

A Wind Profiling Radar-Based Dynamical Index for Tracking India's Monsoon Onset

Rona Maria Sunil and M.G. Manoj

Abstract – The Indian summer monsoon onset is a critical climatic event with widespread impacts on agriculture, water resources, and weather systems. Traditional onset detection methods, which primarily rely on precipitation and broad circulation features, often miss the subtle atmospheric transitions that preceded the arrival of the monsoon. In this study, we present a wind-based Monsoon Onset Index (MOI) derived from high-resolution 205-MHz very-high-frequency radar observations (2017–2024) and ERA5 reanalysis data (2000–2024) over Cochin, Kerala (10.04°N, 76.33°E). The MOI integrates the following five key variables: the intensities of the low-level jet and the tropical easterly jet, the depth of the westerlies, the vertical wind shear, and the vertical velocity. Two independent onset detection strategies—quantile thresholding and change point detection—are employed. Validation against IMD onset records confirms the index's robustness and scalability. A Gated recurrent unit–long short-term memory neural model trained on atmospheric variables (2000–2022) forecasted post-May wind dynamics for 2023 to 2024, enabling MOI-based onset detection within ± 3 days of IMD dates, highlighting the predictive strength of wind signals.

1. Introduction

The Indian summer monsoon (ISM) is one of the most significant and complex weather systems, driven by the thermal contrast between the heated Asian landmass and the cooler Indian Ocean. The arrival of the monsoon is not just a meteorological phenomenon; rather, it dictates agricultural cycles, water resource management, and economic stability across the Indian subcontinent. Despite its importance, defining its exact onset remained a challenge due to the lack of a universally accepted robust criterion. Traditionally, the monsoon onset is identified based on a shift in wind patterns and an increase in rainfall; however, these surface-level indicators often fail to capture the underlying atmospheric dynamics that govern monsoon evolution.

Over the years, various methods have been developed to determine the onset of the monsoon, relying on rainfall thresholds [1], vertically integrated moisture transport [2], wind speed anomalies [3], and atmospheric temperature variations [4]. However, precipitation-based detection is inherently reactive, limiting its usefulness for

early warning systems. Wind is a fundamental driver of monsoon progression, controlling heat transport, moisture convergence, and convective activity, yet its role in onset detection remains underused.

This study focuses on the monsoon low-level jet (LLJ), a powerful cross-equatorial flow in the lower troposphere, which plays a pivotal role in monsoon moisture transport [5]. The strength and position of the LLJ influence the active and break phases of the monsoon [6], making it an ideal parameter for detecting the onset. Previous research by Joseph and Raman [6] and Kalapureddy et al. [7] has demonstrated the importance of wind profilers in characterizing the MLLJ; however, systematic attempts to develop a scalable, wind-based onset detection framework remain limited.

While radiosonde data and reanalysis datasets have been extensively used for monsoon studies they often suffer from a coarse temporal resolution and limited real-time applicability. On the other hand, ultra-high-frequency and very-high-frequency (VHF) wind profilers provide high-resolution vertical profiles of three-dimensional wind, making them invaluable for studying wind shear, turbulence, and monsoon onset dynamics [7, 8, 9]. Research in both mid- and high-latitudes regions and tropical areas [9] has demonstrated their effectiveness; however, the potential of these models for detecting the onset of a monsoon in India remains largely unexplored.

To address this gap, our study develops a unified wind-based Monsoon Onset Index (MOI), capturing transitions in LLJ, tropical easterly jet (TEJ), vertical motion, and depth of westerly winds (DoW). This index is designed to scale from point observations to regional applications. By leveraging high-resolution wind radar data (2017–2024) and ERA5 reanalysis data (2000–2024), we develop a MOI that is not only dynamically constructed but also objectively interpreted using statistical thresholding methods such as quantile-based detection and change point analysis. Further, it is evaluated using a gated recurrent unit (GRU) and long short-term memory (LSTM) neural network trained on historical MOI sequences.

2. Data and Methodology

This study examines the onset of the monsoon over Cochin (10°04'N, 76°33'E), Kerala, the gateway to the Indian summer monsoon. A 205-MHz VHF system installed at the Advanced Centre for Atmospheric Radar Research provides high-resolution vertical profiles of zonal (u), meridional (v), and vertical (w) wind components from 0.315 to approximately 20 km. Data are available from 2017 to 2024, sampled at 45-m intervals in the lower troposphere and 150-m intervals in

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upper levels. The analysis focuses on the period from March 1 to June 30, ensuring comprehensive coverage of the pre-monsoon and onset-phase dynamics required for training the model. To ensure temporal extension and robustness, we also use ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts for the period of 2000 to 2024. The daily mean profiles of wind variables were extracted over Cochin, matching the radar vertical extent and resolution.

The MOI is formulated by combining five primary atmospheric variables that characterize monsoon onset as follows: the mean intensity of westerlies (representative of LLJ); the mean intensity of TEJ (representative of TEJ); the DoW, defined as the maximum altitude where zonal winds (u) are westerly; the vertical shear of horizontal winds ($U_{TEJ} - U_{LLJ} / \Delta Z$); and the mean vertical velocity (w) up to DoW capturing the convective ascent. These variables were selected to provide a dynamic representation of the evolving atmospheric conditions that preceded the arrival of the monsoon.

To ensure the objective and accurate identification of monsoon onset, individual thresholds were applied to each variable based on its climatological significance. Further, wind shear was multiplied by DoW (to have the same unit of $m s^{-1}$ of all the other three variables) with a threshold of 3.5; LLJ intensity was constrained to values exceeding $5 m s^{-1}$, vertical velocity (w) was filtered to retain values above $1.5 m s^{-1}$, and a threshold of $15 m s^{-1}$ for TEJ. The final MOI was computed as follows:

$$MOI = \log_{10}[|LLJ| + w + (DoW \times \Delta U / \Delta Z) + |TEJ|]$$

Two independent methods were employed to detect the monsoon onset from the MOI time series. The first was quantile thresholding, where onset was identified as the first day on which the MOI exceeded the 60th percentile for at least three consecutive days during the pre-monsoon window (May–June). The second method involved change point detection (CPD) using the PELT algorithm with a radial basis function kernel implemented via the ruptures package. This approach objectively captured abrupt shifts in MOI trends, which were interpreted as dynamic transitions indicative of monsoon onset.

In addition to the dynamical MOI framework, a GRU and LSTM hybrid model was trained on the time series of constituent meteorological variables (2000–2022) to evaluate its predictive utility. Using a sliding window of 65 days (March 1–May 5) as input, the model forecasted the evolution of the five key MOI variables–LLJ, DoW, vertical shear, vertical velocity, and TEJ–extending into the monsoon onset phase. From these forecasts, MOI was reconstructed for 2023 and 2024, and the onset was detected using the same objective criteria. This hybrid approach integrates real-time diagnostics with AI-based foresight, offering an advanced tool for operational monsoon forecasting.

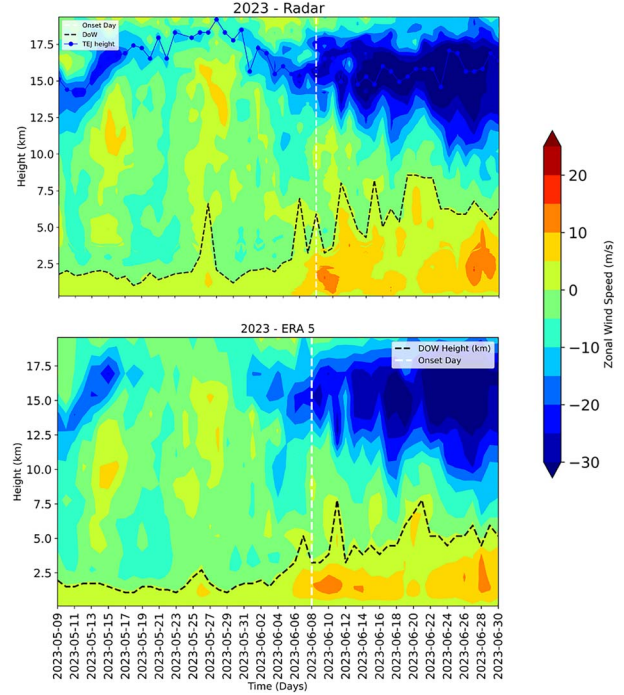


Figure 1. Contour plot of zonal wind ($m s^{-1}$) with DoW being overlaid, showing wind transitions leading to monsoon onset from (a) radar and (b) ERA-5.

3. Results and Discussion

The MOI was evaluated using high-resolution wind profiler data (2017–2024) and ERA5 reanalysis (2000–2024) to detect monsoon onset over Cochin. The analysis includes the following: (1) comparison with IMD-reported onset dates, (2) regional validation using gridded ERA5 data, and (3) evaluation of onset predictability using both statistical methods (quantile thresholding, CPD) and AI-based forecasting (GRU–LSTM).

A crucial characteristic of the monsoon transition is the gradual but systematic shift from pre-monsoon easterlies to strong westerlies. Figure 1 presents the evolution of zonal wind and DoW derived from wind profiler (205-MHz VHF radar) observations and ERA5 reanalysis data. The black dashed line represents DoW, marking the altitude at which zonal wind shifts from westerly to easterly.

A clear transition from upper-level easterlies to deepening lower-level westerlies is observed around the MOI-identified onset date. TEJ intensification is also evident in the upper troposphere (>10 km) preceding onset, consistent with the hypothesized vertical coupling within the troposphere. The vertical coherence between DoW (1000–600 hPa) and TEJ position (200–100 hPa) provides a robust dynamical signature of monsoon transition.

3.2 Evolution of MOI

Figure 2 compares the evolution of the MOI trends for 2023. Radar-based MOI for 2023 exhibits a

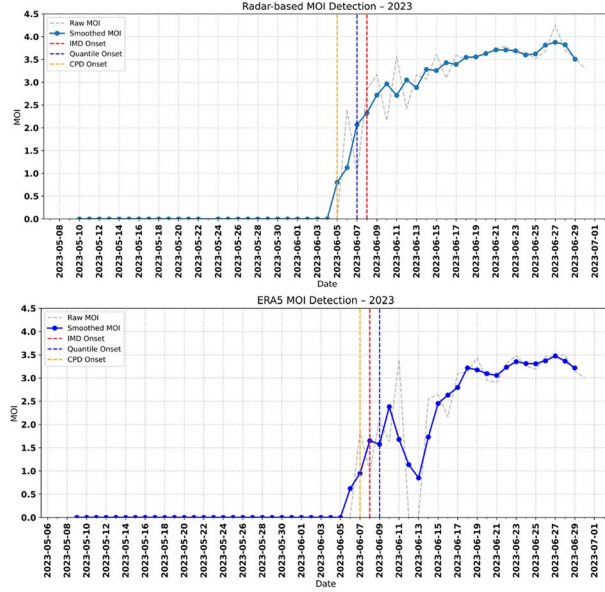


Figure 2. (a) Radar- and (b) ERA-5-based MOI evolution with precipitation.

sharp increase beginning on June 4, indicating a sudden intensification of the LLJ, deepening of westerlies, and enhanced vertical shear. The CPD method identifies this transition on June 5, while quantile thresholding detected onset on June 7 and IMD onset on June 8, providing reasonable agreement.

The ERA5-based MOI shows a similar rise beginning on June 5, with CPD detecting the onset on June 7 and quantile detection occurring slightly later on June 9. Although the transition in ERA5 is smoother due to coarser resolution, the overall pattern matches well with radar and IMD.

Together, these results demonstrate that MOI captures the dynamical onset with high fidelity. Radar offers sharper detection due to real-time vertical resolution, while ERA5 ensures long-term consistency—both supporting the robustness of the framework across observational and reanalysis domains.

3.3 Performance of Onset Detection Methods Across Years

The robustness of the MOI was evaluated over 25 years (2000–2024) using two independent detection strategies as follows: quantile thresholding and CPD. Figure 3 displays MOI evolution for each year, with IMD-declared onset dates (red), CPD-based (orange), and quantile-based (blue) detections overlaid. The MOI consistently rises before or near IMD onset in most years, with both methods capturing the key dynamical transition with high fidelity. In years such as 2000 and 2021, CPD detected earlier onsets, indicating sensitivity to abrupt atmospheric regime shifts, even when rainfall was delayed.

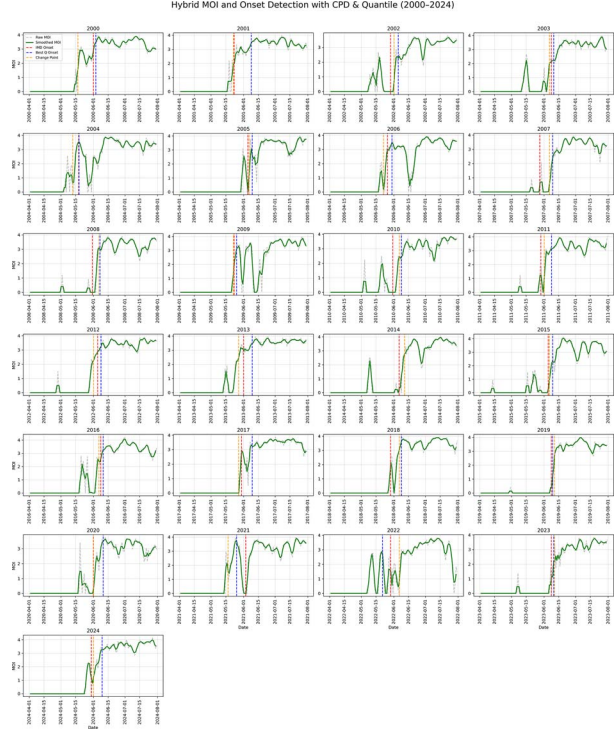


Figure 3. Annual MOI evolution from 2000 to 2024 with overlaid monsoon onset dates detected by CPD (orange), quantile thresholding (blue), and IMD (red).

Figure 4 presents the difference between IMD-reported onset dates and those identified by MOI using change point detection (CPD, orange) and quantile thresholding (blue) from 2000 to 2024. The CPD method frequently detects onset earlier than IMD, particularly in 2000 and 2021, highlighting its sensitivity to abrupt dynamical shifts in wind fields that may precede surface rainfall. In contrast, the quantile method generally exhibits a positive bias, predicting onset later than IMD in years such as 2001 and 2007 due to its reliance on sustained MOI elevation. While both methods show deviations in select anomalous years, most predictions fall within a ± 5 -day window, indicating strong agreement with operational onset. These results suggest that CPD may offer early-warning advantages in dynamically

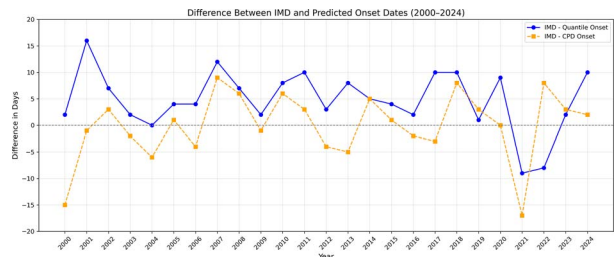


Figure 4. The difference in monsoon onset dates between IMD and MOI-derived detection using quantile thresholding (blue) and CPD (orange) methods from 2000 to 2024.

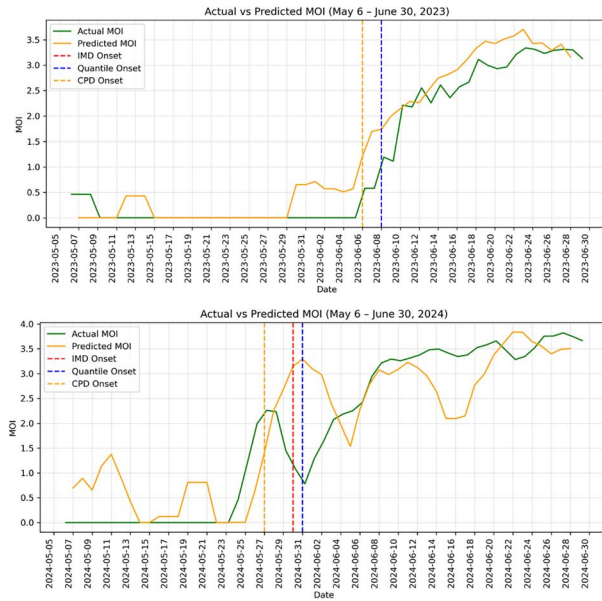


Figure 5. Predicted and actual MOI for 2023 and 2024 using the GRU-LSTM model trained on 2000 to 2022 data. The predicted MOI (orange) and actual MOI (green). Quantile-based (blue) and CPD-based (orange dashed) onsets are also shown for reference.

active years, while quantile-based detection provides consistent alignment during smoother transitions.

3.4 Artificial Intelligence–Based Prediction of Monsoon Onset

A GRU–LSTM model was trained using 23 years (2000–2022) of pre-onset sequences (March 1–May 5) of the five core MOI variables to forecast their evolution into the onset period (May–June). This approach avoids directly training on onset dates, instead leveraging learned dynamics to reconstruct post-May atmospheric behavior. For both 2023 and 2024, the model successfully predicted the five variables, from which MOI was computed and analyzed using the same CPD and quantile-based methods. The predicted MOI (orange) closely follows the pattern of the actual MOI (green), capturing both the timing and structure of the onset transition.

As shown in Figure 5, in 2023, the model anticipates the onset around June 6, two days before the IMD-declared onset (June 8), aligning well with CPD (June 6) and preceding quantile-based detection (June 8). In 2024, the model detects the onset around May 29, again matching CPD and leading to IMD onset by 2 days.

Unlike earlier rainfall-based objective criteria, such as those proposed by Pai et al. [10], or extended range model forecasts, as in Pattanaik et al. [11], this approach learns dynamic transitions from high-resolution wind profiles, offering a physically interpretable and real-time onset prediction system. With a demonstrated ± 3 -day prediction accuracy, the artificial

intelligence-enhanced MOI framework bridges the gap between deterministic thresholds and operational forecast systems, advancing the scope for short-lead monsoon onset alerts.

4. Conclusion

This study presents a wind-based MOI derived from high-resolution radar and ERA5 data to capture the atmospheric transition leading to monsoon onset. The index integrates five key variables, LLJ, DoW, vertical wind shear, vertical velocity, and TEJ, and is validated over 25 years (2000–2024) using two independent methods–quantile thresholding and CPD.

The MOI framework shows strong agreement with IMD onset dates, with most deviations within ± 5 days, and often detects earlier dynamical transitions missed by rainfall-based methods. A GRU–LSTM model trained on historical MOI constituent variables further demonstrated enhanced predictive skill by forecasting the 2023 and 2024 onsets within ± 3 days.

Together, these results establish MOI as a reliable, scalable, and machine-learning-compatible tool for objective monsoon onset detection. Its ability to capture both sharp and gradual atmospheric transitions offers significant potential for operational forecasting and early warning systems.

5. References

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