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Characteristics and atmospheric drivers of hiatus events during Indian summer monsoon progression

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Abstract

The northward progression of the Indian summer monsoon (ISM) following its onset over Kerala is frequently interrupted by short lived dry spells, referred to as monsoon progression hiatuses. The mechanisms governing these events remain poorly understood. In this study, an objective framework is developed to identify hiatus events between monsoon onset over Kerala and central India using rainfall and circulation criteria for the period 1971-2025. Composite analyses of long duration hiatuses using IMD rainfall and ERA5 reanalysis datasets reveal that such events are characterized by suppressed rainfall, weakened deep convection, reduced moisture transport and enhanced atmospheric stability. To investigate the underlying mechanism, the vertically integrated moisture deficit flux (VIMDF) is employed to quantify the transport of dry air from the northwest. The results demonstrate that enhanced northwest dry air intrusion precedes and persists throughout the long duration hiatus events, opposing the advancing moist southwesterly monsoon flow and delaying the establishment of a sufficiently moist atmosphere required for sustained convection. Analysis of the long-term record further indicates an increasing frequency of hiatus days during the recent decades. These findings establish dry air intrusion as a key dynamical mechanism regulating interruptions in monsoon progression and provide a physically consistent framework for understanding onset variability and improving sub seasonal prediction.

Keywords: Indian summer monsoon, hiatus in northward progression, dry air intrusion

1. Introduction

Across most regions of India, the southwest monsoon season (June to September) accounts for approximately 75% of the total annual rainfall (Guhathakurta et al. 2015). The onset, duration and rainfall quantity are crucial factors that determine agricultural planning, food security and

livelihood of people in India (Krishna Kumar et al. 2004; Gadgil and Rupa Kumar 2006). The onset of monsoon rains occurs in May over the southern Andaman Sea (Zhang et al. 2004; Ding and Sikka 2006) after which monsoon winds progress northwestward across the Bay of Bengal (Pai et al. 2020). After advancing over the Bay of Bengal, the monsoon sets over South India, particularly over the state of Kerala early June (Pai and Rajeevan 2009). The monsoon onset over Kerala, hereafter referred to MOK, signifies the beginning of its advancement over India (Pai and Rajeevan 2009), and marks a transition from hot-dry season to rainy season (Fasullo and Webster 2003). The traditional IMD definition of monsoon onset is based on the establishment of sustained rainfall over Kerala along the southwest coast of India. According to this definition, the climatological onset date is 1 June, with an interannual standard deviation of approximately 8-9 days (Ju and Slingo 1995; Krishnamurthy and Shukla 2000). This onset is accompanied by intense rainfall over the southern peninsula, primarily driven by the cross-equatorial low-level jet (LLJ) (Joseph and Sijikumar 2004). Following its onset over Kerala, the Northern Limit of Monsoon (NLM) identified as isochrones, gradually advances northward, typically covering the entire Indian subcontinent by mid-July (Tyagi et al. 2011). It is noticed that the advance is generally faster along the West coast and northeastern edge near the Himalayas than it is through central India (Recchia et al. 2021).

The monsoon onset and progress dates across the Indian region is determined subjectively by the India Meteorological Department (IMD) operationally, based on a sharp increase in rainfall, its sustenance for several days and the corresponding changes in atmospheric circulation patterns (Pai et al. 2020). In this way, IMD regularly updates the isochrones in the monsoon onset map to reflect these subjectively determined onset and progress dates, ensuring that the map accurately represents the evolving patterns of monsoon advancement based on real-time observations of rainfall and atmospheric circulation changes. Although several studies have estimated monsoon onset and advance dates over specific stations or regions based on rainfall and circulation features (Ananthakrishnan and Soman 1988; Fasullo and Webster 2003; Wang et al. 2009; Misra et al. 2018), the IMD declared onset charts provide a definitive and widely accepted standard, making them a more reliable choice for any analysis. After the MOK, the northward advance of monsoon happens along the western coast, westward along the foothills of the Himalayas, and northwestward from the Bay of Bengal into northwestern India, covering the entire country by

about 15 July. Fig. 1 illustrates a schematic of isochrones of mean onset dates over India as determined by IMD.

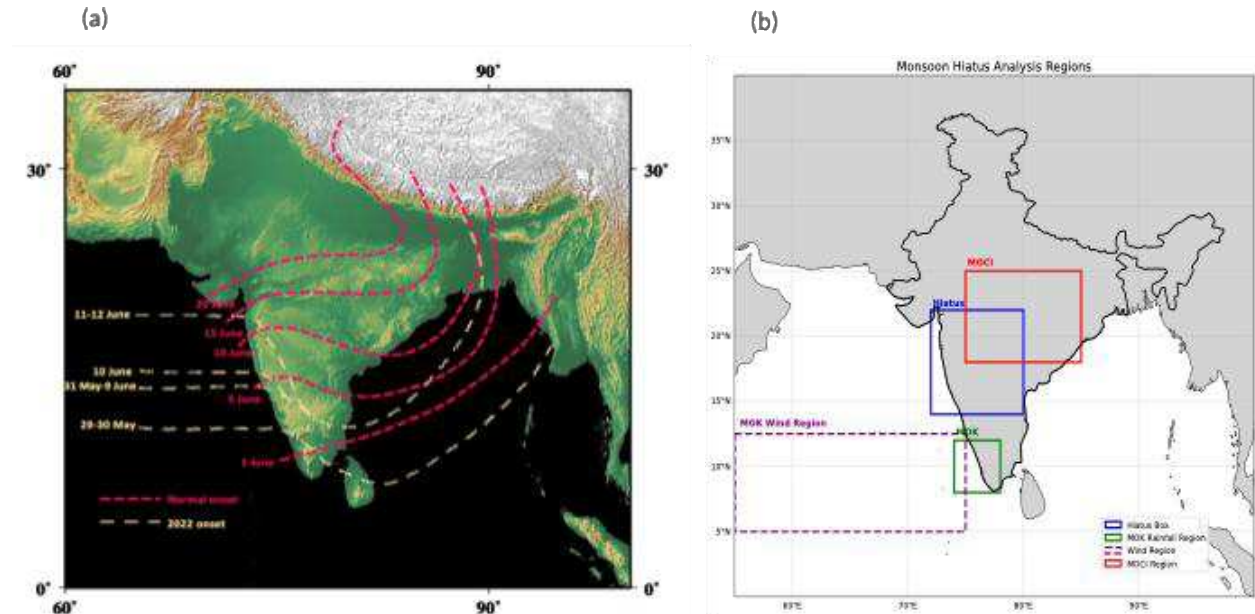


Fig 1 Monsoon onset progression during a hiatus event and regions chosen for developing the objective criterion. a) Schematic showing the progression of Indian summer monsoon onset. The red lines show the isochrones corresponding to normal onset. The light-yellow lines show the isochrones for 2022 onset with pauses identified from 31 May to 9 June. Isochrones adapted from IMD onset maps. Image generated using GMT with elevation tiles from GLOBE database. b) Regions chosen for the objective criteria of hiatus defined in this manuscript.

Several mechanisms have been proposed to explain the timing of monsoon onset over the Indian subcontinent, including land-sea thermal contrast, upper tropospheric warming over the Tibetan Plateau, cross-equatorial moisture transport, and largescale changes in the tropical circulation (Li and Yanai 1996; Fasullo and Webster 2003; Goswami and Xavier 2005). While these provide valuable insight into the seasonal transition from dry to monsoon regime, they address the large-scale onset process and do not fully explain the observed structure of the monsoon advancement toward the northwest. MOK is marked by enhanced convection and a strengthened low-level jet. However, rather than advancing continuously northward, the monsoon onset often undergoes a brief period of weakening and reorganization before resuming its rapid progression across the Indian subcontinent, a characteristic feature highlighted in many studies (Joseph et al. 2006).

This year-to-year variability in northward progression has significant implications on agriculture planning and management. Some years, the monsoon takes longer to reach central India, after which it rapidly progresses to the rest of the country. In other cases, there exists a swift progression to central India but slows down later. From Fig. 1a, it is seen that the northwestward propagation of the onset isochrones happens in pulses (Rajeevan et al. 2025), largely influenced by the monsoon intraseasonal oscillations with moistening of soil by shallow convection acting as a precursor to northward progression (Krishnamurti et al. 2012). The rate at which monsoon onset progresses depends on frequency and duration of dry spells during the onset phase. There are years with prolonged stagnation in northward progression right after MOK over the south peninsula (Sikka 2011). This period is henceforth referred to as hiatus in monsoon progression (as in Fig. 1a for the year 2022). The duration and frequency of such hiatuses critically govern the meridional advancement of onset isochrones and drive interannual variability in rainfall distribution across the country (Chakraborty and Agrawal 2017), especially during the month of June. The advance of monsoon rainfall belt does not simply follow the moisture transport by the mean low-level flow (Parker et al. 2016), implying additional dynamical and thermodynamical processes regulating its progression. Consequently, periods during which monsoon temporarily stalls or weakens provide a valuable framework for understanding processes that control monsoon advancement.

The hiatus holds significant agricultural implications. After the monsoon onset over Kerala, farmers rely on the timely arrival of monsoon rains to plan their seed sowing and to procure necessary resources in advance (Gadgil and Rupa Kumar 2006). Any delay in onset can lead to financial losses due to wasted efforts in land preparation, irrigation, and other pre-sowing activities, particularly affecting the Kharif crops that depend heavily on monsoonal rainfall. The societal importance of monsoon onset timing is highlighted by the extreme cases of 2013 and 2014. The rapid northward advance of monsoon in 2013 which covered the entire country by 16 June, was associated with exceptionally heavy rainfall and devastating floods over Uttarakhand (Joseph et al. 2015; Pattanaik et al. 2015). In contrast, the delayed and sluggish progression of the 2014 monsoon contributed to prolonged hot and dry conditions over large parts of northern and central India (Vaid and Kripalani 2021). Between 1960-2024, the average monsoon hiatus lasted 6 days, with a standard deviation of 3 days (Rajeevan et al. 2025). From the IMD data of monsoon progression, a statistically significant increasing trend in the hiatus duration was found, indicating

that since 1960, the number of hiatus days has increased by approximately 4 days (Rajeevan et al. 2025).

According to the literature, the hiatus has long been shown to be associated with the intrusion of dry midlatitude air from northwest of India and adjoining West Asia (Krishnamurti et al. 2010; Parker et al. 2016) which inhibits the convective activity associated with monsoon onset and thus the pace of monsoon. As the monsoon progresses across India, the moisture advection from Arabian Sea intensifies, gradually moistening the mid-level dry air from below. This enhanced moistening reduces the depth of the dry air layer allowing the NLM to advance northwestward (Parker et al. 2016). The unsteady progression of the monsoon toward northwest India is thus governed by the interplay of diverse air masses and shaped by a combination of multiscale factors, including midlatitude dynamics, transient weather systems and local diabatic processes (Volonté et al. 2020). Saini et al. (2011) highlights the role of warm air advection and upward motion over northern India as key factors in the northward progression of the NLM following the initial MOK. Many studies have identified dry air intrusions as an important mechanism contributing to the break phase of the monsoon (Singh and Sandeep 2022, 2024; Deoras et al. 2026). However, considerably less attention has been paid to their potential influence during the monsoon onset phase and its subsequent northward progression. Given that a range of atmospheric and oceanic processes can modulate the advance of the monsoon, there is a clear need to identify and characterize the mechanisms that influence monsoon onset and progression. This can be achieved through developing a unified framework that lays out complex interactions that drive monsoon onset. Recently, Deoras et al. (2026), proposed the vertically integrated moisture deficit flux (VIMDF) as a physically based metric to quantify the transport of dry air in the troposphere. Given the potential influence of dry air intrusions on monsoon progression, the VIMDF framework is employed in the present study to investigate their role during monsoon hiatus events. This manuscript aims to establish the presence of a hiatus in the northward progression of the ISM, explore its underlying mechanisms, and explain its long-term trends.

The rest of the manuscript focuses on identifying and characterizing hiatus events in the northward progression of the Indian summer monsoon, using the definition developed herein to objectively capture this phenomenon. The manuscript is structured as follows: section 2 details the data sources and methodologies used to identify and characterize the hiatus events, section 3 presents the key results including spatial and temporal characteristics of hiatus period and associated

atmospheric features and evidence of a long-term trend in their duration. Section 4 discusses the key findings and their broad implications while section 5 summarizes the main conclusions of the study.

2. Data and methods

2.1 Data

The analysis makes use of daily gridded rainfall data with horizontal resolution of $0.25^{\circ} \times 0.25^{\circ}$, developed using observations from rain gauge stations across India and obtained from the IMD for the period 1971-2025 (Pai et al. 2014). We also used the ERA5 post-processed daily statistics data (Hersbach et al. 2020) for total precipitation at $0.25^{\circ} \times 0.25^{\circ}$ resolution since IMD data covered only land rainfall. The atmospheric parameters used in this study (wind fields and OLR) are obtained from ERA5. The suitability of using ERA5 data for monsoon circulation and thermodynamic fields were assessed by multiple studies (Deoras et al. 2024, 2026) and were found reliable. All variables considered in this study are daily statistics.

2.2 Definition of hiatus

The northward progression is documented each year by the IMD through a set of isochrones that delineate the NLM on successive dates. While these maps provide the most widely used depiction of monsoon advance, the determination of local onset beyond Kerala incorporates a degree of expert judgement and may therefore be subject to temporal inconsistencies. To overcome this limitation and ensure reproducibility, we develop an objective criterion to identify hiatus events in monsoon progression. Specifically, the IMD isochrones are used only to establish the climatological pathway of monsoon advance, while the occurrence and duration of hiatus events are determined using objectively defined rainfall-based conditions applied consistently across the entire analysis period. This approach removes subjective interpretation from the identification of hiatuses and provides a transparent framework for examining interruptions in the northward progression of the monsoon.

An objective methodology is developed to identify hiatus events during the northward progression of the Indian summer monsoon for the period 1971-2025. The method consists of three steps: determination of MOK, identification of monsoon onset over Central India (MOCI), and detection

of hiatus spells occurring between these two milestones. The respective regions chosen for the following analysis are shown in Fig 1b.

I) Determination of MOK

The date of the MOK was determined using a combination of rainfall and lower tropospheric westerly wind criteria. Daily area-averaged rainfall was computed over the Kerala region (8° - 12° N, 74° - 78° E). Simultaneously, zonal wind at pressure levels between 1000 and 600 hPa was averaged over the southeastern Arabian Sea (5° - 12.5° N, 55° - 75° E)

After 15 May of each year, the first day satisfying both of the following conditions was identified as the MOK date:

- i) Area-averaged rainfall over the Kerala box exceeded 4 mm/day for at least three consecutive days.
- ii) Vertically averaged zonal wind exceeded 3 m/s for at least ten consecutive days.

The use of both rainfall persistence and sustained low-level westerlies ensures that the identified onset reflects an established monsoon circulation rather than isolated rainfall events. The adopted criteria are consistent with existing monsoon onset definitions (Pai and Rajeevan 2009) and their subsequent use (Chakraborty and Agrawal 2017).

II) Determination of MOCI

Following the identification of MOK, the progression of the monsoon into the central India was tracked using rainfall. Daily area-averaged rainfall was computed over Central India (18° - 25° N, 75° - 85° E). The MOCI date was defined as the first day after MOK on which rainfall exceeded 5 mm/day for three consecutive days. This criterion identifies the establishment of sustained monsoon rainfall over central India and provides an objective endpoint for evaluating interruptions in northward progression of monsoon and closely follows the objective definition (Chakraborty and Agrawal 2017) previously used for MOCI determination.

III) Identification of hiatus events

Hiatus events were identified within the period bounded by MOK and MOCI over a region representative of the climatological pathway of monsoon advance across peninsular India (14° - 22° N, 72° - 80° E). Daily area-averaged rainfall was computed over this domain. The selected domain encompasses the climatological corridor through which the monsoon advances from

Kerala toward central India and therefore provides a representative measure of interruptions in its northward progression.

A hiatus spell was defined as a period of at least three consecutive days during which the average rainfall remained below 3 mm/day. All such dry spells occurring between MOK and MOCI were identified for each year. The duration of this longest spell was taken as the annual hiatus duration. In years with multiple hiatus spells, the longest dry spell was selected as the representative hiatus event. This approach provides an objective and reproducible measure of interruptions in the northward progression of the monsoon between its establishment over Kerala and its subsequent advance into central India. The domain used for the identification of hiatus events is shown in Fig 1b.

2.3 VIMDF calculation

To quantify the dry-air intrusions associated with monsoon hiatus events, we employ the Vertically Integrated Moisture Deficit Flux (VIMDF) (Deoras et al. 2026). The VIMDF represents horizontal transport of atmospheric moisture deficit and is defined as

$$VIMDF = \frac{1}{g} \int_{850}^{300} \mathbf{u} (q_e - q) dp$$

where $\mathbf{u}$ is the horizontal wind vector, q_e is the saturation specific humidity, q is the specific humidity, p is pressure and g is acceleration due to gravity. Unlike saturation deficit indices that characterize only the local dryness of an air mass (Singh and Sandeep 2022), the VIMDF explicitly accounts for the vertically integrated horizontal transport of moisture-deficient air and is therefore better suited for identifying dry-air intrusions advected into the monsoon region (Deoras et al. 2026). Previous studies have shown that dry intrusions influencing monsoon onset, breaks and withdrawal are predominantly of mid-tropospheric in origin, with a core near 600 hPa, although they may occasionally extend to lower levels (Bhat 2006; Krishnamurti et al. 2010; Deoras et al. 2024, 2026). To capture the full vertical structure of these intrusions, the VIMDF is vertically integrated between 850 and 300 hPa. Daily VIMDF anomalies are calculated relative to the climatological daily mean for the study period, with positive anomalies indicating enhanced transport of anomalously dry air relative to climatology. Area-averaged VIMDF anomalies relative to hiatus onset as lead-lag composites are subsequently used to investigate the evolution and contribution of dry air intrusions during long-duration hiatus events.

2.4 Northwest dry air index

Following the VIMDF based index formulation (Deoras et al. 2026), a Northwest Dry Intrusion Index (NW-DII) was derived to quantify the strength of dry air intrusion from the northwest during monsoon hiatus events. The index was calculated as the area averaged magnitude of VIMDF over 26° - 32° N and 64° - 70° E, a domain encompassing northwestern India and adjoining eastern Pakistan (Deoras et al. 2026). Here, the VIMDF based index is referred to as NW-DII to specifically characterize the northwest dry air intrusion associated with monsoon hiatus events. The index was calculated for each day relative to hiatus onset, with Day 0 representing the first day of the hiatus.

2.5 Anomaly calculations

To investigate the evolution of large-scale atmospheric conditions associated with long-duration hiatus events, anomaly composites were constructed relative to the hiatus onset day. Following the pentad-based approach commonly adopted in monsoon studies (Wang and LinHo 2002), atmospheric fields were composited over the five days preceding (lead) and following (lag) hiatus onset. Pentad averaging reduces high-frequency synoptic variability and highlights the dominant monsoon-scale and sub seasonal circulation signals associated with monsoon progression and interruption. To further examine the temporal evolution of dry-air intrusion, VIMDF anomalies were composited separately for each lead and lag day (-5, -4, -3, -2, -1, +1, +2, +3, +4, and so on) relative to hiatus onset, allowing the day-to-day development and onset of moisture-deficit transport associated with the hiatus events to be quantified.

3. Results

3.1 Characteristics of monsoon hiatus events

Applying the hiatus identification criterion described in section 4, we identified 39 monsoon hiatus events during the 1971-2025 (Table S1). The identified events occurred between late May and early June mostly, with considerable interannual variability in their timing and duration. The onset and end date of hiatus are listed in Table S1, providing basis for examining the temporal characteristics and associated atmospheric conditions. The hiatus duration ranges from 3 days (e.g., 1971, 1976, 1980, 1991, 2000, 2007 and 2017) to 14 days (2009, 2020 and 2024). Several

years (e.g., 1973 and 2013) did not exhibit any hiatus event during the progression from Kerala to central India, and are indicated by NA (or zero duration) in Table S1.

The climatological characteristics of monsoon hiatus events are summarized in Fig 2. Hiatuses occur preferentially during the MOK phase, with highest frequency observed from late May to early June (Fig 2a). The occurrence frequency decreases gradually toward mid and late June, indicating that the interruptions to monsoon progression are most common during the transitional stage when the large-scale monsoon circulation is still evolving. Once the monsoon becomes more firmly established, the frequency of hiatus days declines substantially. The duration distribution (Fig 2b) shows that most hiatus events are relatively short-lived, typically lasting between 3 and 6 days. The frequency decreases with increasing duration, although several events persist for more than 10 days, demonstrating that prolonged interruptions in monsoon advancement can occasionally occur. Together, these results suggest that monsoon hiatuses are a recurrent feature of the onset season, with few cases evolving into extended hiatus episodes.

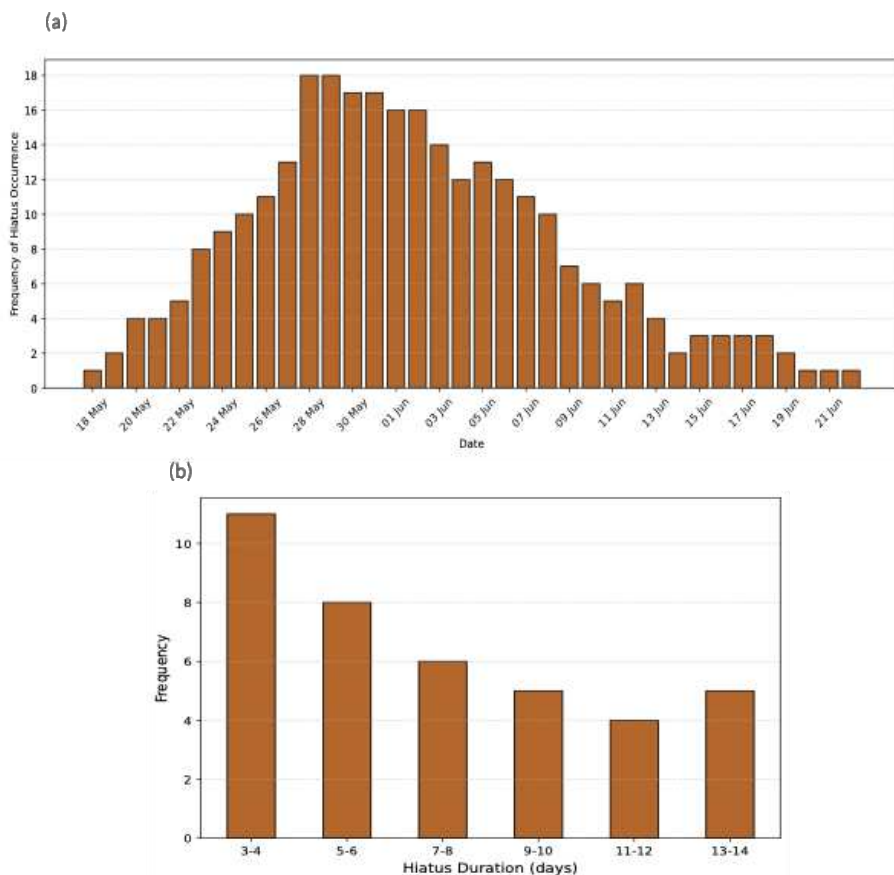


Fig 2 The climatological characteristics of monsoon hiatus events during 1971-2025. a) Frequency of occurrence of hiatus days defined in Table S1. The X axis shows the distribution of dates and the Y axis represents the number of years in which each specific date fell within a hiatus period. The frequency is computed using the entire duration of each hiatus event rather than only the onset date. b) Frequency distribution of hiatus duration, showing the number of events within each duration class.

Over the period 1971-2025, hiatus durations ranged from 3 days to 14 days, while several years did not exhibit a hiatus event. Considering all years, including those with zero duration, the 75th percentile of the duration distribution is 8.5 days. Accordingly, hiatus events exceeding this threshold (≥ 9 days) are classified as long-duration hiatuses and are used for subsequent composite and mechanism analysis. This percentile-based approach allows the focus to be placed on the most persistent hiatus events while retaining a sufficient sample size for robust statistical assessment. A total of 14 such events were identified for the 1971-2025 period. Anomaly composites of these long-duration hiatus events were constructed for different lead and lag days relative to the hiatus onset day to examine the evolution of the associated large-scale atmospheric conditions.

3.2 Meteorological signatures

Since the northward progression of the monsoon is closely linked to the spatial distribution and persistence of rainfall, precipitation anomalies are examined to characterize the hydroclimatic signature of the identified hiatus events and to assess the extent of suppressed precipitation associated with interruptions in monsoon progression.

Composite anomalies of rainfall from the IMD data, analyzed over three different periods (before, during and after hiatus as discussed in section 4) for the identified long-duration hiatus events, reveal distinct features (Figs 3a-c). Before the start of the hiatus, there is a clear increase in rainfall over the southern parts of the Indian peninsula, indicating the northward advancement of the monsoon convergence zone up to 18°N, representing the MOK. During the hiatus period, the composite anomalies show significant drying, particularly over the northern parts of Western Ghats, a region typically experiencing heavy rainfall after MOK (Revadekar et al. 2018) and over central India. After the end of hiatus, rainfall intensity gradually increases over the southern

peninsula and central India, accompanied by the northward extension of the NLM. To validate these findings, we compared the results with ERA5 rainfall estimates, which produced similar results. ERA5 analysis confirms that, before the hiatus, monsoon onset over the Kerala coast is evident, along with positive rainfall anomalies over the Arabian Sea and Bay of Bengal (Saini et al. 2011) (Fig S1). During the hiatus, drying is observed across the Indian mainland and surrounding ocean, particularly over the Arabian Sea. Interestingly, during this period, enhanced rainfall is noted over the Vietnam coast/South China Sea region. After the hiatus, rainfall recovers over the Arabian Sea, and the NLM advances further into central India, accompanied by positive rainfall anomalies across surrounding oceans. This analysis establishes that hiatus is a prominent feature of the Indian monsoon advancement after its onset over Kerala.

To further quantify the temporal evolution of rainfall associated with major hiatus event, Fig 3d presents the lead-lag composite of area averaged rainfall anomalies over the core hiatus region (14° - 22° N, 72° - 80° E). Consistent with the spatial composites (Fig 3a-c), positive rainfall anomalies prevail during the five days preceding the onset of the hiatus, indicating enhanced convective activity over the region. The anomalies reach their maximum approximately three days before the hiatus onset, exceeding 2.5mm/day. During the hiatus period, the rainfall decreases abruptly, transitioning into a significant negative anomaly of about -1.2mm/day, which marks the suppression of monsoon convection during the hiatus period. Following the hiatus period, the rainfall recovers rapidly with positive anomalies reappearing from Day +1 onward. The recovery strengthens after Day +6 and rainfall anomalies exceed 2 mm/day around Day +9 to +10, indicating the re-establishment of active monsoon conditions. The error bars represent the inter-event standard deviation highlighting the event-to-event variability while demonstrating that the composite evolution exhibits robust transition from enhanced rainfall before the hiatus to suppressed rainfall during the hiatus, followed by a gradual recovery afterward.

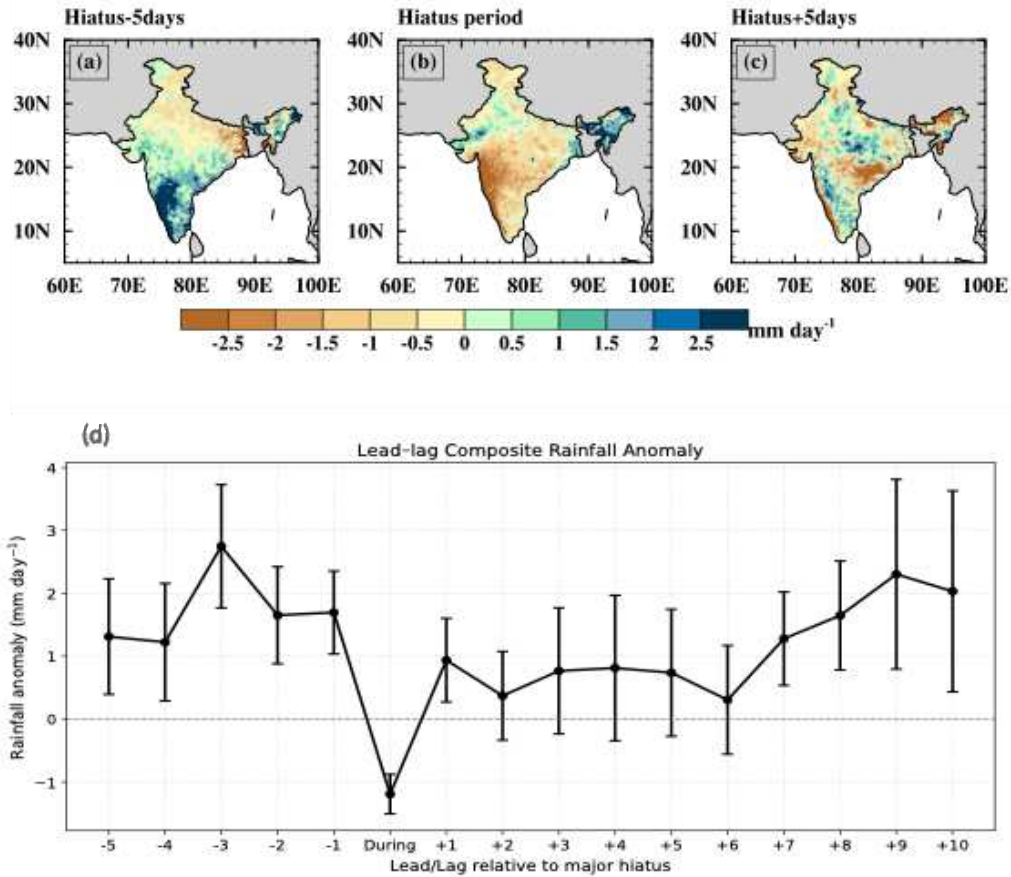


Fig 3 Composite anomaly of rainfall (a) Average of 5 days preceding the onset of hiatus, (b) Average of hiatus days and (c) Average of 5 days following the end date of hiatus from IMD rainfall. (d) shows lead-lag composite rainfall anomaly relative to the major hiatus events over the hiatus region (14°-22°N, 72°-80°E), with error bars showing the inter-event standard deviation. All figures are plotted considering only the long-duration hiatus events from 1971-2025.

While the rainfall composites establish the temporal evolution of precipitation associated with major hiatus events, they do not reveal the accompanying changes in deep convection and the large-scale monsoon circulation. Figure 4a shows the composites of ERA5 OLR anomalies during long-duration monsoon hiatus events. Five days prior to hiatus onset (Fig 4a), a pronounced region of negative OLR anomalies is evident over southern peninsular India and surrounding oceans, indicating enhanced convection and increased cloudiness, suggesting active monsoon conditions. The spatial extent of convective enhancement extends from peninsular India into the northern Bay

of Bengal, reflecting a well-established monsoon circulation and vigorous rainfall-producing systems. During the hiatus period, the anomaly pattern undergoes a marked reversal. Positive OLR anomalies emerge over central India and the adjoining Arabian Sea, with the largest values concentrated over south-central India. The increase in OLR indicates suppressed deep convection and reduced cloud cover, consistent with the substantial decrease in rainfall observed during hiatus conditions. Concurrently, negative OLR anomalies develop over the western North Pacific and parts of Southeast Asia, suggesting a redistribution of convective activity away from the Indian monsoon region. The transition from widespread negative OLR anomalies prior to hiatus onset to positive anomalies during the hiatus demonstrates a large-scale weakening of monsoon convection over India. The close spatial correspondence between enhanced OLR and reduced rainfall confirms that hiatus events are characterized not only by temporary stagnation of monsoon progression but also by a pronounced suppression of deep convective activity over the monsoon region.

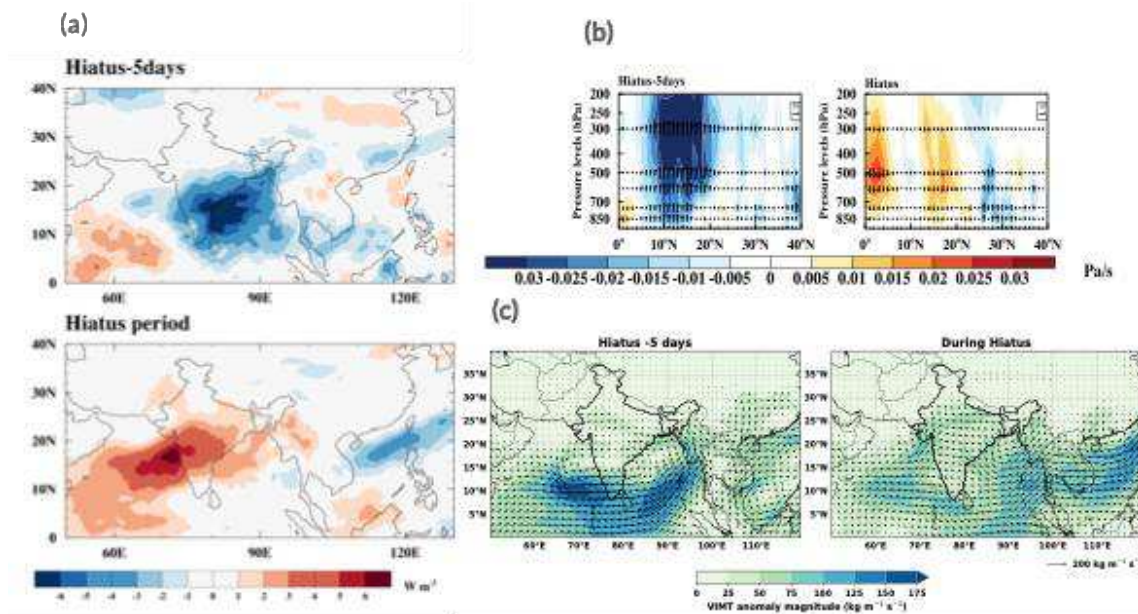


Fig 4 Composite anomaly of meteorological characteristics a) Outgoing longwave radiation (in W/m^2), b) Vertical cross-section of vertical velocity and meridional circulation (in Pa/s , scaled by a factor of $\ast -500$, with upward motion shown as negative values) averaged across 70°E - 90°E latitude band and c) Vertically integrated moisture transport between 950-500 hPa with shading denoting magnitude of vimt anomaly, for 5 days preceding the onset of hiatus and during the hiatus days, considering only long-duration hiatus events from 1971-2025.

The zonally averaged (70° - 90° E) latitude-pressure cross section of vertical velocity anomalies further confirms the changes in the large-scale monsoon circulation during the major hiatus events (Fig 4b). A pronounced anomalous descending motion is observed over the core monsoon latitudes (10° - 20° N). This subsidence is strongest between the 500 and 300 hPa and is consistent with OLR anomalies, indicating suppression of deep convection during the hiatus period. The vertical extent of the anomalies implies that the hiatus is associated with a weakening of the climatological monsoon Hadley circulation, characterized by reduced ascent over the monsoon rain belt and enhanced subsidence over the Indian landmass. These circulation changes provide a dynamical explanation for the marked reduction in rainfall observed during the major hiatus events.

Changes in convective activity during the hiatus are closely coupled with variations in the large-scale transport of atmospheric moisture, which regulates the supply of water vapor to the Indian monsoon region (Simmonds et al. 1999; Fasullo and Webster 2003). To examine the evolution of the moisture transport associated with hiatus events, composite anomalies of vertically integrated moisture transport (VIMT) integrated between 950 and 500 hPa are analyzed for the five days preceding the onset of the hiatus and during the hiatus period (Fig 4c). This layer consists of the primary moisture bearing portion of the tropical atmosphere and captures the bulk of horizontal transport associated with the summer monsoon circulation. Prior to the onset of hiatus, enhanced anomalous southwesterly moisture transport is evident over the Arabian Sea and southern peninsular India, extending northwestward towards the Bay of Bengal. The transport pathway reflects an active supply of moisture from the Arabian Sea, supporting the northward progression of convection during the monsoon onset phase. The strongest anomalies are confined to the southern Arabian Sea and southern peninsular India, consistent with the establishment of monsoon flow and the increasing moisture availability over the Indian subcontinent (Findlater 1969; Fasullo and Webster 2003). During the hiatus period, the anomalous moisture transport weakens substantially over the Arabian Sea and peninsular India, while the transport vector becomes less coherent over central India. The reduction in the magnitude and organization of the anomalous southwesterly moisture transport indicates a weakened horizontal supply of moisture. This is consistent with the concurrent suppression of convection inferred from the positive OLR anomalies and weakened ascending branch of the meridional circulation, suggesting that reduced

moisture availability contributes to the interruption of the northward propagation of monsoon convection.

While the rainfall and OLR composites clearly demonstrate the suppression of convection during major hiatus events, an important question remains: What dynamical processes are responsible for the abrupt weakening of convection and rainfall over the monsoon region? To address this, the large-scale circulation associated with major hiatus events is examined.

3.3 Plausible mechanism

The pronounced concentration of hiatus events during the active phase of monsoon progression suggests a linkage with transient large-scale dynamical processes that can temporarily suppress the northward advance of the monsoon. To identify the processes driving the observed hiatus in monsoon progression, it is essential to examine large-scale atmospheric conditions that can influence convection and circulation during this transitional phase. One such process is the mid-level dry air intrusion during the monsoon onset phase, which plays a critical role in modulating the monsoon rainfall and convection (Bhat 2006; Parker et al. 2016). The intrusion of dry air mainly comes from subtropical regions into the monsoon regions around 600-700hPa (Minoura et al. 2003; Recchia et al. 2021) explains a multilayer idealized model of ISM onset, based on moisture conservation along a vertical atmospheric section extending from northwest to southeast India. It explains respective roles of low-level convection and moisture replenishment as well as an upper-layer advection.

Previous studies have primarily quantified these intrusions using measures of low to mid tropospheric moisture deficit or saturation deficit (Singh and Sandeep 2022, 2024) which effectively describe the thermodynamic state of the atmosphere. However, these metrics do not explicitly account for the dynamical transport of dry air by the circulation. To quantify the transport of dry air into the monsoon region, we employ the vertically integrated moisture deficit flux (VIMDF) defined by Deoras et al. (2026) for investigating the role of dry air intrusions during the monsoon break events. Unlike conventional humidity or saturation deficit-based diagnostics, VIMDF explicitly combines the atmospheric moisture deficit with the horizontal wind field, thereby quantifying the transport of dry air rather than merely its presence. Since mid-level dry northerly intrusions can suppress deep convection, they delay the monsoon onset and progress. Therefore, the weakening of these intrusions, likely play a crucial role in the transition to active

monsoon conditions. We apply this framework to assess whether enhanced dry air transport serves as a precursor to the onset and maintenance of major hiatus events. To examine this hypothesis, composite anomalies of VIMDF are constructed for the lead-lag period spanning five days before to five days after the onset of major hiatus events. Figure 5 presents the composite anomalies of VIMDF and the associated moisture deficit flux vectors for the five days preceding the hiatus, during the hiatus and five days after its termination.

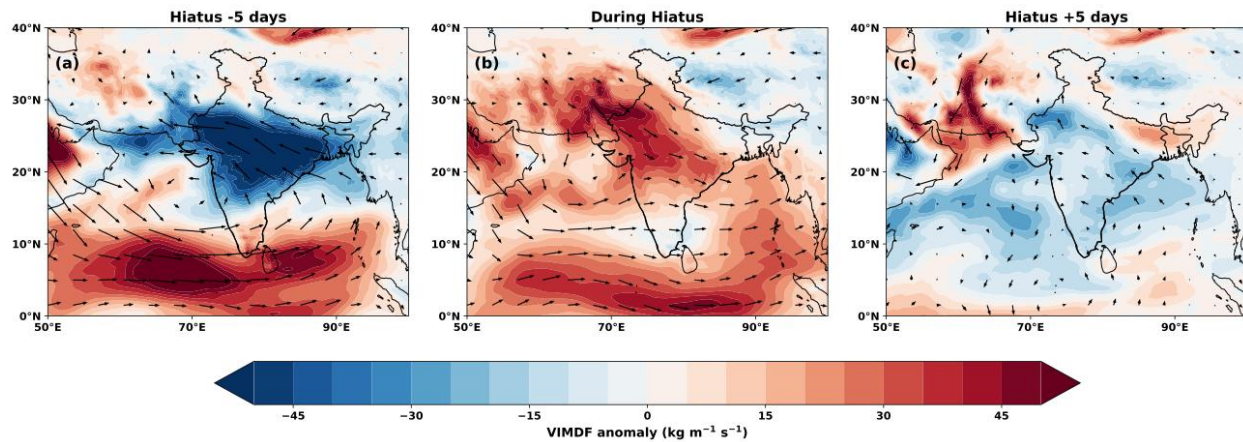


Fig 5 Composite anomaly of VIMDF. Average of VIMDF for a) 5 days preceding the onset of hiatus b) hiatus duration and c) 5 days after the end of hiatus, considering only long-duration hiatus events from 1971-2025.

Five days prior to the hiatus, a broad region of negative VIMDF anomalies is evident over central and peninsular India, extending from 65° - 90° E and 15° - 28° N (Fig 5a). These anomalies indicate a weakening of dry air transport into the monsoon region, consistent with enhanced moisture availability and active convective conditions identified in the rainfall and OLR composites associated with MOK. The moisture deficit flux vectors are relatively weak over the monsoon region, suggesting limited intrusion of dry air. During the hiatus, the VIMDF pattern undergoes a marked reversal (Fig 5b). Strong positive anomalies develop over northwestern and central India and extend southeastward into the core monsoon region, accompanied by anomalous moisture deficit flux vectors directed toward the Indian subcontinent. This pattern indicates an enhanced transport of dry mid-tropospheric air into the monsoon region, consistent with the suppression of deep convection inferred from OLR and rainfall anomalies. The coincidence of strengthened VIMDF with the hiatus period suggests that the dry air advection plays an important role in

maintaining the suppressed convective state. Following the hiatus, positive VIMDF anomalies weaken substantially and are replaced by widespread negative anomalies over much of India (Fig 5c) indicating restoration of moist environments favorable for deep convection, consistent with the recovery of rainfall.

To quantitatively examine the temporal evolution of dry air transport during major hiatus events, a northwest dry intrusion index (NW-DII) is constructed by area-averaging the VIMDF anomalies over the principal dry air intrusion region (26° - 32° N, 64° - 70° E). This northwestern sector was identified by Deoras et al. (2026) as the primary source region of dry air intrusions influencing the Indian summer monsoon break events and was used to define an analogous dry intrusion index based on VIMDF. The resulting NW-DII provides a quantitative measure of the strength of dry air transport from northwest subtropics into the Indian monsoon region. To assess its influence on monsoon activity, the lead lag evolution of NW-DII is compared with the area averaged rainfall anomaly over the defined hiatus region (14° - 22° N, 72° - 80° E).

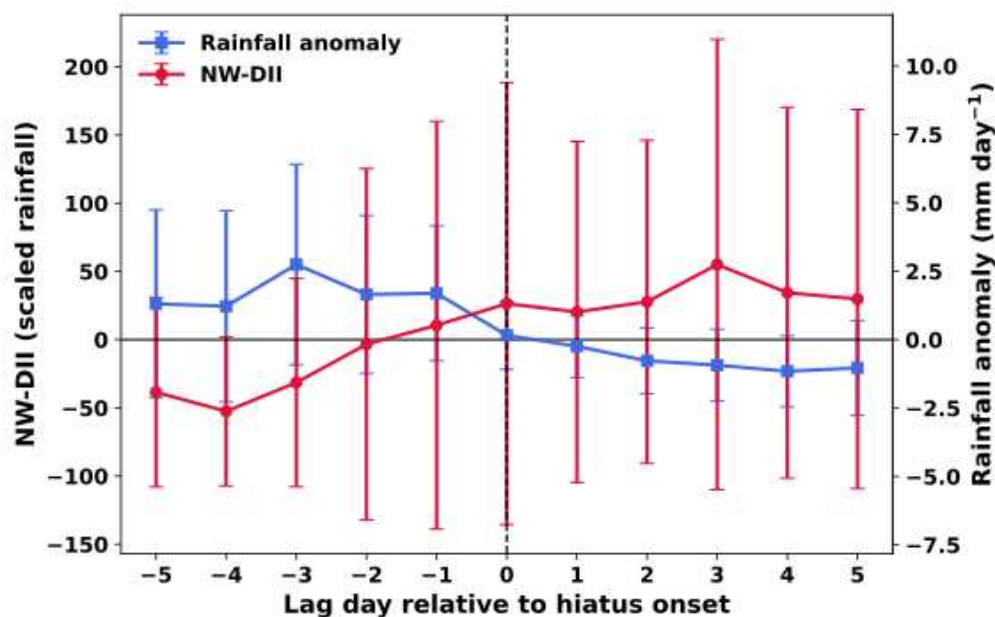


Fig 6 Lead-lag evolution of NW-DII and rainfall. The northwest dry intrusion index (NW-DII) (red) and the area averaged rainfall anomaly over the hiatus region (blue) relative to the onset day of major monsoon hiatus events. Error bars denote one standard deviation across all major hiatus events.

Figure 6 illustrates the lead lag evolution of NW-DII together with rainfall anomaly relative to the onset of major hiatus events. The rainfall anomaly remains positive during the five days preceding the hiatus, indicating active convective conditions over the hiatus region, whereas the NW-DII is predominantly negative, implying weak dry air transport from the northwest. Around the onset of hiatus (Day 0), the two indices exhibit a clear transition, with rainfall decreasing rapidly while NW-DII becomes positive, indicating an intensification of dry air transport into the monsoon region. The NW-DII continues to strengthen after the onset, reaching its maximum around Day +3, whereas rainfall remains suppressed. Throughout the duration of the objectively defined hiatus, NW-DII remains persistently positive, while the rainfall anomaly remains negative, demonstrating the sustained influence of enhanced dry air transport during the hiatus period.

The composite analyses presented above establish that enhanced northwestern dry air transport is closely associated with the initiation and maintenance of major hiatus events. The coherent evolution of VIMDF, NW-DII, rainfall and convection suggest that dry air intrusion is a key dynamical mechanism regulating the occurrence of these events. This raises the question of whether the occurrence of monsoon progression hiatuses has changed over the observational period. In particular, examining the long-term variability in the duration of hiatus events can provide insights into whether major/long-duration hiatuses have become more or less prevalent over the decades. We therefore next investigate the long-term changes in the number of hiatus days over the study period.

3.4 Long-term trend in number of hiatus days

Having examined the mechanisms driving hiatuses in monsoon progression, we now turn to the long-term variability associated with the frequency of hiatus days each year. Rajeevan et al., investigated such events over the period 1961-2024 and reported a significant increasing trend subjectively using IMD charts(Rajeevan et al. 2025). Figure 7 extends this analysis by highlighting the temporal evolution and identifying trends across different decades, offering insights into how the frequency of hiatus days has changed over time.

Figure 7 shows the interannual variability and long-term trend in the annual number of hiatus days during 1971-2025 defined as per our objective criteria (section 4). Considerable year to year variability is evident, with hiatus days ranging from no major events in several years to more than

14 days in others. Over the entire analysis period, the number of hiatus days exhibits an increasing trend of 0.062 days/yr, although the trend is only marginally significant ($p=0.077$). A more pronounced feature, however, is the contrasting behavior before and after the late 1990s. During 1971-1997, the number of hiatus days shows a weak decreasing tendency (-0.132 days/yr) whereas 1998-2025 is characterized by a significant increasing trend (0.267 days/yr; $p=0.036$). The post 1998 period is also marked by a greater frequency of years experiencing prolonged hiatus conditions, suggesting that major hiatuses have become increasingly common in recent decades. These trends are of particular concern given that the hiatus period coincides with the onset phase of the ISM, a critical window for agricultural planning and water resource management. The emergence of a significant increase in hiatus days after the late 1990s raises an important question: Has the large-scale dry air transport associated with these events also undergone a systematic change? Although dry air intrusion from northwest is a key characteristic of individual hiatus events, our analysis did not reveal a robust long-term increase in the associated VIMDF during 1971-2025. This suggests that the observed increase in hiatus days may arise from changes in multiple interacting dynamical and thermodynamical processes rather than from a monotonic strengthening of dry air intrusion alone.

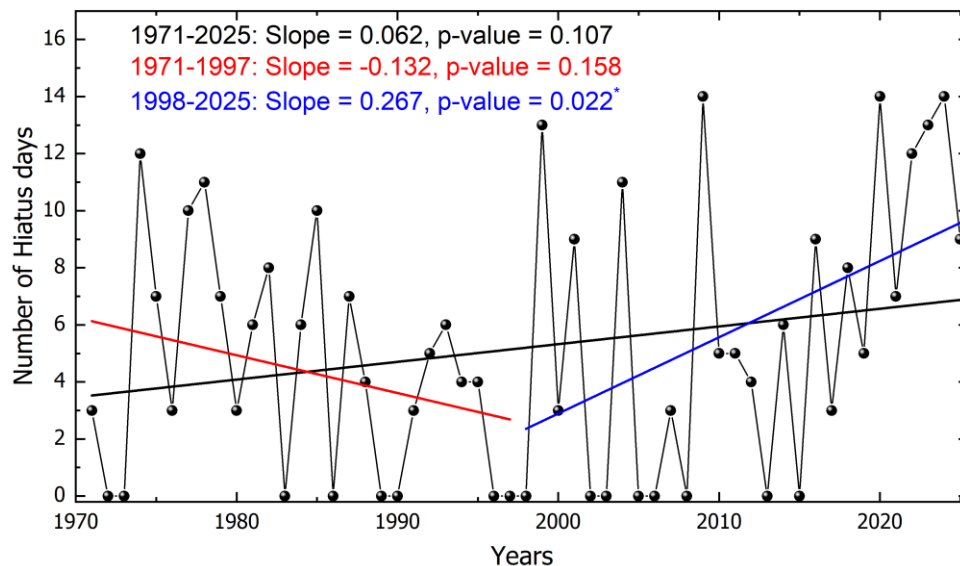


Fig 7 Time series of frequency of hiatus days from 1971-2025 derived using the objective criteria. The linear regression estimates are shown with annotation indicating slope and p values with significant trend indicated by asterisk.

3.5 Summary

During the pre-monsoon season, northwest India and the adjoining arid regions are characterized by hot, dry continental air, whereas the establishment of the summer monsoon marks a seasonal transition from a dry to a moist atmospheric regime through the northward propagation. The present study suggests that the monsoon hiatus occurs when this transition is temporarily interrupted by episodes of enhanced northwest dry air intrusion. This dry air intrusion counteracts the advancing moist monsoon flow, delaying the establishment of a deep, humid atmosphere that is necessary for sustained convection. As dry air penetrates into the monsoon domain, vertically integrated moisture deficit flux increases, reducing the atmospheric moisture availability and reinforces the low-level inversion, thereby inhibiting the vertical development of convective clouds. Although moisture transport from Arabian Sea and Bay of Bengal continues during these periods, the enhanced stability prevents efficient conversion of the available moisture into organized deep convection. This leads to a temporary interruption in the northward advance of the monsoon rainfall belt. This suppression persists until the influence of dry air intrusion diminishes and a sufficiently moist and unstable environment is reestablished, allowing northward progression of monsoon to resume. The proposed mechanism provides a physically consistent framework and also offers a coherent interpretation of observed circulation, thermodynamic and moisture transport signatures documented in this study. Figure 8 presents a conceptual schematic summarizing the proposed mechanism.

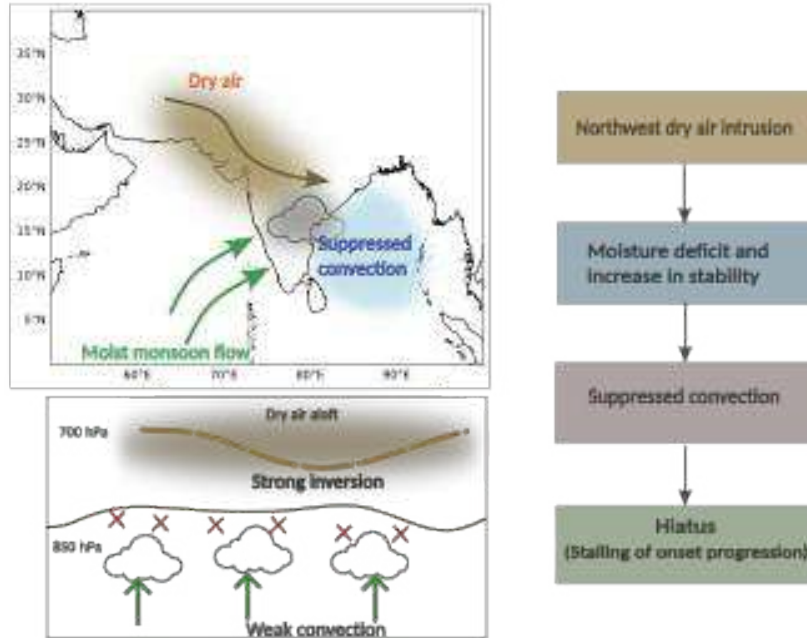


Fig 8 Schematic diagram illustrating the proposed mechanism responsible for the occurrence of monsoon hiatus events during the northward progression of the Indian summer monsoon. Dry air intrusion from northwest India transports moisture deficit air into the Indian region, where it competes with the moist southwesterly monsoon flow. The resulting moisture deficit enhances atmospheric stability and strengthens the low-level inversion, suppressing deep convection despite continued moisture transport from surrounding oceans. The reduction in convective activity interrupts the northward propagation of the monsoon, leading to a hiatus in onset progression. The flowchart summarizes the sequence of the processes linking dry air intrusion to monsoon hiatus.

4. Discussion and conclusion

The Indian summer monsoon onset represents the seasonal transition from the hot, dry pre-monsoon atmosphere to a deep, moist convective regime sustained by persistent southwesterly moisture transport. While the large-scale processes governing monsoon onset have been extensively studied (Fasullo and Webster 2003; Goswami and Xavier 2005), considerably less attention has been given to understanding why the northward progression of the monsoon occasionally stalls after its initial onset over Kerala. The present study demonstrates that these interruptions are not random fluctuations in rainfall but represent dynamically coherent events characterized by simultaneous changes in convection, moisture transport, atmospheric stability and

large-scale circulation. By objectively identifying hiatus events and examining their associated circulation anomalies, we propose a physically consistent framework linking northwest dry air intrusions with temporary interruptions in monsoon progression.

The proposed mechanism should be interpreted within the broader context of seasonal monsoon evolution. Prior to monsoon onset, northwest India and the adjoining regions are occupied by dry continental air. As the monsoon advances northward, this dry air mass is progressively replaced by moist maritime air transported by the low-level southwesterlies. The identified hiatus events represent a temporary interruption of this climatological transition. During the hiatus periods, enhanced transport of continental dry air opposes the advancing moist monsoon flow, delaying the establishment of deep humid troposphere required for sustained deep convection.

Previous studies have largely inferred the influence of dry air intrusions using humidity or saturation deficit diagnostics, which describe the thermodynamic state of the atmosphere but not the transport of dry air itself. By employing VIMDF diagnostic, the present study demonstrates that hiatus events are associated with enhanced horizontal transport of moisture deficient air into the monsoon domain. The close correspondence between VIMDF anomalies and suppressed rainfall suggests that the transport of dry air, rather than merely its local presence plays a central role in maintaining hiatus conditions. The strength and frequency of northwest dry air intrusions are ultimately governed by large-scale extratropical circulation and its interaction with the monsoon system. Although present study demonstrates the central role of these intrusions in initiating and maintaining monsoon hiatus events, a detailed diagnosis of the extratropical processes controlling their variability lies beyond the scope of the present work. Our findings align with the Rodwell-Hoskins “monsoon-desert” hypothesis (Rodwell and Hoskins 1996, 2001) emphasizing that precipitation over northern India is suppressed by subsidence and essentially awaits the arrival of the large-scale circulation and associated warm advection.

The increase in hiatus days after the late 1990s is not accompanied by a statistically robust long-term increase in VIMDF, suggesting that the increasing occurrence of hiatus events cannot be attributed solely to stronger dry air transport. Instead, the observed trend likely reflects changes in the combined influence of circulation, thermodynamic stability and sub seasonal variability, which together determine the persistence of dry air intrusion.

The northward progression during 2026 provides a recent example broadly consistent with the mechanism proposed in the present study. Following its onset over Kerala, the southwest monsoon

advanced rapidly across southern peninsular India before reaching northern Karnataka by early June. Thereafter, the northward progression stalled for nearly two weeks (Fig S2) with the NLM remaining almost stationary over parts of Karnataka and adjoining regions between 8 and 21 June, before resuming its advance into Maharashtra and central India. During this period, successive operational bulletins and onset charts issued by the IMD indicated that the NLM remained unchanged (Fig S2) while also reporting that the large-scale environment was unfavorable for sustained northward progression of the monsoon.

From this perspective, the northward progression of the Indian summer monsoon may be viewed as a dynamic competition between the advancing moist southwesterly monsoon and episodic intrusions of dry continental air from northwest India. This balance between these opposing air masses ultimately determines whether the monsoon progresses northward or temporarily stalls as a hiatus event.

The increasing trend in hiatus days in recent decades poses a serious concern for agricultural and hydrological planning in South Asia. Even a small increase in rainless days during this season can have serious implications for crop sowing, groundwater recharge, and regional climate resilience. Understanding these mechanisms is critical for improving seasonal forecasts and resilience strategies under changing climatic conditions. Future studies should investigate the large-scale extratropical processes that regulate the timing and intensity of northwest dry air intrusions, as well as evaluate their representation in weather and climate models. Such efforts will improve our understanding of monsoon onset variability and its response to a changing climate.

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Data Availability: The data that support the findings of this study are all freely available. The IMD high resolution gridded dataset is available at https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html. The ERA5 daily data on

pressure levels are available at <https://cds.climate.copernicus.eu/datasets/derived-era5-pressure-levels-daily-statistics?tab=overview> and that on single level is available at <https://cds.climate.copernicus.eu/datasets/derived-era5-single-levels-daily-statistics?tab=overview>. NCL and Python were used for the analysis and visual presentations. The codes are available from corresponding author upon request.

Author Contributions: M.N.R conceptualized the study. S.J.V and K.H.U performed the analysis. S.J.V drafted the manuscript. All authors contributed to the interpretation of the results reviewed the manuscript and approved the final version.

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