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Dynamical Controls on Interannual ITCZ Variability over the Indian Summer Monsoon Domain

Priya Kumari[1,2,*], Preethi Bhaskar[1], Milind Mujumdar[1]

[1]Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology, Ministry of Earth Sciences (MoES), Pune, India

[2]Department of Atmospheric and Space Science, Savitribai Phule Pune University, Pune, India

* *Correspondence to*: Priya Kumari (kumaripriya2626@gmail.com)

Abstract

The Intertropical Convergence Zone (ITCZ) is a narrow band of intense convection formed by the convergence of tropical trade winds, leading to intense convection and precipitation. Its seasonal and interannual variations have significant socio-economic impacts, particularly over the Indian subcontinent, where the shifts in ITCZ position influence monsoon rainfall. Using long-term precipitation and atmospheric reanalysis data, this study investigates the interannual variability of boreal summer ITCZ latitudes, quantified using multivariate probabilistic approach, over the Indian region and its associated circulation changes. Extreme northward ITCZ shift years are associated with enhanced convection, strengthened monsoon westerlies, and intensified ascent leading to increased precipitation over the monsoon core zone along with poleward-displaced regional Hadley circulation, while extreme southward shift exhibits opposite features. Large-scale climate modes such as the El Niño–Southern Oscillation modulate tropical heating and circulation, influencing ITCZ position. Additionally, a significant long-term northward shift of the ITCZ during 1940–2022 is identified, which is closely linked to changes in moist static energy transport. A corresponding poleward shift of the meridional energy transport indicates that this migration is driven by changes in atmospheric energy balance.

1.Introduction

The Intertropical Convergence Zone (ITCZ) is a narrow band along the equator spanning the globe, where the tropical trade winds of the Northern and Southern Hemispheres converge (Sawyer, 1952; Zhang et al., 2021), and is characterized by strong convergence, convection, and intense precipitation.

The ITCZ accounts for approximately 32 % of global precipitation and shapes climate and society in the tropics (Byrne et al., 2018). Thus, understanding the variability and long-term changes in the ITCZ is crucial because its position and intensity strongly regulate tropical rainfall, monsoon systems, and large-scale atmospheric circulation. Factors affecting the ITCZ position and the dynamics behind its shifts are currently a key research focus. Even small shifts in the ITCZ can lead to significant regional hydroclimatic impacts, including floods, droughts, and food security risks for densely populated tropical regions.

Several studies have examined ITCZ variability on seasonal and interannual timescales using observations and reanalysis data. The earlier studies include utilization of Highly Reflecting Cloud (HRC) dataset for computing global as well as regional climatology of the ITCZ location and its variability (Waliser and Gautier 1993).

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

However, the HRC dataset was available for only a few years, which is insufficient to understand long-term variability. Also, they talked about mean ITCZ latitude anomaly time series for different regions as well as globally but did not discussed about trend. Interannual shifts of the zonal-mean ITCZ, computed using precipitation, on global scale gave no significant global trend in the annual mean ITCZ position except for a northward shift over the American sector and a southward shift over the western Pacific (Adam et al. 2016) while pronounced year-to-year variability have been observed in ITCZ position and intensity across different ocean basins (Liu et al. 2020). Other studies have investigated the structure and organization of ITCZ convection using satellite and radio occultation observations, although these analyses are limited to relatively short time periods (Basha et al, 2015). Previous studies have mostly investigated seasonal and interannual migrations of the ITCZ either on a global scale or over the Atlantic and Pacific oceans (Žagar et al., 2011; Schneider et al. 2014; Hohenegger, 2020). In monsoon regions, especially the Indian Summer monsoon, ITCZ variability is particularly important**,** as seasonal rainfall is tightly linked to the position and migration of associated deep tropical convection (Blandford, 1886; Gadgil, 2018). Growing evidence suggests that monsoon circulation is fundamentally driven by diabatic heating associated with deep convection within the ITCZ, which generates large-scale atmospheric responses (Hoskins and Rodwell, 1995; Chao, 2000; Chao and Chen, 2001). Thus, meridional shifts of the ITCZ play a crucial role in regulating rainfall over monsoon regions in both hemispheres (Wang et al., 2014; Biasutti et al., 2018).

Over the Indian monsoon domain, the ITCZ exhibits behavior distinct from that in the equatorial regions. While precipitation variability near the equator is often associated with east–west displacements of the ITCZ, the Indian summer monsoon is characterized by a pronounced north–south migration of the ITCZ (Goswami, 1997). Changes in the meridional position of the ITCZ have been linked to major hydroclimatic variations. For instance, a southward shift of the ITCZ from the Holocene thermal maximum to the onset of the Little Ice Age coincided with a weakening of Indian summer monsoon rainfall (Schneider et al., 2014). Similarly, during the latter half of the twentieth century, a southward migration of the ITCZ was associated with widespread droughts over North China, South Asia, and the African Sahel (Biasutti and Giannini, 2006; Bollasina et al., 2011; Song et al., 2014; Wodzicki and Rapp, 2016). In contrast, the strengthening of the Indian summer monsoon after 2002 has been linked to a pronounced northward shift of the ITCZ over the Indian subcontinent (Hari et al., 2020).

Although many studies have identified the climatological location and structural patterns of the ITCZ, such as northern, southern, and double ITCZ configurations, (Waliser and Gautier, 1993; Bain et al., 2011; Chen et al., 2008) comparatively fewer studies have quantified its interannual variability, particularly in terms of changes in position and convective intensity. As a result, the relationship between variability in ITCZ characteristics and the associated large-scale circulation and hydrological cycle remains poorly understood (Wodzicki and Rapp, 2016). This gap is especially critical over the Indian monsoon domain, where year-to-year variations in ITCZ latitude strongly influence the spatial distribution and intensity of monsoon rainfall. The latitudinal position and extreme shift of the ITCZ may be in response to the changes in the large-scale Walker circulation, but may also be a direct consequence of the local SST anomalies which are themselves part of the global pattern of SST anomalies associated with El Nino (Ju and Slingo, 1994). Thus, in this study this gap is addressed by examining the interannual variability of the seasonal mean ITCZ location over the Indian monsoon domain and investigating the associated large-scale circulation dynamics.

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

2. Data and Methodology

2.1 Data

The dataset used here, for the period 1940–2022, consists of monthly means of geopotential height, pressure velocity, velocity potential and the zonal, specific humidity, temperature, meridional and vertical component of wind at standard pressure levels, obtained from the ERA-Interim reanalysis (Hersbach et al., 2020) with grid size of 0.25° latitude by 0.25° longitude. The domain considered in this study is the Indian summer monsoon region (Equator–30°N, 60°–100°E). The rainfall anomalies are examined using the global precipitation dataset from CRU (Climate Research Unit), with a horizontal resolution of 0.5° x 0.5° and available for the period 1901 to 2020 (Harris et al., 2020). Monthly SST data is derived from the Hadley Centre Global Sea Surface Temperature (HadISST) dataset developed by Rayner et al. 2003 with a grid size of 1° latitude by 1° longitude.

2.2 Methodology

The ITCZ location is generally identified using single variable based metrices, but they are having large discrepancy over the south Asian region. Mamalakis et al. (2021) used multivariate probabilistic tracking framework to compute ITCZ location globally in terms of probability density function (pdf) based on precipitation and outgoing longwave radiation (olr) data. A similar approach is followed by Kumari et al. (2026) and has developed an index for ITCZ location by combining thermodynamical and dynamical parameters, namely precipitation and meridional mass flux, respectively. This index is found to better represent the spatial variation of ITCZ location over the south Asian domain during different phases of monsoon (Kumari et al. 2026).

In this study, the ITCZ location is computed following Kumari et al. (2026). For each season and sliding longitudinal window, zonal-mean values of selected ITCZ-related variables are computed as functions of latitude. At each latitude, variables are converted to marginal non-exceedance probabilities using rank-based empirical cumulative distribution functions. These marginal probabilities are combined to estimate a joint non-exceedance probability across all variables. Latitudes where the joint probability exceeds a prescribed threshold (0.85) are identified as likely ITCZ locations. The distribution of these locations across all longitude windows is then summarized using a probability density function, from which the seasonal mean ITCZ latitude is derived. The analysis performed in this study is focused on the boreal summer monsoon season, i.e., JJAS (June-September).

To study the interannual variability of the ITCZ over the Indian monsoon region, we follow the same probabilistic tracking approach (Kumari et al, 2025). First, the analysis is performed for the JJAS season for each individual year. The longitude range is divided into overlapping windows of fixed width. For each longitude window and year, zonal-mean of precipitation and mass flux are calculated as functions of latitude. At each latitude within a window, the values of precipitation and mass flux are ranked relative to all other latitudes in the same window. These ranks are then converted into marginal non-exceedance probabilities, which indicate how large the values are compared to other latitudes. Next, the marginal probabilities of precipitation and mass flux are combined to compute a joint non-exceedance probability at each latitude. Latitudes where this joint probability exceeds a prescribed threshold are identified as potential ITCZ locations. For each longitude window, the latitude with the

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

maximum joint probability is selected as the ITCZ position. This procedure is repeated for all longitude windows, and the ITCZ latitudes are averaged over longitude to obtain a single ITCZ latitude for each year. Repeating this for all years produces a time series of ITCZ latitude, which is used to analyse its interannual variability.

Moist Static Energy (MSE) is computed as follows:

$$MSE = gz + C_p T + Lq \quad \text{.....(1)}$$

where g (acceleration due to gravity) = 9.8 ms^{-2} , z is geopotential height, C_p (Specific heat capacity at constant pressure) = 1004 $JK^{-1}Kg^{-1}$, T is temperature , L (Latent heat of vaporisation) = 2.5×10^6 JKg^{-1} and q is specific humidity.

3.Results and Discussion

To understand the preferred latitudinal position of the Intertropical Convergence Zone (ITCZ) during the monsoon season, the PDF of the ITCZ latitude was computed for the JJAS period over the Indian monsoon domain. The PDF provides information about the most frequently occurring latitudinal locations of the ITCZ. During the JJAS season, highest PDF values (0.04–0.05) are observed between 15°N and 20°N, indicating that the ITCZ most frequently resides within this latitude band during the monsoon season over the Indian monsoon domain as shown in Figure 1. This latitude range corresponds to the active monsoon trough and regions of intense convection over the Indian subcontinent. Thus, during the summer monsoon season, ITCZ remains predominantly north of the equator, with negligible occurrence near the equator.

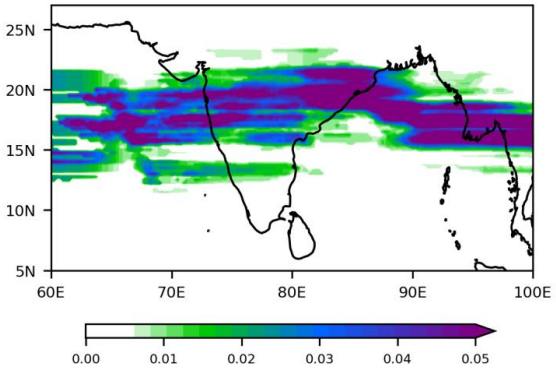


Figure 1: Climatological ITCZ during JJAS season using Probability Density Function (PDF) for the period 1940-2022.

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

The JJAS mean ITCZ latitude during 1940–2022 over the South Asian monsoon region is located at 18.55° N, with a standard deviation of 2.85 degrees, indicating substantial interannual variability in its position as shown in Fig. 2.

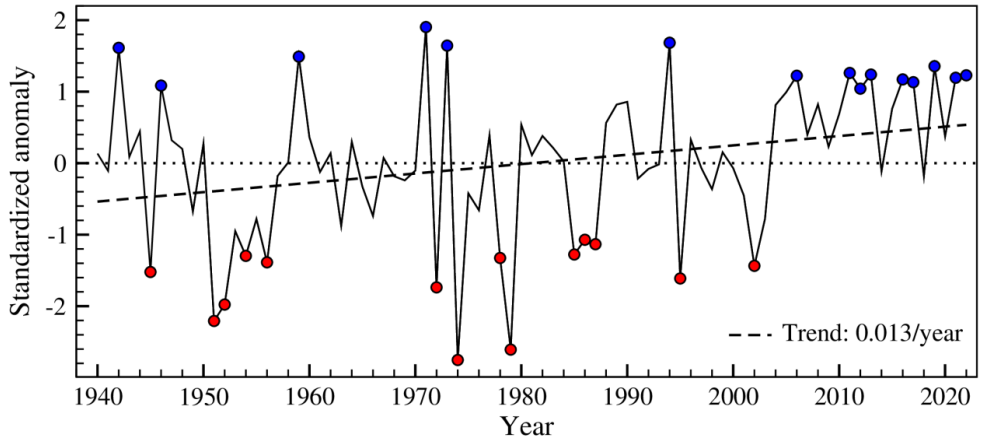


Figure 2: Interannual variability of the JJAS mean ITCZ latitude expressed as standardized anomalies for the period 1940-2022 over the region 60-100 °E. Green dots represent the years with extreme northward shift and red dots represent years with extreme southward shift of ITCZ from its climatological mean. The black dashed line shows linear trend.

There is a significant increasing trend of approximately 0.013° latitude per year, implying a gradual northward displacement of the ITCZ during JJAS season over the study period. These results are consistent with previous studies that observed a northward propagation of ITCZ and strengthening of the Indian summer monsoon since the early 2000s using reanalysis dataset (Hari et al, 2020). Similarly, a satellite-based analysis finds the tropical convection band contracting and moving toward the Northern Hemisphere at ~30 km/decade over land (Aumann et al, 2024). Moreover, CMIP6 projections also point to a robust northward shift of ITCZ in the Eurasian (20°E–130°E) sector under 21st century warming (Mamalakis et al, 2021). The proposed possible drivers of this shift include enhanced Northern Hemisphere (and Indian Ocean) warming and rising sea-surface temperature (SST) asymmetry (Weller et al, 2014; Sun et al , 2024) along with reduced aerosol cooling over South Asia (Hari et al, 2020).

The position of the ITCZ is fundamentally controlled by the large-scale energy balance. It lies at the foot of the ascending branch of the tropical Hadley circulation close to where the near surface zonal mean meridional Moist static energy (MSE) flux vanishes or changes sign. (Adam et al, 2016). MSE is a combination of internal, latent, and potential energy, (Equation (1)) which together govern large-scale circulation and energy transport and is a direct measure of convection. A higher value of MSE represents higher energy to carry the moisture upwards, which leads to condensation of the moisture and hence rainfall (Polcher,1995).

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

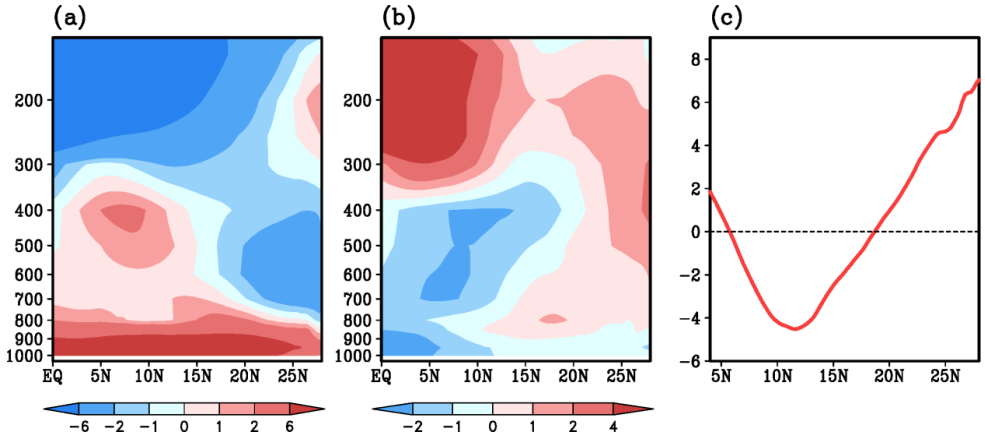


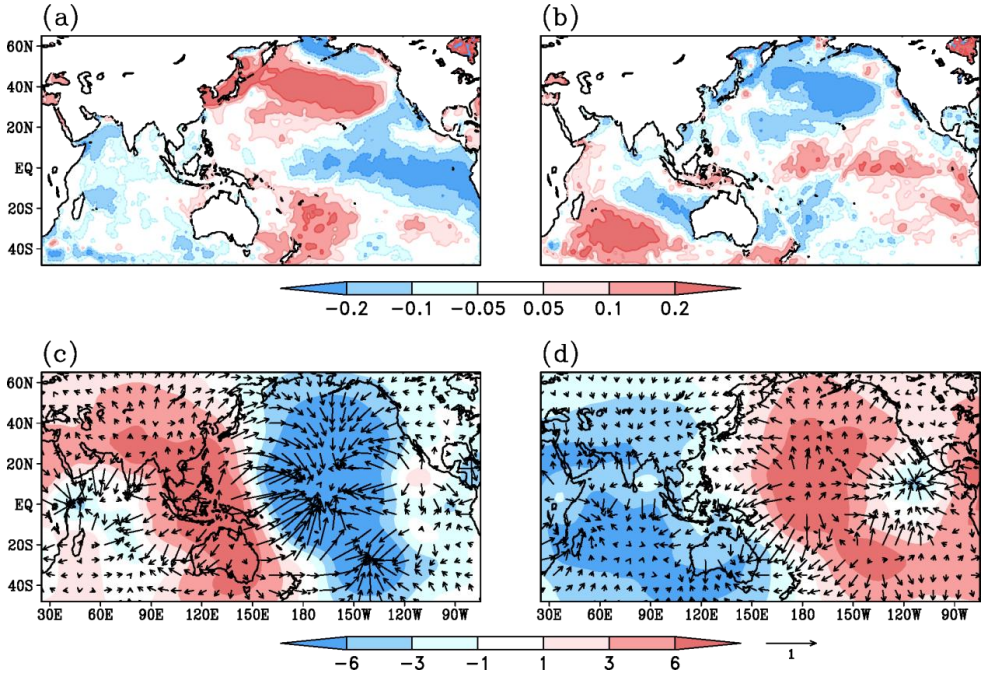
Figure 3: (a) Climatological Vertical profile of zonally averaged meridional MSE flux (×10^5 J/m/s) (b) Linear trend of the zonal mean meridional MSE flux (×10^3 J/m/s/year) and (c) Linear trend of the vertically integrated zonally averaged meridional MSE flux (×10^6 J/m/s/year) over the period 1940-2022 for JJAS season.

The climatological structure of meridional MSE flux over the 60°–100°E domain during JJAS season (Fig 3a) exhibits a well-defined overturning circulation, with strong northward transport in the lower troposphere (~850–1000 hPa) and a compensating southward return flow aloft in the upper troposphere (~100–300 hPa), indicating that energy is exported away from the ITCZ in the upper branch. This vertical dipole structure reflects a thermally direct circulation associated with the monsoon Hadley cell, where energy is carried poleward near the surface and returned equatorward aloft. Figure 3b shows the trend in MSE flux over the study area. The lower troposphere (700–900 hPa) shows a marked increase in northward MSE flux north of 15°N, highlighting strengthened energy transport into higher latitudes. In contrast, the mid-troposphere (400–700 hPa) exhibits a significant decrease in MSE flux south of about 10–15°N, indicating a reduction in energy transport in the equatorial and southern regions. The upper troposphere (100–300 hPa) shows a broad positive trend, suggesting enhanced export of energy aloft. Together, these features form a clear meridional dipole pattern, characterized by decreasing transport to the south and increasing transport to the north, which indicates a poleward shift of the atmospheric energy transport. This vertically coherent structure reflects a reorganization of the large-scale monsoon Hadley circulation and implies a northward displacement of the energy convergence zone. Furthermore, the column integrated MSE flux trend (Fig 3c) is positive (negative) north (south) of 18°N. Positive trend implies increasing northward transport whereas negative trend means decrease in northward transport. Thus, northward energy transport is increasing north of 18 N which in turn shifts ITCZ northward whereas south of 18°N the northward transport is decreasing. This is a dynamically consistent explanation for the observed poleward migration of the ITCZ over the Indian monsoon domain.

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

Despite this long-term poleward shift, pronounced year-to-year fluctuations remain a dominant feature. Years exceeding +1 standard deviation (SD) are classified as extreme northward ITCZ shift, while years with anomalies below -1 SD are categorised as extreme southward ITCZ shift from their climatological mean position. Based on the standardized JJAS ITCZ latitude anomalies, 16 years – 1942, 1946, 1959, 1971,1973, 1994, 2005, 2006, 2011, 2012, 2013, 2016, 2017, 2019,2021, and 2022 – are classified as extreme northward shift of ITCZ while 14 years – 1945, 1951, 1952, 1954, 1956, 1972, 1974, 1978, 1979, 1985, 1986, 1987, 1995 and 2002 – are classified as extreme southward shift of ITCZ. The figure also indicates pronounced oscillations in ITCZ position prior to 1970, with extreme shifts occurring both northward and southward. During the period 1970–2000, the ITCZ exhibited predominantly extreme southward shifts. In contrast, after 2000, most years were characterized by pronounced northward shifts of the ITCZ. The extreme years provide a basis for composite analysis, allowing isolation of circulation and thermodynamic anomalies associated with extreme ITCZ shifts during the JJAS season.

In the northward shift composite (Fig.4a), warm SST anomalies across much of the tropical Indian ocean including Arabian sea and Bay of Bengal is observed. Warm anomalies are also evident in the Western and central Pacific whereas relatively cool anomalies are observed in eastern equatorial Pacific. This pattern resembles La-Nina like conditions (Philander, 1990; McPhaden et al, 2006). In contrast, southward ITCZ shift composite (Fig.4b) coincide with widespread cooling over the Indian Ocean and warming in the central-eastern Pacific, consistent with El-Nino like condition (Philander, 1990; Trenberth, 1997; McPhaden et al, 2006).



https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

Figure 4: Composite SST anomaly (°C) for (a) northward and (b) southward shift of ITCZ and Velocity Potential anomaly (s^{-1}) for (c) northward and (d) southward shift of ITCZ during JJAS season over the Indian region.

The velocity potential (VP) composite anomalies at 200 hPa are dynamically consistent with the underlying SST pattern. During the northward ITCZ shift (Figure 4c), positive VP anomalies dominate over the Indian Ocean and the Indian subcontinent, indicating enhanced upper-tropospheric divergence and large-scale ascent over the monsoon region, while negative VP anomalies over the central eastern equatorial Pacific reflect upper-level convergence and suppressed convection there. This zonal contrast in VP signifies a westward-displaced Walker circulation, favoring enhanced convective activity and hence an anomalous increase in diabatic heating over the Indian sector. In contrast, the composite analysis during the southward ITCZ shift is characterized by strong positive VP anomalies over the central–eastern equatorial Pacific and negative VP anomalies over the Indian Ocean and adjoining land areas, indicating a reversal of the zonal overturning circulation with enhanced ascent over the Pacific and anomalous subsidence over the Indian landmass and adjoining seas.

The Indian summer monsoon consists of both planetary-scale and regional-scale circulation components, with the regional circulation playing a dominant role in governing monsoon rainfall variability. During boreal summer, the ITCZ shifts northward from its wintertime equatorial position to about 15–20°N over the Indian region, while remaining closer to the equator over the western Pacific. This latitudinal displacement creates a strong zonally asymmetric off-equatorial heat source over India near 20°N. According to Gill's (1980) theoretical framework, such off-equatorial heating preferentially generates a strong regional Hadley circulation. Being a convectively coupled system, the seasonal mean rainfall is strongly correlated with the regional Hadley circulation associated with rising vertical motions along the regional ITCZ (Goswami et al, 1999; Bajrang et al, 2023). As a result, the Indian summer monsoon can be viewed as a superposition of a regional Hadley circulation driven by monsoon heating over ~15–20°N, and a planetary-scale Walker circulation associated with equatorial heating, particularly over the Pacific.

The composite anomalies of the local Hadley circulation further illustrate how this dynamical framework responds during ITCZ shifts. During northward ITCZ shift years (Fig.5a), anomalous ascent is enhanced over ~10–25°N and extends through much of the troposphere, accompanied by compensating subsidence over lower latitudes. This pattern indicates a strengthened and poleward-displaced regional Hadley circulation in response to the increased diabatic heating due to the westward shift of the ascending branch of the Walker cell during La Niña.

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

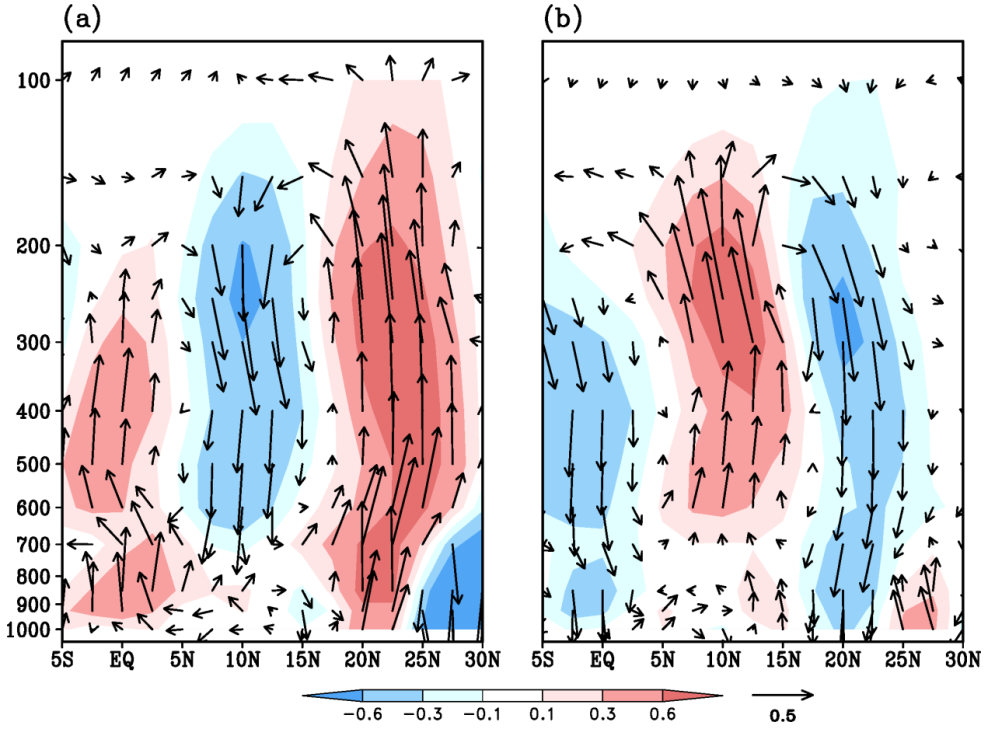


Figure 5: Local Hadley cell anomaly during JJAS season for years with (a) northward (left) and (b) southward shift (right) composites.

In contrast, during southward ITCZ shift years (Fig 5b), anomalous ascent is confined closer to the equator, while pronounced subsidence dominates over nearly 17-25°N, reflecting a weakened and equatorward-shifted local Hadley circulation. These results demonstrate that interannual ITCZ shifts over the Indian monsoon domain arise from a coupled adjustment of zonal (Walker) and meridional (regional Hadley) overturning circulations, in which Walker circulation anomalies modulate the longitudinal distribution of heating, while the regional Hadley circulation determines the meridional position of the ITCZ.

Consistent with these vertical overturning anomalies, the composite analysis of 850-hPa wind (Figure 6), also known as southwesterly flow which is a dominant source of moisture transport for South Asian summer monsoon region (Preethi et al 2017), reveals distinct low-level circulation signatures associated with each ITCZ shift phase. The southwesterly flow over Indian Ocean is a dominant source of moisture transport for South Asian summer monsoon region. During northward ITCZ shift years (Figure 6a), anomalous southwesterlies over the Arabian Sea and strengthened cross-equatorial flow from the southern Indian Ocean converge over the Indian subcontinent, particularly north of 20°N. This enhanced low-level convergence supports increased moisture transport and leads to deep convection over northern latitudes, anchoring the ascending branch of the regional Hadley circulation poleward of its climatological position.

https://doi.org/10.5194/egusphere-2026-2861
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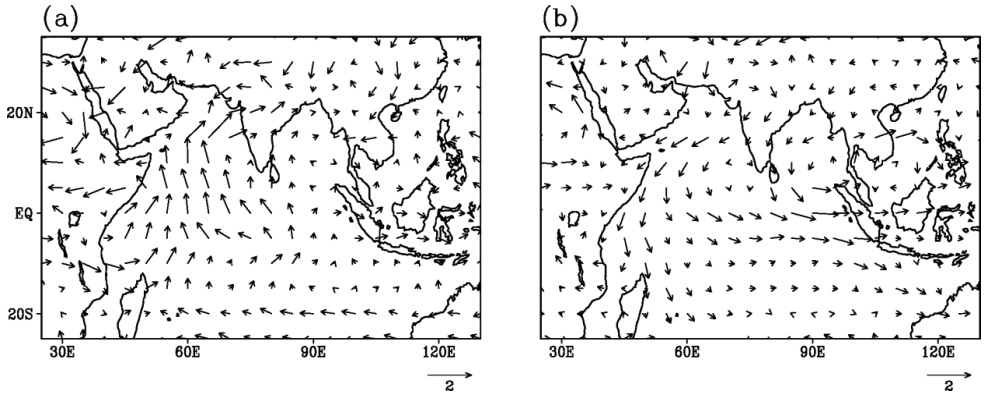


Figure 6: Wind anomalies at 850 hPa during JJAS season for years with northward (left) and southward shift (right) composites.

In contrast, southward ITCZ shift years (Figure 6b) are characterized by weakened monsoon westerlies and anomalous northerly to northeasterly flow over the Indian region, leading to reduced moisture influx and diminished low-level convergence over land. As a result, convergence and ascent remain confined closer to the equator, favoring an equatorward displacement of the ITCZ.

These contrasting low-level wind patterns indicate that it is not the basin-wide strength of convergence but the meridional relocation of the convergence maximum that governs ITCZ shifts. By modulating the latitude of diabatic heating through changes in moisture transport and convergence, the low-level circulation plays a crucial role in translating large-scale ENSO forcing into regional ITCZ and monsoon variability over the Indian domain.

Following the low-level circulation anomalies, the upper-tropospheric response is further illustrated by the 200-hPa geopotential height (GPH) composite anomalies (Fig. 7).

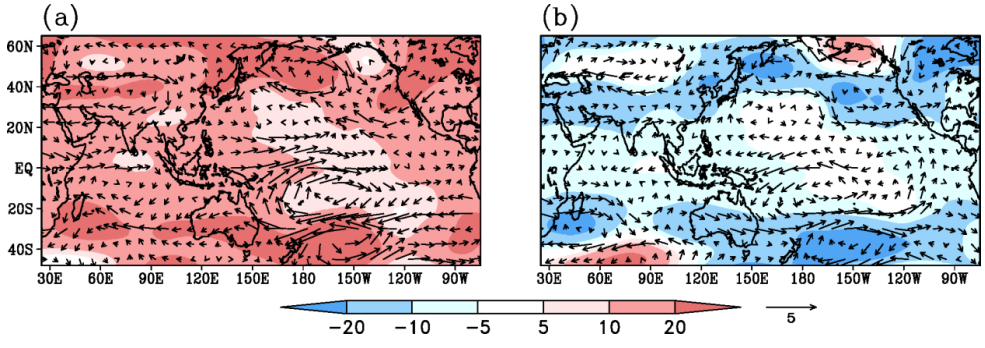


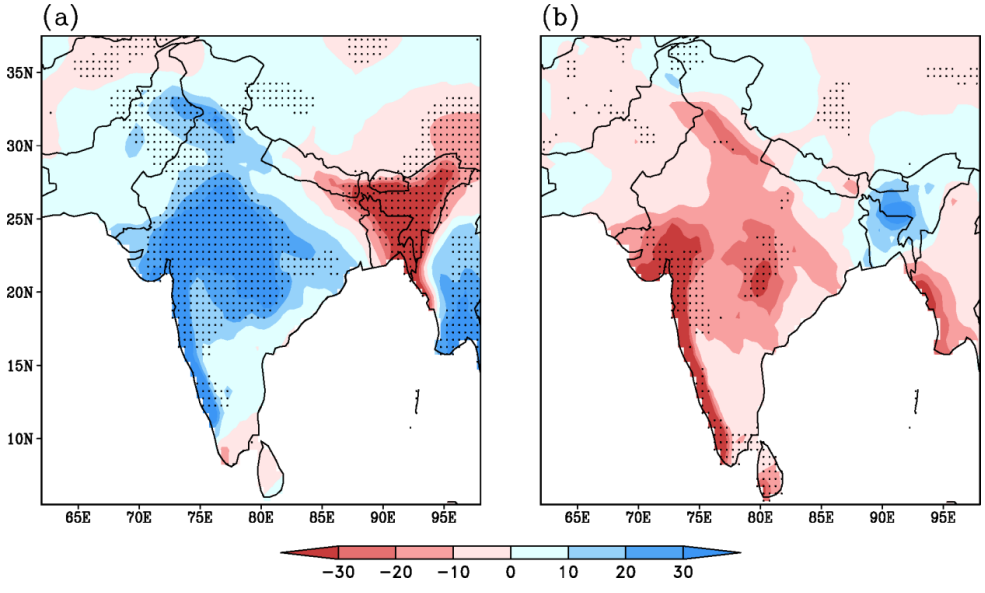
Figure 7: Geopotential height anomalies at 200 hPa during JJAS season for years with northward (left) and southward shift (right) composites represented by shading and vector arrows represent composite wind anomaly at 200hPa.

https://doi.org/10.5194/egusphere-2026-2861
Preprint. Discussion started: 1 July 2026

During northward ITCZ shift years (Fig. 7a), positive GPH anomalies dominate over the Indian subcontinent and adjacent regions, indicating a warm upper-tropospheric column associated with enhanced diabatic heating and deep convection over northern latitudes. This upper-level height rise is consistent with strengthened divergent outflow at 200 hPa and reflects the development of an anomalous anticyclonic circulation aloft, a canonical response to intensified monsoon heating. Such an upper-tropospheric mass redistribution supports sustained ascent in the northern branch of the regional Hadley circulation, thereby reinforcing the poleward displacement of the ITCZ. In contrast, southward ITCZ shift years (Fig. 7b) exhibit negative GPH anomalies over the Indian region, indicative of a cooler tropospheric column and suppressed latent heat release. The weakened upper-level anticyclonic response and enhanced convergence aloft are consistent with reduced deep convection and diminished monsoon heating. As a result, the ascending branch of the regional Hadley circulation shifts equatorward, confining convection closer to the equator and favoring a southward displacement of the ITCZ.

Taken together, the low-level wind anomalies, upper-level velocity potential, and geopotential height responses provide a dynamically consistent picture in which ENSO-driven modulation of tropical heating reorganizes both the lower- and upper-tropospheric circulation, leading to systematic shifts in the regional Hadley circulation and the meridional position of the ITCZ over the Indian region.

During northward ITCZ shift years (Fig. 8a), significant enhanced precipitation anomalies are concentrated over monsoon core zone and northern India (~15–25°N), while negative anomalies appear to the south, indicating a poleward displacement of the convective heating maximum. This northward relocation of latent heat release strengthens ascent in the northern branch of the local Hadley circulation, reinforcing the poleward shift of the ITCZ.



https://doi.org/10.5194/egusphere-2026-2861
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Figure 8: Precipitation anomalies (mm day^{-1}) for the JJAS season based on CRU dataset for the northward and southward shift composite. The hatches represent significant values at the 95% confidence level.

In contrast, southward ITCZ shift years (Fig. 8b) exhibit a significant suppression of rainfall over much monsoon core zone , reflecting an equatorward displacement of deep convection and associated heating. Thus, the precipitation composite anomalies further confirm the heat-driven nature of the ITCZ shifts over the Indian region.

4. Conclusion

This study demonstrates a clear northward shift in the ITCZ location over the Indian monsoon domain during the JJAS season. This shift is linked to changes in moist static energy transport, with more energy moving toward higher latitudes. This indicates that changes in atmospheric energy balance are driving the movement of the ITCZ over the Indian monsoon region.

The interannual time series highlights years with extreme latitudinal shifts of the ITCZ over the Indian monsoon domain. Before 1970, the ITCZ exhibited strong oscillations with both extreme northward and southward shifts. During 1970–2000, extreme southward shifts dominated, whereas after 2000, the ITCZ predominantly showed extreme northward shifts.

Moreover, interannual shifts of the ITCZ over the Indian region during the boreal summer are primarily governed by the coupled adjustment of the zonal (Walker) and meridional (local Hadley) overturning circulations, rather than by a direct local Walker subsidence over India. ENSO-related modulation of the Walker circulation alters the longitudinal distribution of tropical convection and upper-tropospheric divergence, leading to a zonally asymmetric heating pattern with a pronounced off-equatorial maximum over the Indian region. Consistent with the Gill (1980) framework, this asymmetric heating excites a strong local Hadley circulation, whose latitude of maximum ascent determines the meridional position of the ITCZ. During northward ITCZ shift years, enhanced convective heating over ~15–25°N strengthens low-level convergence, cross-equatorial monsoon flow, and upper-level divergence, resulting in an intensified and poleward-displaced local Hadley cell. In contrast, southward shift years are characterized by weakened monsoon westerlies, reduced upper-level divergence, and an equatorward shift of ascent, leading to a southward displacement of the ITCZ. These circulation changes are coherently reflected in the composites of velocity potential, geopotential height, low-level winds, and precipitation anomalies, underscoring the dynamically consistent response of the atmosphere to changes in the spatial structure of monsoon heating.

Overall, the results highlight that ITCZ variability over the Indian monsoon domain arises from a heat-driven shift of the regional Hadley circulation, modulated remotely by ENSO-induced changes in the Walker circulation. This coupled zonal–meridional framework provides a physically consistent explanation for ITCZ shifts and emphasizes the central role of regional-scale circulation in shaping Indian summer monsoon variability. Future studies can employ climate model simulations to further investigate the mechanisms controlling ITCZ variability over the Indian monsoon domain.

Author contributions

https://doi.org/10.5194/egusphere-2026-2861
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P.K. and P.B. conceived the study. P.K. performed the data analysis and wrote the original drafts of the paper and the methods section. P.K. and P.B. generated the figures. M.M. supervised the project. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

Data used here can be downloaded from the following: CRU (https://crudata.uea.ac.uk/cru/data/hrg/), ERA5 (https://cds.climate.copernicus.eu/datasets), and HadISST (https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html).

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