

In this study, Kumari et al. propose a mechanism to explain the long-term variations of the ITCZ over the Indian subcontinent. The authors suggest that the ITCZ is shifting northward over the Indian sector due to changes in MSE export, while attributing its interannual variations to ENSO-modulated shifts in the Walker circulation.

While the manuscript addresses an important aspect of Indian summer monsoon dynamics, the overarching novelty of the study remains unclear. Furthermore, the proposed mechanisms appear fragmented and are not fully developed.

My primary concern centres on how meridional shifts in the ITCZ within the Indian sector are framed. The authors attempt to explain interannual variability entirely through meridional shifts; however, as shown in their Fig. 7, East-West (zonal) shifts are actually more prevalent—a finding consistent with Walker cell dynamics. Additionally, the manuscript invokes different physical mechanisms for long-term trends (meridional MSE transport) versus interannual variations (zonal Walker cell shifts) without explaining why these two timescales operate under distinct regimes or what fundamentally drives the long-term trends in MSE transport.

In my opinion, a major overhaul of the manuscript is required to address these conceptual and diagnostic gaps. I recommend **Major Revision**. The study could be substantially strengthened by refocusing on a clear, core question—for instance: *Why have southern excursions of the ITCZ reduced post-2000 AD?*

We thank the reviewer for the suggestions/comments. This motivated us to improve the manuscript further. Based on the comments from the reviewer, we have revised the manuscript and incorporated appropriate modifications in the manuscript. Our point-by-point response is attached below.

## Major Comments

### 1. Conceptualization of Long-Term Shifts

The authors claim there is a long-term northward shift of the ITCZ over the Indian region. However, as shown in Figure 1, the pattern is primarily characterized by a reduction of the southern excursions of the ITCZ latitude, rather than a northward shift of its northern boundary. A reduction in southern excursion does not strictly equate to a northward shift of the whole convergence zone. Does this truly qualify as a "northward shift"? Clarification and refined terminology are needed.

We thank the reviewer for this important observation. We agree that a positive trend in the diagnosed ITCZ latitude does not necessarily imply a uniform northward displacement of the entire convergence zone. Our analysis identified a single representative ITCZ latitude for each JJAS season; it does not independently track changes in the northern and southern boundaries of the convergence zone. We have therefore revised the terminology throughout the manuscript

to describe the result as a “long-term northward tendency in the diagnosed seasonal-mean ITCZ latitude”. The improvement had been done in the discussion as well as the conclusion.

## 2. Physical Mechanism of Long-Term Shifts

The authors attribute long-term ITCZ shifts to a northward movement of MSE export—specifically, the latitude where vertically integrated MSE flux vanishes (the Energy Flux Equator, or EFE). However, this is not conclusively demonstrated:

- **Missing Diagnostic:** A plot showing the latitude of the EFE over the study period is essential to support this claim directly.
- **Contradiction at 18N:** In Fig. 3c, the trend in vertically integrated MSE flux is zero near 18N, which is the mean latitude of the ITCZ in the Indian sector. A zero trend at the mean ITCZ position implies no local change in MSE flux, contradicting the argument of a forced shift.
- **Underlying Drivers:** The fundamental physical causes driving these long-term trends in MSE and MSE flux are left unexplained.

We thank the reviewer for this important comment. We agree that the original manuscript placed too much emphasis on the role of moist static energy (MSE) transport in explaining the long-term ITCZ tendency. In particular, the original analysis did not directly diagnose the temporal evolution of the Energy Flux Equator (EFE), nor did it establish a causal relationship between changes in MSE flux and the long-term ITCZ displacement. We therefore agree that the available MSE analysis was insufficient to support the interpretation that the long-term ITCZ shift was driven by a northward displacement of the EFE.

In the revised manuscript, we have consequently removed the MSE and EFE-based interpretation and the associated discussion. We no longer attribute the long-term northward tendency of the ITCZ to changes in MSE transport or atmospheric energy balance. We have instead reframed the long-term result more cautiously as a significant northward tendency in the seasonal mean ITCZ latitude during 1940–2022, accompanied by changes in the frequency of extreme northward and southward excursions.

We have also removed the corresponding MSE-related figure/discussion, rather than adding an EFE diagnostic, which is outside the revised scope of the study. The revised manuscript focuses on the mechanisms that are directly supported by our diagnostics,

namely the contrasting apparent heating, Walker circulation, regional Hadley circulation, moisture transport, and precipitation associated with northward and southward ITCZ excursions. These analyses fit well with the title and objective of our manuscript.

### **3. Zonal (East-West) vs. Meridional Shifts**

The manuscript focuses almost exclusively on meridional shifts in the ITCZ. However, zonal shifts are equally critical in this region (e.g., Boos & Korty, 2016), as corroborated by the rainfall anomalies presented in Fig. 7. A comprehensive assessment must account for both zonal and meridional components of ITCZ variability.

We thank the reviewer for highlighting the importance of zonal ITCZ variability. We acknowledge that both zonal and meridional displacements are important for understanding monsoon rainfall variability over the Indian region. However, the present study focuses specifically on the interannual variability in the meridional position of the ITCZ over the Indian land region and its associated precipitation changes. A comprehensive investigation of the coupled zonal and meridional variability requires a separate analysis and is beyond the scope of the present study. We have acknowledged the importance of examining zonal ITCZ variability as future work in the conclusion.

### **4. Marine vs. Terrestrial ITCZ**

During the boreal summer, two distinct convergence zones coexist in the Indian sector: the equatorial Marine ITCZ and the Terrestrial Convergence Zone (15-20N). The manuscript does not explain how its objective ITCZ definition accounts for this bimodal structure. For example, in Fig. 5a, the presence of the equatorial Marine ITCZ is evident during years marked by "northward shifts," yet this dual-zone interaction is left unaddressed.

We thank the reviewer for highlighting this important point. We agree that during boreal summer, the Indian Ocean–South Asian sector can exhibit distinct regions of convergence associated with the equatorial marine ITCZ and the northern terrestrial monsoon convergence zone. Our multivariate probabilistic framework identifies the latitude of the dominant joint precipitation–meridional mass-flux probability within the Indian summer monsoon domain (0–30°N). The resulting JJAS probability distribution shows its maximum predominantly between 15° and 20°N, consistent with the dominant monsoon convergence zone over the Indian region. The equatorial marine ITCZ may coexist at lower latitudes, but it does not represent the dominant joint probability maximum used to define the ITCZ latitude in our analysis.

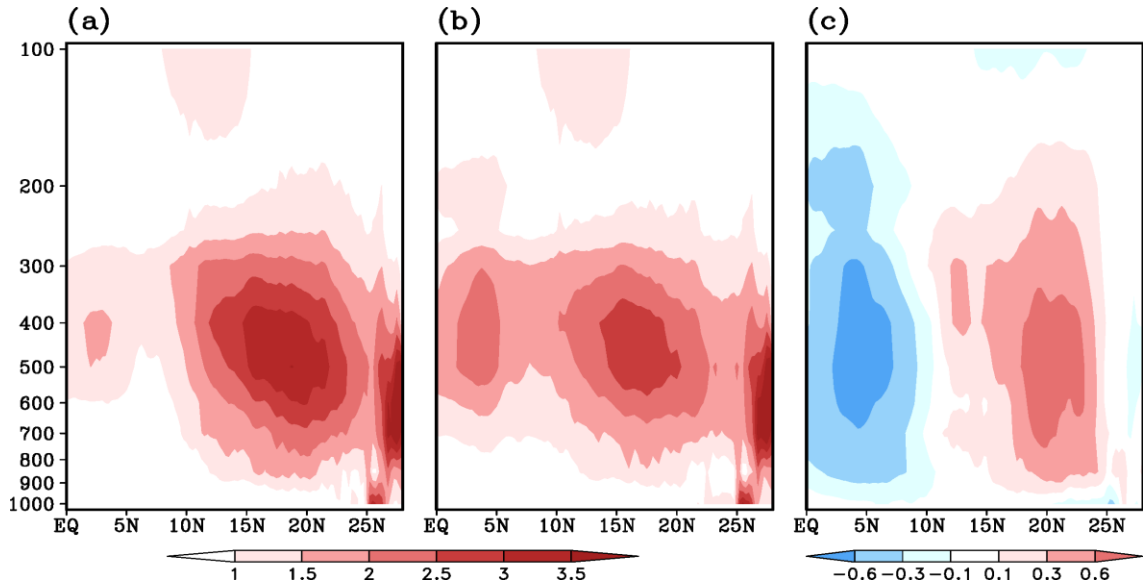
## 5. Mechanism of Interannual Variability

- **Novelty:** The attribution of interannual variability to ENSO-modulated Walker circulation shifts is already well established in monsoon literature. The unique contribution of this manuscript needs to be clearly articulated.

We thank the reviewer for this important observation. We agree that the influence of ENSO on the Walker circulation and monsoon variability is well established, and we do not claim this relationship as a novel finding. The novelty of the present study lies in the objective characterization of interannual meridional ITCZ excursions over the Indian monsoon domain using a multivariate probabilistic framework and the systematic comparison of the associated atmospheric conditions during northward and southward ITCZ years. By examining apparent heating alongside vertical motion, low-level circulation, moisture transport, precipitation, and upper-level circulation, the study provides an integrated assessment of the thermodynamic and dynamical characteristics associated with these contrasting ITCZ states.

**Physical Linkage:** The authors do not adequately explain *how* a zonal displacement of the Walker cell physically induces a meridional shift in the ITCZ over India.

We have revised the Discussion to explain this relationship using the observed composite circulation and newly analysed apparent-heating patterns. The apparent heating ( $Q_1$ ) composites (Fig. 4, attached below) show that the difference between northward and southward ITCZ years is characterized by negative anomalies mainly at lower latitudes (approximately 0–10°N) and positive anomalies predominantly over 18–25°N, particularly in the middle troposphere. This pattern indicates a redistribution of apparent heating toward northern monsoon latitudes during northward ITCZ years, compared with southward ITCZ years. When considered alongside upper-level circulation anomalies and contrasting regional Hadley circulation, low-level wind, and precipitation patterns, these results are consistent with adjustments in regional atmospheric circulation accompanying large-scale Walker circulation variability. Thus, ENSO-related SST anomalies may alter the longitudinal distribution of tropical convection and heating, with associated regional circulation adjustments influencing vertical motion, cross-equatorial moisture transport, and precipitation.



**Figure 4.** Meridional–vertical cross-sections of composite apparent heat source ( $Q_1$ ;  $\text{K day}^{-1}$ ) during (a) northward ITCZ years, (b) southward ITCZ years, and (c) the difference between northward and southward ITCZ composites (northward minus southward) for JJAS. In panel (c), red shading indicates enhanced apparent heating and blue shading indicates reduced apparent heating during northward ITCZ years relative to southward ITCZ years.

- **Inconsistent Frameworks across Timescales:** The manuscript uses thermodynamic diagnostics (MSE fluxes) for long-term trends, but shifts to pure dynamics for interannual variability. How do MSE fluxes and the EFE behave on interannual timescales? Long-term SST trends and interannual variations in vertically integrated MSE flux (and the EFE) can be evaluated within a single, unified framework.

We thank the reviewer for this insightful suggestion. We agree that examining long-term trends and interannual variability within a unified thermodynamic framework, including vertically integrated MSE fluxes and the Energy Flux Equator (EFE), could provide a more comprehensive understanding of ITCZ variability across timescales. However, the primary focus of the present manuscript is the interannual variability of the ITCZ over the Indian monsoon domain, the associated remote and regional influences, and their relationship with monsoon precipitation changes. The original MSE analysis did not sufficiently establish the relationship between MSE transport, EFE displacement, and the long-term ITCZ tendency. We have therefore removed the MSE/EFE-based interpretation from the revised manuscript to avoid unsupported

causal attribution. Instead, the revised study examines the associated apparent heating, Walker circulation, regional Hadley circulation, moisture transport, and precipitation patterns during northward and southward ITCZ excursions. A unified thermodynamic analysis of long-term trends and interannual variability, including MSE fluxes and EFE displacement, remains a valuable direction for future research.

- **Role of ENSO:** It is well known that ENSO accounts for only a fraction of Indian summer monsoon variability. Stating that ENSO governs interannual variations in ITCZ latitude oversimplifies the influence of other factors E.g. Indian Ocean Dipole.

We thank the reviewer for this important observation. We agree that ENSO is an important influence on Indian summer monsoon variability, but it does not explain all its interannual variability. For example, Chakraborty and Singhai (2021) estimated that ENSO accounts for approximately 29% of the interannual variability of Indian summer monsoon rainfall, highlighting the contribution of other processes. Our SST composites (Figure 4) exhibit a prominent ENSO-like pattern during northward and southward ITCZ years rather than a distinct canonical IOD pattern. However, this does not preclude a contribution from regional Indian Ocean SST anomalies. In particular, the composites show contrasting SST anomalies over the southwestern subtropical Indian Ocean, near the Mascarene High region. During northward ITCZ years, relatively cooler SST anomalies in this region co-occur with stronger southwesterly and cross-equatorial low-level flow, whereas southward ITCZ years exhibit relatively warmer SST anomalies and weaker cross-equatorial flow. These contrasting patterns suggest that regional southern Indian Ocean conditions may also be relevant to the observed variations in monsoon circulation and ITCZ latitude. We have added a new section (section 3.3) to address this comment.

### **Causal Relationship Between Diabatic Heating and ITCZ Shifts**

The authors argue that ENSO-driven Walker cell shifts alter the location of monsoon diabatic heating, which subsequently drives shifts in the ITCZ. This framing presents a logical inconsistency: diabatic heating and ITCZ convergence are co-located, coupled manifestations of the same convective system. Stating that one leads or causes the shift of the other should be supported with enough evidence.

We thank the reviewer for this important observation. The causal linkage has been established by doing a newly analysed apparent-heating patterns in Fig.4. This has also been addressed in Discussion as well as discussed in response of comment 5 above.

## Minor Comments

1. **Lines 33–34:** Please add appropriate citations to support this statement.

We thank the reviewer for this helpful suggestion. We have added relevant references to support the statement regarding the regional hydroclimatic impacts of ITCZ shifts.

2. **Lines 35–36:** Please include relevant citations here.

We have added relevant references to support the statement.

3. **Line 40:** Change "*discussed about trends*" to "*discuss the trends*".

We have corrected the wording from “discussed about trends” to “discuss the trends” in the revised manuscript.

4. **Line 48:** Change "*Summer*" to lowercase "*summer*".

“Summer” has been replaced by lowercase “summer”.

5. **Line 90:** Change "*they are having*" to "*they have*".

We have replaced "*they are having*" by "*they have*".

6. **Line 91:** Correct "*south Aisan region*" to "*South Asian region*".

We have corrected it.

7. **Line 93:** Remove word "*data*".

It has been removed in the revised manuscript.

8. **Line 93:** Change "*and has*" to "*who have*".

“and has” has been replaced by “who have”

9. **Line 122:** Change "*Kg*" to lowercase "*kg*" (standard SI notation).

Since the MSE analysis has been removed from the revised manuscript, the corresponding text and units are no longer applicable.

10. **Line 152:** Clarify precisely which SST asymmetry metric/region is being referred to here.

We thank the reviewer for pointing out this ambiguity. We have removed this part in the revised manuscript as it is irrelevant.

11. **Lines 157–159:** Clarify the statement that large-scale circulation is driven directly by MSE. Large-scale atmospheric circulations are primarily governed by the sources and sinks of MSE (i.e., net atmospheric energy input; see Neelin & Held, 1987). Please revise and add appropriate citations.

We thank the reviewer for this important clarification. We agree that our original wording was overly simplistic in implying that large-scale atmospheric circulation is driven directly by MSE. The relevant discussion of MSE transport and its interpretation has been removed from the revised manuscript because the original analysis. We have therefore removed the associated statement to avoid an unsupported interpretation.

12. **Line 162:** Please add a line plot showing vertically integrated MSE flux as a function of latitude.

We thank the reviewer for this suggestion. As part of the revision, we have removed the MSE transport analysis and its associated interpretation because the original analysis did not establish a direct relationship between the meridional MSE flux and the long-term ITCZ tendency. Consequently, the requested latitude profile of vertically integrated MSE flux is no longer included in the revised manuscript. The revised study instead focuses on the interannual variability of the ITCZ and its associated thermodynamic and dynamical characteristics, including apparent heating, Walker circulation, regional Hadley circulation, moisture transport, and precipitation.

13. **Lines 197 & 201:** The description of Indian Ocean SST spatial patterns in the text does not match the corresponding figures. Please re-check the figure references.

We thank the reviewer for this observation. We corrected the description related to the figure references.

14. **Lines 218–219:** The assertion that regional circulation patterns dominate interannual ITCZ latitude variations conflicts with the authors' prior claim that interannual variations are driven by ENSO (a large-scale, remote phenomenon). Please reconcile this statement.

We thank the reviewer for pointing out this apparent inconsistency. We agree that our previous wording did not clearly distinguish between the remote large-scale forcing and the regional dynamical response. We have revised the statement accordingly. We do not consider ENSO and regional circulation to represent competing mechanisms. Rather, ENSO-related tropical SST anomalies modulate the large-scale Walker circulation and redistribute tropical convection and atmospheric heating, which are subsequently expressed through changes in the regional Hadley circulation, moisture transport, and precipitation over the Indian monsoon domain. Thus, ENSO represents an important large-scale source of interannual variability, while the regional circulation provides the dynamical pathway through which this remote influence is associated with meridional ITCZ displacement. We have considered this comment in section 3.