



Multiscale ENSO–IOD–MJO Interactions Modulating Indian Summer Monsoon Rainfall Variability

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सार – भारतीय ग्रीष्मकालीन मानसून वर्षा (Indian Summer Monsoon Rainfall–ISMR) एल नीनो-दक्षिणी दोलन (ENSO), हिंद महासागर द्विध्रुव (Indian Ocean Dipole–IOD) तथा मैडेन-जूलियन ऑसिलेशन (Madden-Julian Oscillation–MJO) से अत्यधिक प्रभावित होती है, किंतु अंतर-वार्षिक और अंतःऋतुकालीन समय-पैमाने पर इनके संयुक्त प्रभावों की पर्याप्त समझ अभी विकसित नहीं हुई है। इस अध्ययन में 1975-2025 के दौरान भारतीय मानसून वर्षा पर इन तीनों घटनाओं के संयुक्त प्रभावों का अध्ययन किया गया है। Niño3.4 तथा डाइपोल मोड इंडेक्स का उपयोग करके मानसून वर्षा को नौ ENSO-IOD श्रेणियों में वर्गीकृत किया गया तथा उष्णकटिबंधीय समुद्र-पृष्ठ तापमान (Sea Surface Temperature–SST) का विकास, मौसमी वर्षा, वायुमंडलीय परिसंचरण, MJO की विशेषताओं तथा चरण-आधारित अंतःऋतुकालीन वर्षा विसंगतियों का विश्लेषण किया गया। मौसमी वर्षा प्रशांत और हिंद महासागर की संयुक्त स्थिति को प्रतिबिंबित करती है। धनात्मक IOD मुख्यतः पूर्वी प्रशांत-प्रकार के एल नीनो से संबद्ध पाया गया, जबकि उदासीन IOD परिस्थितियों में मध्य प्रशांत-प्रकार का एल नीनो प्रतिरूप देखा गया। इन भिन्न समुद्री पृष्ठभूमि परिस्थितियों के कारण मानसूनी परिसंचरण और वर्षा की प्रतिक्रियाएँ भी अलग-अलग रहीं। ऋणात्मक IOD के साथ ला-नीना की स्थिति में भारत के ऊपर सर्वाधिक प्रबल धनात्मक वर्षा विसंगतियाँ उत्पन्न हुईं। ENSO-IOD की पृष्ठभूमि के अनुसार MJO के आयाम और विभिन्न चरणों में इसकी उपस्थिति भी व्यवस्थित रूप से परिवर्तित हुई। ऋणात्मक IOD के साथ ला-नीना में MJO के चरण 1-2 में इसकी उपस्थिति अधिक रही, जबकि धनात्मक IOD के साथ एल-नीनो में चरण 5-6 के दौरान MJO की गतिविधि अधिक प्रबल रही। इससे संबद्ध अंतःऋतुकालीन वर्षा प्रतिक्रिया में भी व्यवस्थित परिवर्तन देखा गया। धनात्मक IOD के साथ एल नीनो में चरण 5-6 के दौरान वर्षा में वृद्धि तथा इसके बाद चरण 7-8 में व्यापक कमी देखी गई, जबकि ऋणात्मक IOD के साथ ला नीना में चरण 4-5 के दौरान सर्वाधिक प्रबल और सुसंगत वर्षा वृद्धि पाई गई। ये निष्कर्ष भारतीय ग्रीष्मकालीन मानसून की परिवर्तनशीलता को निर्धारित करने में प्रशांत एवं हिंद महासागर की SST स्थितियों, MJO के चरणों तथा अंतःऋतुकालीन वर्षा परिवर्तनशीलता के बहु-पैमानी अंतःक्रियाओं के महत्व को रेखांकित करते हैं तथा परिचालनात्मक मौसमी पूर्वानुमान प्रणालियों में ENSO के प्रकार, IOD की स्थिति और MJO के चरणों को सम्मिलित करने की संभावित उपयोगिता के अध्ययन का आधार प्रदान करते हैं।

ABSTRACT. The Indian Summer Monsoon Rainfall (ISMR) is strongly influenced by the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden–Julian Oscillation (MJO), but their combined influence across interannual and intraseasonal timescales remains insufficiently understood. This study investigates their joint influences on Indian monsoon rainfall during 1975–2025. Monsoon years were classified into nine ENSO–IOD categories using the Niño3.4 and Dipole Mode Index, and tropical sea surface temperature (SST) evolution, seasonal rainfall, atmospheric circulation, MJO characteristics, and phase-dependent intraseasonal rainfall anomalies were examined. Seasonal rainfall reflects the combined state of the Pacific and Indian Oceans. Positive IOD is predominantly associated with an Eastern Pacific-like El Niño, whereas neutral IOD conditions exhibit a Central Pacific-like El Niño pattern. These distinct oceanic backgrounds produce contrasting monsoon circulation and rainfall responses, with La Niña accompanied by a negative IOD generating the strongest positive rainfall anomalies over India. MJO amplitude and phase occupancy also vary systematically with the ENSO–IOD background. La Niña accompanied by a negative IOD shows enhanced MJO phase occupancy during Phases 1–2, whereas El Niño with a positive IOD exhibits stronger MJO activity during Phases 5–6. The associated intraseasonal rainfall response also varies systematically, with El Niño accompanied by a positive IOD

showing enhanced rainfall during Phases 5–6 followed by widespread suppression during Phases 7–8, while La Niña accompanied by a negative IOD exhibits the strongest and most coherent rainfall enhancement during Phases 4–5. These findings highlight the importance of multiscale interactions among Pacific and Indian Ocean SST conditions, MJO phase characteristics, and intraseasonal rainfall variability in shaping ISMR variability and provide a basis for exploring the potential value of incorporating ENSO flavor, IOD state, and MJO phase characteristics into operational seasonal prediction frameworks.

Keywords – Indian summer monsoon rainfall, El-Niño southern oscillation, Indian ocean dipole, Madden-Julian oscillation, Multiscale interactions.

1. Introduction

The Indian Summer Monsoon Rainfall (ISMR), received during the June to September (JJAS) season, is one of the most energetic components of the global climate system and serves as the primary source of freshwater for the Indian subcontinent (Parthasarathy *et al.*, 1987; Webster & Yang, 1992). Since a large fraction of the Indian population directly or indirectly depends on monsoon rainfall, even small variations in the seasonal mean rainfall can have profound impacts on food security, economy, and water management. Therefore, understanding the variability and improving the seasonal prediction of ISMR continue to remain major scientific challenges.

The ISMR exhibits strong variability on intraseasonal, interannual, and decadal timescales (Krishnamurthy & Goswami, 2000; Goswami & Xavier, 2005; Wang *et al.*, 2000). Previous studies have shown that the variability of ISMR is strongly influenced by slowly varying boundary forcings and large-scale ocean-atmosphere interactions (Charney & Shukla, 1981). Among the dominant climate drivers influencing the monsoon, the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Madden-Julian Oscillation (MJO) play particularly important roles. ENSO and IOD are the major modes of interannual climate variability, whereas the MJO is the leading mode of tropical intraseasonal variability (Madden & Julian, 1971; Zhang, 2005). Numerous studies have independently examined the influence of these climate modes on ISMR (Rasmusson & Carpenter, 1983; Saji *et al.*, 1999; Ashok *et al.*, 2004; Pai *et al.*, 2011). However, the monsoon response is often governed by the interaction among these climate drivers rather than by any single forcing acting in isolation.

ENSO is recognized as one of the strongest modulators of ISMR variability. The warm phase of ENSO (El Niño) is generally associated with deficient monsoon rainfall over India, whereas the cold phase (La Niña) tends to enhance seasonal rainfall (Kumar *et al.*, 1999; Ashok *et al.*, 2004) mainly through modifications in the Walker circulation and large-scale tropical convection over the Indo-Pacific region. Despite this well-established relationship, the ENSO-ISMR association is not always consistent. Several studies have reported temporal changes in the ENSO-monsoon relationship, including a weakening

after the late 1970s and a partial recovery during recent decades (Kumar *et al.*, 1999; Krishnamurthy & Goswami, 2000; Yang & Huang, 2021). Furthermore, some strong El Niño years, such as 1997, were associated with near-normal ISMR, while certain La Niña years failed to produce excess rainfall over India (Chakraborty, 2018; Gadgil *et al.*, 2023; Sharma *et al.*, 2024; Srinivasan *et al.*, 2026). Musale *et al.*, (2024) showed that even the prolonged triple-dip La Niña event during 2020–2022 resulted in contrasting monsoon rainfall across the three years, emphasizing that persistent ENSO forcing alone is insufficient to determine seasonal monsoon performance. These inconsistencies indicate that additional climate processes, including the state of the Indian Ocean and intraseasonal variability, modulate the ENSO influence on ISMR.

The IOD, characterized by anomalous sea surface temperature (SST) gradients between the western and eastern equatorial Indian Ocean (Saji *et al.*, 1999), is another important driver of monsoon variability. Positive IOD events generally favor enhanced monsoon rainfall through strengthened cross-equatorial flow and enhanced moisture transport toward the Indian region, while negative IOD events are often associated with suppressed rainfall conditions (Ashok *et al.*, 2001; Ratna *et al.*, 2024; Ratna *et al.*, 2021). Previous studies have also demonstrated that the IOD can substantially alter the ENSO-ISMR relationship. For example, positive IOD conditions can compensate for the adverse influence of El Niño on ISMR, as observed during the strong 1997 El Niño event (Ashok *et al.*, 2004). Similarly, combined La Niña and negative/positive IOD conditions can lead to different monsoon responses compared to isolated ENSO or IOD events (Mohanty & Padhi, 2023). These studies suggest that the state of the Indian Ocean plays a crucial role in modulating the monsoon response to Pacific forcing.

In addition to interannual climate modes, the MJO exerts a strong influence on monsoon variability at intraseasonal timescales. The MJO is characterized by the eastward propagation of large-scale convective anomalies from the Indian Ocean toward the Pacific Ocean with a periodicity of about 30–60 days (Madden and Julian, 1971; Zhang, 2005). The phase and amplitude of the MJO strongly modulate monsoon onset, active-break cycles, low-level circulation, and moisture transport over the Indian region (Pai *et al.*, 2011; Taraphdar *et al.*, 2018).

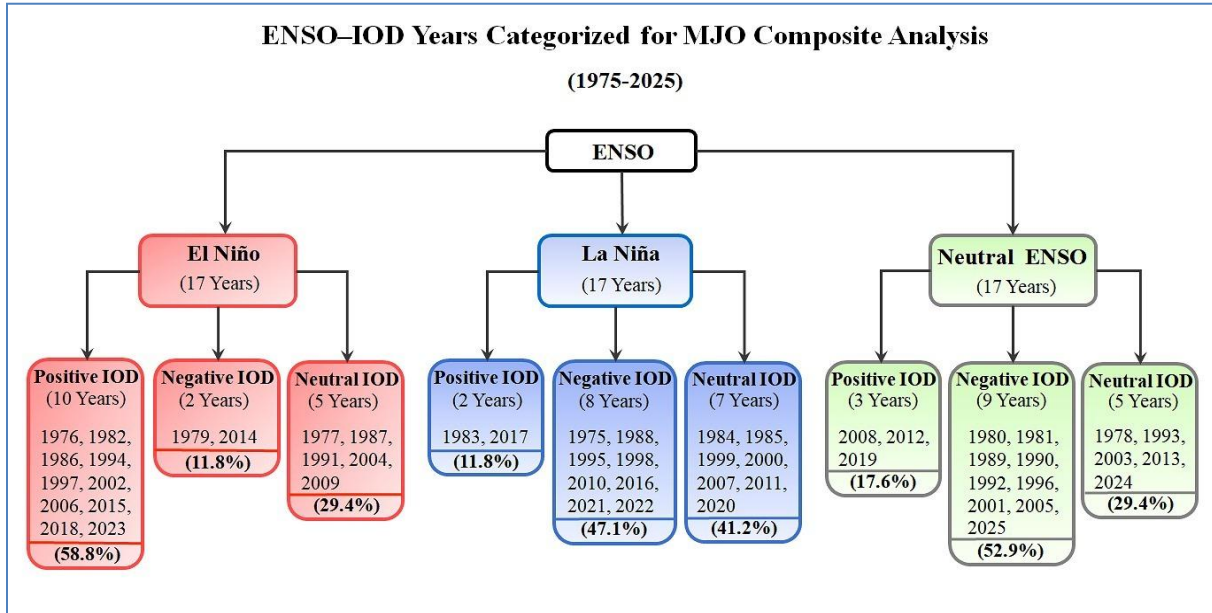


Fig. 1. Classification of study years (1975–2025) into nine ENSO–IOD categories used for MJO composite analysis. Years were classified according to the concurrent phases of ENSO (El Niño, La Niña, and Neutral) and IOD (Positive, Negative, and Neutral) based on Niño-3.4 and DMI indices during the monsoon season, as discussed in Section 2.2. The number of years in each category is shown in brackets, while the percentages indicate the relative occurrence of each IOD phase within the corresponding ENSO category

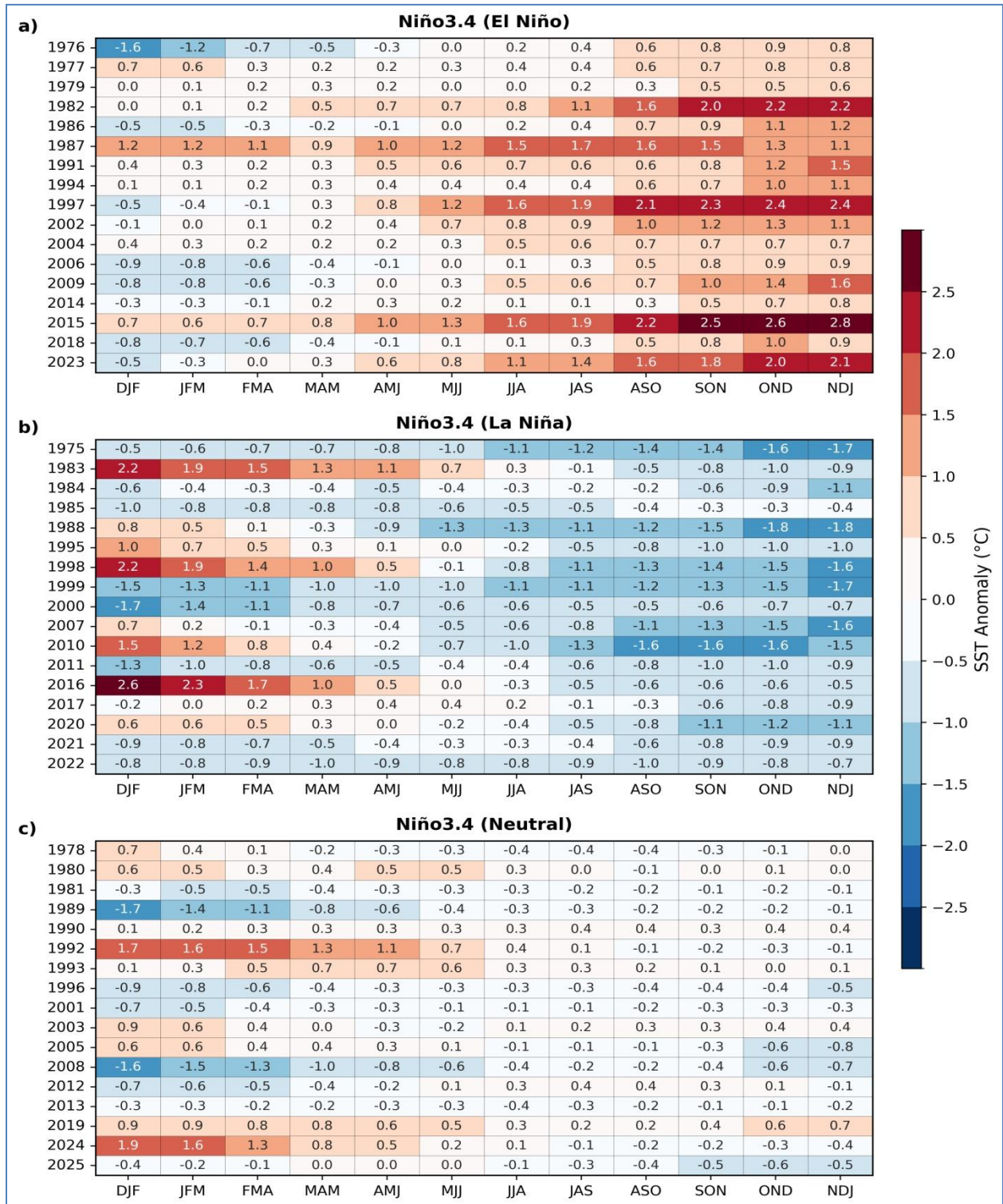
Depending on its location and persistence, the MJO can either enhance or suppress convection over the Indian subcontinent during the monsoon season. Recent studies have further shown that the propagation characteristics and persistence of MJO events have undergone substantial changes in recent decades, particularly over the Indo-Pacific warm pool region (Wang & Wang, 2023; Kim, 2024). Such changes may influence the interaction between MJO and interannual climate modes, thereby affecting ISMR variability and predictability.

Previous studies suggest that ENSO, IOD, and MJO interact with each other through complex coupled ocean–atmosphere feedback mechanisms. ENSO can influence the propagation and amplitude of MJO events (Hendon *et al.*, 2007; DeMott *et al.*, 2018), while MJO-related wind bursts and convection anomalies can contribute to the evolution of ENSO and IOD conditions (Kessler & Kleeman, 2000; Rao & Yamagata, 2004). Similarly, the background state associated with IOD events can modify convective activity and circulation patterns favorable for MJO propagation (Wilson *et al.*, 2013). Therefore, the ISMR response often depends on the simultaneous state of multiple climate modes operating across different timescales.

A few recent studies have explored the combined influence of these climate drivers on ISMR. Ratna *et al.*, (2024) investigated the role of MJO during super El Niño and positive IOD years and highlighted the importance of intraseasonal variability by MJO in modulating the

monsoon response during 1997 and 2015. Similarly, Srinivasan *et al.*, (2026) examined the influence of MJO phase persistence during La Niña and IOD conditions and demonstrated that the persistence and organization of MJO phases can substantially alter seasonal monsoon outcomes. Although these studies significantly improved our understanding of the combined ENSO–IOD–MJO influence on ISMR, they mainly focused on specific event categories or selected case studies. To the best of our knowledge, no study has systematically examined all possible combinations of ENSO phases (El Niño, La Niña, neutral ENSO), IOD phases (positive, negative, neutral), and all the MJO phases together within a unified framework.

The present study attempts to address this important research gap by comprehensively examining the combined influence of ENSO, IOD, and MJO on ISMR during the period 1975–2025. The monsoon years were first classified into ENSO–IOD categories, after which MJO amplitude, phase occurrence, and phase-dependent rainfall responses were examined within each category. The objective is to understand how interactions among these interannual and intraseasonal climate drivers modulate all-India and regional monsoon rainfall variability during the JJAS season. By analyzing the full spectrum of ENSO–IOD–MJO combinations, this study aims to provide a more comprehensive understanding of the multiscale processes governing ISMR variability and contribute to improving seasonal monsoon prediction.



Figs. 2(a-c). Seasonal evolution of Niño3.4 SST anomalies (°C) from DJF to NDJ for **a)** El Niño, **b)** La Niña, and **c)** neutral ENSO years during 1975–2025. Individual rows correspond to selected years, and columns represent overlapping three-month seasons. Color shading indicates SST anomaly magnitude

The manuscript is organized as follows. Section 2 describes the datasets and methodology used in the study. Sections 3 and 4 present the major results and discussion, respectively. Finally, the main conclusions are summarized in Section 5.

2. Data and methodology

2.1. Data

We have used the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed monthly sea surface temperature version 5 (ERSSTv5) dataset (Huang *et al.*, 2017) with spatial resolution: $2^\circ \times 2^\circ$, for the period 1975–2025. For rainfall, we used the India Meteorological Department (IMD) gridded dataset (with spatial resolution $0.25^\circ \times 0.25^\circ$) for the period 1975–2025 (Pai *et al.*, 2014). MJO was characterized using the daily Real-time Multivariate MJO (RMM) indices (Wheeler and Hendon, 2004), obtained from the Australian Bureau of Meteorology (BoM). The RMM dataset provides daily MJO amplitude and phase based on a multivariate empirical orthogonal function analysis of equatorial outgoing longwave radiation and zonal winds at 850 and 200 hPa.

To examine the associated atmospheric circulation anomalies, monthly 850 hPa zonal (u) and meridional (v) winds, together with 500 hPa vertical velocity (ω), were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Climate Data Store (CDS) ERA5 reanalysis dataset (Hersbach *et al.*, 2020). These fields were used to construct composite circulation anomalies corresponding to the different ENSO–IOD categories during the JJAS season.

2.2. Methodology

2.2.1. Identification and Evolution of ENSO Events

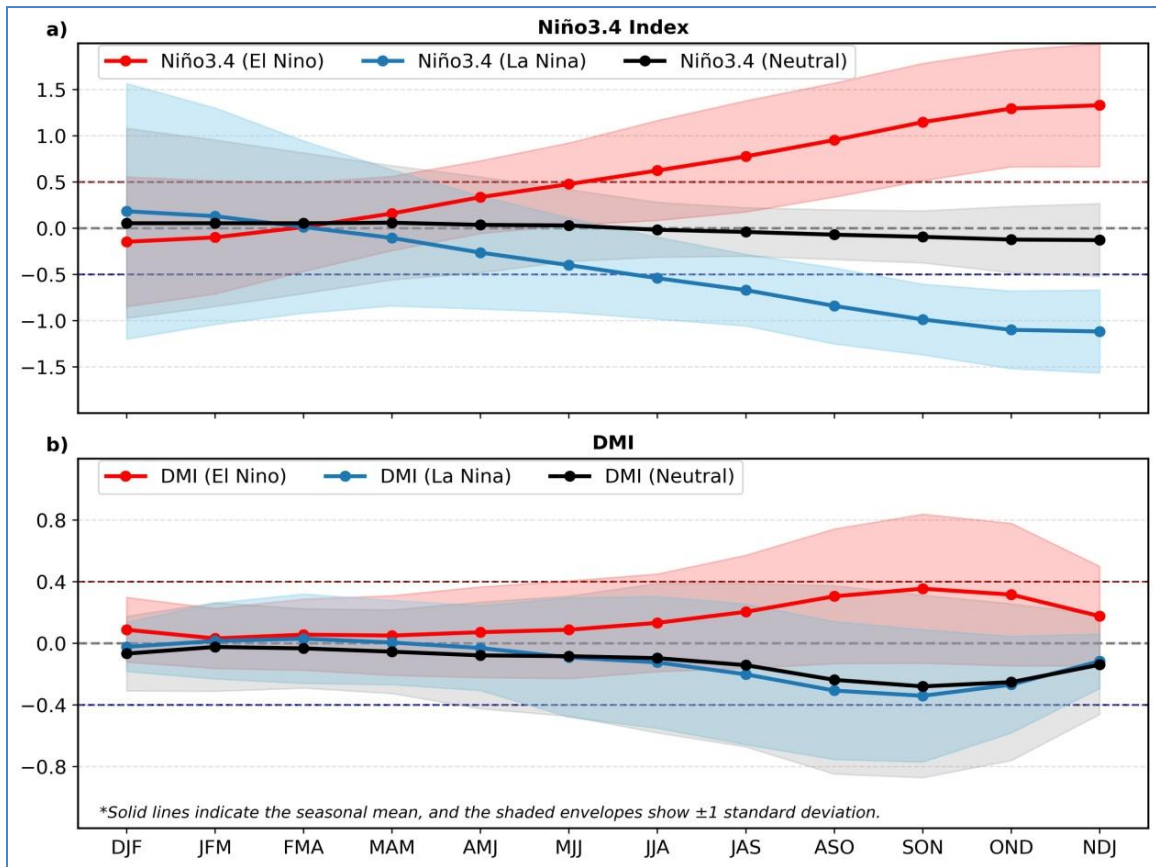
The ENSO was characterized using the Niño3.4 index computed from ERSSTv5 anomalies averaged over the Niño3.4 region (5°N – 5°S , 170°W – 120°W ; Barnston *et al.*, 1997). SST anomalies were first detrended to remove the long-term warming signal. Following the criteria of the NOAA Climate Prediction Center (CPC), an El Niño (La Niña) event was defined when the Niño3.4 index was greater than or equal to $+0.5^\circ\text{C}$ (less than or equal to -0.5°C) for at least five consecutive overlapping three-month seasons. Since the present study focuses on the ISMR, only ENSO events whose evolution overlapped the monsoon season were considered. The years that did not satisfy either threshold during these seasons were classified as Neutral ENSO years. Based on these criteria, 17 El Niño, 17 La Niña, and 17 Neutral ENSO years were identified

during the period 1975–2025 (Fig. 1). To examine the seasonal evolution of ENSO, overlapping three-month mean Niño3.4 SST anomalies were calculated from December–February (DJF) through November–January (NDJ). The resulting seasonal evolution was analyzed separately for El Niño, La Niña, and Neutral years to investigate the onset, growth, mature phase, and decay characteristics of ENSO events throughout the annual cycle.

The present study focuses on the concurrent relationship between tropical SST anomalies and Indian Summer Monsoon Rainfall (ISMR). Although ENSO exhibits statistically significant lead–lag relationships with ISMR, previous studies have shown that the strongest inverse relationship between the Niño-3.4 index and seasonal monsoon rainfall occurs during the concurrent JJAS season (Peings and Douville, 2010; Crétat *et al.*, 2017). Accordingly, the JJAS monsoon season is used as the reference season to define the monsoon year and to investigate the associated ocean–atmosphere interactions under different ENSO–IOD–MJO background conditions.

2.2.2 Identification and Evolution of IOD Events

The IOD was represented using the Dipole Mode Index (DMI), defined as the difference in SST anomalies between the western equatorial Indian Ocean (WEIO: 50° – 70°E , 10°S – 10°N) and the eastern equatorial Indian Ocean (EEIO: 90° – 110°E , 10°S – 0°), by Saji *et al.* (1999). For the same ENSO years identified in Section 2.2.1, seasonal DMI values were calculated using three-month running means from DJF through NDJ. Following the standard criterion adopted by the NOAA, a Positive (Negative) IOD event was defined when the seasonal mean DMI was greater than or equal to $+0.4^\circ\text{C}$ (less than or equal to -0.4°C) during at least one of the overlapping three-month seasons JJA, JAS, ASO, or SON, thereby capturing IOD events that influence the monsoon while accounting for their seasonal evolution. The inclusion of SON is particularly important because many IOD events continue to strengthen during the late monsoon and post-monsoon period and often reach their mature phase during SON. Years with DMI values remaining between -0.4°C and $+0.4^\circ\text{C}$ throughout these seasons were classified as Neutral IOD years. Using these criteria, each ENSO year was further classified into nine combined ENSO–IOD categories such as for El Niño and three phases of IOD (EN&IODp, EN&IODn, EN&IODu), La Niña and three phases of IOD (LN&IODp, LN&IODn, LN&IODu), and neutral ENSO and three phases of IOD (NN&IODp, NN&IODn, and NN&IODu) where EN, LN, and NN denote El Niño, La Niña, and Neutral ENSO conditions, respectively, while IODp, IODn, and IODu represent positive, negative, and neutral IOD states. The



Figs. 3(a&b). Seasonal mean and standard deviation evolution of a) Niño3.4 SST anomalies ($^{\circ}\text{C}$) and b) Dipole Mode Index (DMI; $^{\circ}\text{C}$) from DJF to NDJ for El Niño, La Niña, and Neutral ENSO years during 1975–2025. Solid lines represent the composite seasonal mean, while the shaded envelopes indicate ± 1 standard deviation

Seasonal progression of DMI was then analyzed under different ENSO backgrounds.

Although nine ENSO–IOD combinations were initially identified, three categories (EN&IODn, LN&IODp, and NN&IODp) contained only two to three events during the period 1975–2025. Owing to the limited sample size and reduced statistical robustness, these categories were excluded from the rainfall, circulation, and subsequent MJO analyses presented in Section 3.3 onwards.

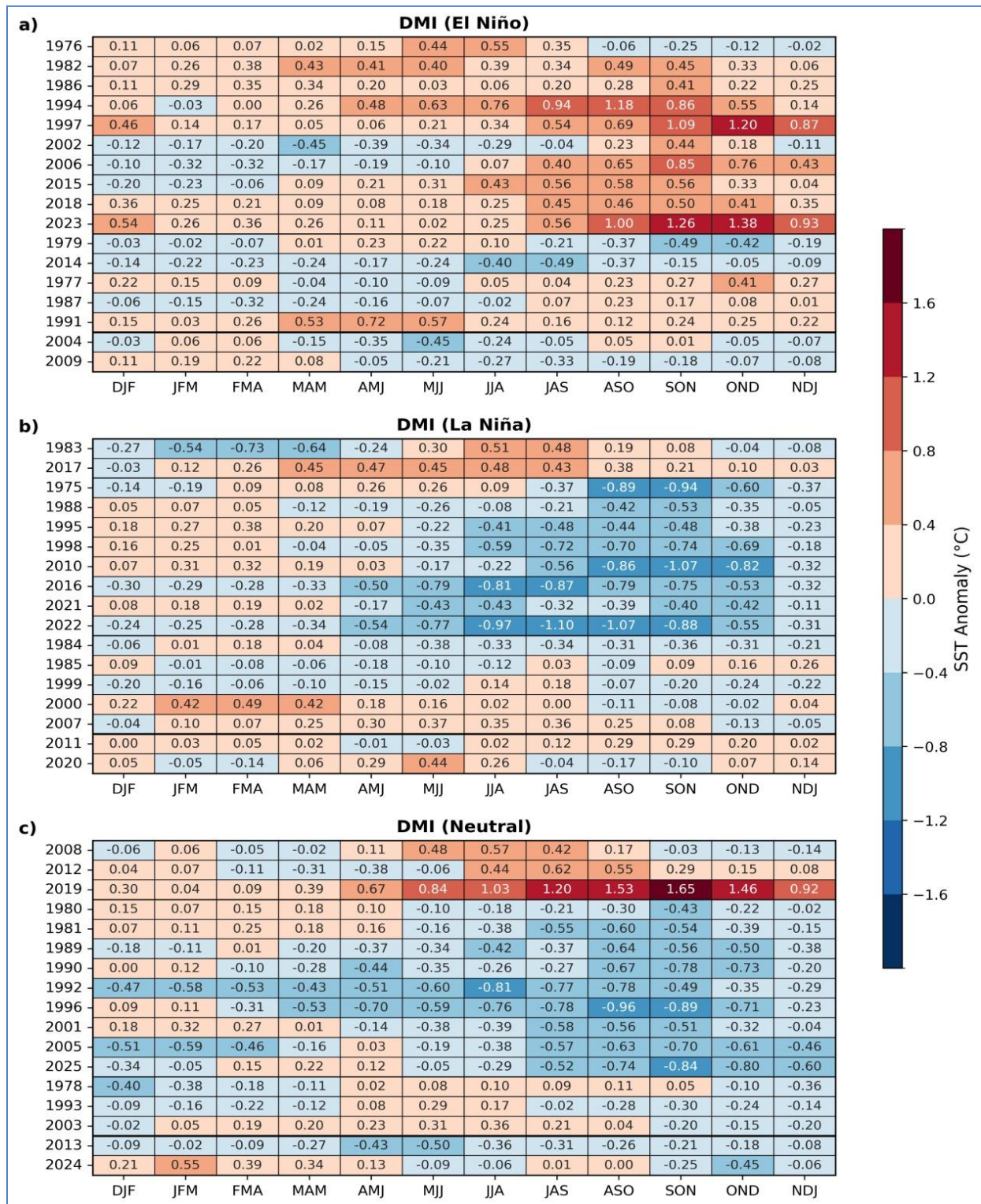
2.2.3 Composite Analysis of Seasonal Rainfall and Associated Atmospheric Circulation

To examine the influence of different ENSO–IOD combinations on ISMR, composite analyses were performed for seasonal rainfall anomalies and large-scale atmospheric circulation during the JJAS season. Seasonal rainfall anomalies were computed relative to the 1975–2025 climatology. Area-averaged rainfall anomalies for All India and the four homogeneous regions (North, Central,

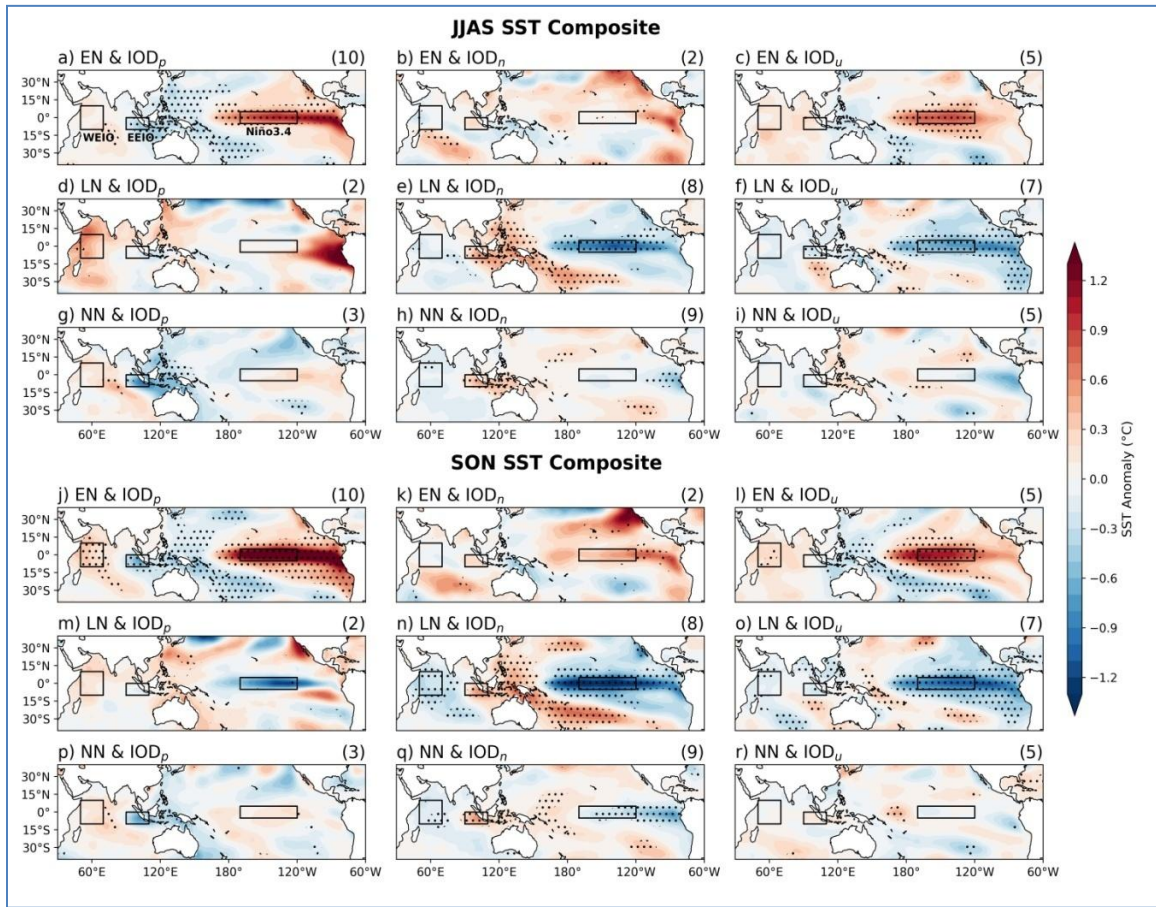
East, and South India) as defined by IMD, and the spatial organization of the rainfall response associated with each ENSO–IOD combination were analyzed. To understand the associated large-scale dynamical environment, composite anomalies of 850 hPa horizontal winds, representing low-level monsoon circulation anomalies, and 500 hPa vertical velocity (ω), representing anomalous ascent and subsidence associated with deep convection, were computed for the JJAS season. Statistical significance of the composite anomalies was assessed using a two-tailed Student's t-test at the 95% confidence level.

2.2.4 MJO Characteristics and the Rainfall Response under Different ENSO–IOD Conditions

The MJO was analyzed using the RMM indices of Wheeler and Hendon (2004). Only JJAS data were considered to focus on the southwest monsoon season. The MJO was considered as active when the RMM amplitude was greater than or equal to one ($\text{RMM} \geq 1$).



Figs. 4(a-c) Seasonal evolution of the Dipole Mode Index (DMI; °C) from DJF to NDJ for **a)** El Niño, **b)** La Niña, and **c)** neutral ENSO years during 1975–2025. Each row represents an individual year, while columns correspond to overlapping three-month seasons. The color shading denotes the magnitude and sign of the DMI anomaly



Figs. 5(a-r). Composite SST anomaly ($^{\circ}\text{C}$) patterns during JJAS (a-i) and SON (j-r) season for the nine combined ENSO-IOD categories during 1975–2025. Black dots show regions where composite anomalies are statistically significant at the 95% confidence level ($p < 0.05$). Rectangles indicate the Niño3.4, western equatorial Indian Ocean (WEIO), and eastern equatorial Indian Ocean (EEIO) regions used to define the ENSO and IOD indices. Numbers in brackets denote the sample size for each composite

Active MJO days were then classified according to the eight standard MJO phases and the six ENSO-IOD categories retained for detailed analysis.

Two metrics were computed to characterize MJO behavior. First, the composite MJO amplitude for each phase was calculated by averaging the RMM amplitudes of all active MJO days within that phase. Second, the number of active MJO days occurring in each phase was determined for every year within each ENSO-IOD category. The percentage contribution of each phase was then calculated relative to the total number of active MJO days during the JJAS season, thereby describing the preferred occurrence of MJO activity under different large-scale oceanic background states. To determine whether the occurrence of active MJO phases differs significantly among the ENSO-IOD categories, a Pearson chi-square test of independence was applied. Under the null hypothesis, MJO phase occurrence is assumed to be independent of the background

ENSO-IOD state. Standardized Pearson residuals (Lefèvre *et al.*, 2010; Sharma *et al.*, 2026) were then calculated to identify significant occurrences of MJO phases. Residuals corresponding to a confidence level of 95% were considered statistically significant. To investigate the intraseasonal rainfall response associated with different MJO phases, daily rainfall anomalies were analyzed over all-India and four homogeneous rainfall regions. Composite rainfall anomalies were then constructed separately for each MJO phase within each ENSO-IOD category.

3. Results and discussion

3.1 Seasonal Evolution of SST Anomalies during ENSO and IOD Phases

To characterize the large-scale oceanic background associated with different phases of ENSO, we first examine

the seasonal evolution of the Niño3.4 SST anomalies from the preceding winter: DJF to the subsequent NDJ season for all identified El Niño, La Niña, and neutral ENSO years during 1975–2025 (Fig. 2). The ENSO categories are defined based on Niño3.4 conditions during the Indian summer monsoon (JJAS) season (Section 2.2).

The El Niño years exhibit a clear transition from weak anomalies during the preceding winter and spring to progressively stronger warming over the equatorial Pacific during the monsoon and post-monsoon seasons (Fig. 2a). The composite mean SST anomaly increases from approximately -0.1°C during DJF to about 1.3°C in OND, illustrating the gradual development and mature phase of El Niño. Several strong events, including 1982, 1997, 2015, and 2023, exceed $+2^{\circ}\text{C}$ during boreal autumn and early winter, whereas weaker events remain below $+1^{\circ}\text{C}$ throughout the year. The standard deviation between years is largest during boreal winter seasons ($0.6\text{--}0.7^{\circ}\text{C}$), indicating considerable diversity in the strength during the mature phase of El Niño events (Fig. 3a). In contrast, La Niña years are characterized by persistent cold SST anomalies that intensify through the annual cycle (Fig. 2b). The composite mean evolves from weak positive anomalies during the preceding winter (0.2°C) to sustained negative anomalies beginning in late spring, reaching peak cooling of about -1.1°C during the NDJ season. Strong La Niña events, such as 1988, 1998, and 2010, exhibit SST anomalies below -1.5°C during the mature phase. The associated standard deviation is highest (1.4°C) during DJF and decreases to $0.4\text{--}0.5^{\circ}\text{C}$ from MJJ onwards (Fig. 3a).

The neutral ENSO years display substantially weaker SST anomalies throughout the seasonal cycle (Fig. 2c). The composite mean remains close to zero across all seasons, ranging from approximately -0.1°C to 0.1°C , confirming the absence of sustained warming or cooling in the equatorial Pacific Ocean. Although some neutral years display weak positive or negative anomalies during particular seasons, these departures are generally short-lived and do not evolve into mature ENSO conditions during the monsoon seasons. The standard deviation decreases steadily from 1.0°C during DJF to $0.3\text{--}0.4^{\circ}\text{C}$ during summer and autumn, reflecting the comparatively small inter-event variability within the neutral category (Fig. 3a).

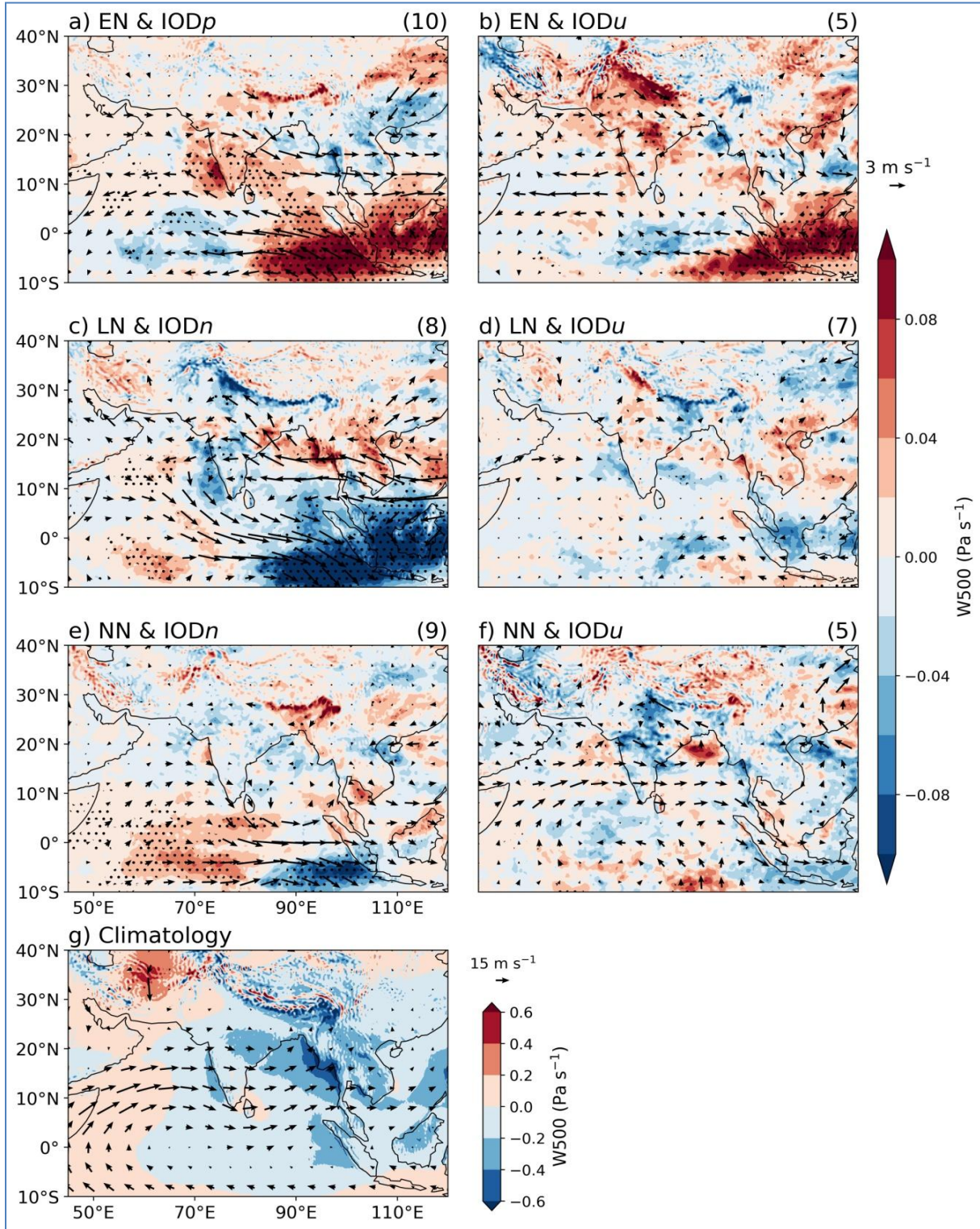
ENSO classification during the monsoon season effectively separates warm, cold, and neutral Pacific conditions while also highlighting substantial event-to-event variability, particularly during the developing and mature phases of El Niño. The mean seasonal evolution captures the growth and decay of ENSO, whereas the

standard deviation reveals that individual events differ considerably in their intensity, onset timing, and persistence. Such diversity suggests that the atmospheric response over the Indian region is likely influenced not only by the ENSO phase itself but also by the magnitude and temporal evolution of the underlying Pacific SST anomalies. These differences motivate examining how the combined ENSO–IOD states and their associated SST structures modulate the ISMR.

To examine the evolution of Indian Ocean variability associated with different ENSO phases, Fig. 4 reveals substantial diversity in the evolution of IOD conditions across the three ENSO categories. During El Niño years (Fig. 4a), positive DMI anomalies are generally more frequent and tend to intensify from boreal summer through autumn. The composite mean remains close to zero from DJF, gradually increasing during the monsoon and post-monsoon seasons, reaching approximately $0.3\text{--}0.4^{\circ}\text{C}$ during ASO–OND, then weakening slightly thereafter (Fig. 3b). Several El Niño events, including 1994, 1997, 2006, 2015, and 2023, exhibit pronounced positive DMI anomalies during the mature IOD season, while weaker events such as 1979, 2014, and 2018 remain near neutral or weakly negative. The standard deviation increases from about 0.2°C during the preceding winter to nearly 0.5°C during SON–OND, indicating that the intensity of the IOD varies substantially among El Niño events despite the tendency toward positive DMI development.

The La Niña years also display a broad range of DMI evolution (Fig. 4b). The composite mean remains close to zero during winter and spring, but gradually becomes negative from JJA onwards, reaching approximately -0.3°C during ASO–OND before weakening slightly in NDJ (Fig. 3b). Strong negative DMI anomalies are evident during several La Niña years, including 1998, 2010, 2016, 2021, and 2022, whereas years such as 1983 and 2017 are characterized by positive DMI anomalies despite concurrent La Niña conditions (Fig. 4b). Similar to the El Niño composites, the standard deviation increases during the developing and mature IOD seasons, reaching a maximum of about $0.4\text{--}0.5^{\circ}\text{C}$ during JJA–ASO, reflecting considerable event-to-event diversity in Indian Ocean conditions (Fig. 3b).

Neutral ENSO years show the largest diversity in DMI evolution (Fig. 4c). The composite mean remains close to zero throughout the seasonal cycle, confirming the absence of a preferred IOD phase when Pacific SST anomalies are weak (Fig. 3b). Nevertheless, individual years exhibit substantial variability. For example, 2019 is associated with a strong positive IOD event despite neutral ENSO conditions, whereas 1992, 1996, 2005, and 2025 exhibit persistent negative DMI anomalies during



Figs. 6(a-g). Composite anomalies of 850 hPa horizontal winds (vectors) and 500 hPa vertical velocity (ω ; color shading, Pa s^{-1}) during the JJAS season for the six ENSO-IOD categories (a to f) during the period 1975–2025. **g)** shows the JJAS climatological mean 850 hPa horizontal winds (vectors) and 500 hPa vertical velocity (ω ; color shading) for the same period (1975–2025). Black dots denote regions where the 500 hPa vertical velocity anomalies are statistically significant at the 95% confidence level based on Student's t-test. Numbers in brackets indicate the number of events in each composite. Negative ω (blue) anomalies indicate enhanced upward motion, whereas positive ω (red) anomalies indicate anomalous subsidence

boreal summer and autumn (Fig. 4c). The standard deviation increases from approximately 0.2–0.3 °C during the preceding winter to about 0.5–0.6 °C during boreal summer and fall, indicating that the Indian Ocean exhibits considerable internal variability even in the absence of strong ENSO forcing (Fig. 3b).

The seasonal evolution of the Niño3.4 and DMI indices reveals substantial diversity in the co-occurrence of ENSO and IOD events across the study period. The relationship between ENSO and IOD is highly variable, with positive, negative, and neutral IOD events occurring within each ENSO category. The absence of a one-to-one correspondence between ENSO and IOD phases suggests that the monsoon response is likely influenced by the combined state of the Pacific and Indian Oceans rather than by either climate mode alone. These distinct oceanic background states provide the physical basis for examining how the combined influences of ENSO, IOD, and the MJO modulate ISMR in the subsequent sections.

3.2 *Spatial Patterns of Tropical SST Anomalies under Combined ENSO–IOD Conditions*

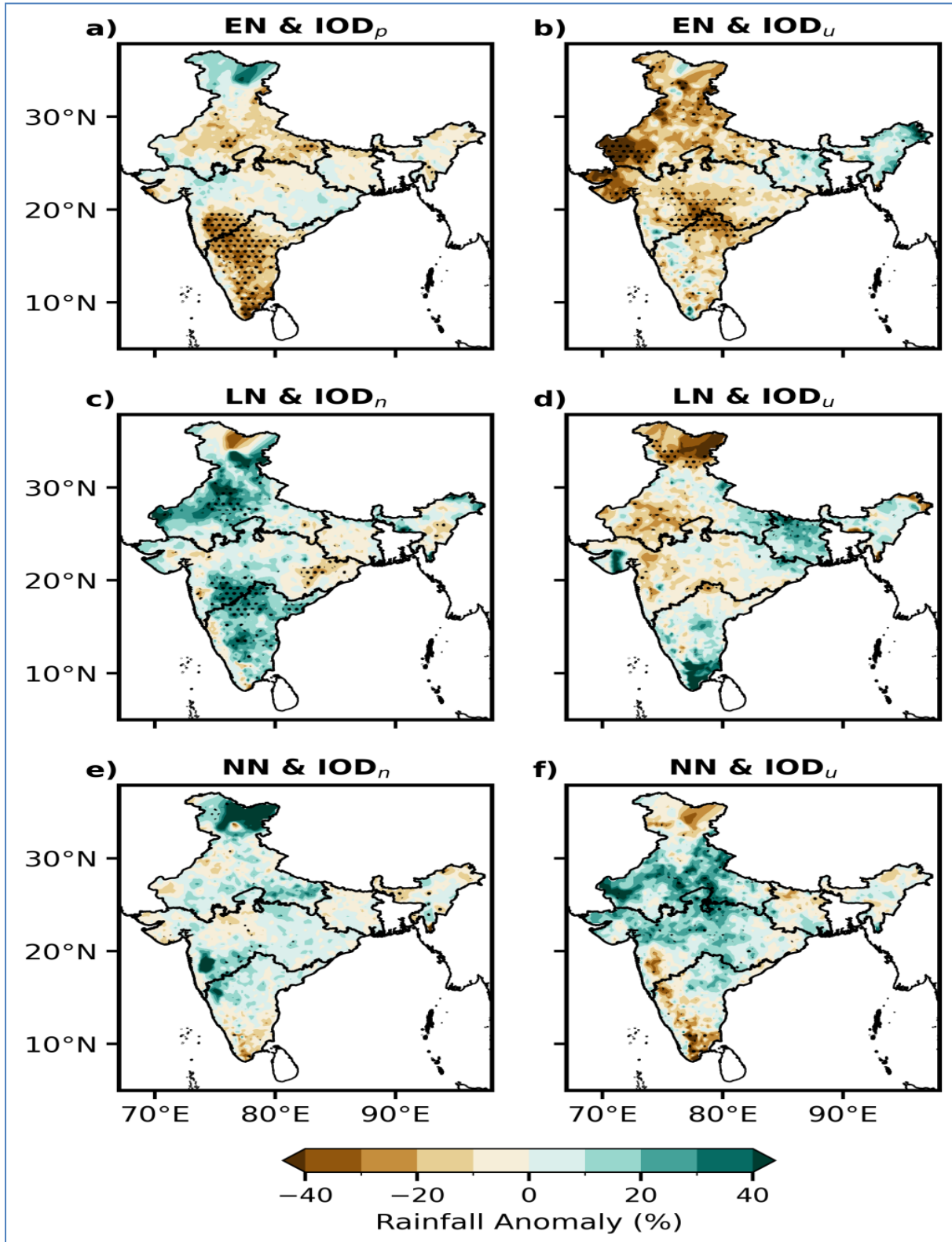
To further examine the large-scale oceanic background associated with each ENSO–IOD category, Fig. 5 presents composite SST anomaly patterns during the monsoon (JJAS) and boreal autumn (SON) seasons. Although the primary focus of this study is the Indian summer monsoon season, the SON season is also examined because ENSO events were identified using overlapping three-month Niño3.4 anomalies extending from JJA through SON, and many IOD events develop and reach maturity during SON. Consequently, restricting the analysis to JJAS alone would not fully capture the evolution of the IOD or its influence on the late monsoon season. The composites reveal substantial differences in the spatial structure of Pacific and Indian Ocean SST anomalies across the nine ENSO–IOD combinations, indicating that the atmospheric forcing of the Indian summer monsoon depends not only on ENSO phase but also on the accompanying IOD state.

During the EN&IODp years, the SST anomaly pattern is characterized by pronounced warming extending across the eastern equatorial Pacific, with maximum anomalies located in the Niño3.4 and eastern Pacific regions. Simultaneously, positive SST anomalies develop over the WEIO, while relatively cooler conditions appear over the EEIO, producing a well-defined positive IOD pattern. This eastward displacement of the Pacific warming is evident during JJAS (Fig. 5a) and becomes even more pronounced during SON (Fig. 5j), indicating that El Niño

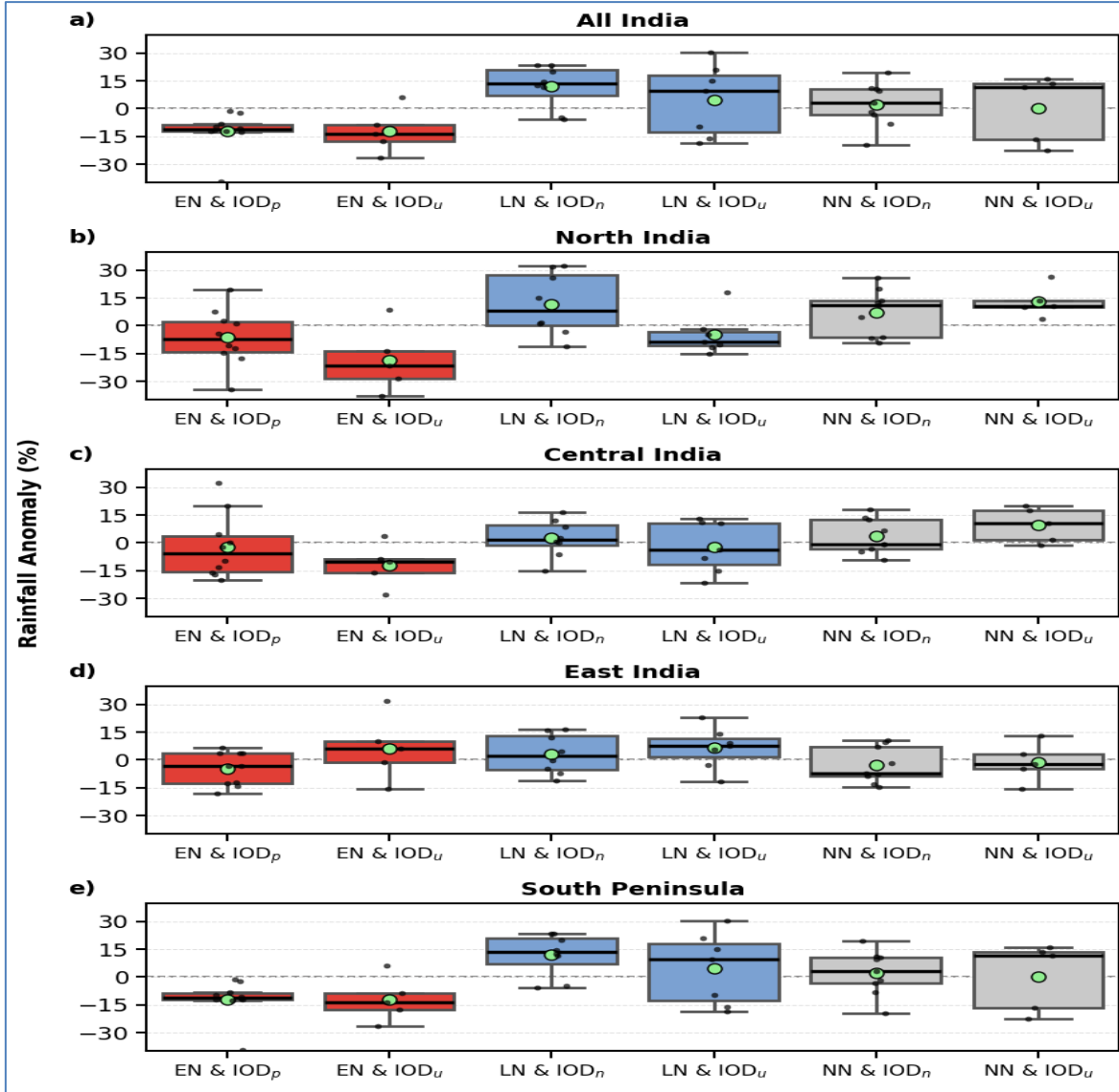
events accompanied by a positive IOD are predominantly Eastern Pacific (EP) El Niño events. However, the EN&IODu composites exhibit their largest warm SST anomalies near the dateline and central equatorial Pacific, while warming over the eastern Pacific is comparatively weaker (Fig. 5c). The Indian Ocean remains largely neutral, with no distinct zonal SST gradient characteristic of the IOD. This central-Pacific-centered warming persists from JJAS (Fig. 5c) into SON (Fig. 5l) and is consistent with the evolution of Central Pacific (CP) El Niño events. The clear separation between the EP-like structure during EN&IODp and the CP-like structure during EN&IODu suggests that different flavors of El Niño preferentially occur with different IOD states. It is worth mentioning that the EN&IODn category (Fig. 5b, 5k) contains only two events and therefore exhibits weaker and spatially less coherent SST anomalies. Although warm anomalies are present in the eastern Pacific, the limited sample size prevents robust identification of statistically significant composite features.

Among the La Niña composites, LN&IODn displays the strongest and most coherent cold SST anomalies across the central and eastern equatorial Pacific together with the characteristic negative IOD pattern of cooler WEIO and warmer EEIO conditions (Fig. 5e). These anomalies strengthen substantially from JJAS to SON, reflecting the mature development of both La Niña and negative IOD during boreal autumn (Fig. 5e, 5n). The LN&IODp composite does not exhibit a well-developed La Niña pattern during JJAS (Fig. 5d). SST anomalies over the equatorial Pacific are weak and spatially fragmented, whereas a clearer La Niña structure emerges only during SON (Fig. 5m) as cooling intensifies across the CP. However, this category contains only two events, and consequently, most anomaly patterns fail to reach statistical significance. The LN&IODu composite shows moderate cooling centered over the CP and extending to the EP, with relatively weak SST gradients across the Indian Ocean, representing La Niña evolution in the absence of a pronounced IOD event.

For the neutral ENSO categories, SST anomalies remain comparatively weak over the Pacific throughout both seasons (Fig. 5g–5i, 5p–5r). Positive and negative IOD composites primarily display variability confined to the Indian Ocean, whereas the neutral IOD composite exhibits near-normal SST conditions over both ocean basins. These results suggest that, in the absence of strong ENSO forcing, Indian Ocean variability becomes the dominant source of tropical SST anomalies. Several studies have documented the occurrence of independent IOD events, such as the strong positive IOD event of 2019, and negative IOD events such as 1992 and 1996, which developed under neutral ENSO conditions, demonstrating that the IOD can evolve through internal



Figs. 7(a-f). Composite JJAS percentage rainfall anomalies (%) over India for the six ENSO–IOD categories during the period 1975–2025. Positive (green) and negative (brown) shading indicate above-normal and below-normal seasonal rainfall, respectively. Black dots denote regions where the rainfall anomalies are statistically significant at the 95% confidence level based on a two-tailed Student's t-test



Figs. 8(a–e). June–September (JJAS) rainfall anomalies (mm) for **a)** All India and **b)–e)** Four homogeneous rainfall regions (North, Central, East, and South India) under the six combined ENSO–IOD conditions during 1975–2025. The horizontal line within each box denotes the median; the box represents the interquartile range (25th–75th percentile); whiskers indicate the spread of the data, excluding outliers; and black dots represent outlying events. The colors of the boxes are red, blue, and gray for the composites associated with El Niño, La Niña, and neutral ENSO, respectively. Green circles denote the composite mean rainfall anomaly for each category

Indian Ocean–atmosphere coupled processes without strong Pacific forcing (Saji *et al.*, 1999; Ashok *et al.*, 2004; Ratna *et al.*, 2024).

The combined ENSO–IOD categories represent physically distinct oceanic states rather than simple combinations of independent climate modes. In particular, positive IOD conditions preferentially coincide with eastern Pacific (EP) like El Niño events, whereas neutral IOD conditions are more closely associated with central

Pacific (CP) like El Niño events. Furthermore, the SST anomaly patterns become considerably more organized during SON than during JJAS, reflecting the seasonal maturation of both ENSO and IOD. However, these distinct oceanic backgrounds provide the physical basis for investigating how different ENSO–IOD combinations modulate the associated ISMR in the following sections.

Although nine ENSO–IOD combinations were identified, three categories: EN&IODn, LN&IODp, and

NN&IODp, contained only two to three events during 1975–2025 (Fig. 1). Owing to the limited sample size and reduced statistical robustness, these categories were excluded from the rainfall, circulation, and MJO analyses presented in the subsequent Section. These analyses focus on the remaining six ENSO–IOD categories.

3.3. *Atmospheric Circulation and Associated ISMR Response under Different ENSO–IOD Conditions*

The SST anomaly patterns shown in the previous section modify the large-scale circulation and the low-level monsoon flow over the Indo-Pacific region, thereby influencing the distribution and intensity of the ISMR. To examine the physical mechanisms linking the different ENSO–IOD oceanic states with ISMR variability, Fig. 6 presents composite anomalies of 850 hPa horizontal winds and 500 hPa vertical velocity (ω) during JJAS, while the associated spatial rainfall anomalies and regional rainfall distributions are shown in Figs. 7 & 8, respectively.

Fig. 6 reveals distinct atmospheric circulation anomalies among the six ENSO–IOD categories. During EN&IODp years (Fig. 6a), pronounced low-level easterly wind anomalies extend across the equatorial Indian Ocean. Significant positive ω anomalies are observed over the EEIO, the Maritime Continent, and much of southern and central India, indicating anomalous subsidence and suppressed convection over the south of the Indian region. The spatial rainfall composites respond to unfavorable large-scale circulation patterns, with below-normal rainfall dominating much of peninsular India, while localized positive anomalies remain confined to parts of northwest and central India (Fig. 7a). The EN&IODu composite (Fig. 6b) exhibits easterly circulation anomalies, with wind anomalies largely confined to the equatorial Indian Ocean and spatially coherent vertical velocity anomalies over central and north-west India. Rainfall deficits become more widespread over central and north-west India (Fig. 7b), consistent with stronger subsidence. These results suggest that the absence of a positive IOD allows El Niño-related subsidence to exert a stronger suppressing influence on the monsoon over central and north-west India.

The LN&IODn composite (Fig. 7c) exhibits widespread positive rainfall anomalies across parts of central, northern, and peninsular India, in agreement with the strengthened southwesterly monsoon flow from the Arabian Sea, presence of active circulation over the Bay of Bengal, and enhanced ascent identified in Fig. 6c. In comparison, LN&IODu (Fig. 7d) show weaker, less spatially coherent rainfall enhancement, with localized

negative rainfall anomalies over northwest and central India, consistent with their comparatively weaker low-level circulation anomalies (Fig. 6d).

The rainfall anomalies during the neutral ENSO composites are considerably weaker than those during ENSO-active years, although the southwesterly flow during NN&IODn (Fig. 6e) is weaker as compared to NN&IODu (Fig. 6f). While NN&IODn exhibits scattered positive rainfall anomalies over central and northern India (Fig. 7e), NN&IODu is characterized by moderate positive rainfall over central and north-west India (Fig. 7f), favored by the well-established southwesterly flow and associated negative ω anomalies (Fig. 6f). Overall, the spatial rainfall composites demonstrate that although ENSO primarily determines the sign of the rainfall anomaly, the accompanying IOD substantially modifies its regional distribution and spatial organization.

Regional rainfall responses exhibit considerable spatial heterogeneity (Fig. 8). At the All-India scale (Fig. 8a), EN&IODu shows larger rainfall reductions than EN&IODp. Conversely, La Niña composites produce positive rainfall anomalies, with LN&IODn exhibiting the highest median and mean seasonal rainfall. Neutral ENSO composites generally show near-normal to moderately positive rainfall, with considerably smaller departures than the La Niña categories. North India (Fig. 8b) experiences the strongest positive rainfall anomalies during LN&IODn, although inter-event variability remains relatively large. Central India (Fig. 8c), the core monsoon rainfall region, exhibits a substantial variability during LN&IODu, as reflected by its relatively large interquartile range and whisker lengths. Eastern India (Fig. 8d) shows comparatively weaker rainfall departures than the other regions, indicating a relatively modest sensitivity to the combined ENSO–IOD forcing. In contrast, South India (Fig. 8e) exhibits the strongest positive rainfall response during LN&IODn, whereas the larger spread during LN&IODu suggests that additional sources of variability also influence seasonal rainfall over this region.

The atmospheric response to different ENSO–IOD combinations provides the dynamical basis for the observed ISMR variability. While ENSO largely influences whether seasonal rainfall is enhanced or suppressed, the accompanying IOD substantially modulates the strength of the monsoon circulation, the spatial organization of convection, and the regional distribution of rainfall. These results provide the physical foundation for examining, in the subsequent section, how intraseasonal variability associated with the MJO further modifies the seasonal monsoon response (Ratna *et al.*, 2024; Srinivasan *et al.*, 2026).

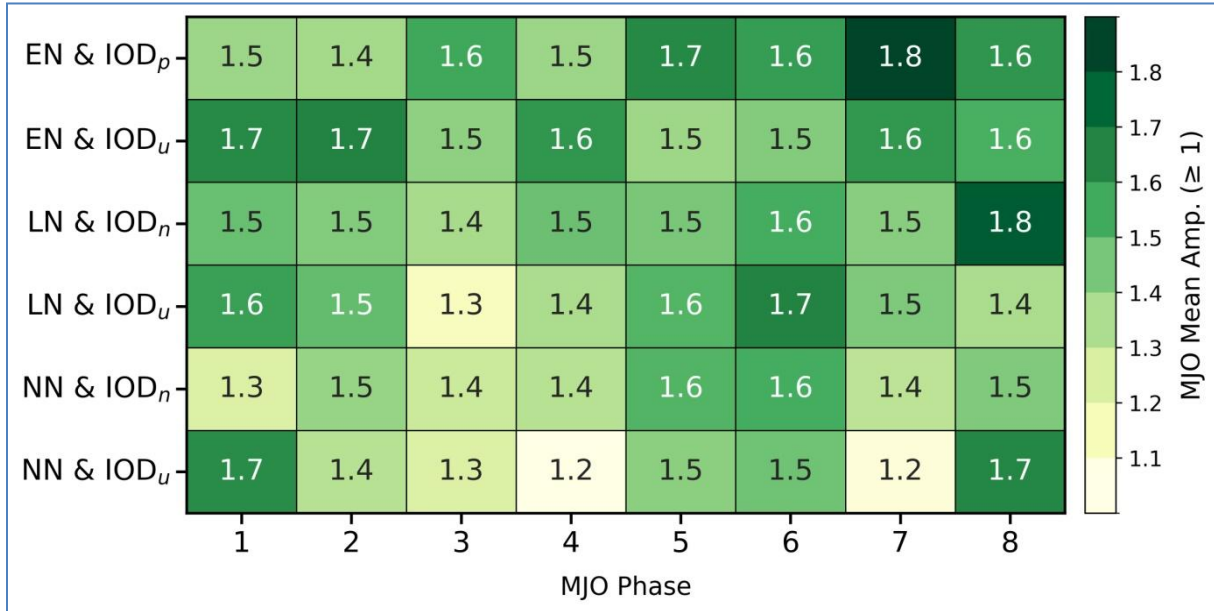


Fig. 9. Composite mean amplitude of active MJO (RMM amplitude ≥ 1) during the JJAS season for the six ENSO–IOD categories during 1975–2025. Larger values (darker green shading) indicate stronger MJO amplitude during that phase, while lighter shading represents comparatively weaker MJO

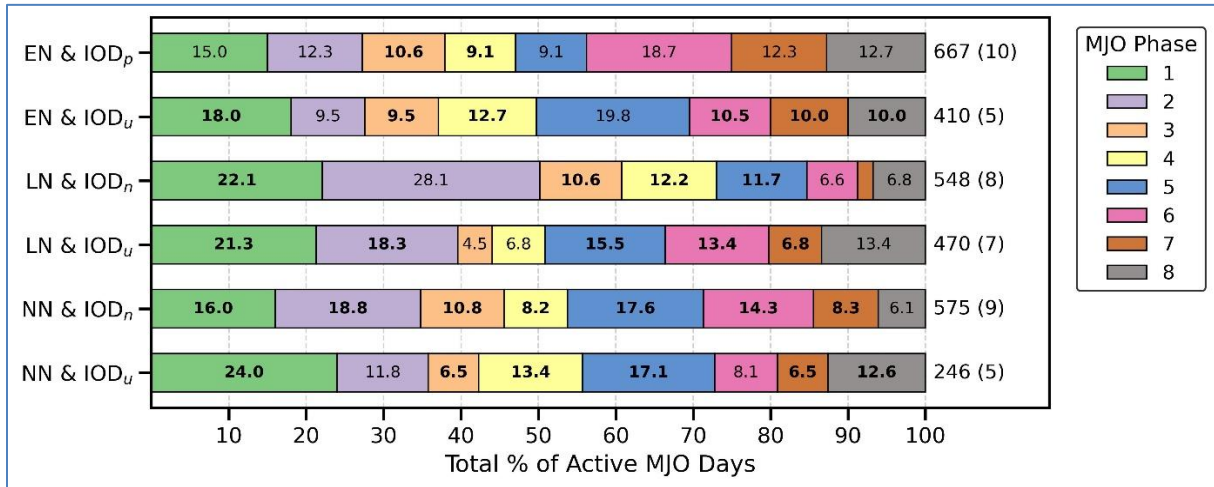


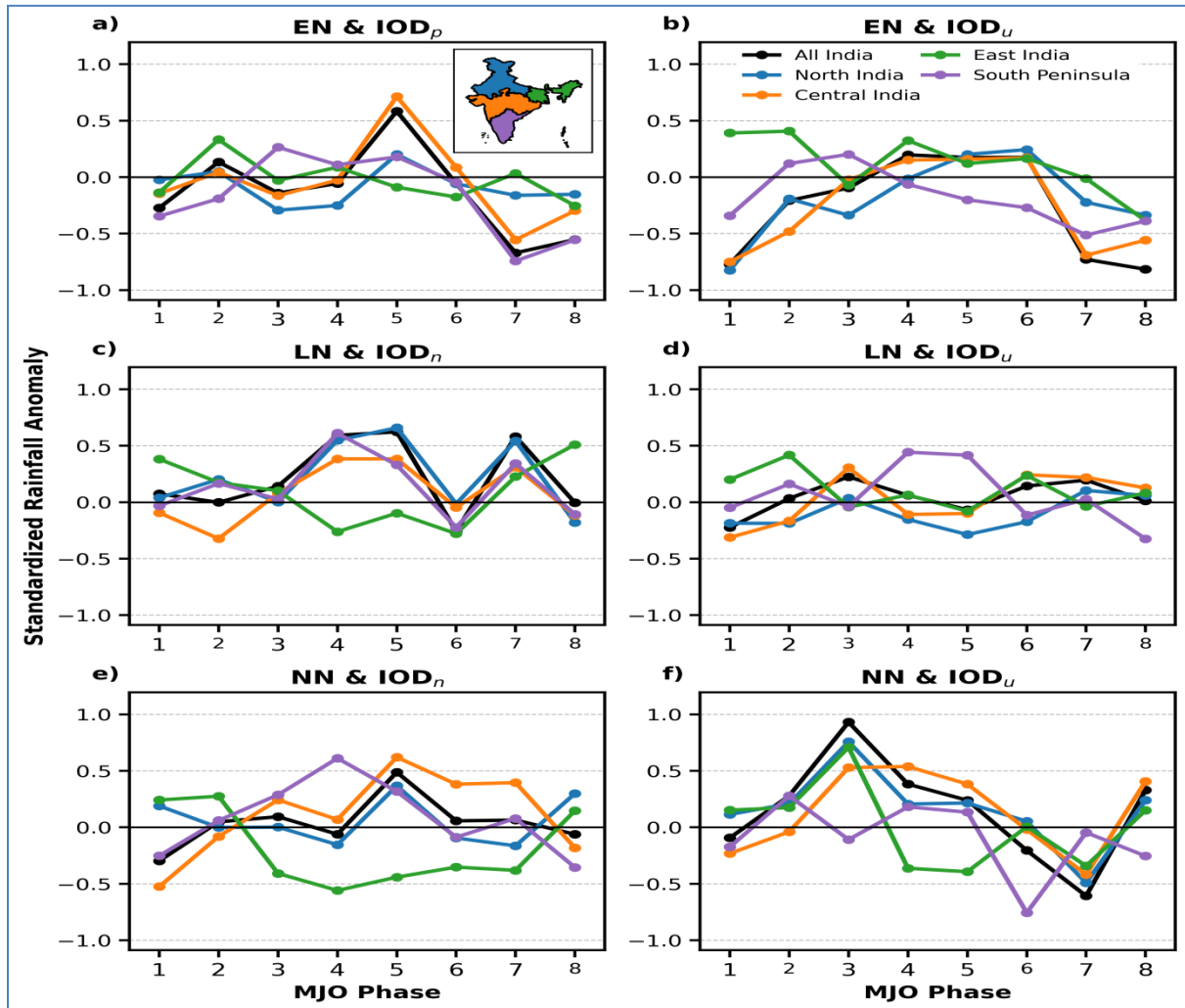
Fig. 10. Percentage distribution of active MJO (RMM amplitude ≥ 1) days among the eight MJO phases during the JJAS season for six ENSO–IOD categories over the period 1975–2025. Values within each coloured segment indicate the percentage of active MJO days occurring in the corresponding MJO phase. Bold numbers denote significant MJO phases based on standardized Pearson residuals from a chi-square test (95% confidence level). The number shown at the end of each horizontal bar indicates the total number of active MJO days included in the composite, while the number in brackets denotes the number of years contributing to each ENSO–IOD category. The EN&IOD_n, LN&IOD_p, and NN&IOD_p categories were excluded because of their limited sample sizes

3.4. Characteristics of MJO Activity under Different ENSO–IOD Background States

The influence of the MJO on ISMR depends not only on its amplitude and persistence but also on its phase occurrence under different large-scale oceanic background states. To investigate this aspect, active MJO days (RMM amplitude ≥ 1) during the JJAS season were classified according to the six ENSO–IOD categories. Two

diagnostics are examined: (i) composite MJO amplitude, and (ii) the MJO phase frequency to get the insight into how the occurrence and strength of MJO activity vary under different ENSO–IOD conditions and potentially influence seasonal monsoon rainfall over India.

Fig. 9 presents the composite mean MJO amplitude for each of the eight MJO phases during active (RMM amplitude ≥ 1) MJO events across the six ENSO–



Figs. 11(a-f). Standardized JJAS rainfall anomalies over All India and the four homogeneous rainfall regions (North India, Central India, East India, and South Peninsula) during the eight MJO phases for the six ENSO–IOD categories **a)–f)** over the period 1975–2025. The inset in **a)** shows the four homogeneous rainfall regions used in the analysis

IOD categories. This highlights the average strength of MJO activity within each phase and therefore provides insight into how the background ENSO–IOD state influences the amplitude of the intraseasonal oscillation. Several noteworthy differences emerge among the six categories.

During El Niño years, MJO amplitudes are relatively stronger than in other categories. The EN&IODp category shows high amplitudes during Phases 5–7, reaching a maximum of 1.8 in Phase 7, whereas the EN&IODu composite displays comparatively uniform amplitudes (1.5–1.7) across all phases without a pronounced peak. These results suggest that although MJO remains active throughout its life cycle, El Niño conditions tend to favor stronger MJO events, particularly during the Maritime Continent and western Pacific phases. Among the La Niña

composites, the strongest MJO amplitude occurs during the LN&IODn category, reaching 1.8 in Phase 8, while amplitudes remain relatively consistent (1.4–1.6) during the remaining phases. The LN&IODu composite displays intermediate amplitudes, with a modest enhancement during Phase 6 (1.7).

For neutral ENSO conditions, the MJO amplitude is generally more homogeneous across phases. The NN&IODn composite exhibits modest variability, with amplitudes ranging between 1.3 and 1.6. The NN&IODu category displays enhanced amplitudes in Phases 1 and 8 (1.7), while comparatively weaker amplitudes are evident during Phases 4 and 7 (1.2).

To examine whether the occurrence of active MJO phases varies under different ENSO–IOD background

states, Fig. 10 presents the mean percentage distribution of active MJO days among the eight MJO phases during the JJAS season. Distinct differences emerge among the six ENSO–IOD categories. During EN&IODp years, active MJO days occur most frequently in Phase 6 (18.7%), followed by Phase 1 (15.0%), whereas Phases 4 and 5 each account for only about 9% of the total active days. Among these, Phase 6 represents a statistically significant preference, indicating that MJO convection occurs more frequently than expected over the Maritime Continent under El Niño, accompanied by a positive IOD. In contrast, EN&IODu years exhibit a more evenly distributed MJO life cycle, although Phase 1 (18.0%) and Phase 5 (19.8%) occur significantly more often than expected. Compared with EN&IODp, the reduced occurrence of Phases 6–8 suggests that the absence of a positive IOD favours a more balanced eastward propagation of MJO convection.

The La Niña composites display a markedly different behavior. Under LN&IODn conditions, nearly half of all active MJO days occur during Phases 1 (22.1%) and 2 (28.1%), demonstrating a strong tendency for MJO convection to persist over the western and central Indian Ocean. Active MJO occurrence decreases rapidly after Phase 2, with Phases 6–8 together accounting for only about 20% of the active days. This phase preference is consistent with enhanced monsoon convection and the widespread positive rainfall anomalies over India (Srinivasan *et al.*, 2026). In LN&IODu years, Phases 1 (21.3%) and 2 (18.3%) remain dominant, substantial occurrence is also observed in Phases 5 (15.5%), 6 (13.4%), and 8 (13.4%), indicating greater eastward propagation of MJO convection compared with LN&IODn years.

Among the neutral ENSO composites, NN &IODn display a relatively balanced phase distribution in Phase 2 (18.8%), Phase 5 (17.6%), and Phase 1 (16.0%). In contrast, NN&IODu show the strong preference for Phase 1 (24.0%), followed by Phase 5 (17.1% statistically significant). The remaining phases each contribute less than about 14%, indicating that, under neutral Pacific conditions, active MJO events are generally more evenly distributed with only a weak but significant preference for initiation over the western Indian Ocean.

This analysis shows that the occurrence of active MJO phases is significantly modulated by the background ENSO–IOD state. La Niña accompanied by a negative IOD, preferentially favours greater phase frequency in MJO Phases 1–2, whereas El Niño with a positive IOD favours enhanced occurrence in Phases 6–8. These statistically significant shifts in MJO phase occurrence provide a physical explanation for the contrasting intraseasonal rainfall responses observed under different ENSO–IOD combinations and demonstrate that the

background oceanic state strongly influences the preferred evolution of MJO convection.

3.5. Intraseasonal Rainfall Response to MJO Phases under Different ENSO–IOD Background States

To examine how intraseasonal rainfall variability is modulated by the background ENSO–IOD state, Fig. 11 presents the standardized JJAS rainfall anomalies over All India and the four homogeneous rainfall regions for eight MJO phases. Considerable differences emerge among the six ENSO–IOD categories, indicating that the rainfall response to MJO propagation is strongly conditioned by the prevailing large-scale ocean-atmosphere background.

During EN&IODp years (Fig. 11a), rainfall anomalies exhibit a coherent evolution across most regions. Rainfall is suppressed during MJO Phases 1 and 3, followed by a pronounced increase during Phases 5–6, when all-India, North India, Central India, and South Peninsula simultaneously experience positive anomalies. The strongest enhancement occurs over Central India, whereas East India exhibits comparatively weak variability throughout the MJO life cycle. After Phase 6, rainfall decreases rapidly, with widespread negative anomalies during Phases 7–8. The EN&IODu composite (Fig. 11b) displays a weaker rainfall evolution. Although East India experiences positive anomalies during the early MJO phases (Phases 1–2), most regions show modest fluctuations around the climatological mean. Rainfall briefly increases during Phases 4–6 over North and Central India before declining during Phases 7–8, when widespread negative anomalies again dominate. As compared to EN&IODp, the absence of a positive IOD in this composite results in a less organized intraseasonal rainfall response.

In La Niña composites, LN&IODn (Fig. 11c) exhibits the strongest and spatially coherent intraseasonal rainfall variability. Positive rainfall anomalies develop over All India, including North India, Central India, and South Peninsula, during Phases 4–5, with anomalies exceeding 0.5 standard deviations in several regions. A secondary rainfall maximum occurs during Phase 7. East India behaves differently from the other regions, showing below-normal rainfall during Phases 4–7 but enhanced rainfall during Phase 8, highlighting the distinct regional response of northeast India to MJO propagation. In contrast, LN&IODu years (Fig. 11d) show considerably weaker phase locking between rainfall and MJO evolution. Regional rainfall anomalies remain relatively small throughout most phases, although the South Peninsula exhibits enhanced rainfall during Phases 4–5, and Central India experiences moderate positive anomalies during Phases 3 and 6–7. The weaker coherence among regions suggests that removal of the negative IOD substantially

reduces the organized intraseasonal rainfall enhancement observed during LN&IODn conditions.

The two neutral ENSO composites also display contrasting behaviour. During NN&IODn years (Fig. 11e), rainfall anomalies remain relatively moderate over All India, but exhibit pronounced regional differences. Central India experiences enhanced rainfall during Phases 5–7, while East India shows persistent negative anomalies from Phases 3–7. South Peninsula reaches its largest positive anomaly during Phase 4. Conversely, NN&IODu (Fig. 11f), when both climate modes (ENSO as well as IOD) are neutral, is characterized by an early rainfall maximum during Phase 3 over All India, North India, and Central India, followed by a transition to below-normal rainfall during Phases 6–7. South Peninsula shows intraseasonal variability among all regions, including a sharp negative anomaly during Phase 6. These findings indicate that the background state of the tropical Pacific and Indian Oceans not only influences the seasonal mean monsoon rainfall but also modulates the regional rainfall response to individual phases of the MJO. In the absence of ENSO and IOD, the MJO variability plays a major role in modulating the ISMR.

3.6. Discussion

The present study demonstrates that the influence of ENSO on the ISMR cannot be interpreted independently of the accompanying state of the Indian Ocean and the intraseasonal variability associated with the MJO. Although El Niño is generally associated with deficient monsoon rainfall and La Niña with enhanced rainfall, the magnitude, spatial organization, and temporal evolution of rainfall vary substantially among the different ENSO–IOD categories. The SST composites further show that these categories represent physically distinct coupled ocean–atmosphere states rather than simple combinations of independent climate modes. These results reinforce previous studies suggesting that the Indian Ocean actively modulates the atmospheric teleconnection between the tropical Pacific and the ISMR (Ashok *et al.*, 2004; Ratna *et al.*, 2021).

One of the important findings of this study is the clear distinction between the SST structures associated with El Niño categories with different IOD states. El Niño events accompanied by a positive IOD exhibit a characteristic EP El Niño pattern, whereas El Niño events occurring under neutral IOD conditions display a CP El Niño structure. This distinction becomes evident during the mature SON season, when both ENSO and IOD reach their peak development. These findings agree with Sun *et al.* (2026), who reported that EP-like El Niño events show stronger coupling with positive IOD, whereas CP-like El Niño events are comparatively independent of IOD variability. The present

analysis further demonstrates that these distinct SST structures are accompanied by different rainfall anomalies and atmospheric circulation patterns over India, suggesting that ENSO flavor provides an additional source of monsoon variability beyond conventional ENSO classification.

The rainfall composites and associated circulation anomalies reveal that the IOD substantially modifies the regional expression of ENSO-related monsoon anomalies. During El Niño years, the absence of a positive IOD results in more widespread rainfall deficits over central India, along with weaker, less organized low-level circulation anomalies. Conversely, La Niña, accompanied by a negative IOD, produces the most coherent enhancement of the monsoon circulation, characterized by strengthened southwesterly winds, widespread ascent over central and peninsular India, and the largest positive rainfall anomalies. These circulation patterns demonstrate that the IOD alters the large-scale Indo-Pacific atmospheric circulation, thereby modulating the influence of Pacific SST anomalies on the ISMR.

Despite these systematic differences, considerable rainfall variability remains within individual ENSO–IOD categories, indicating that interannual SST forcing alone cannot fully explain seasonal monsoon behaviour. This motivates the examination of intraseasonal variability associated with the MJO. The occurrence of active MJO phases is significantly influenced by the background ENSO–IOD state. The Pearson residual analysis identifies statistically preferred MJO phases under each ENSO–IOD background. During El Niño with a positive IOD, active MJO occurs significantly more frequently over Phases 3–4, whereas El Niño with neutral IOD exhibits enhanced occurrence in Phases 1. In contrast, La Niña, accompanied by a negative IOD, significantly favours Phases 3–4, indicating prolonged residence of MJO convection over the central Indian Ocean. These statistically significant phase preferences suggest that the background oceanic state not only modifies seasonal circulation but also influences the preferred evolution of the MJO itself.

The rainfall response associated with individual MJO phases is likewise strongly conditioned by the prevailing ENSO–IOD background. During El Niño years, rainfall generally increases during the middle MJO phases before rapidly declining during the later phases as convection shifts toward the Maritime Continent and western Pacific. However, the positive IOD background produces a more coherent intraseasonal rainfall evolution than neutral IOD conditions, suggesting that the positive IOD background may partly mitigate the suppressing influence of El Niño on monsoon convection. These findings extend the conclusions of the recent study by Ratna *et al.* (2024), which examined two contrasting super El Niño–positive

IOD years (1997 and 2015) and demonstrated that nearly identical ENSO and IOD conditions produced markedly different seasonal rainfall due to differences in MJO evolution. In 1997, prolonged MJO activity over the favorable Indian Ocean phases supported enhanced convection and near-normal monsoon rainfall, whereas in 2015, persistent activity over the western Pacific favored anomalous subsidence and contributed to severe monsoon deficiency. The present study extends those findings by demonstrating that such MJO-dependent modulation is not restricted to isolated case studies but represents a systematic characteristic across multiple ENSO–IOD combinations.

The strongest interaction between seasonal and intraseasonal variability is observed during the La Niña–negative IOD composite. This category exhibits the most coherent low-level circulation anomalies, the largest seasonal rainfall enhancement, statistically preferred MJO occurrence, and pronounced positive rainfall anomalies during Phases 3–4. The reduced occurrence of later suppressed phases and the coherent rainfall evolution are consistent with the mechanism discussed by Srinivasan *et al.* (2026). They showed that wet La Niña years are characterized not simply by the occurrence of favorable MJO phases, but also by their sustained persistence and reduced residence in suppressed phases. Although the present study examines phase occurrence rather than persistence, enhanced low-level southwesterlies, widespread ascent, increased moisture convergence, and equatorial wave activity likely facilitate the effective transfer of favorable large-scale La Niña conditions into enhanced monsoon rainfall over India (Srinivasan *et al.* 2026).

In neutral ENSO composites, although seasonal rainfall anomalies are comparatively moderate, distinct regional differences remain evident in the MJO rainfall response, particularly over Central India and the South Peninsula. These results suggest that, in the absence of strong ENSO forcing, the MJO, together with Indian Ocean SST anomalies, becomes the dominant source of monsoon variability, allowing rainfall anomalies to more closely follow the canonical eastward propagation of MJO convection. ENSO establishes the large-scale tropical Pacific forcing, the IOD modifies the Indo-Pacific SST gradient and associated atmospheric circulation, and the MJO regulates the timing and regional organization of monsoon convection on intraseasonal time scales. The present analysis shows that the rainfall response over India to a given MJO phase varies systematically with the prevailing ENSO–IOD background.

Despite these encouraging results, several limitations should be acknowledged. First, three ENSO–IOD

categories (EN&IODn, LN&IODp, and NN&IODp) contained only two or three events during 1975–2025 and therefore could not be included in the rainfall, circulation, and MJO analyses. Second, the analysis is based on approximately five decades of observations (1975–2025), due to the availability of MJO data, limiting the sample size for some combinations. Third, while the present study investigates MJO amplitude, statistically preferred phase occurrence, and phase-dependent rainfall responses, it does not explicitly examine MJO propagation characteristics, phase persistence, moisture budget processes, or air–sea feedbacks, which may further improve understanding of the underlying physical mechanisms. Future studies using longer observational datasets, coupled climate model experiments, and subseasonal prediction systems will help isolate these processes and improve confidence in the mechanisms underlying them.

From an operational forecasting perspective, the present results suggest that seasonal outlooks based solely on ENSO indices are likely to overlook important sources of predictability. Incorporating information on the IOD phase, ENSO flavor (EP versus CP El Niño), preferred MJO phase occurrence, and anticipated MJO evolution could potentially improve probabilistic forecasts of both all-India and regional monsoon rainfall. Because rainfall responses to MJO activity vary systematically with the background ENSO–IOD state, understanding these interacting climate modes offers a pathway to improve seasonal monsoon predictions.

4. Conclusions

This study investigated the combined influence of ENSO, IOD, and MJO on the variability of the ISMR during 1975–2025 by systematically classifying monsoon years into different ENSO–IOD categories and examining their associated oceanic, atmospheric, and intraseasonal characteristics. The principal findings are summarized as follows:

(i) The seasonal evolution of Niño3.4 SST anomalies captures the canonical development of El Niño and La Niña from boreal spring to autumn, while substantial event-to-event variability highlights differences in ENSO intensity, persistence, and timing. The IOD also exhibits considerable diversity across ENSO phases, with positive, negative, and neutral events occurring during El Niño, La Niña, and Neutral ENSO years, demonstrating that Indian Ocean variability is not uniquely determined by Pacific SST forcing.

(ii) The combined SST composites indicate that the ENSO–IOD categories represent physically distinct coupled ocean–atmosphere states rather than simple

combinations of independent climate modes. El Niño associated with a positive IOD predominantly exhibits an EP-like El Niño structure, whereas El Niño under neutral IOD conditions is characterized by a CP-like El Niño pattern. These differences become more pronounced during the mature SON season and are accompanied by contrasting atmospheric circulation anomalies.

(iii) Seasonal rainfall varies substantially among the ENSO–IOD categories. Although El Niño generally suppresses and La Niña enhances ISMR, the accompanying IOD phase significantly modifies both the magnitude and regional distribution of rainfall anomalies across India. These rainfall variations are dynamically supported by changes in the large-scale circulation, with strengthened southwesterly monsoon flow and enhanced mid-tropospheric ascent during wet categories, and anomalous subsidence together with weakened monsoon circulation during dry categories.

(iv) Active MJO events occur under all ENSO–IOD conditions but exhibit systematic differences in both amplitude and phase occupancy. El Niño, accompanied by a positive IOD, preferentially favors stronger MJO activity during the Maritime Continent and western Pacific phases (Phase 5–6), whereas La Niña, accompanied by a negative IOD, shows enhanced phase occupancy during Phases 1–2 over the Indian Ocean. The background oceanic state is associated with systematic differences in MJO amplitude and phase occupancy, which in turn are reflected in contrasting intraseasonal rainfall responses.

(v) The intraseasonal rainfall response to MJO phases is strongly influenced by the background ENSO–IOD state. EN&IODp show coherent phase-dependent rainfall evolution, with enhanced rainfall during MJO Phases 5–6 followed by widespread suppression during Phases 7–8, whereas EN&IODu displays a comparatively weaker rainfall response. In contrast, LN&IODn exhibit the strongest and most coherent phase-dependent rainfall enhancement, particularly during MJO Phases 4–5, while LN&IODu show substantially weaker phase locking between rainfall and MJO evolution. Under neutral ENSO conditions, rainfall anomalies become more regionally heterogeneous; notably, the NN&IODu composite exhibits a distinct transition from enhanced rainfall during MJO phase 3 to suppressed rainfall during Phases 6–7, highlighting the dominant role of MJO variability in modulating monsoon rainfall when both ENSO and IOD forcing are weak.

Overall, the results demonstrate that ISMR variability cannot be adequately understood from ENSO alone. Instead, seasonal monsoon rainfall reflects the combined interaction of Pacific SST anomalies, Indian Ocean

variability, and intraseasonal tropical convection associated with the MJO. The background ENSO–IOD state governs not only the large-scale circulation over the Indian region but also the strength, phase occupancy, and rainfall response of individual MJO phases. Consequently, identical MJO phases can produce markedly different rainfall patterns depending on the prevailing interannual oceanic conditions.

Although some ENSO–IOD combinations contain relatively few events and therefore require cautious interpretation, the proposed classification provides a comprehensive framework for investigating multi-scale climate interactions influencing the Indian monsoon. The results further suggest that incorporating ENSO flavour, IOD state, and MJO phase characteristics into operational seasonal forecasting systems could improve probabilistic prediction of both all-India and regional monsoon rainfall. Future studies using longer observational records, large climate model ensembles, and process-based diagnostics will help refine the understanding of these coupled interactions and improve seasonal monsoon predictability.

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Data Availability

The National Oceanic and Atmospheric Administration (NOAA) extended reconstructed monthly sea surface temperature version 5 (ERSSTv5) dataset accessible on their website at <https://psl.noaa.gov>. India Meteorological Department (IMD) gridded rainfall dataset is available on the website https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html. MJO was characterized using the daily Real-time Multivariate MJO (RMM) indices (Wheeler and Hendon, 2004), obtained from the Australian Bureau of Meteorology (BoM). Monthly 850 hPa zonal (u) and meridional (v) winds, together with 500 hPa vertical velocity (ω), were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Climate Data Store (CDS) ERA5 reanalysis dataset.

Code Availability

The underlying code for this study may be made available to qualified researchers on reasonable request from the corresponding author.

Competing Interest

All authors declare no financial or non-financial competing interests.

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