usually suppresses the rainfall over India, but this study shows that additional moisture supply through the reverse flow is likely to moderate the El Niño effect in some years. Thus, a monsoon season characterized by a stronger low-frequency variability and further the west Pacific moisture augmented by a the reverse flow is likely to alter the regional distribution of the rainfall pattern over India in some years (Table 2, case II).

To support our conjecture, we examined the Hadley and the Walker cells for possible summer monsoon conditions, such as normal monsoon years as well as El Niño and La Niña associated years in the context to the Indian monsoon (Fig. S4). It is evident from the simulated vertical circulations that the patterns of regional convection over Indian region during the El Niño years are nearly the same as the other conditions (up to latitude 35° N and longitude 100° E). That is, the Hadley cell circulations show a good resemblance in the convection pattern between 5° N–35° N and up to 600–500 hPa (Fig. S4, I) and the Walker cell circulations (Fig. S4, II) reveal that the descending branch suppressed the convection significantly over the western Pacific (100° E–140° E) rather than in the tropical Indian Ocean region during the El Niño years. This conjecture is still debatable and hence holds promise as El Niño and weakening of Indian monsoon are strongly associated but their negative correlation has failed for several years.

4 Mechanism and timescale of the reversal event

Here, we discuss the circumstances under which the wind reversals may take place during the summer months. This

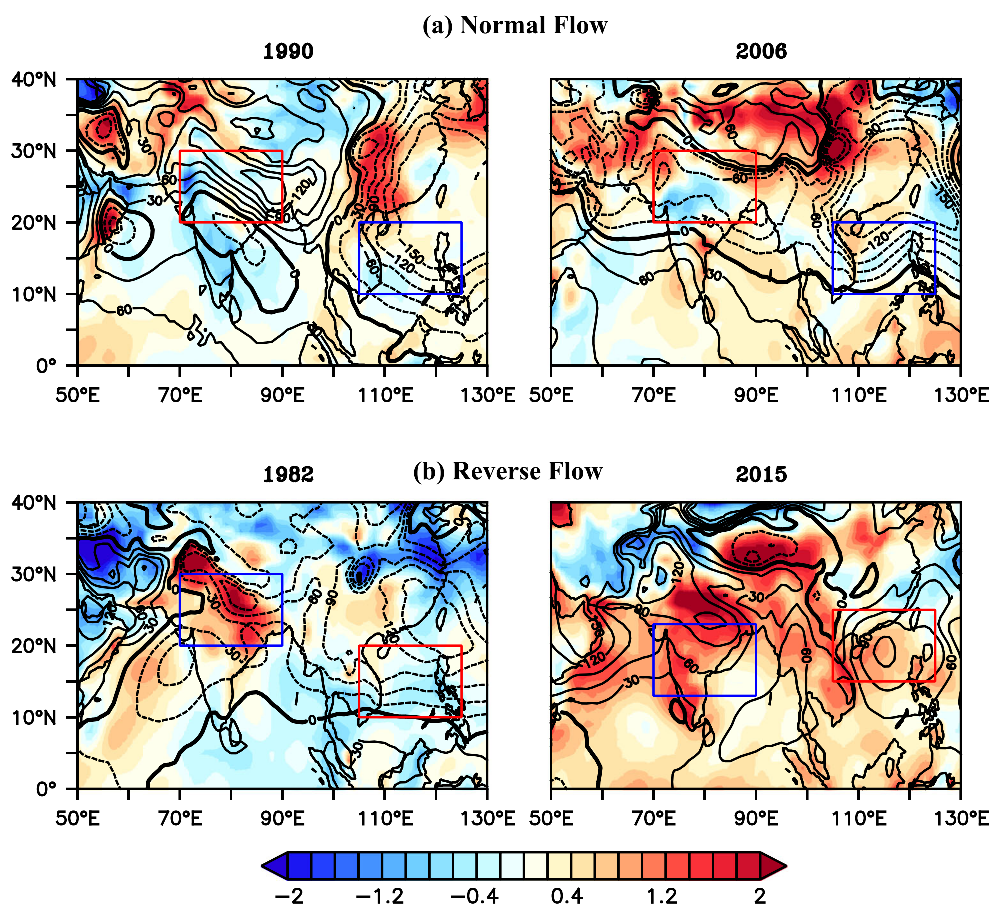

Fig. 7 Surface temperature (shaded, K) and pressure (contour, Pa) anomaly for a month (e.g., Jul or Aug) of Indian summer monsoon. Two examples of corresponding normal and reverse flow circumstances, i.e., (a) case I: 1990 and 2006 and (b) case II: 1982 and 2015 respectively

includes not only understanding the mechanism but also an estimation of the timescale of the reverse flow of the south BoB branch.

a. Possible mechanism

It is known that the atmospheric circulation is primarily controlled by temperature and pressure gradient that govern the wind flow from high- to low-pressure regions. Therefore, to understand the driving mechanism for the observed reversal events, we have investigated the surface temperature and pressure anomalies over the study region. Surface pressure and temperature analysis characterizes change in spatial pattern of the anomalies over the Indian and the SCS regions. Firstly, NASA Goddard Institute for Space Studies Surface Temperature Analysis (GISSTEMP) online portal (https://data.giss.nasa.gov/gistemp/maps/) has been utilized. The parameters used to run GISTEMP and to plot surface temperature anomalies are documented in the supplementary information. The spatial temperature anomaly plots reveal relatively negative (positive) temperature anomalies over the central Indian region and positive (negative) over the SCS for the July 1980 (1982) as shown in Fig. S5. Secondly, we calculated monthly surface temperature and pressure anomalies using various datasets and plotted for each observed patterns for different years from case I and case II (e.g., Fig. 7, Fig. S1.2, and Fig. S1.3). In Fig. 7, the red box represents an area of positive pressure anomalies (negative temperature anomalies) relative to an area enclosed by the blue box. We found that the changes in relative pressure anomalies over the two regions may modulate the normal flow of the south BoB branch. We examined several years and noted that the reversal of the south BoB branch could evolve with the weakening of low-pressure over the SCS region and the extent of low-pressure over central India. For the normal flow, temperature (pressure) anomaly over the central Indian region during mid-monsoon months is found to be negative (positive) relative to the SCS (Fig. 7(a)). However, Fig. 7(b) shows the reverse flows may evolve in some years under circumstances that are opposite in nature during ISM. One more point to be noted here is that due to the low-pressure area and strong westerlies over the northwestern Pacific, only a fraction of the south BoB or the Pacific moisture may contribute to the Indian region via such kind of reversals. As we mentioned, there are two years with no reverse flow of the south BoB branch, although they were strong El Niño years and shown similar anomaly spatial patterns of temperature/pressure as case II years. The observed wind patterns for those years (vector, Fig. S6) also indicate a weak summer monsoon. Additionally, the spatial patterns reveal that the positive temperature anomaly (shaded, Fig. S6) and

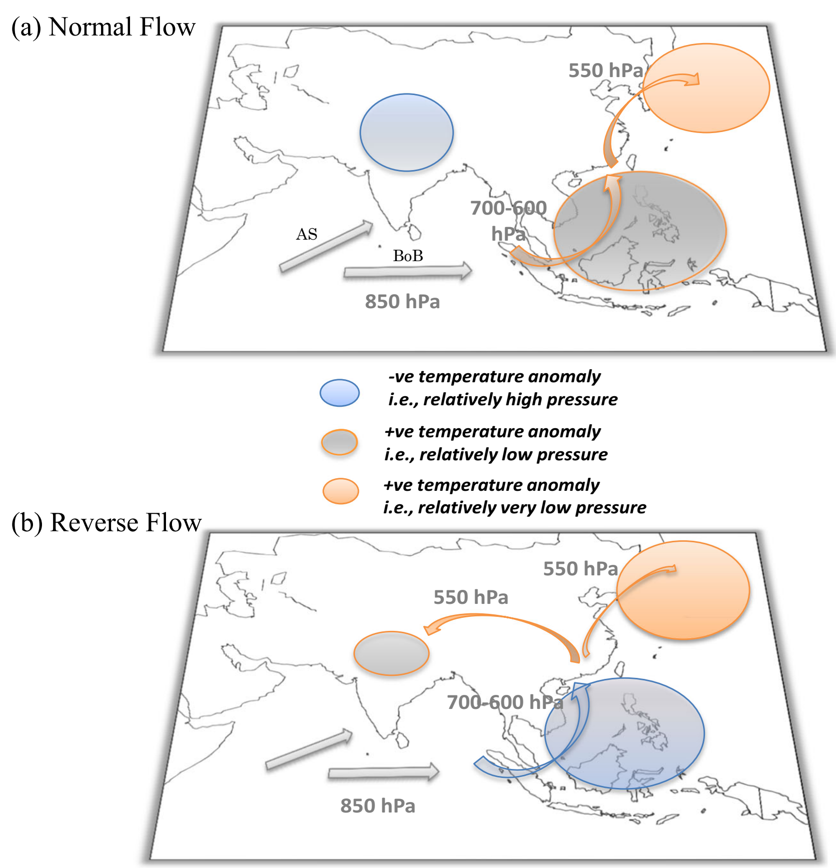

Fig. 8 Two different cases are shown as schematic diagrams for (a) normal and (b) reverse flow of the south BoB branch during Indian summer monsoon. Temperature and pressure anomalies are based on the years 1980–2015 climatology. Arrows represent wind circulation with pressure levels derived from investigation of monthly wind circulations on different levels and daily trajectory analysis

low-pressure (not shown) zone are shifted toward the west of central India; thus, the dry winds are ascendant from the northwest direction. Hence, we believe that this could be one of the reasons for deficit summer monsoon; however, it needs to be tested with several such cases. The proposed mechanism corroborated the observed results of the trajectory and wind circulation analyses. A schematic diagram explaining the mechanism for the two distinct pathways of the south BoB branch is shown in Fig. 8 as normal flow and reverse flow in upper and lower panels respectively.

b. Timescale of the event

The reversal of the south BoB branch from the SCS to central Indian region, discussed in this study as an event and the matter has been further investigated toward the timescale of the event. We found that the reverse flow occurs through the changes in the anomaly of surface parameters (pressure/temperature) over central India (negative/positive) and the SCS (positive/negative), otherwise normal flow. Although, the high surface pressure (and associated low temperature) over the western Pacific (including the SCS) could be the result of an anomalous air-mass subsidence during the El Niño event and may persist during the El Niño years. But, the monsoon intraseasonal oscillations (MISOs) govern the movement of low-pressure area (ITCZ) over the Indian region (Yasunari 1979; Sikka and Gadgil 1980) and result from superposition of 10–20-day and 30–60-day oscillations. Hence, considering high pressure over the SCS during the event, the variability of low pressure over the Indian central region will regulate the timescales of the event (reverse flow). Thus, the occurrence of El Niño may be a necessary condition but not sufficient to initiate a reversal of the south BoB branch. That is, the movement of the ITCZ toward the central Indian region on intraseasonal timescale coupled with monthly to seasonally persistent high pressure over the SCS may be governing the timescales of the reversal events. Additionally, the daily trajectory analysis revealed that approx. 35% reversal events take place in a month. In brief, this study proposes a reversal of the south BoB branch of monsoon circulation during certain El Niño years taking place on the intraseasonal timescale. That may have a seminal role in the monthly mean circulation of ISM, which in turn would control the seasonal/monthly spatial moisture and rainfall distribution especially in the central Indian region.

5 Conclusions

In this study, we identified an anomalous pathway of moisture transport from the South Bay of Bengal to the Indian region and proposed a reversal mechanism for moisture which acts as internal modulation pathway. In general, southwest wind flows en route the Southeast Asian region from the south BoB to the western Pacific during the ISM (normal flow); however, under certain circumstances, fraction of the south BoB branch of circulation after reaching the SCS region reverses back toward the Indian landmass (reverse flow). The reversal mechanism is based on a change in surface parameters, such as pressure and temperature anomaly. The proposed mechanism may modulate the internal variability of the summer monsoon. Our results show that the negative temperature anomalies over the SCS (e.g., during El Niño) drive the reverse flow of the south BoB branch under the well-developed low-pressure system over the central Indian region. Thus, the occurrence of this event in a particular year may affect the moisture distribution and rainfall pattern of the Indian subcontinent on the intraseasonal scale. Trajectory analysis and wind circulations over the study region help distinguish the south BoB branch's normal and reverse flow, in turn, the different pathways of south BoB moisture flow. The isotopic analysis of rainfall from the Andaman regions as well as from the mainland India also supports proposed moisture transport pathways of the south BoB branch (Sinha et al. 2018). However, long-term daily isotope data from the source and receiving regions is required to establish the dual-site isotopic tracking method. The present study also brings out one of the causes of significant changes in the rainfall pattern over the Indian region on the intraseasonal scale associated with internal modulations induced by SCS. The shifting of low-pressure system center and an amplified effect through the reversed branch of BoB in the SCS may explain the changes in rainfall distribution over the central and northeast India during the El Niño associated years.

In addition to the reversal mechanism, the current study also shows the large-scale modulation of monsoon Hadley cell based on large-scale teleconnection induced by the SCS. Most of the earlier studies on rainfall distribution were only limited to this external teleconnections associated with ENSO-monsoon relationship thereby modulating the seasonal rainfall through SW monsoonal flow. In this study, we show that in addition to this internal modulation by the reversal mechanism as discussed earlier, the SCS can modulate the subseasonal variability of spatial distribution of summer monsoon rainfall through an external teleconnection pathway. This teleconnection (i.e., SCS-monsoon) pathway is paving the way for monsoonal subseasonal modulation and is similar to earlier studies which exclusively focus on ENSO-monsoon (i.e., central to east Pacific) pathway (Joseph et al. 2011; Gill et al. 2015). We show the subsidence of air-mass over the western Pacific (viz. the SCS) during El Niño, thereby, changing the seasonal mean background of surface meteorological parameters acting as low-frequency background (mean-state) modulators and facilitate the south BoB moisture intrusion pathway through the west Pacific toward Indian region. Further analysis consisting of several years of observations is required to quantify the reverse flow moisture contribution associated with the internal modulation and to determine its timescale. Once the south BoB branch of circulation is well understood, its interpretation in terms of Pacific teleconnection in general circulation models may improve the prediction/simulation of summer monsoon rainfall pattern over the Indian continent.

Acknowledgments The Indian Institute of Tropical Meteorology, Pune (IITM), is fully supported by the Earth System Science Organization of the Ministry of Earth Sciences, Govt. of India. The authors thank the Director of IITM for providing support and encouragement to carry out this research. We also thank Jyoti Jadhav for her comments on an earlier draft of this manuscript. The figures are prepared using PyFerret.

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