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Real-Time Objective Extended-Range Prediction of the 2025 Monsoon Onset over Kerala

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सार – चूंकि केरल में मॉनसून की शुरुआत (MOK) की घोषणा में मौसम विशेषज्ञों का अपना आकलन शामिल होता है, इसलिए डायनामिकल मॉडल पर आधारित एक निष्पक्ष तरीका विशेषज्ञों को MOK की घोषणा में होने वाली गलतियों को कम करने के लिए सही मार्गदर्शन दे सकता है। इस स्टडी में, 2025 के मॉनसून की असल शुरुआत की तारीख का अनुमान लगाने के लिए रियल-टाइम 'एक्सटेंडेड रेंज फोरकास्ट' (ERF) से लिए गए चार निष्पक्ष पैमानों का इस्तेमाल किया गया है। ये पैमाने अरब सागर के ऊपर पश्चिमी हवाओं की ताकत और गहराई, केरल तट पर बारिश, और पश्चिमी तट के साथ उत्तर-दक्षिण दबाव के अंतर (मेरिडियनल प्रेशर ग्रेडिएंट) को दिखाते हैं। MOK को उस पहले दिन के तौर पर परिभाषित किया जाता है जब लगातार पांच दिनों तक: (i) केरल तट पर बारिश उसके औसत (क्लाइमेटोलॉजिकल मीन) के 80% से ज्यादा हो, (ii) अरब सागर के ऊपर 850 hPa ज़ोनल हवा अपनी औसत गति के 70% से ज्यादा हो, (iii) 600 hPa ज़ोनल हवा पश्चिमी दिशा की हो जाए, और (iv) ERF में पश्चिमी तट के साथ दक्षिण-उत्तर दबाव का अंतर 2 hPa से ज्यादा हो।

2025 के मॉनसून पर इन पैमानों को लागू करने पर, 30 अप्रैल की शुरुआती स्थिति पर आधारित 'वीक-4 ERF फोरकास्ट' (जो 22-28 मई के लिए मान्य था) ने मॉनसून से जुड़ी हवाओं के घूमने (सर्कुलेशन) और बारिश का संकेत दिया, जिससे केरल में मॉनसून के जल्दी आने का पता चला। इसके बाद 7 मई और 14 मई को शुरू किए गए ERF ने भी उसी समय के दौरान जल्दी MOK होने के लगातार संकेत दिए। इस निष्पक्ष तरीके ने 7 मई और 14 मई के ERF के आधार पर क्रमशः 22 मई और 23 मई को मॉनसून की शुरुआत की तारीख का अनुमान लगाया—जो IMD द्वारा 24 मई 2025 को घोषित असल शुरुआत की तारीख से काफी मेल खाता है।

ABSTRACT. Since the declaration of the Monsoon Onset over Kerala (MOK) involves subjective assessment by forecasters, an objective approach based on a dynamical model can provide forecasters with appropriate guidance to reduce errors in MOK declarations. In this study, four objective indices derived from the real-time Extended Range Forecast (ERF)—representing the strength and depth of westerlies over the Arabian Sea, rainfall over the Kerala coast, and the meridional pressure gradient along the west coast—are used to predict the actual onset date of the 2025 monsoon. The MOK is defined as the first day when, for five consecutive days: (i) rainfall over the Kerala coast exceeds 80% of its climatological mean, (ii) 850 hPa zonal wind over the Arabian Sea exceeds 70% of its mean, (iii) 600 hPa zonal wind becomes westerly, and (iv) the south–north pressure difference along the west coast exceeds 2 hPa in the ERF.

Applying these criteria to the 2025 monsoon, the week-4 ERF forecast (valid for 22–28 May) based on the initial condition of 30 April indicated circulation and rainfall associated with the monsoon, suggesting an early onset of monsoon over Kerala. Subsequent ERFs initialised on 7 May and 14 May also showed consistent signals of an early MOK during the same period. The objective method predicted onset dates of 22 May and 23 May, respectively, based on 7th and 14th May ERFs—closely matching the actual onset declared by IMD on 24 May 2025.

Key words – Monsoon onset over Kerala, Extended range forecast, Dynamical onset of monsoon, Coupled model.

1. Introduction

The onset of the southwest monsoon over Kerala (MOK), located at the southern tip of India, marks the commencement of the rainy season across the country and holds vital significance for its agriculture-dependent economy. The India Meteorological Department (IMD) determines the onset date each year primarily based on daily rainfall observations from multiple stations across Kerala (Ananthakrishnan and Soman, 1988). The onset is associated with a major seasonal transition in both regional and large-scale atmospheric circulation. It is characterized by a northward shift of the mid-latitude westerly jet beyond the Tibetan Plateau (Yin, 1949) and the establishment of a strong tropical easterly jet (TEJ) around the 150 hPa level along the southern flank of the Tibetan high (Koteswaram, 1960).

A key characteristic of MOK is the pronounced vertical wind shear over the Indian subcontinent, arising from the coexistence of an upper-level easterly jet and a low-level westerly jet. Earlier studies, including those by Rao (1976), Soman and Kumar (1993), and Simon and Joshi (1994), have highlighted a significant increase in mid-tropospheric moisture (700–500 hPa) approximately 8–10 days before onset. During MONEX, Krishnamurti and Ramanathan (1982) documented the role of energy exchanges and differential heating, while Sikka and Gadgil (1980) identified a northward-propagating convective band—termed the “maximum cloud zone”—over southern India during onset, a feature later corroborated by Joseph *et al.* (1994). As the monsoon advances, shifts in weather patterns at both regional and larger scales have led researchers to propose varied criteria for defining its onset. More recent studies, including those by Fasullo and Webster (2003), Joseph *et al.* (2006), Lu and Chan (1999), Lu *et al.* (2009), Taniguchi and Koike (2006), Wang *et al.* (2009), and Zeng and Lu (2004), Pattanaik and Bushair (2024), have each suggested objective methodologies for this purpose.

Ananthakrishnan *et al.* (1968), later followed by Soman and Kumar (1993), described monsoon onset as the point when rainfall transitions from light to heavy. According to their approach, if the average daily rainfall during the first five days after this transition totals at least 10 mm, the date is designated as the onset. Expanding on this concept, Fasullo and Webster (2003) introduced the Hydrological Onset and Withdrawal Index (HOWI), which identifies the transition based on atmospheric moisture transport. Joseph *et al.* (2006) associated the onset with the depth of westerly winds and the expansion of convection around Kerala, while Wang *et al.* (2009) emphasised the establishment of strong, persistent 850-hPa winds over the southern Arabian Sea. Similarly, Zeng

and Lu (2004) and Lu *et al.* (2009) employed measurements of precipitable water to define the onset. In contrast, the IMD applies the criteria formulated by Pai and Rajeevan (2009), which integrate three factors: rainfall observations from multiple Kerala stations, the depth of westerly winds up to 600 hPa, and satellite-derived outgoing longwave radiation (OLR) north of the equator.

In recent years, IMD has operationalised a suite of global, regional, and coupled models to meet user needs across multiple time scales—ranging from short-range forecasts (up to 3 days) and medium-range forecasts (up to 7 days) to extended-range forecasts (up to 3–4 weeks). For extended-range forecasting (ERF), IMD employs an operational system based on the Climate Forecast System version 2 (CFSv2), a coupled model developed by the National Centre for Environmental Prediction, USA (Saha *et al.* 2014) and adopted by IMD (Pattanaik *et al.* 2019; 2020; 2021; 2022). Research has demonstrated that this operational ERF can skilfully predict key transitional phases of the monsoon—such as onset, withdrawal, and active–break–active cycles—up to 2–3 weeks in advance. In addition, IMD has adopted a high-resolution Global Forecast System (GFS) model at 12 km horizontal resolution for operational medium-range forecasts. In addition, IMD has also implemented the multi-model ensemble (MME) framework for district-level forecasts during the monsoon season, delivering 5-day medium-range predictions using outputs from five global models (Bushair *et al.* 2022).

A recent study by Pattanaik and Bushair (2024) demonstrated the application of ERF in determining the monsoon onset over Kerala (MOK) through four forecast indices: (i) rainfall over Kerala, (ii) the intensity of the low-level jet at 850 hPa over the Arabian Sea, (iii) mid-tropospheric winds at 600 hPa, and (iv) the north–south pressure difference along the west coast exceeding a threshold. These indices differ slightly from those proposed by Joseph *et al.* (2015), who utilized ERF runs at the Indian Institute of Tropical Meteorology (IITM), Pune, focusing primarily on low-level winds and rainfall. Notably, the operational ERF system was officially implemented at IMD in 2017. The study also reported that forecasts based on four indices outperformed those using three, with the mean error between IMD’s declared observed MOK date and ERF-predicted dates being 1.6 days and 4.2 days, respectively, for the 2003–2022 period. Building on the demonstrated success of IMD’s objective, dynamical extended-range forecasting systems, the present study assesses the performance of monsoon onset forecast over Kerala based on IMD’s operational extended and medium range forecast models during the 2025 monsoon, which featured an unusually early onset over

Kerala on 24 May, compared with the climatological normal of 1 June.

2. Data and methodology

2.1. Observed rainfall data used

Daily gridded rainfall used in this study was obtained from the IMD, Pune. The gauge-based gridded rainfall analysis is generated from quality-controlled rain gauge observations collected over India and objectively interpolated onto a regular latitude–longitude grid, making it suitable for climate diagnostics, monsoon studies, and model validation (Rajeevan *et al.*, 2006; Pai *et al.*, 2014). For comparison and validation of numerical weather prediction products, the IMD gauge observations have also been merged with satellite-derived precipitation estimates to produce the NCMRWF–IMD merged satellite–gauge rainfall analysis. This merged product employs a successive correction objective analysis technique, using satellite rainfall estimates as the first guess and IMD rain gauge observations to correct systematic biases and improve the spatial representation of rainfall, particularly during the Indian summer monsoon (Mitra *et al.*, 2009). The merged rainfall analysis has been extensively used for the verification and evaluation of operational numerical weather prediction models over the Indian region.

2.2. Extended Range Forecast (ERF) model used

The present ERF system of the IMD was initially developed at the IITM, Pune. The modelling framework is capable of predicting the active–break cycle of the Indian summer monsoon and has been applied in various contexts (Pattanaik *et al.* 2019; Sahai *et al.* 2013; Sahai *et al.* 2015). The system utilises the Climate Forecast System version 2 (CFSv2), which comprises the atmospheric component, GFS model, and the oceanic component, the GFDL Modular Ocean Model version 4 (MOM4). The suite consists of four model configurations: CFSv2 at T382, CFSv2 at T126, GFSbc (bias-corrected SST from CFSv2) at T382, and GFSbc at T126, each with four ensemble members, resulting in a total of 16 members. The operational ERF is initialised weekly using atmospheric and oceanic initial conditions (ICs) from the Global Data Assimilation System (GDAS) and Global Ocean Data Assimilation System (GODAS), respectively, produced at the National Centre for Medium Range Weather Forecasting (NCMRWF) and the Indian National Centre for Ocean Information Services (INCOIS). Forecasts are generated every Friday for four weeks, extending through Thursday. In addition to ERF, IMD has implemented a Multi-Model Ensemble (MME) system for district-level medium-range forecasts during the monsoon

season (Bushair *et al.* 2022; Pattanaik, 2022). The MME approach integrates outputs from five numerical weather prediction (NWP) models: (i) GFS operational at both IMD and NCEP; (ii) the Global Ensemble Forecasting System (GEFS) at IMD; (iii) the Unified Model (NCUM) at NCMRWF; and (iv) the Global Spectral Model (GSM) of the Japan Meteorological Agency (JMA). The GFS was first introduced at IMD in 2010 with a resolution of T382L64 and its current version, GFS 14.1.0, operates at a spectral resolution of T1534 (≈ 12.5 km horizontal resolution) with 64 hybrid vertical levels (Johny *et al.* 2020; Prasad *et al.* 2021).

2.3. Objective method of defining onset date over Kerala

The onset date over Kerala is determined using the daily forecast output from the model based on a set of threshold conditions, objectively using the rainfall over the Kerala coast, zonal wind at 850 hPa and 600 hPa over the southeast Arabian Sea and the mean south–north pressure difference along the west coast. The onset is declared when the area-averaged rainfall over the domain bounded by 8°N – 12°N and 74°E – 78°E exceeds 80% of its long-term mean, the area-averaged 850 hPa zonal wind over the region 5°N – 12°N and 55°E – 75°E exceeds 70% of its climatological mean, the 600 hPa zonal wind over the same region becomes positive, and the mean south–north pressure difference along the west coast reaches or exceeds a threshold value of 200 Pa (2 hPa).

3. Results and discussion

3.1. Onset of monsoon over Kerala during 2025

As illustrated in Fig. 1, the southwest monsoon advanced into parts of the south Bay of Bengal, south Andaman Sea, Nicobar Islands, and portions of the north Andaman Sea on 13 May 2025 (IMD, 2025; End of Season Report). Further progress was observed on 19 May, with the monsoon advancing into additional parts of the south Arabian Sea, Maldives–Comorin region, south Bay of Bengal, central Bay of Bengal, and northeast Bay of Bengal. Thus, the monsoon had reached close to the southern tip of India by this date, advancing nearly a week ahead of its climatological onset date of 26 May. With regard to the further progress of the monsoon to the mainland of India, the southwest monsoon reached the southern tip of India (Kerala) on 24 May 2025, a week earlier than its climatological onset date of 1 June (Fig. 1). Consequently, the onset occurred 8 days ahead of its normal date over Kerala and 12 days earlier than normal over northeast India. This represents the earliest onset over Kerala since 2009, when it advanced on 23 May. In 2016, the IMD introduced revised criteria for declaring the

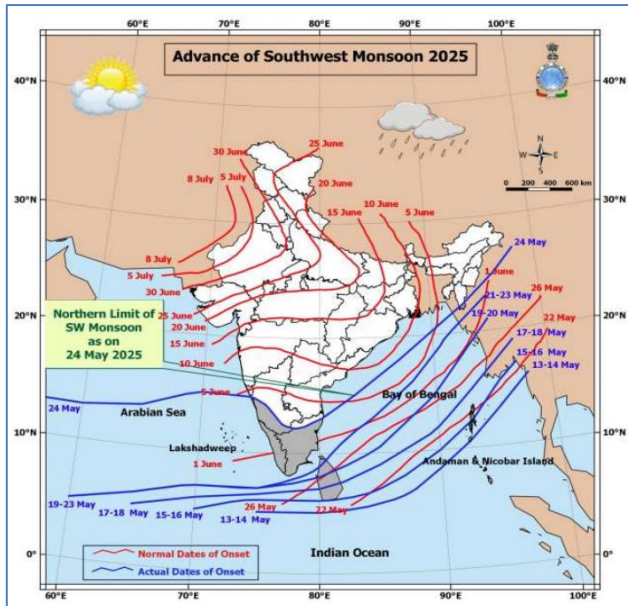


Fig. 1. Onset of monsoon line (Isochrones) over the Bay of Bengal, the Arabian Sea and different parts of India during 2025 monsoon season. (a) As on 19th May 2025 and (b) As on 24th May 2025

MOK. These updated guidelines, available on the IMD website (<https://mausam.imd.gov.in/>), incorporate daily rainfall observations from 14 stations across Kerala and neighbouring regions, along with wind field data and OLR measurements over the southeast Arabian Sea. The criteria emphasize identifying a sharp and sustained increase in rainfall over Kerala, concurrent with the establishment of large-scale monsoon flow and the northward extension of westerlies up to the 600 hPa level over the Arabian Sea. Under these criteria, MOK is declared after 10 May if at least 60% of the 14 designated stations along the west coast of India record rainfall ≥ 2.5 mm for two consecutive days. The onset date is then defined as the second day, provided that three additional conditions are also satisfied.

(i) The depth of westerlies within the Arabian Sea, defined by the region between the $Eq-10^{\circ}N$ and $55^{\circ}E-80^{\circ}E$, must extend up to the 600 hPa level.

(ii) The zonal wind speed at 925 hPa, within the area bordered by $05^{\circ}N-10^{\circ}N$ and $70^{\circ}E-80^{\circ}E$, should fall within the range of 15 to 20 knots.

(iii) The OLR value within the specified box, confined by $05^{\circ}N-10^{\circ}N$ and $70^{\circ}E-80^{\circ}E$, should be less than 200 watts/m².

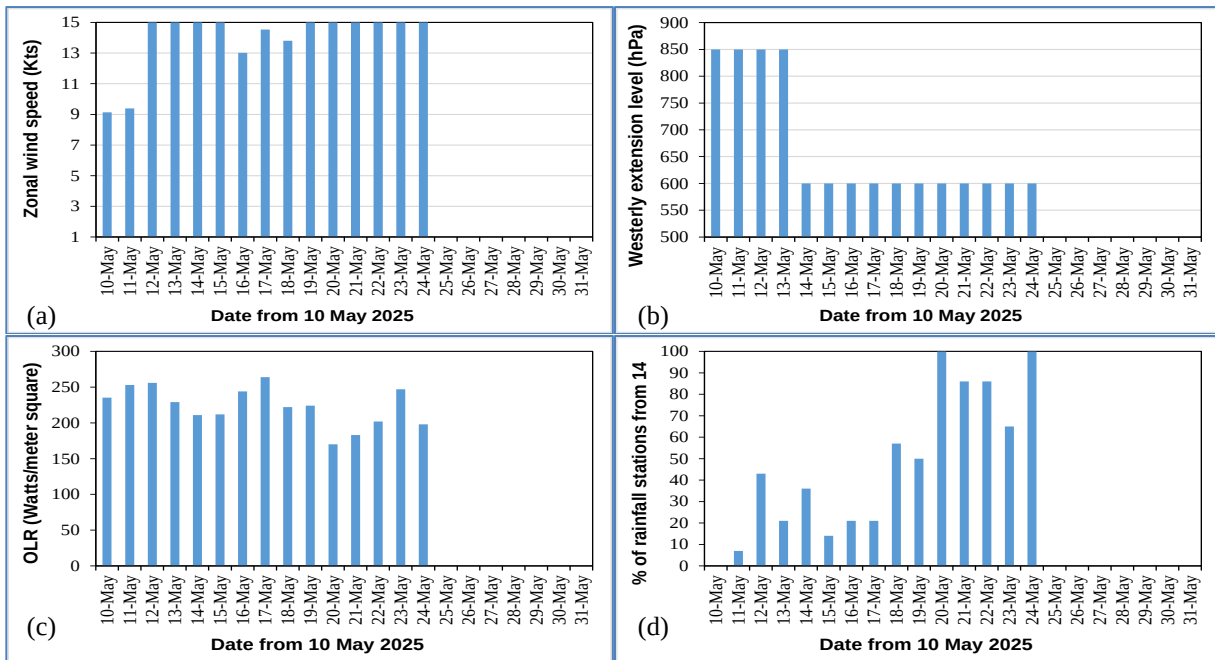
During the 2025 monsoon season, the relevant onset parameters were monitored from 10 May onward (Fig. 2). The 925 hPa zonal wind over the southeast Arabian Sea

exceeded the threshold of 15 kts during 12–15 May and again from 19 May onward. The depth of westerlies over the South Arabian Sea extended up to the 600 hPa level beginning 14 May. Enhanced convective activity over the southeast Arabian Sea and adjoining peninsular India was evident from 20 May onward, with OLR values falling below 200 W/m². Concurrently, more than 60% of the designated rainfall stations in Kerala (≥ 9 of 14) reported daily rainfall of at least 2.5 mm from 20 May onward, thereby satisfying the rainfall criterion. Thus, as seen from Fig. 2, all the meteorological conditions became conducive for the declaration of monsoon onset over Kerala by the forecasters for any day after the 3rd week of May. Widespread rainfall activity occurred on 23 May, followed by heavy to very heavy rainfall over several parts of Kerala on 24 May. Considering the fulfilment of all objective criteria, the southwest monsoon was officially declared to have set in over Kerala on 24 May 2025 (Fig. 2). Daily accumulated rainfall averaged over the districts of 3 southern Indian states (Kerala, Karnataka and Tamil Nadu) during 20–25 May 2025 is shown in Fig. 3. On 20 May, many districts of Kerala received rainfall, followed by a temporary decline over southern Kerala between 21–23 May. Subsequently, on 24 May, the rainfall over the west coast of India increased, and the amount further increased on 25 May; thereby, the onset over Kerala was more appropriately declared on 24 May 2025 as shown in Fig. 1.

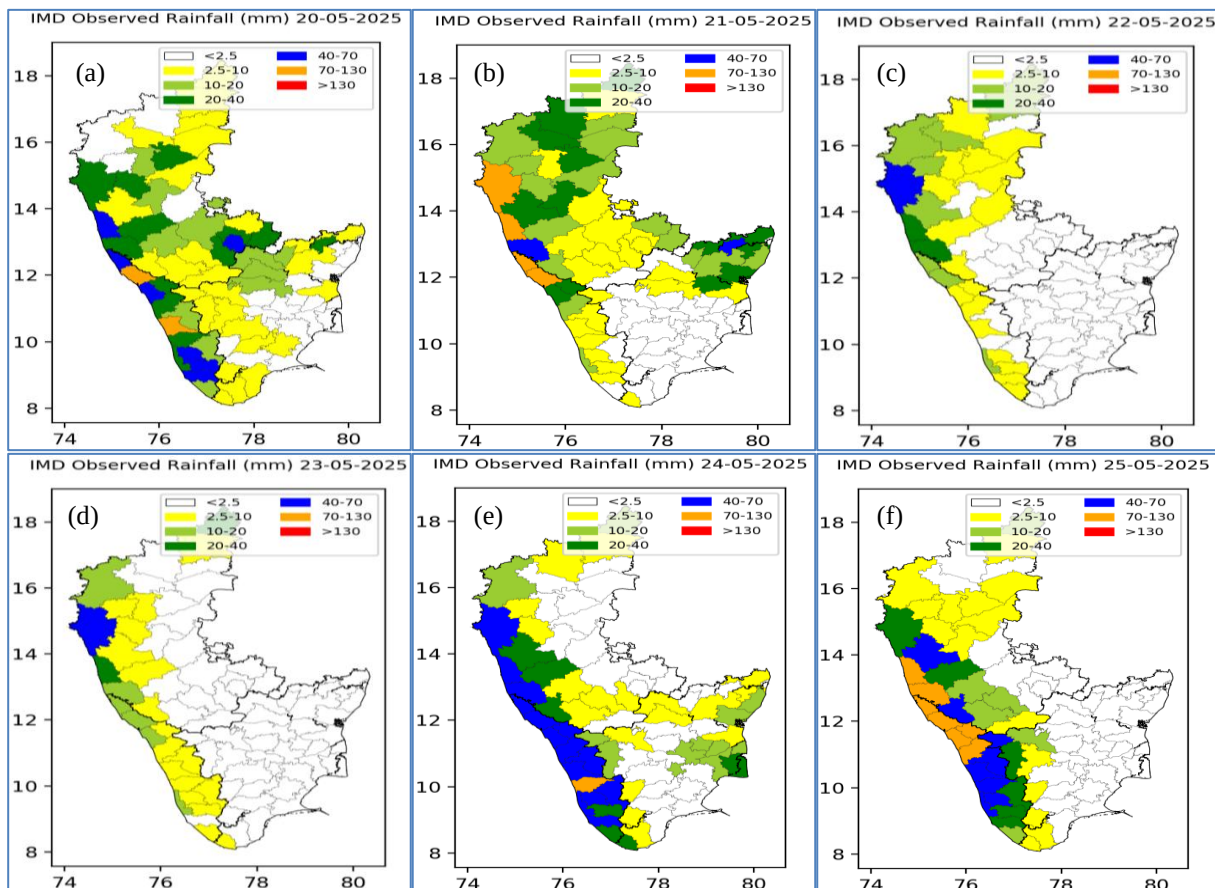
3.2 Extended Range Forecast of Monsoon Onset over Kerala during 2025

The ERF of the 2025 monsoon onset over Kerala, based on the operational coupled model at IMD (Pattanaik *et al.* 2019; 2020; 2021; 2022), is presented here. As described by Pattanaik and Bushair (2024), the ERF-based MOK date is determined using four forecast indices: (i) rainfall over Kerala, (ii) the intensity of the low-level jet at 850 hPa over the Arabian Sea, (iii) mid-tropospheric winds at 600 hPa, and (iv) the north–south pressure difference over the west coast exceeding a threshold. These indices differ slightly from those employed by Joseph *et al.* (2015), who defined onset using low-level winds and rainfall based on ERF runs at IITM, Pune. The operational ERF system implemented at IMD in 2017 incorporates these updated criteria.

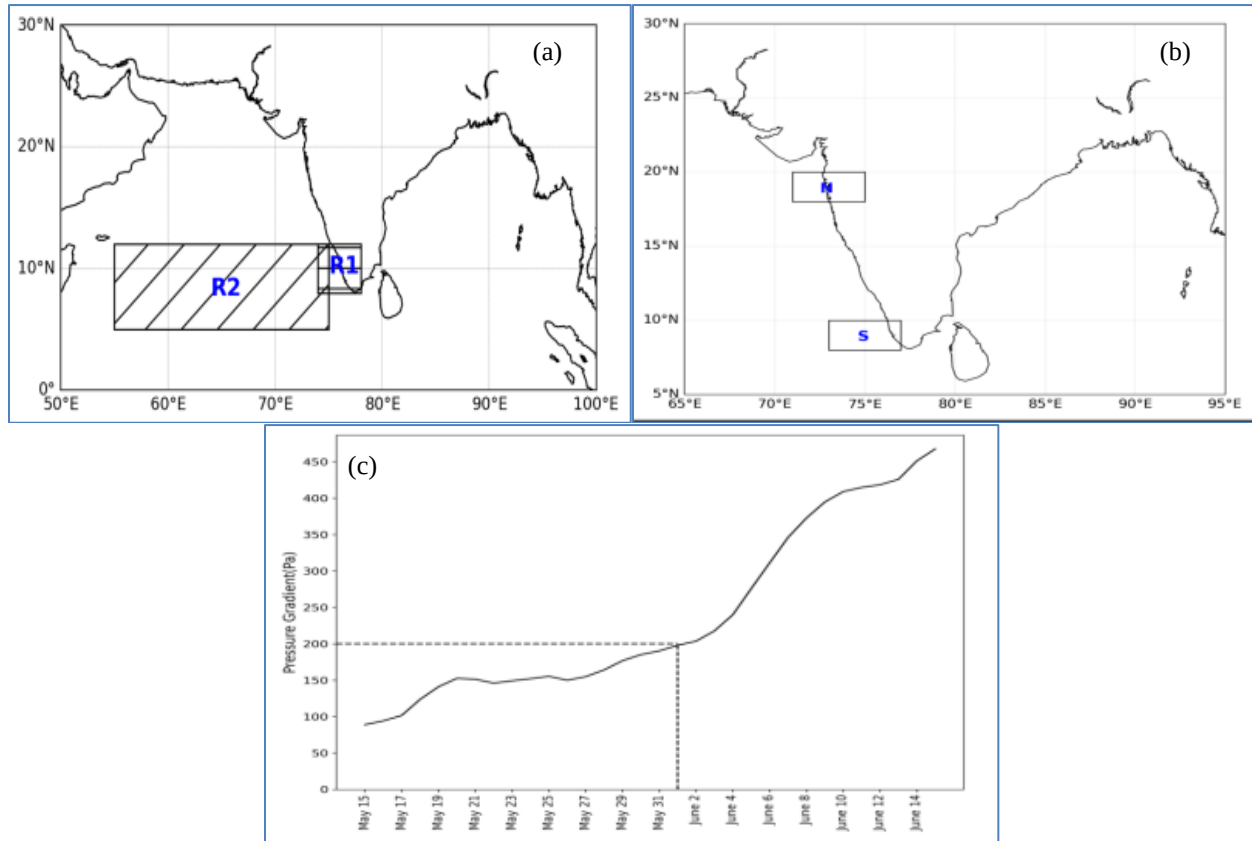
As Pattanaik and Bushair (2024) outlined, the forecast of monsoon onset over Kerala (MOK) is determined using the following indices from the ERF variables. First, the domain-averaged rainfall (R1 in Fig. 4a), bounded by $08^{\circ}N-12^{\circ}N$ and $74^{\circ}E-78^{\circ}E$, must exceed 80% of its climatological mean. Since rainfall is a key variable in the declaration of monsoon onset over Kerala (MOK), an appropriate rainfall threshold is essential for



Figs. 2(a-d). Monitoring the met variables for declaring Monsoon Onset over Kerala (MOK) from 10th May during the 2025 monsoon season. (a) 925 hPa zonal wind (b) vertical extension of westerly wind over (c) OLR in watts/m² and (d) % stations with rainfall of 2.5 mm or more out of 14 stations



Figs. 3(a-f). Districtwise daily averaged observed rainfall over the 3 met-subdivisions (Kerala, Karnataka and Tamil Nadu) during the period from 20 to 25 May 2025



Figs. 4(a-c). (a) Regions selected for defining three indices with rainfall averaged over 08–12N, 74–78E (R1); Zonal wind at 850 and 500 hPa averaged over 050–120N, 550–750E (R2). (b) The regions used for calculation of the South (08–10N, 73–77E) - North (18–20N and 71–75E) normal mean sea level pressure gradient along the west coast of India from 15 May to 15 June. (c) The climatological South-North pressure gradient (Pa) along the west coast, with the normal onset date over Kerala of 1st June, indicates the threshold value

objectively determining the onset date. The threshold of 80% of the climatological mean was selected based on an assessment of the Extended Range Forecast (ERF) performance during the 17-year hindcast period (2003–2019). To determine the most suitable rainfall threshold, three thresholds i.e., 70%, 80%, and 90% of the climatological mean, were evaluated. For each threshold, the ERF-based MOK was defined as the first day on which the rainfall criterion was satisfied for five consecutive days. The ERF-based MOK dates obtained using the 70%, 80%, and 90% rainfall thresholds, together with the corresponding observed onset dates, are presented in Table 1. The results show that the 80% threshold yields the lowest Mean Absolute Difference (MAD) of 6.06 days, compared with 6.41 days for both the 70% and 90% thresholds. Furthermore, the number of years in which the predicted onset date falls within ± 2 days of the observed date is 6, 7, and 5 for the 70%, 80%, and 90% thresholds, respectively. Thus, the 80% threshold provides the best overall agreement with the observed MOK during the hindcast period and is therefore adopted as the rainfall criterion for determining MOK from the ERF.

Second, the zonal wind at 850 hPa, averaged over the region 5°N–12°N and 55°E–75°E (R2 in Fig. 4a), should surpass 70% of its mean value. Third, the zonal wind at 600 hPa over the same area (R2) must be greater than zero. In addition to these three parameters, MOK is associated with an increase in the north–south pressure difference along the west coast. To capture the climatological characteristics of this pressure gradient reversal, two boxes over the west coast region are considered (Fig. 4b). Following the onset of land heating in May, the south–north pressure difference begins to increase from 15 May onwards. The threshold value for defining MOK is derived from the climatological threshold of the south–north pressure difference across these two boxes (Fig. 4c). When plotted from 15 May to 15 June, this difference reaches approximately 200 Pa (2 hPa) around the climatological onset date of 1 June. This north–south pressure difference establishes the necessary pressure gradient to drive strong southwesterly monsoon winds from the Arabian Sea toward the Kerala coast. The ERF-based monsoon onset over Kerala is defined as the first day when all three prescribed conditions are satisfied for five consecutive days, accompanied by a south–north

TABLE 1

The ERF-based Monsoon Onset Dates obtained using the 70%, 80%, and 90% rainfall thresholds, together with the corresponding observed onset dates during the hindcast period from 2003 to 2019

Year	Estimated date based on 70% threshold	Estimated date based on 80% threshold	Estimated date based on 90% threshold	Observed MOK Date
2003	May 28 (11)	May 28 (11)	May 28 (11)	June 8
2004	May 18 (0)	May 18 (0)	May 21 (3)	May 18
2005	May 31 (5)	May 31 (5)	June 3 (2)	June 5
2006	May 24 (2)	May 24 (2)	May 24 (2)	May 26
2007	May 26 (2)	May 26 (2)	June 3 (6)	May 28
2008	May 26 (5)	May 27 (4)	May 28 (3)	May 31
2009	May 19 (4)	May 19 (4)	May 19 (4)	May 23
2010	May 20 (11)	May 20 (11)	May 21 (10)	May 31
2011	May 30 (1)	May 30 (1)	May 31 (2)	May 29
2012	June 1 (4)	June 1 (4)	June 1 (4)	June 5
2013	May 24 (8)	May 27 (5)	May 28 (4)	June 1
2014	June 1 (5)	June 4 (2)	June 4 (2)	June 6
2015	May 16 (20)	May 16 (20)	May 16 (20)	June 5
2016	May 17 (22)	May 17 (22)	May 17 (22)	June 8
2017	May 28 (2)	May 29 (1)	May 29 (1)	May 30
2018	May 29 (0)	May 31 (2)	June 5 (7)	May 29
2019	June 1 (7)	June 1 (7)	June 2 (6)	June 8
Mean Absolute Difference (MAD)	6.41 days	6.06 days	6.41 days	

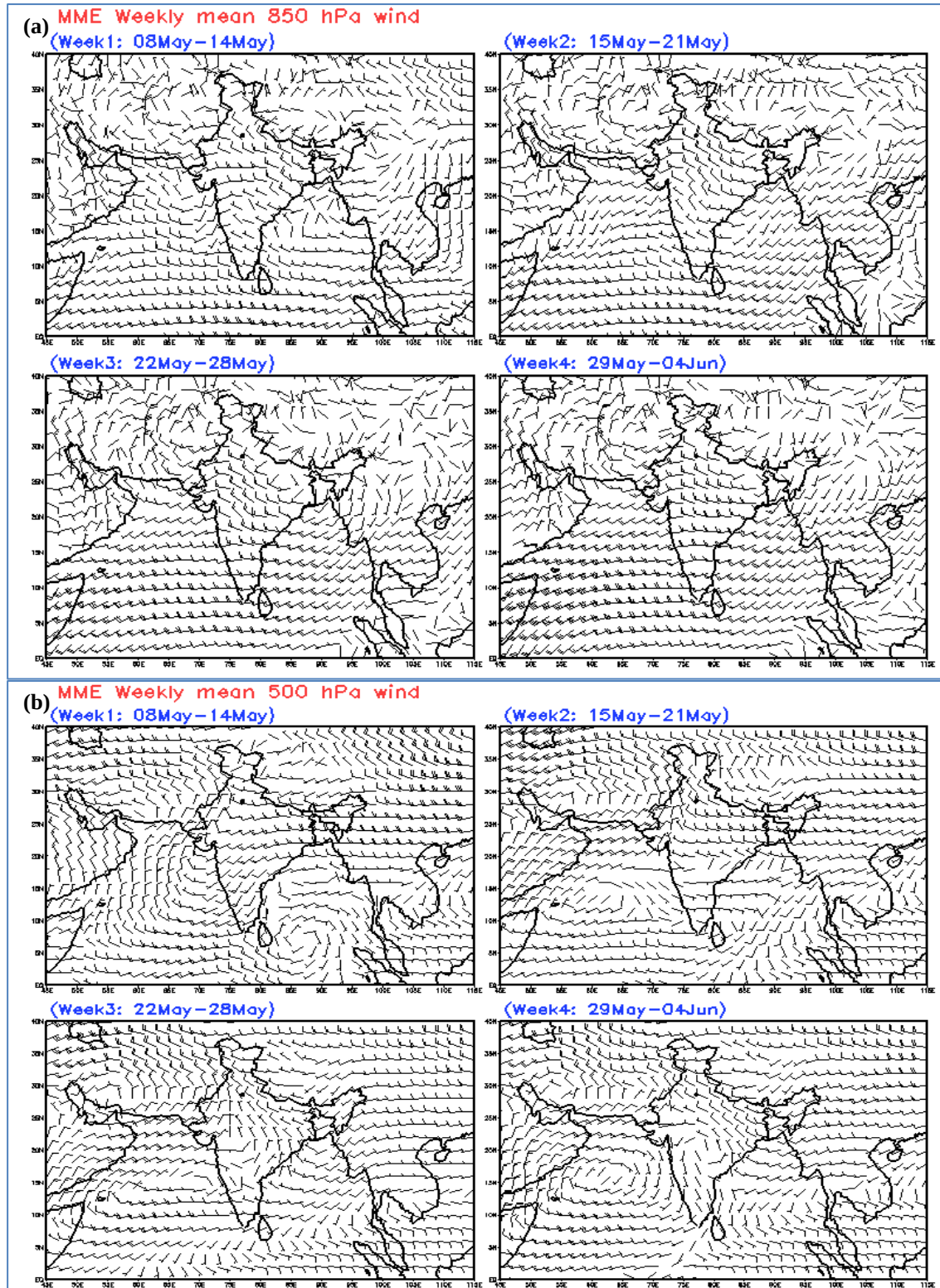
Note: Numbers in brackets indicate the absolute difference in days between the estimated and observed dates.

pressure difference exceeding the threshold value of 2 hPa. A previous study by Pattanaik and Bushair (2024) has shown that the forecasts using four indices outperform those with three, with the mean error between IMD-declared observed MOK dates and ERF-predicted dates over the 2003–2022 period being 1.6 days and 4.2 days, respectively. Thus, the current study establishes the dynamical model-based objective prediction of MOK using the four indices from ERF variables as described below.

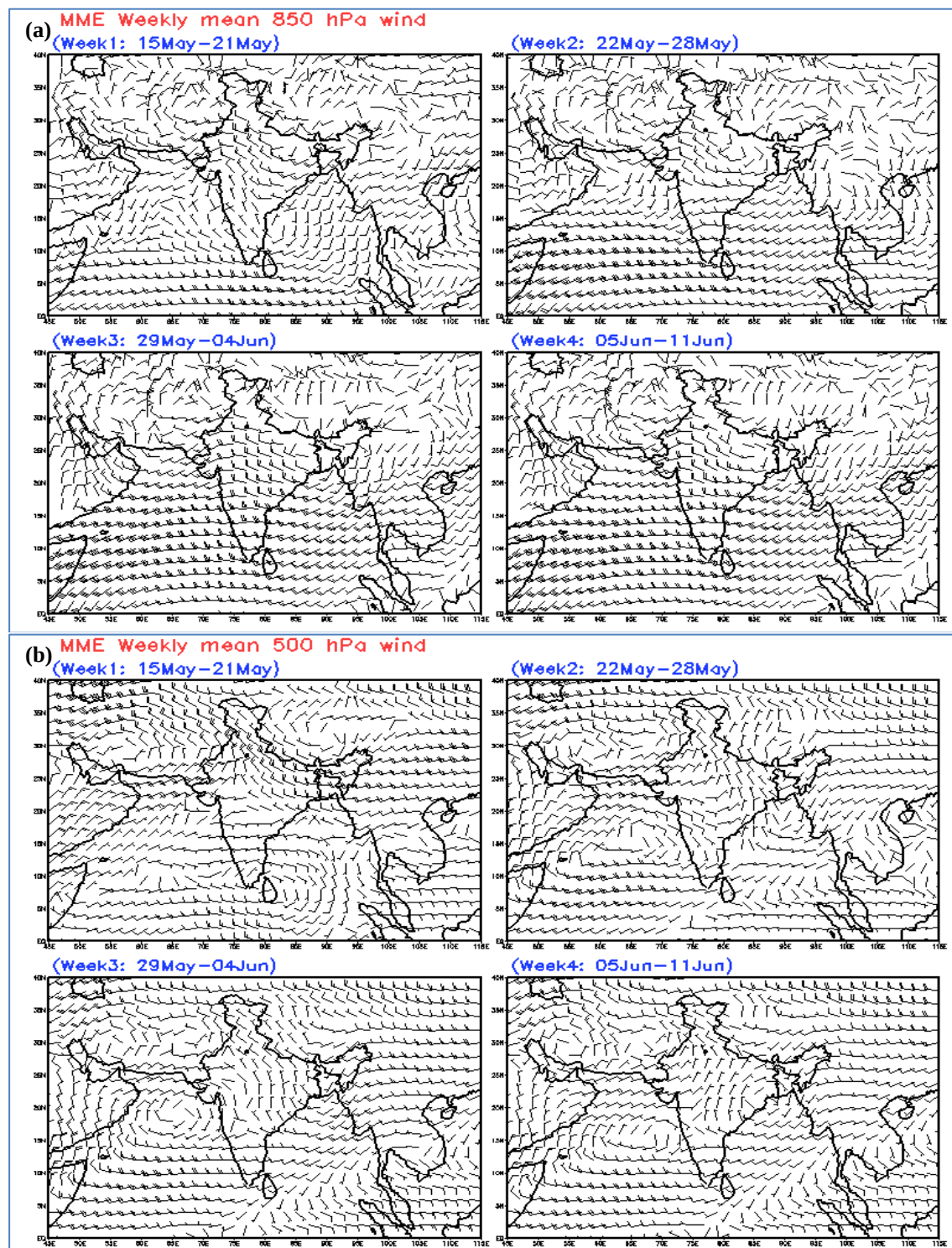
- (i) Rainfall averaged over the domain (R1) bounded by 08°N – 12°N , 74°E – 78°E exceeds 80% of their long term mean;
- (ii) The zonal wind at 850 hPa, calculated as an average over the region spanning 05°N – 12°N , 55°E – 75°E (referred to as R2), should surpass 70% of its mean value;
- (iii) The zonal wind at 600 hPa over the same geographic area (R2) should be greater than zero.
- (iv) When the mean south-north pressure difference over the west coast reaches a threshold value of 200 Pa (2 hPa)

The extended-range forecast of 850 hPa mean winds, based on the initial condition (IC) of 7 May 2025, indicated a strong cross-equatorial flow and enhanced monsoon circulation over the southeast Arabian Sea from week 2 (15–21 May), which persisted through week 3 (22–28 May) and week 4 (29 May–4 June) as shown in Fig. 5a. To see the vertical extension of monsoon westerly in the ERF based on 7 May, the corresponding 500 hPa mean wind is also plotted in Fig. 5b, which indicated westerly wind over the southeast Arabian Sea and east-west shear line to the north of it in week 2 (15–21 May), which is more established in week 3 forecast (22–28 May) and also persisted in week 4 forecast (29 May–04 Jun).

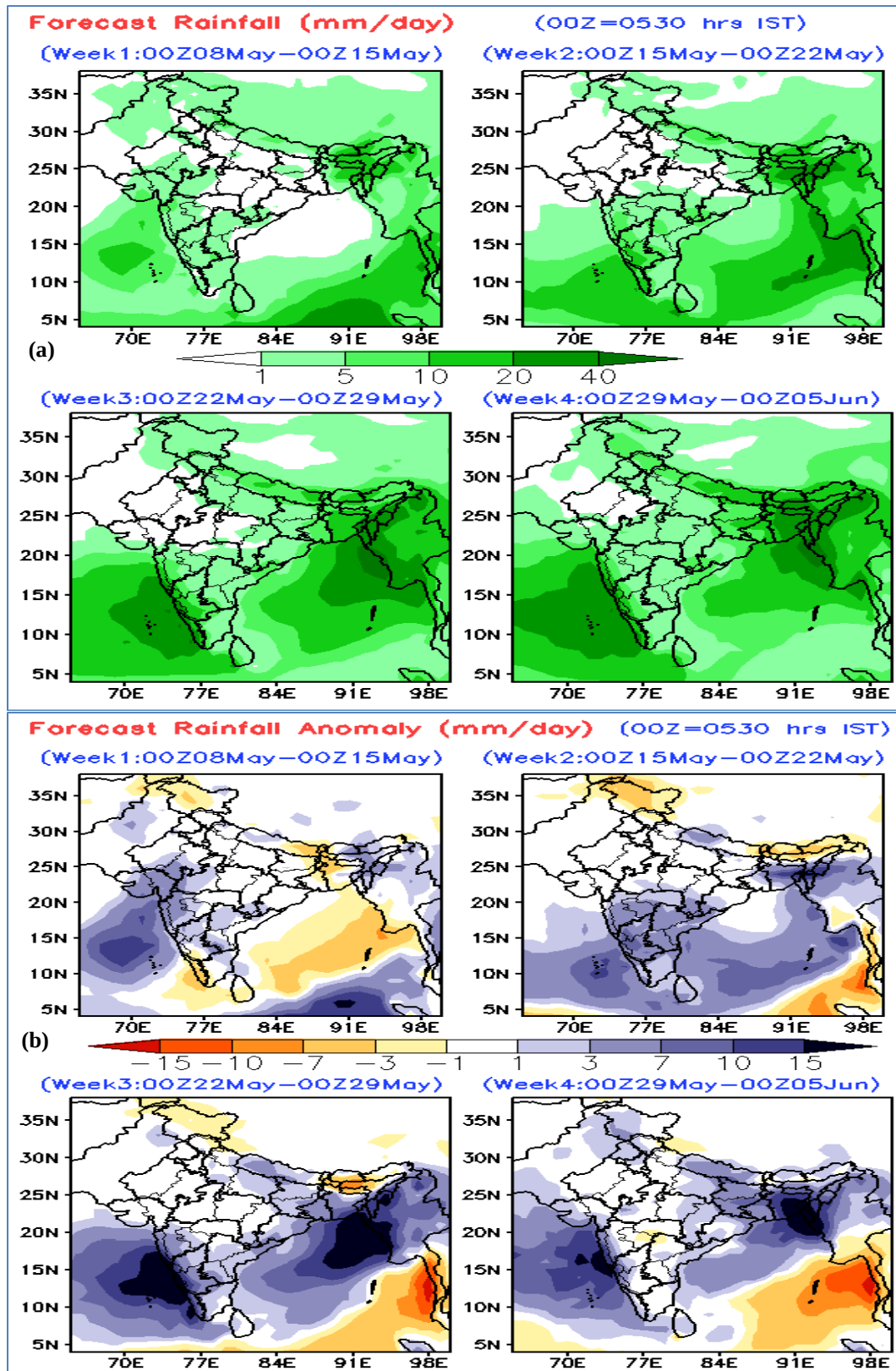
Similarly, the 850 and 500 hPa mean wind forecasts based on the initial condition of 14 May also showed a strong cross-equatorial flow at lower levels with intensified monsoon westerlies over the southeast Arabian Sea in the week 1 forecast (15–21 May), followed by further strengthening in week 2 (22–28 May) as shown in Fig. 6a. The 500 hPa mean wind forecast (Fig. 6b) also showed westerly flow over the southeast Arabian Sea, with an east–west shear line to its north in the week-1 forecast valid for 15–21 May. This feature became more



Figs. 5(a&b). Top panel (a) : The extended range forecast 850 hPa weekly mean wind for four weeks based on 7th May initial condition and valid for the period from 8th May–4th June, 2025. Bottom panel (b) Same as 'a' but for 500 hPa wind forecast



Figs. 6(a&b). Top panel (a) : The extended range forecast 850 hPa weekly mean wind for four weeks based on 14th May initial condition and valid for the period from 15 May to 11 June, 2025. Bottom panel (b) Same as 'a' but for 500 hPa mean wind forecast



Figs. 7(a&b). Top panel (a) : The extended range forecast weekly mean rainfall for four weeks based on 7th May initial condition and valid for the period from 8th May-04 June, 2025. Bottom panel (b) Same as 'a' but for rainfall anomaly forecast

pronounced in the week-2 forecast (22–28 May) and continued to persist in the week-3 and week-4 forecasts (29 May–04 June). Accordingly, the ERF wind pattern suggested southwest monsoon circulation associated with onset of monsoon during 15–21 May, with a distinct onset signal emerging clearly in the period 22–28 May 2025.

The ERF of mean and anomaly rainfall for the four weeks, based on ICs of 7 and 14 May 2025, are presented in Fig. 7 and Fig. 8, respectively. Forecasts from 7 May IC (Fig. 7) indicated an increase in mean rainfall over the Kerala coast during week 2 (15–21 May), accompanied by positive rainfall anomalies along the west coast region. Week 3 forecasts (22–28 May) showed further enhancement of rainfall across the entire west coast, with large positive anomalies. These features suggest characteristic of monsoon patterns and indicate early monsoon onset over Kerala during the week from 15–21 May, which is more prominent in the week from 22–28 May 2025. Similarly, the rainfall forecasts based on the initial condition of 14 May (Fig. 8) indicated increased rainfall along the west coast in week 1 (15–21 May) with substantial positive anomalies, followed by further enhancement in week 2 (22–28 May). These findings are in agreement with the ERF issued on 7 May, jointly pointing to an early onset of the southwest monsoon over Kerala, with greater confidence for the period 22–28 May 2025.

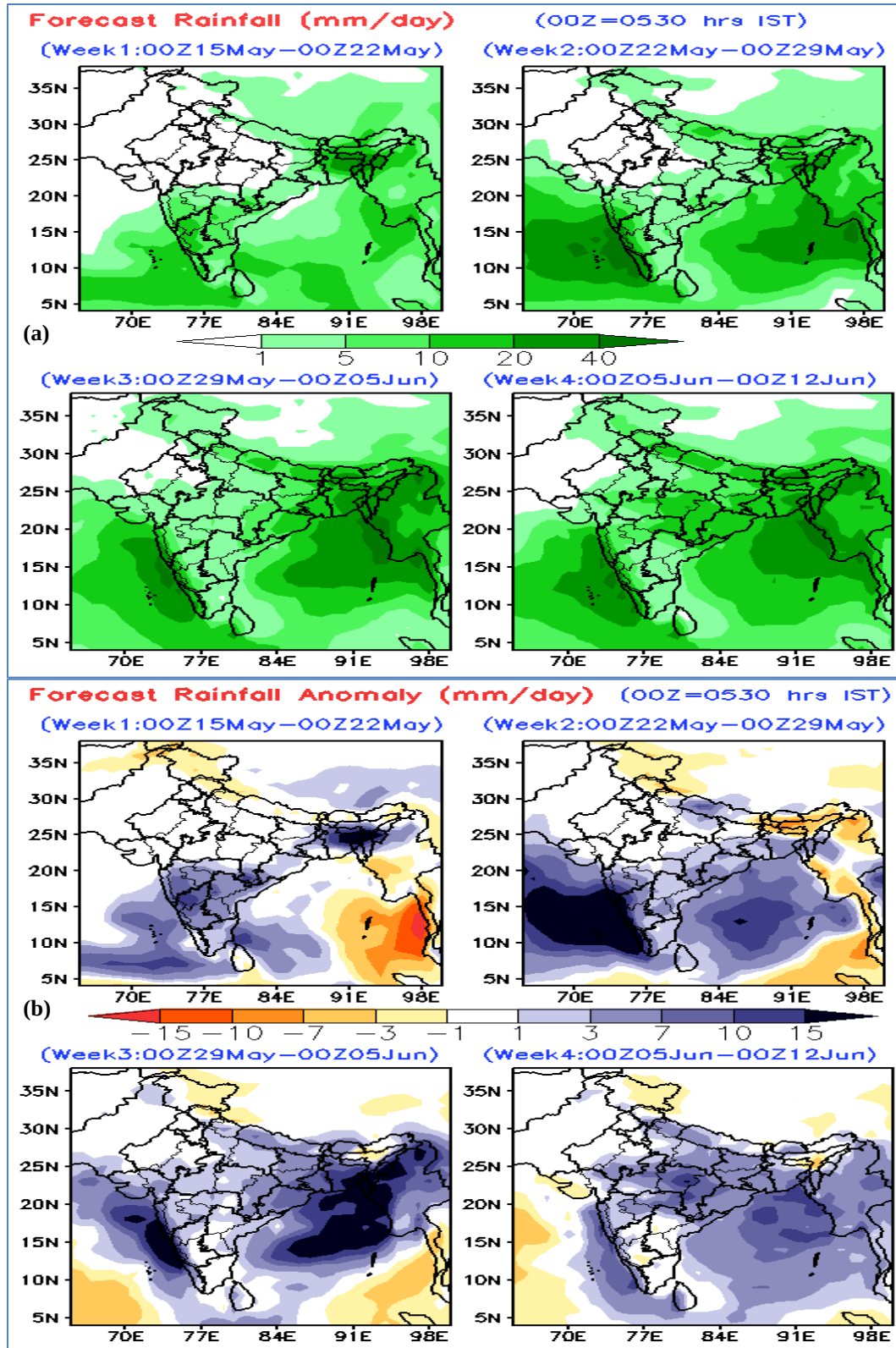
3.3. Objective prediction of monsoon onset date over India based on ERF

To determine the onset date using the objective criteria proposed by Pattanaik and Bushair (2024), four indices were evaluated from the real-time ERF. The forecast time series of rainfall over Kerala, the strength of the low-level jet at 850 hPa over the Arabian Sea, and mid-tropospheric winds at 600 hPa based on the initial condition (IC) of 7 May 2025 are shown in Fig. 9a. These three indices correspond to rainfall over Kerala (Region R1 in Fig. 4) and the strength and depth of the low-level westerly jet over the Arabian Sea (Region R2 in Fig. 4). The fourth index-the south-north mean sea level pressure (MSLP) difference along the west coast-based on the same IC is shown in Fig. 9b. Applying the objective criteria using 3 indices from Fig. 9a, the ERF-derived Monsoon Onset over Kerala (MOK) date was determined as 20 May 2025 and when all the 4 indices are considered the date is found to be 22 May, 2025. For consistency, the ERF forecast time series based on the IC of 14 May was also examined. The rainfall over Kerala, 850 hPa low-level jet, and 600 hPa winds (Fig. 10a) collectively indicated an MOK date of 22 May 2025. When the 4th index of MSLP difference, as shown in (Fig. 10b) is also collectively integrated in defining the onset, the MOK is

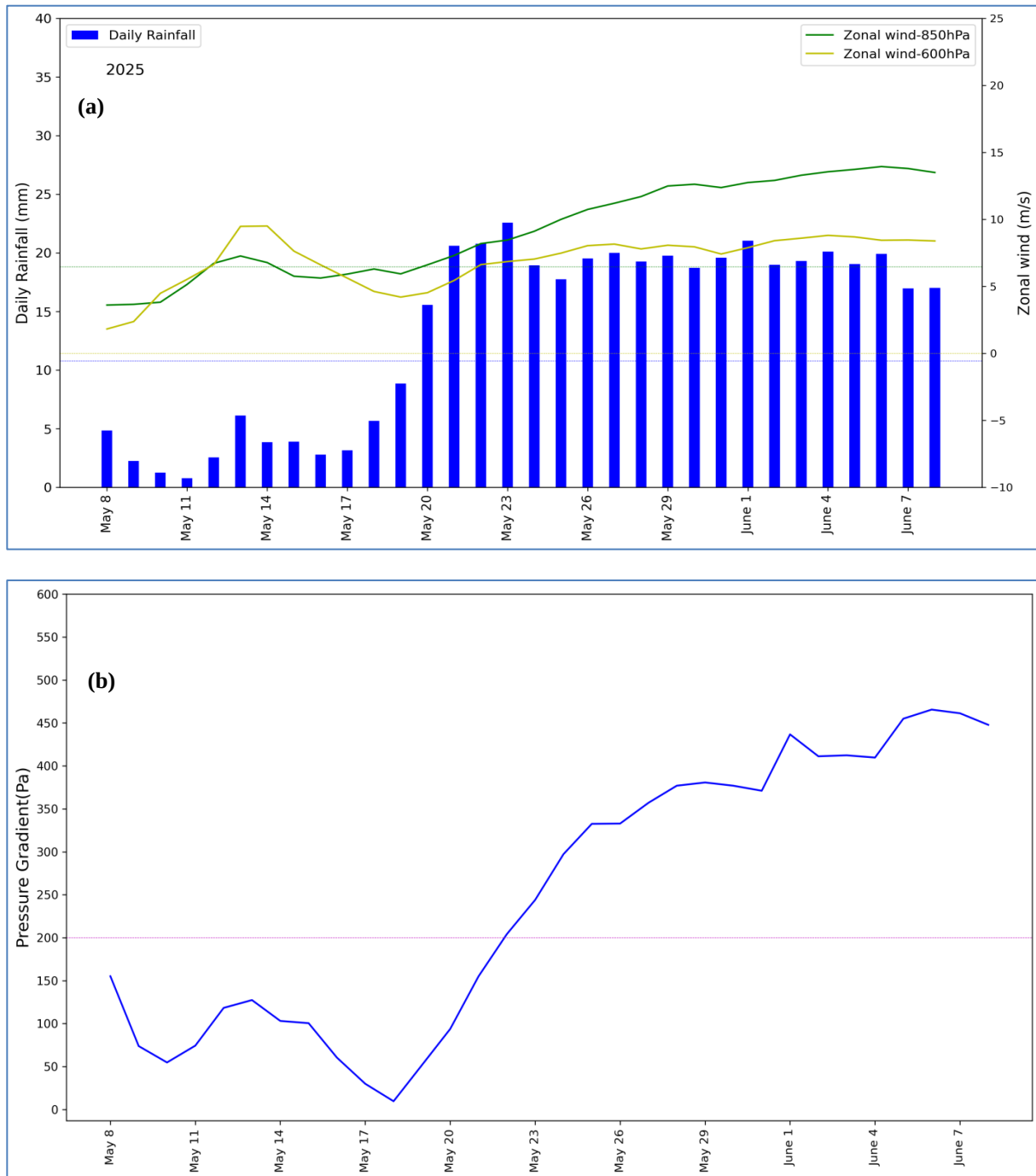
found to be 23 May, 2025. Thus, the objective method applied to operational ERF outputs clearly signalled an early onset of the monsoon between 20 and 23 May 2025. Furthermore, ERF forecasts based on the IC of 15 May 2024 captured the monsoon onset, showing a positive rainfall anomaly during the first week. It is further indicated that the ERF based on the initial condition of 30 April also indicated the likely onset of the monsoon over Kerala, with 3 conditions satisfied for the onset on 19 May (Fig. 11a), whereas when the 4th index of MSLP difference (Fig. 11b) is also considered, it was indicated to be 27 May. Thus, even the week 4 forecast also indicated an early onset of monsoon over Kerala based on the operational ERF with the earliest initial condition of 30 April, 2025.

It is further demonstrated that the district-level forecast in the medium range (up to 5 days in advance), based on the Global Forecast System (GFS) operational medium range NWP model of IMD provides valuable complementarity to the dynamical prediction of the MOK date from the operational ERF system, which gives guidance about three weeks in advance. The medium-range forecast allows for refinement of the exact onset date within a 5-day forecast horizon, as shown by Pattanaik and Bushair (2024). In 2025, rainfall forecasts from the Global Forecast System model, initialized on 23 May and valid for the subsequent five days, are shown in Fig. 12. The day-1 forecast valid for 24 May indicated heavy rainfall (65.5–115.5 mm) over several coastal districts of north Kerala and Karnataka. By day-2 (25 May), this intensified to very heavy rainfall (115.4–204.5 mm) over many districts of coastal Karnataka. The day-3 forecast (26 May) further indicated extremely heavy rainfall (>204.5 mm) over north Kerala and adjoining south Karnataka. By day-4 (27 May), the area of heavy rainfall expanded, covering most of Kerala and Karnataka with widespread very heavy to extremely heavy rainfall. As the monsoon advanced in surges, the day-5 forecast (28 May) showed a slight reduction in rainfall over Kerala, with the focus shifting northward into Karnataka, consistent with the northward progression of the monsoon isochrones.

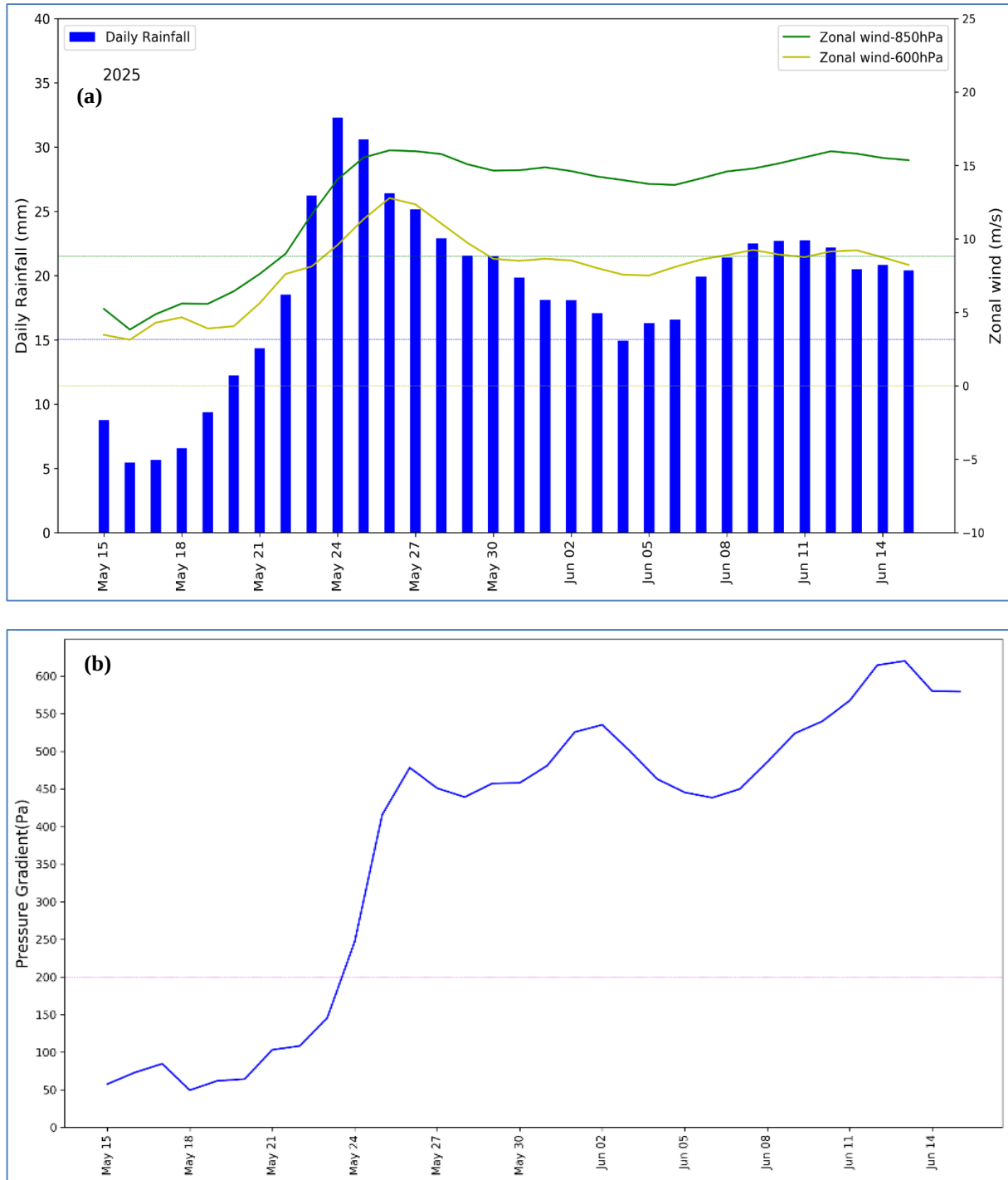
The better performance of the objective criteria in 2025 can be interpreted mainly in terms of the clear and coherent evolution of the monsoon circulation and rainfall signals captured by the ERF system. The relatively good performance of the objective criteria in 2025 may be attributed to the coherent and persistent evolution of the large-scale monsoon circulation and rainfall signals, which were consistently captured by successive extended range forecasts. The ERFs from 30 April, 7 May and 14 May consistently indicated the development of monsoon-like circulation and rainfall during 22–28 May. Such



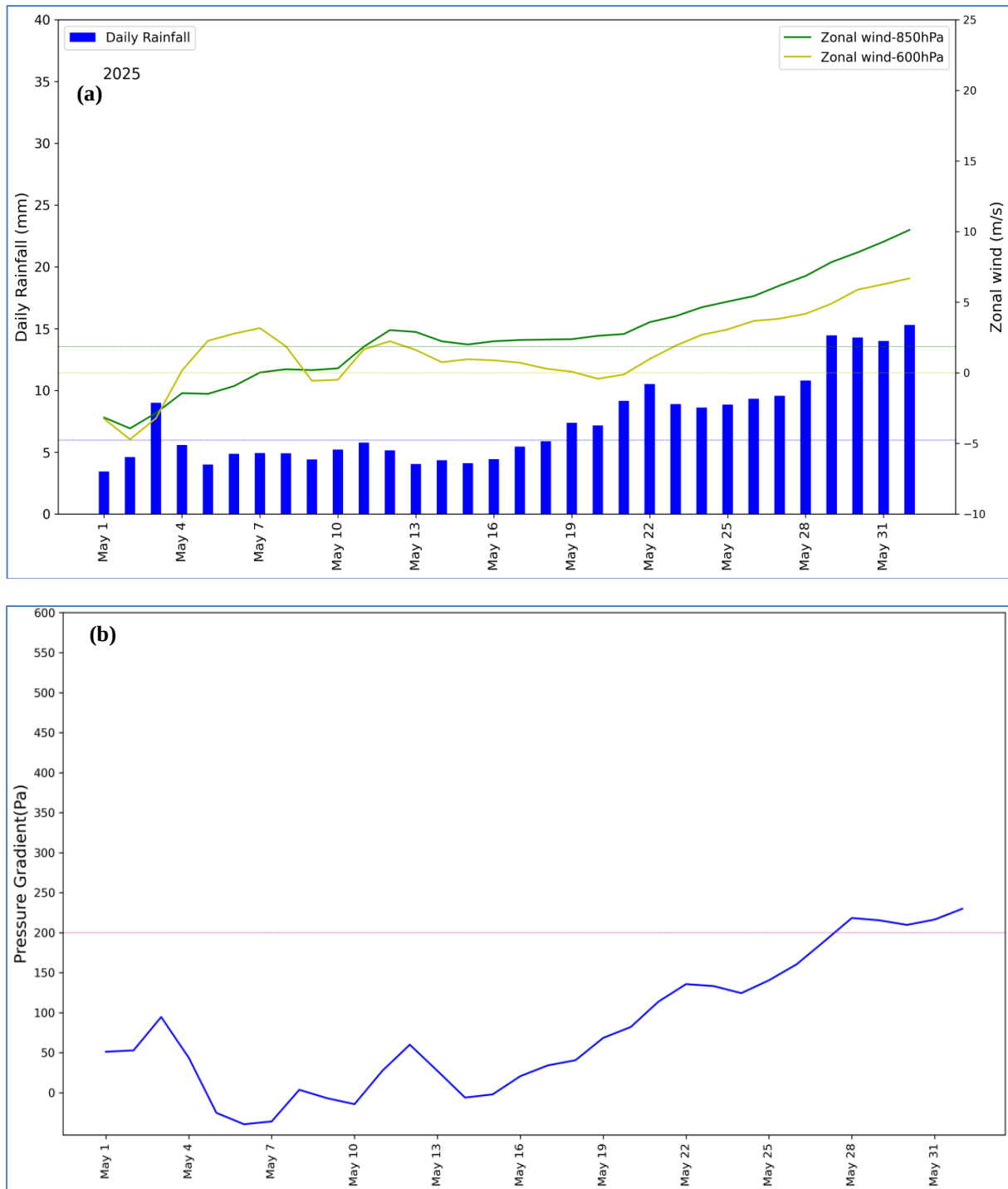
Figs. 8(a&b). Top panel (a) : The extended range forecast weekly mean rainfall for four weeks based on 7th May initial condition and valid for the period from 8th May-04 June, 2025. Bottom panel (b) Same as 'a' but for rainfall anomaly forecast



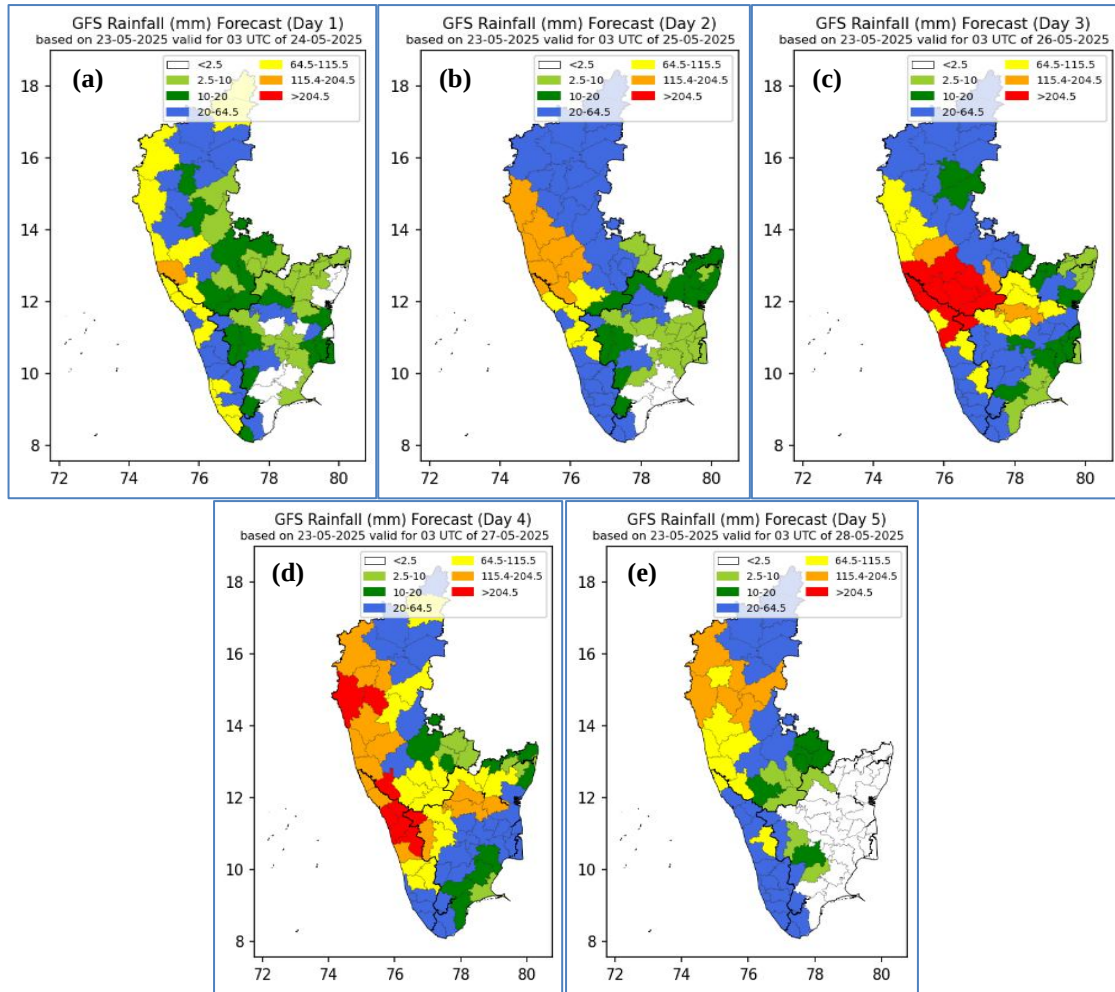
Figs. 9(a&b). (a) The time-series of extended range forecast rainfall for 32 days based on 07 May averaged over the region 'R1' in Fig. 4a as vertical lines along with the horizontal line in dotted blue color representing 80% of their mean starting from 8th May to 8th June, 2025. Similarly, the Zonal wind at 850 hPa averaged over the region 'R2' represented by a dark green line exceeds 70% of its mean (represented by a horizontal dotted line). The depth of westerly, the Zonal wind at 600 hPa averaged over the region 'R2' represented by dark yellow, exceeds zero, represented by the dotted yellow line. (b) The corresponding time-series of the mean sea level pressure difference (South-North MSLP) in Pa bounded by the givens in Fig. 4b



Figs. 10(a&b). (a) The time-series of extended range forecast rainfall for 32 days based on 14 May averaged over the region 'R1' in Fig. 4a as vertical lines along with the horizontal line in dotted blue color representing 80% of their mean starting from 15th May to 15th June, 2025. Similarly, the Zonal wind at 850 hPa averaged over the region 'R2' represented by a dark green line exceeds 70% of its mean (represented by a horizontal dotted line). The depth of westerly, the Zonal wind at 600 hPa averaged over the region 'R2' represented by dark yellow, exceeds zero, represented by the dotted yellow line. (b) The corresponding time series of the mean sea level pressure difference (South-North MSLP) in Pa bounded by the regions as given in Fig. 4b.



Figs. 11(a&b). (a) The time-series of extended range forecast rainfall for 32 days based on 14 May averaged over the region 'R1' in Fig. 4a as vertical lines along with the horizontal line in dotted blue color representing 80% of their mean starting from 1st May to 1st June, 2025. Similarly, the Zonal wind at 850 hPa averaged over the region 'R2' represented by a dark green line exceeds 70% of its mean (represented by a horizontal dotted line). The depth of westerly, the Zonal wind at 600 hPa averaged over the region 'R2' represented by dark yellow, exceeds zero, represented by the dotted yellow line. (b) The corresponding time series of the mean sea level pressure difference (South-North MSLP) in Pa is bounded by the regions as given in Fig. 4b



Figs. 12(a-e). GFS model forecast rainfall for 5 days, valid for 24th to 28 May, based on 23 May 2025 over the districts of Kerala, Karnataka, and Tamil Nadu during 24 to 28 May 2025

consistency across successive initial conditions suggests that the large-scale monsoon transition was reasonably well captured by the model. In particular, the concurrent strengthening of low-level and mid-tropospheric westerlies, enhancement of rainfall over Kerala, and establishment of the west-coast north-south pressure gradient resulted in a consistent crossing of the prescribed thresholds, thereby enabling the objective criteria to closely reproduce the observed onset date.

4. Conclusions

The dynamical model-based objective prediction system for monsoon onset over Kerala based on the real-time operational extended range forecast systems of IMD is tested for the southwest monsoon season 2025. The objective definition of MOK is defined by using four forecast indices based on rainfall over (i) Kerala, (ii) the strength of the low-level westerly over the

Arabian Sea at 850 hPa, (iii) mid-tropospheric level wind at 600 hPa level and (iv) the north-south pressure difference over the west coast region exceeding a threshold value. For declaring the onset, the ERF rainfall over the Kerala domain should exceed 80% of its climatological mean, and the low-level westerlies over the southeast Arabian Sea should exceed 70% of their climatological mean, with the westerly flow extending vertically up to 600 hPa. The MOK is defined on the first day, if all three given conditions are satisfied for consecutive 5 days in the ERF, along with the criteria that the south-north pressure difference on the west coast exceeds the threshold value of 2 hPa in the ERF. Applying these criteria for the 2025 monsoon, it is observed that the week 4 forecast valid for the period from 22-28 May 2025, based on the initial condition of 30 April, indicated the characteristics of southwest monsoon circulation and rainfall patterns for the likely early monsoon onset over Kerala. Similarly, the ERF based on ICs of 7 May and 14 May also indicated favourable monsoon circulation and

rainfall for the MOK during week 3 and week 2 forecasts, respectively, valid for the week from 22-28 May 2025. As per the objective criteria, the MOK based on the ICs of 7th and 14th May is found to be 20th to 23rd May, respectively, which is very close to the actual onset declared by IMD on 24 May.

The present study is limited to demonstrating the real-time application of the previously established objective criteria for the 2025 monsoon onset. While the criteria have been validated over a multi-year period in an earlier study, the present analysis is based on a single season and therefore primarily demonstrates their operational utility rather than further assessing their long-term statistical performance.

Data availability

Daily rainfall data used here is available from IMD Pune.

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The contents and views expressed in this research paper are the views of the authors and do not necessarily reflect the views of their organizations.

Authors' contributions

D. R. Pattanaik (DRP): The conception and design of the study and drafting the article.

C. J. Johny (CJJ): Carried out the model integration. (email- johnycjimd@gmail.com).

M. T. Bushair (MTB): Prepared the graphics used in this study. (email- bushair.imd@gmail.com).

S. D. Sanap (SDS) : Provided the input on monsoon onset, which was incorporated in the paper (email- sakha.sanap@gmail.com)

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