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**Ocean-atmosphere processes determining the onset of Indian summer monsoon: Differential
Influence of synoptic to sub-seasonal scale drivers**

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36 **Abstract**

37 The present study investigates the ocean–atmosphere processes associated with the onset of Indian
38 Summer Monsoon rainfall by classifying onset years into six categories: too early (before 20 May),
39 very early (21–24 May), early (25–29 May), normal (30 May–2 June), late (3–7 June), and very late
40 (after 7 June). This classification helps identify interactions among processes operating at different
41 temporal and spatial scales that influence the timing of monsoon onset, thereby improving the
42 understanding of its underlying mechanisms and predictability. The analysis shows that the too-early
43 onset (before 20 May) is mainly controlled by large-scale climatic patterns. These include La Niña
44 conditions in the Pacific Ocean, cooling in the Indian Ocean during April–May and strong upper-
45 level Rossby wave interactions over the Indian landmass. These factors enhance the northward
46 movement of convection and facilitate early monsoon onset, while the Madden–Julian Oscillation
47 (MJO) or intraseasonal oscillation (ISO) signal remains weak. Thus, the anomalous basic state for the
48 onset is largely determined by large-scale forcing. During very early onset years, La Niña conditions
49 and upper-level wave activity are present but weaker compared to the too-early onset cases. Instead,
50 warm sea surface temperature (SST) anomalies over the equatorial and northern Indian Ocean and
51 their northward propagation play an important role in triggering convection and initiating the
52 monsoon onset. In early and normal onset years, warm SST anomalies over the equatorial and
53 northern Indian Ocean persist until the onset pentad, supporting the northward propagation of
54 convection. In these cases, MJO-related anomalies help propagate convective signals from the
55 equator to about 35°N, contributing to the onset between 25 May and 2 June. In contrast, late onset
56 years are influenced by El Niño-related warming in the Pacific and subsidence over the Indian Ocean,
57 which suppress convection and delay the monsoon onset.

58 **Key words-** Monsoon onset | Intraseasonal Oscillation | Rossby wave | Rainfall.

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1. Introduction

The Indian Summer Monsoon (ISM) Rainfall is one of the most essential regular seasonal phenomena influencing the Indian economy and biodiversity. Over 70% of India's annual rainfall occurs during the summer monsoon season from June to September (Parthsarathy et al. 1994). The onset of the monsoon over Kerala (MOK), India, has been considered the beginning of the ISM. The date of MOK, which marks the beginning of the monsoon rains over the southern Indian peninsula (Ananthakrishnan et al. 1983), is an important event in the socioeconomic life of the people of India, particularly in agricultural planning that affects food production and the lives of over one billion people. Any delay in onset leads to water scarcity, reduced crop yields and increased economic inflation (Raju et al. 2005; Amale et al. 2023). Hence, an accurate forecast of the MOK date is crucial for the model development community.

The sustained increase in rainfall at the stations over Kerala and the associated changes in the upper and lower-troposphere circulation are key features of the monsoon onset. The steady increase in convection over the South Arabian Sea (AS) is associated with the cross-equatorial flow (Rajeevan et al. 2017). Furthermore, the increasing depth of the low-level jets (LLJ) marks the monsoon onset and subsequent evolution of the onset. Previous studies highlighted that the differential heating between the South Asian landmass and the IO is a fundamental mechanism driving the ISM rainfall (Li and Yanai, 1996).

At the onset, south-westerly winds strengthen due to the temperature and pressure contrasts between the land and the ocean (Ananthakrishnan et al. 1983; Pradhan et al. 2019). Baburaj et al. (2021) analysed cyclone and non-cyclone years at onset and found that tropical cyclones (TCs) over the north IO may influence the progression of the monsoon surge, either accelerating or retarding the monsoon current. It further showed that TC formation alters both the low-level jet (LLJ) at 850 hPa and the tropical easterly jet (TEJ) at 150 hPa. The thermodynamic state is equally important; the onset date is marked by a change from negative to positive meridional gradients of tropospheric temperature (ΔT) (Webster et al. 1988). Goswami and Xavier (2007) define the monsoon onset as the TT difference between the Land (40°E - 100°E , 5°N - 35°N) and the Ocean (40°E - 100°E , 15°S - 5°N), averaged between the 600hpa and 200hpa pressure levels. The recent study Bin wang et.al (2009), defines Objective circulation index (OCI) based on the monitoring of the westerlies over the southern AS (5°N - 15°N , 40° - 80°E), the first day of period where the OCI is continuously exceed the 6.2 m/s for more than seven days which indicates the rapid change in the large-scale circulation during the seasonal transition. Fasullo and Webster (2002) defined the Hydrological Onset and Withdrawal Index (HOWI) based on vertically integrated moisture transport. However, this index can sometimes indicate a false (bogus) onset due to transient synoptic-scale disturbances. The evaporation of the IO supplies most of the moisture required for this; it depends on the strength of the low-level winds. In

105 addition, negative anomalies in geopotential height at 500 hPa and an enhancement of total
 106 precipitable water (TPW) favour convection and rainfall over the Western Ghats and the adjoining
 107 Sea, whereas the opposite anomalies suppress monsoon activity (Bhowmik et al. 2019).
 108 Previous studies have shown the role of different external factors such as El Nino southern Oscillation
 109 (ENSO), intraseasonal oscillation depending on the phase of Madden Julian Oscillation (MJO) and
 110 other synoptic scale variability (Soman and Slingo 1997, Joseph et al 1994, Goswami et.al, 2005,
 111 Joseph et al. 2011, Lin et al. 2025, Taraphdar, S. et.al , 2018). Soman and Slingo (1997) showed that
 112 El Nino, positive phase of ENSO delays the monsoon onset, while the La Nina, cold phase of ENSO
 113 tends to advance the time of monsoon onset. Joseph et al. (1994) showed that, among the 22 years of
 114 delayed onset during their study period, 16 cases were associated with strong or moderate El Niño
 115 events and the delay was greater than 8 days. Their study further revealed that delayed MOK is
 116 associated with warm SST anomalies at and south of the equator in the Indian and Pacific Oceans and
 117 with cold SST anomalies in the tropical and subtropical oceans to the north during the pre-monsoon
 118 season (March to May). Another study by Goswami et al. (2005) showed that El Niño-Southern
 119 Oscillation (ENSO) controls the ISM rainfall by influencing the length of the rainy season (LRS);
 120 during El Niño events, ΔTT is reduced, the onset is delayed and the withdrawal is advanced compared
 121 to La Niña years. In the context of the study, intraseasonal Oscillation (ISO) plays an essential role in
 122 the onset of the monsoon (Joseph et al.; Lin et al. 2025). The monsoon onset is tele-connected to
 123 global climatic processes such as ENSO, IOD and MJO. Taraphdar et.al (2018) studied the
 124 relationship between the monsoon onset and Madden-Julian oscillation (MJO) and concluded that for
 125 the monsoon onset, two significant factors play a role: 1) Background conditions associated with
 126 seasonal transition and 2) intraseasonal variations associated with the active MJO. The synoptic event
 127 during the onset plays a key role in the timing of monsoon onset (Saini et al. 2022). The transition
 128 from light to heavy rainfall on the first date, Soman et al. (1993) studied the space-time evolution of
 129 meteorological features associated with monsoon onset, treating north and southern Kerala separately,
 130 using daily rainfall from the first pentad and after the transition, with values not less than 10 mm.
 131 RavindraBabu et al. (2019) studied the relationship between the ISMR onset and tropopause
 132 parameters, noting that the tropopause height decreases and temperature increases during onset.
 133 Pearce and Mohanty (1984) studied the onset for the year 1979 and divided the monsoon onset into
 134 two phases: 1) a moisture build-up over the AS during which synoptic and mesoscale transient
 135 disturbances develop. 2) a rapid intensification of the AS winds and a substantial increase in the latent
 136 heat release. Ramesh Kumar et al. (2012) examine the presence of the monsoon vortex over the AS
 137 (AS), which helps set monsoon onset over Kerala.
 138 The prediction of the monsoon onset date criteria was first standardized by the India Meteorological
 139 Department (IMD) in 1943 based on a subjective definition of the five-day rainfall observation at

multiple stations in Kerala state (IMD, 1943; IMD weather information is available online at <http://www.imd.gov.in>). Due to the lack of monotonicity in monsoon onset, it is necessary to investigate onset dates separately. Several factors influence the onset of the monsoon, making its understanding and prediction complex (Saini et.al. 2023). Monsoon onset timing is crucial for agricultural crop sowing, water resources management, etc. Therefore, the study of the timing of monsoon onset and its interannual variability is significant. The monsoon onset over Kerala varies yearly and can be categorized as early, normal, or late (Raju et al. 2005). However, our present analysis noticed that within the one category (for example, early onset) itself, there is large variability in onset dates say from before 20th May onwards (based on 1980 onwards data) and is like another late category also. The onset occurs due to the changes in the sea surface temperature, moisture transport, LLJ speed and direction, land-sea thermal contrast and convection over the IO. The timing of these changes determines whether the onset is early or late. This study examines the mechanism behind the different time scales of onset. Previous studies have examined the monsoon onset over Kerala. The distinct features of early, delayed and normal onsets remain unclear. This study aims to address this gap by analysing 45 years (1980–2024) of reanalysis and observational data to characterize the variability of different onset types and the underlying mechanisms. The data used for this study are discussed in Section 2. The evolution of meteorological parameters at different onset times is discussed in Section 3. Finally, the results and conclusions are summarized in Section 4.

2. Data and Methodology-

The primary data set used in this study is the daily reanalysis data from the National Centre for Environmental Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR). Daily variables include air temperature (AT), specific humidity (SHUM), geopotential (GPT), precipitable water (PW), mean sea level pressure (MSLP), and wind vector (U, V) data at a spatial resolution of 2.5 X 2.5. The daily sea surface temperature (SST) from the National Oceanic and Atmospheric Administration (NOAA) Optimum interpolation SST 0.25 X 0.25 resolution data set (Huanget al. 2021). Daily mean interpolated outgoing longwave radiation (OLR) data were obtained from NOAA on a 2.5 X 2.5 horizontal grid and used as an indicator of large-scale convective activity during the analysis period (Liebmann and Smith, 1996). The daily gridded IMD rainfall data at 0.25 X 0.25 spatial resolution over the Indian continent were used for the rainfall analysis. The Monsoon Onset dates are calculated based on the Tropospheric Temperature (TT) difference between the Land (40°E-100°E, 5°N-35°N) and Ocean (40°E-100°E, 15°S-5°N) averaged between the 600hpa and 200hpa pressure level, when it turns Positive and is declared as the Onset (Xavier and Goswami, 2007). The NCEP-NCAR reanalysis prepared the air temperature data for the period 1980-2024. Based on the 45

174 years onset dates categorized the Too Early (<20 May), Very early Onset (20 May -24 May), Early
175 Onset (25 May-29 May), Normal Onset (30 May- 02 June), Late Onset (03 June- 07 June) and Very
176 Late Onset (> 07 June) on the basis of the TT value. The details of these different categories are
177 provided in Table 1. We analyse the composite dynamics of the onset over pentads (5-day averages)
178 for the three pentads before the Onset Date and the three pentads after the Onset Date. Daily anomalies
179 are calculated by subtracting the daily climatological mean (1980-2024) from the original data.
180 To analyse the intraseasonal variability of convection, a 30-60-day band-pass filter was applied to
181 OLR anomalies, which were analysed using the space-time spectral filtering method proposed by
182 Wheeler and Kiladis (1999). The propagation of the 60° E-90°E region, which corresponds to the core
183 zone of monsoon onset and active phase development zone, was investigated. The eastward
184 propagation of negative OLR anomalies highlights the role of the intraseasonal oscillation in the onset
185 of the monsoon. Further, we analyse the composite of monthly Plumb (1985) horizontal wave flux
186 activity during the monsoon onset period using monthly zonal winds and geopotential heights at
187 200hPa. The flux was derived from the perturbation quasi-geostrophic stream function anomalies,
188 defines as $\psi' = (g/f) * Z'$, where 'Z' is the deviation of geopotential height anomaly from its zonal
189 mean. The flux activity is a powerful diagnostic for understanding atmospheric energy propagation,
190 revealing the direction and strength of the Rosby wave train. The wave flux shows how disturbances
191 influence the distant region and highlights the key connection between monsoon circulation and
192 intraseasonal variability. The two-dimensional horizontal wave activity flux is defined as:

$$194 \quad F_x = \frac{p}{2a^2 \cos \phi} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right], \quad F_y = \frac{p}{2a^2} \left[\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \right. \\
195 \quad \left. \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right] \quad \dots(\text{Eq.1})$$

196
197 Where g is the gravitational force, Fx, Fy are the horizontal wave activity flux components, p is the
198 pressure level, a radius of the earth, φ latitude, λ longitude, ∂/∂λ, ∂/∂φ are the partial derivatives.

Too Early Onset (<20 May)	Very Early Onset (20-24 May)	Early onset (25-29 May)	Normal onset (30 May- 02 Jun)	Late onset (03-07 Jun)	Very late onset (>07 June)
16/05/1990	21/05/1988	27/05/1981	01/06/1982	03/06/1980	12/06/1992
17/05/2000	20/05/1989	26/05/1984	02/06/1987	05/06/1983	08/06/2019
18/05/2004	22/05/1999	25/05/1985	02/06/1991	06/06/1986	08/06/2023
	24/05/2001	27/05/1996	30/05/1994	05/06/1993	09/06/2024
	24/05/2013	25/05/2006	02/06/2002	04/06/1995	18/06/2009
	23/05/2022	28/05/2008	01/06/2005	06/06/1997	
		29/05/2017	30/05/2012	05/06/1998	
		28/05/2018		04/06/2003	
				04/06/2007	

				04/06/2010	
				06/06/2011	
				07/06/2014	
				06/06/2015	
				07/06/2016	
				04/06/2021	
				03/04/2020	

Table-1. Category wise onset dates relative to TT values.

3. Results and Discussion.

In the present study, tropospheric temperature (TT) anomalies are used to define the onset as per the definition of Xavier and Goswami (2007). According to the TT value, the study period is categorized into too early onset years (onset before 20th of May), very early onset (20-24 of May), early onset (25-29 May), normal onset (30 May-3 June), late onset (4-7 June) and very late onset (after 7th June). The number of years falling under each category is provided in Table.1. A composite analysis of ocean-atmosphere variables for these different onsets categories is performed on a pentad (5-day average) basis, spanning three pentads before and three pentads after the onset.

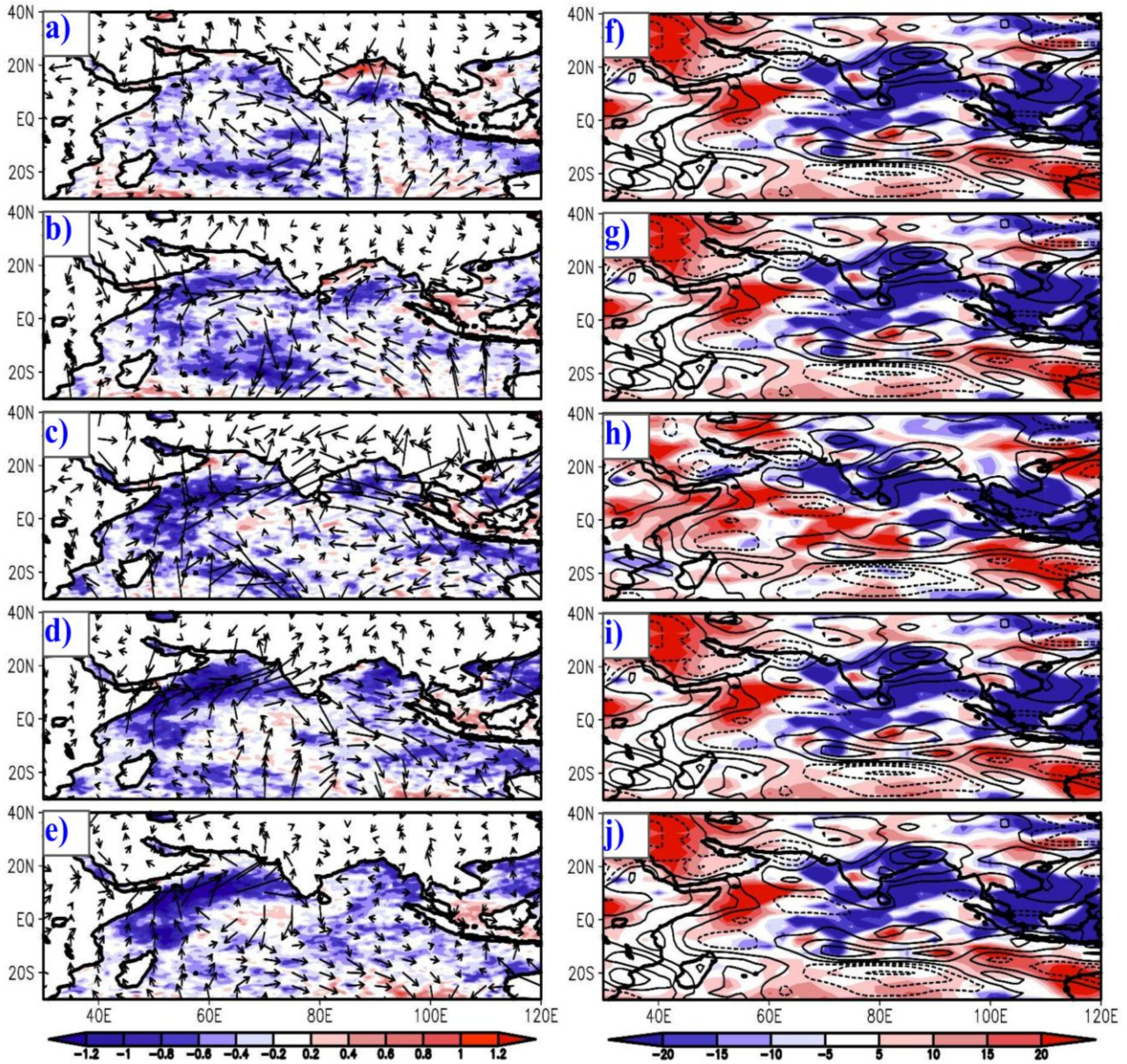
The pentad-wise evolution of each category is discussed in the following sections to understand the changes in both the atmosphere and ocean surface that led to monsoon onset.

3.1 Evolution of ocean-atmosphere processes associated with different types of onsets

a. Too early onset years (onset before 20th May).

Figure 1 shows the pentad-wise evolution of SST (shaded), 850hpa wind (vector), OLR (shaded) and PW anomalies (contour) from two pentads before the onset (P-2) to two pentads after the onset (P+2) of monsoon as per TT criteria. Here, SST anomalies are warm in the equatorial IO and AS during P-3, with a cyclonic circulation centred in the southern part of India. As shown in Fig.1 (left panel), cooling in the AS initiates during pentad -1, intensifies with the monsoon onset and persists through the subsequent three pentads. Also, the wind anomaly indicates that the increase in the cross-equatorial flow with the presence of cyclonic circulation over the north AS region (Fig. 1b). A weak cyclonic flow over the southern part of the equatorial IO triggers the cross-equatorial flow (Fig.1b). These favourable conditions support the initiation of convection from pentad-2 onwards. Both OLR and precipitable water anomalies are convection-favouring over India from P-2 onwards, over the entire India and persist until P+2 (Fig.1- right panel). The 850-hPa wind from BOB to the land region as part of the cyclonic circulation during P-2 and the AS cyclonic circulation development during the

231 P-1 can also contribute to the anomalous increase of PW over the monsoon region during that time.
 232 However, the IMD rainfall distribution is organised over the southern region of India by pentad 0 and
 233 extends northward during pentads 1 to 3 (see S.1- 1st row). Earlier studies have shown that the
 234 relationship between precipitable water and rainfall is nonlinear over tropical regions (Rushley et al.
 235 2018). This analysis shows that wind preconditioning exists in the equatorial Indian Ocean well
 236 before the onset of the monsoon around mid-May during these years.



237 **Fig.1-** Pentad-composite anomalies for too early onset years P-2 to P+2. Left: SST (shaded, °C) and
 238 850-hPa winds (vectors, m s⁻¹). Right: OLR (shaded, W m⁻²) and PW (contours, mm).
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241 b. Very early onset years (onset between 20-24 May)

242 Figure 2 presents the pentad evolution of SST (shaded), 850hpa wind (vector), OLR (shaded) and PW
243 anomalies (contour) from P-2 to P+2 for the Very early onset category (onset between 20-24th May).
244 Fig. 2 indicates that the north IO SST anomalies remain warm through P-1 in these cases. The north
245 IO SST cools with the onset of convection during P0 and this persists for lead 1 to 3 pentads (Fig. 2b-
246 e). Westerly wind anomalies are persistent south of the Indian region from pentad -3 onward,
247 becoming stronger at the onset of pentad and persisting further, without development of any cyclonic
248 circulation anomaly as seen in the too-early-onset category. OLR and PW support the progression of
249 convective activity by P-1 in equatorial IO and extend to India by P0 and persist for 2 more pentads
250 (Fig. 2h-j). IMD rainfall indicates increased rainfall over the western side of India from pentad -1
251 through pentad 2(Supplementary fig.1- 2nd row).

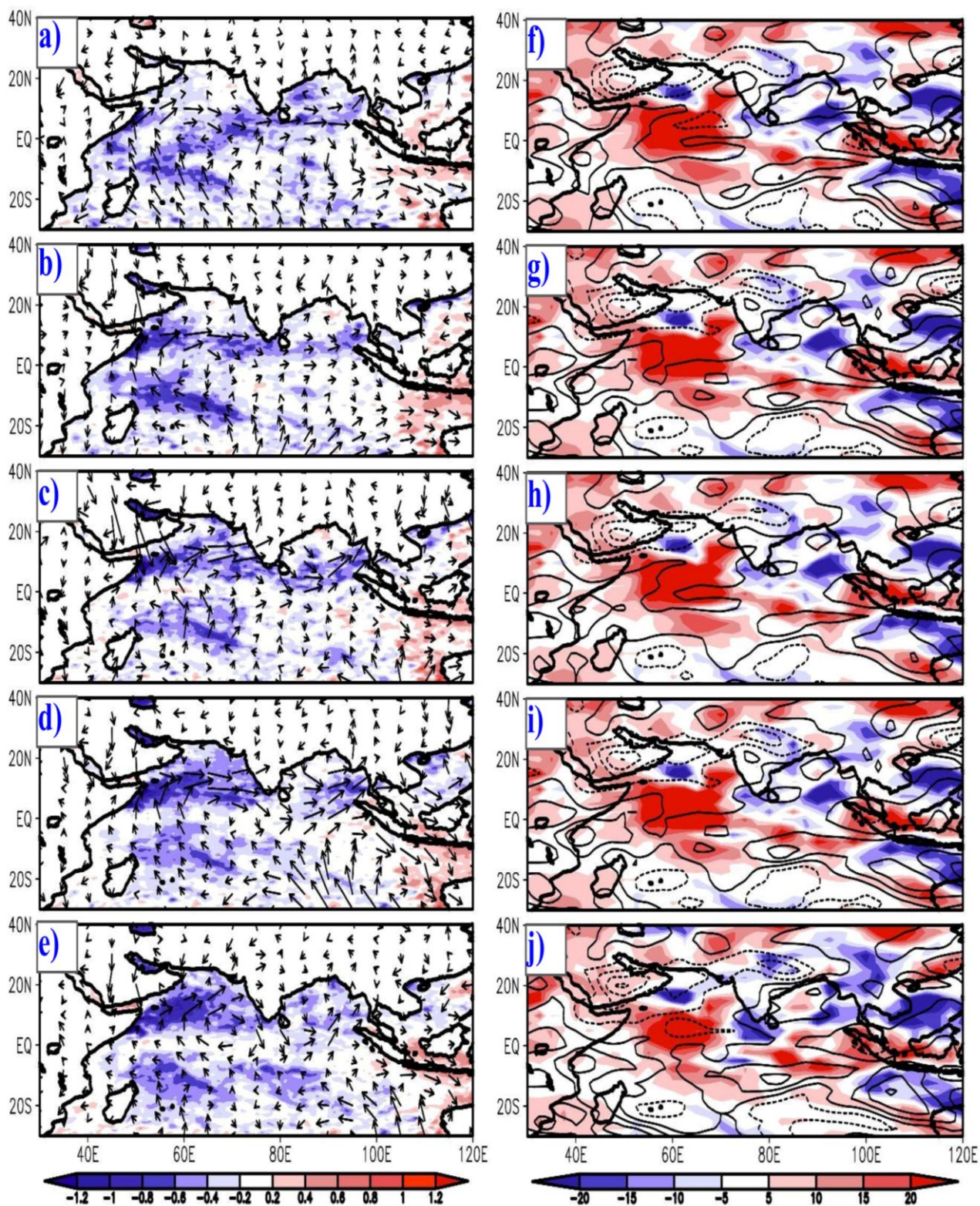
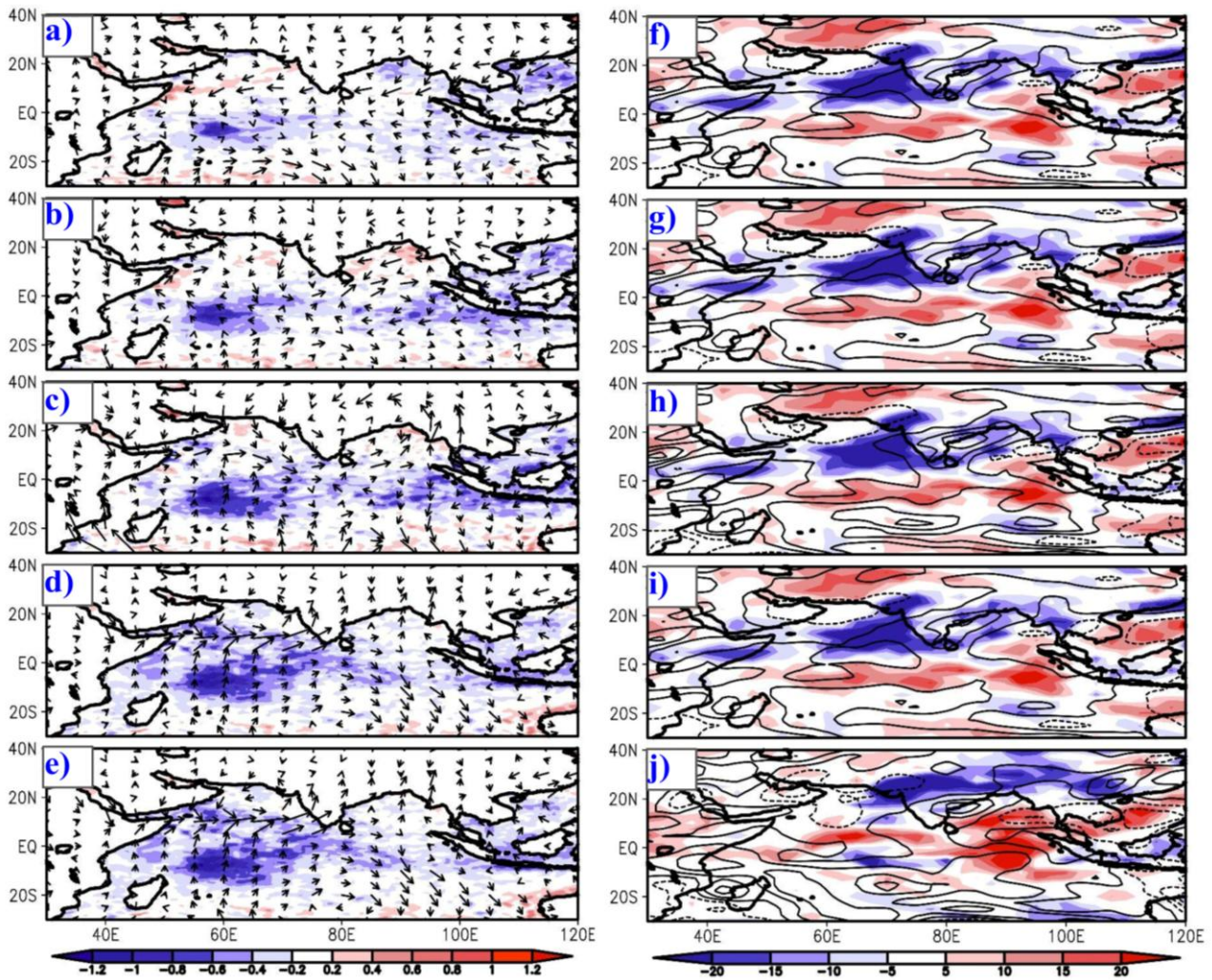


Fig.2- Pentad-composite anomalies for very early onset years P-2 to P+2. Left: SST (shaded, °C) and 850-hPa winds (vectors, m s⁻¹). Right: OLR (shaded, W m⁻²) and PW (contours, mm).

259 *c. Early onset years (onset between 25May-29May)*

260 Figure 3 illustrates the pentad evolution of the SST (shaded), 850hPa wind (vector), OLR (shaded)
 261 and PW (contour) anomalies from P-2 to P+2 for early monsoon onset years. A warm SST anomaly
 262 persists over the north IO through pentad 0, while the cooling is initiated in the south equatorial IO
 263 and propagates northward to the northern IO by P+1, indicating the northward migration of the
 264 convection. Here, the SLP changes from the positive anomalies to negative anomalies at P-1 and
 265 sustains through P+2. Low-level circulation exhibits negligible wind anomalies prior to P0, weak
 266 westerly anomalies formed at the onset P0 and strengthened thereafter. PW from the equatorial IO
 267 reaches the Indian region by P0 and continues northward propagation over the next two pentads. Also,
 268 a positive rainfall anomaly is seen during this period (S.1 - 3rd row). Notably, the anomaly during
 269 this period is comparatively subdued due to the higher climatological mean of meteorological
 270 parameters in late May-early June.

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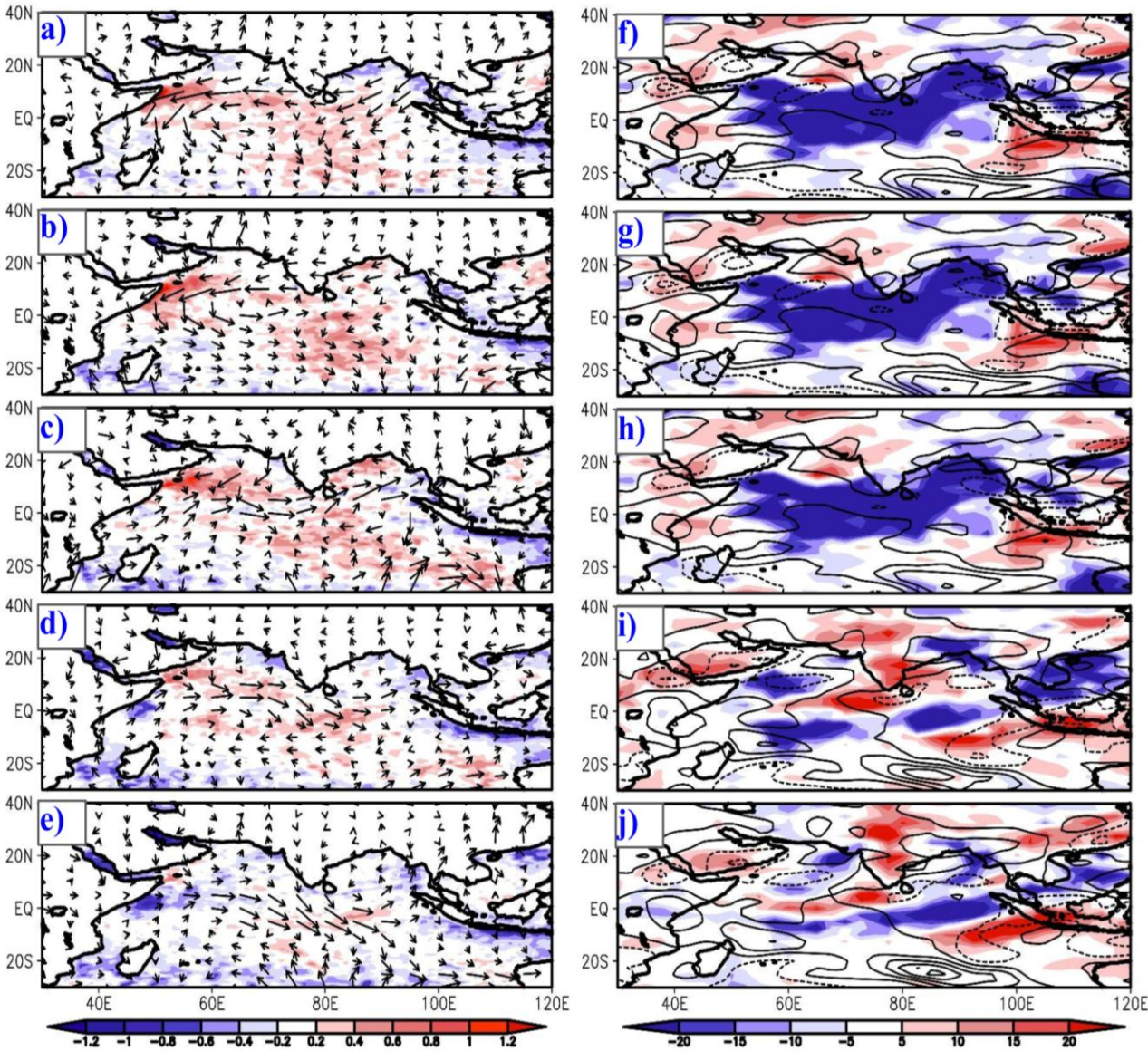
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273 **Fig.3-** Pentad-composite anomalies for early onset years P-2 to P+2. Left: SST (shaded, °C) and
 274 850-hPa winds (vectors, m s⁻¹). Right: OLR (shaded, W m⁻²) and PW (contours, mm).

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d. *Normal onset (onset between 30May -02 June)*

For normal onset year cases, the pentad evolution of SST (shaded), 850hPa wind (vector), OLR (shaded) and PW (contour) anomalies from P-2 to P+2 is shown in Fig.4. The SST anomalies are warm over the northern IO through P+1, with negative anomalies during P+2, reflects the associated with the northward propagation of convection from equatorial region (Fig 4c-e). Westerly wind anomalies advance into the equatorial IO by P0 and remain sustained through P+2 (Fig. 4c-e). This circulation coincides with the convection and PW anomalies; both reach the India region by P-0 and propagate northward through P+2. This is associated with convection over western India at this time. The rainfall anomalies are consistent after the onset date, suggesting that the rainfall is supported by the convective activity (S.1- 4th row).



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288 **Fig.4-** Pentad-composite anomalies for too normal onset years P-2 to P+2. Left: SST (shaded, °C)
289 and 850-hPa winds (vectors, m s⁻¹). Right: OLR (shaded, W m⁻²) and PW (contours, mm).

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291 *e. Late onset (onset between 03– 07 June)*

292 During the late-onset year cases, the pentad evolution of SST (shaded), 850 hPa wind (vector), OLR
293 (shaded), and PW (contour) anomalies from P-2 to P+2 is shown in Figure 5. The IO exhibits a distinct
294 pattern of delayed dynamical evolution. A weak positive SST anomaly persists uniformly across the
295 entire IO basin from P-2 to P+2, with maximum warming over the Wester AS near the African coast,
296 a signature of weakened cross-equatorial flow (Fig. 5a-e). This indicates that the anomalous westerly
297 wind pattern across the IO is absent until P+2, confirming the absence of convection during the first
298 two pentads after the onset. Convection initiates late, emerging over the equatorial IO only at P0, but
299 due to the weak wind flow, the westward and northward propagation gets delayed.

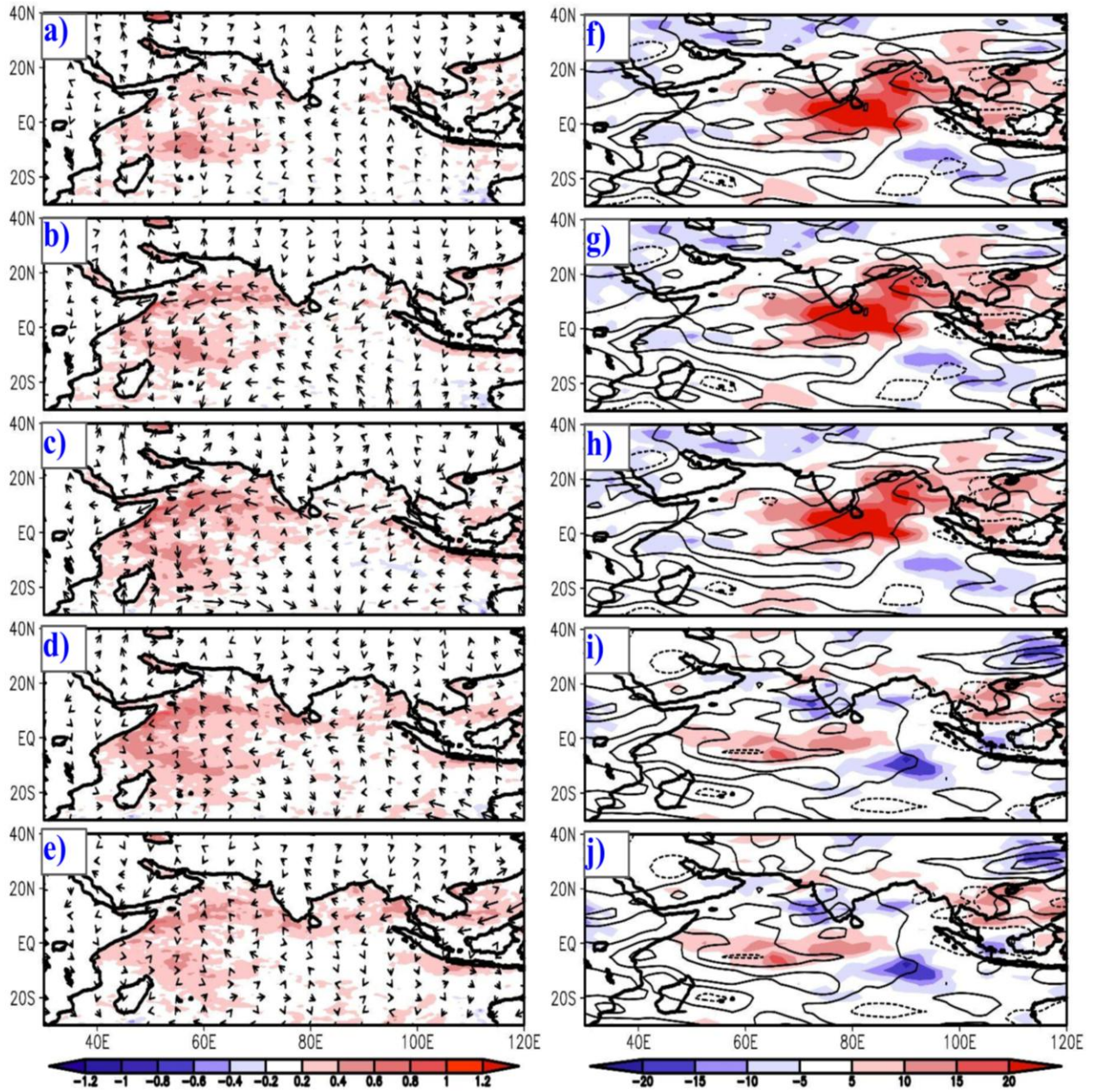
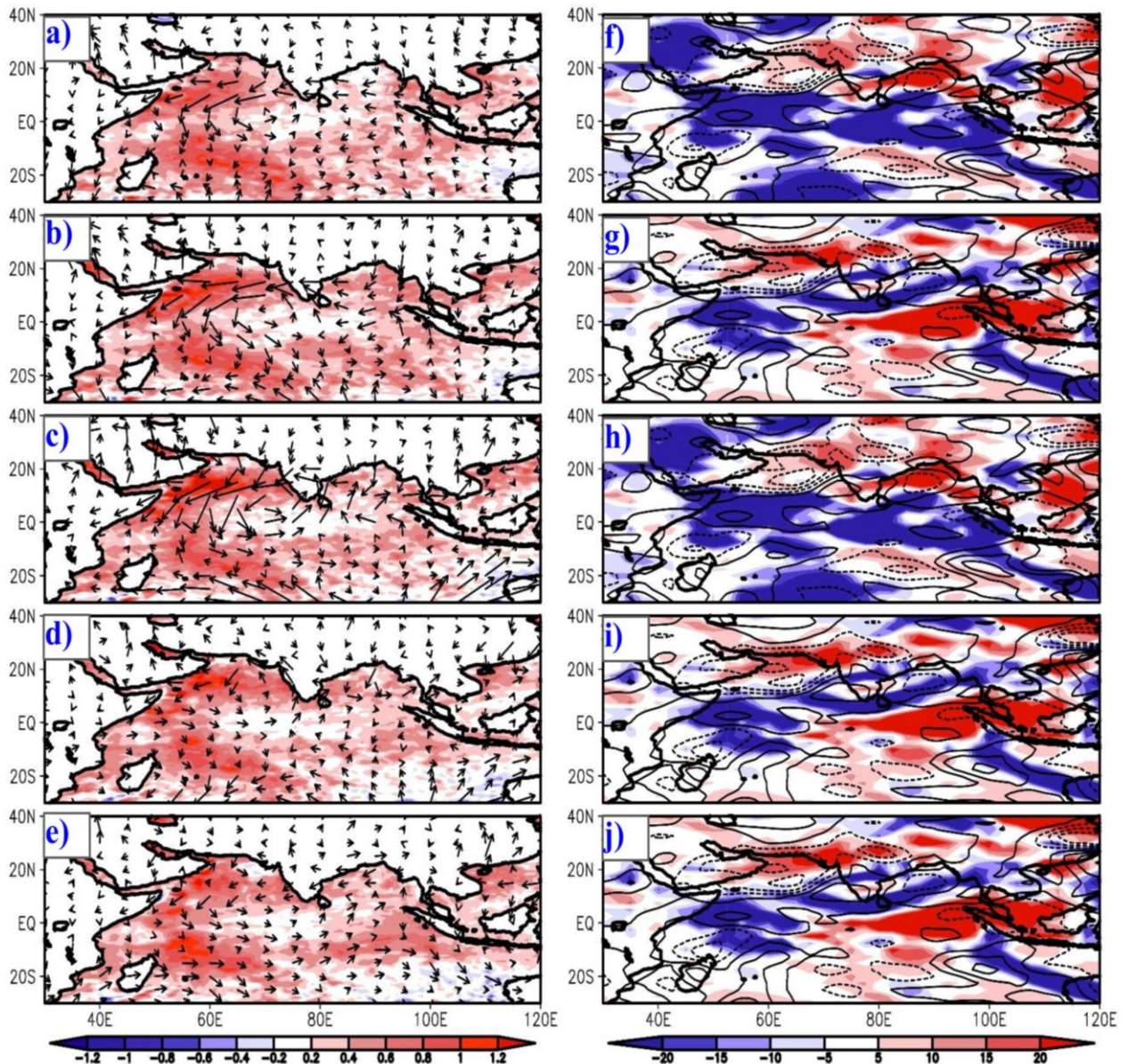


Fig.5- Pentad-composite anomalies for late onset onset years P-2 to P+2. Left: SST (shaded, °C) and 850-hPa winds (vectors, m s⁻¹). Right: OLR (shaded, W m⁻²) and PW (contours, mm).

f. Very late onset (onset after 07 June)

Figure 6 depicts the pentad evolution of SST (shaded), 850hPa wind (vector), OLR (shaded) and PW (contour) anomalies from P-2 to P+2. Throughout the pentads (P-2 to P+2), northern IO maintains a warm SST anomaly, with pronounced warming in western AS, indicative of weak monsoon flow, as seen in the late-onset case. A notable feature is that a weak cyclonic circulation develops over the AS during P-1 to P0, which enhances moisture and convection over the western part of India at P0, as evident in the OLR and PW. However, organised convection is south of India only during pentad 0

311 onward, as westerly wind anomalies occur below the Indian land region. PW and convection are also
 312 enhanced in the equatorial region during P0 and P+1.
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 315 **Fig.6-** Pentad-composite anomalies for very late onset years P-2 to P+2. Left: SST (shaded, °C) and
 316 850-hPa winds (vectors, m s^{-1}). Right: OLR (shaded, W m^{-2}) and PW (contours, mm).

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 318 The above analysis across the six ISM onset categories reveals a systematic progression in the
 319 intensity and spatiotemporal evolution of ocean-atmospheric coupling. For instance, the too early
 320 onset (<20May) and Very Early (20May-24May) periods are characterized by anomalous cooling of
 321 SST, associated with increased convection and the establishment of cross-equatorial westerly
 322 anomalies from the P-3 period. Following this, convection rapidly propagates northward from the
 323 equatorial IO to India, accompanied by reduced OLR anomalies across the entire region from P-2 to

P0. Notably, in too-early-onset cases, pre-onset cyclonic circulation develops over the AS, whereas in very early-onset cases, the westerlies develop without cyclonic circulation. Moving to the early onset case, the establishment of all parameters begins with P-2; westerly anomalies start during P-1, with SST anomalous cooling over the equatorial IO, and marked increased convection from P-2 onwards. At the same time, OLR anomalies show the transition during this period. Approaching the normal onset period (30May-02June), SST anomalies over the equatorial IO remain warm up to P+1, and the westerlies strengthen while convection, which starts by P0 onwards, propagates further northward. In contrast, during late (03June-07June) and very late (>07June) onset cases, SST anomalies over the IO remain warm after onset (especially in the western AS), and there are negligible low-level wind anomalies during post-onset pentads.

Thus, the anomalies evolve differently across the categories, resulting in marked contrast in how favourable conditions are generated for the rainfall. For onsets occurring before 25 May, favourable rainfall conditions are established prior to P0. For onsets between 25 May and 02 June, these conditions align around P0, whereas for onsets after 03 June, they develop only after P0. The pentad composite describes the immediate onset mechanism, so we need to observe the precondition before the onset months. Thus, factors point to the role of the background states, such as intra-seasonal or monthly states, in the monsoon onset. Underlying the principle is the existence of a large-scale seasonal or monthly pattern in these years, which may be modified by intra-seasonal and other day-to-day variability that led to rainfall during these years. In the following sections, the role of large-scale monthly and sub-monthly scale (ISO) variability in the different types of onsets is analysed.

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3.2 Contribution of monthly variability to ISMR onset.

The monsoon onset is a large-scale phenomenon governed by various atmospheric parameters; the temporal alignment of these favourable factors determines the onset time. A significant factor in the onset of the monsoon is the differential heating of land and sea (Webster, 1987). The long-term mean onset date of the monsoon over Kerala is between May 30 and June 2, with a standard deviation of 8-9 days (Ananthakrishnan and Sonam, 1988). Joseph et al. (1992) noted that the migration time of the equatorial convective cloudiness maximum (ECCM) to the westward and northward determines the time of monsoon onset. The positive (Negative) Surface Air Temperature (SAT) over central India in June corresponds to a delay (Early) in monsoon onset and tends to occur during post-El Niño summer (Zhou et al. 2019). Previous studies show that monthly variations in pre-monsoon heating, low-level circulation and moisture transport strongly influence monsoon onset (Ananthakrishnan et al. 1988; Wang et al. 2009).

357 April-May month average pattern of these different onset year composites of SST (shaded), 850hPa
358 wind (vectors), 200hPa wave-flux (right panel) activity are provided in the present section for all the
359 onset case composites and are shown in Fig.7. Here, the cool SST and westerly wind anomalies are
360 stronger over the north IO in April-May for the too-early and very early onset years with a developing
361 La Niña in the Pacific. In the case of early onset, IO cooling and stronger westerly wind anomalies
362 are evident only in the equatorial IO, while La Nina anomalies are stronger. Similarly, in late-onset
363 cases, the equatorial Indian Ocean is warmer and wind convergence is evident there. At the same
364 time, there are El Niño-related warm SST anomalies in the Pacific Ocean. This underlines earlier
365 studies that large-scale circulation favours the La Niña pattern in years with early onset of the Indian
366 summer monsoon, while El Niño-induced circulation anomalies occur in years with late monsoon
367 onset.

368 The wave-flux activity also indicates that there is strong upper-level Rossby wave flow to the
369 monsoon region for the too-early-onset case, indicating the presence of convergence and convection
370 well before the onset (Fig.7, right panel), as shown by the pentad composites. The wave flux activity
371 is weaker but persists across all early-onset cases. The centre is shifting eastward across the monsoon
372 region as the onset dates move towards June. However, in the delayed-onset cases, a divergence is
373 observed at 200 hPa, indicating that the April-May months basic state is not favourable to convection
374 or convergence.

375 This monthly analysis will answer the different questions raised in the previous sections. The cool
376 SST anomalies in the Indian Ocean during the entire pentad analysis period for the early-onset cases
377 and the opposite anomalies during the late-onset cases can be attributed to the monthly pattern in
378 these different onset years. The very early onset period is characterized by a La Niña pattern and a
379 cool Equatorial Indian Ocean during April-May. This will lead to westerly wind anomalies over the
380 north Indian Ocean during monsoon onset. Thus, during the pentad analysis, the anomalous PW and
381 OLR indicate a chance of convection earlier. At the same time, the presence of El Niño and the warm
382 IO and associated convergence will delay the propagation of convection into the land region during
383 late-onset cases. Here, the IO remains warm for the pentads of late and very late onset also. The wave-
384 flux activity clearly indicates the presence of subtropical flow into the monsoon region for the very
385 early onset case in May. This supports the idea of mid-latitude interaction during the early onset of
386 the monsoon. The wave flux weakens as the onset date is later than 20th May and it disappears for
387 normal and late-onset events. These indicate the differential role of large-scale background flow in
388 determining the different onset dates of ISMR.

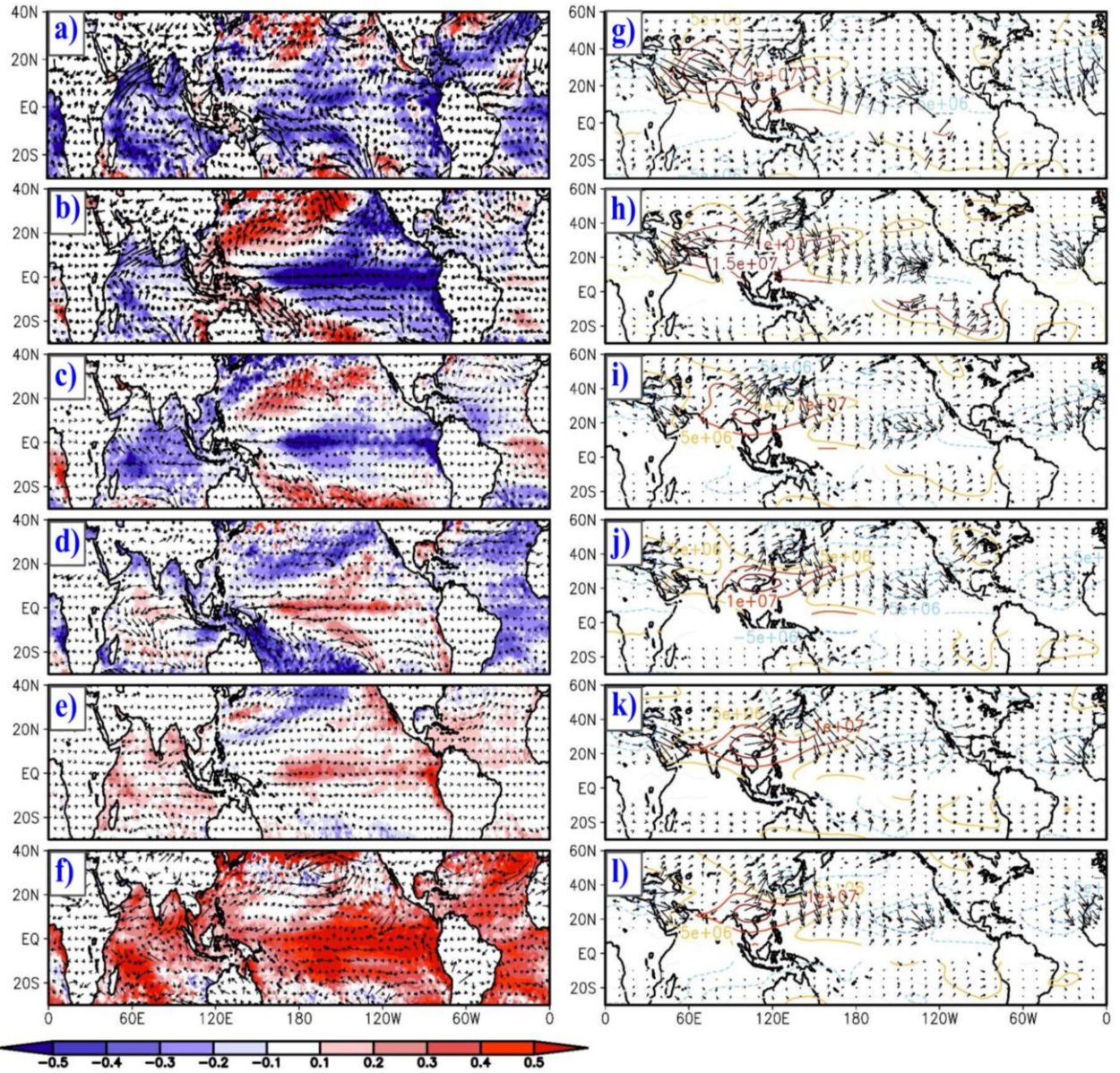


Fig.7- April–May composites for six onset categories: (a,g) too-early, (b,h) very-early, (c,i) early, (d,j) normal, (e,k) late, (f,l) very-late. Left (a–f): SST (shaded, °C) + 850-hPa winds (vectors, m s^{-1}). Right (g–l): Wave activity flux (vectors, W m^{-2}).

3.3 Contribution of MJO-related anomalies

The MOK is closely associated with the evolution of deep tropical convection propagating from the western to eastern IO in response to the reversal of winds (from anomalous easterlies to westerlies) at lower levels (Lawrence et al. 2002). The monsoon onset vortex and the strong convective activities (reflected by negative OLR) are believed to relate to the wet phases of an MJO. Here, in the present analysis, MJO-related OLR and its propagation are studied across different onset cases. The 30–60 day filtered OLR anomaly represents the MJO band; the unfiltered OLR anomaly represents the raw anomaly and the difference between these two represents the residual (background state) anomalies, as demonstrated by Taraphadar et al. (2018).

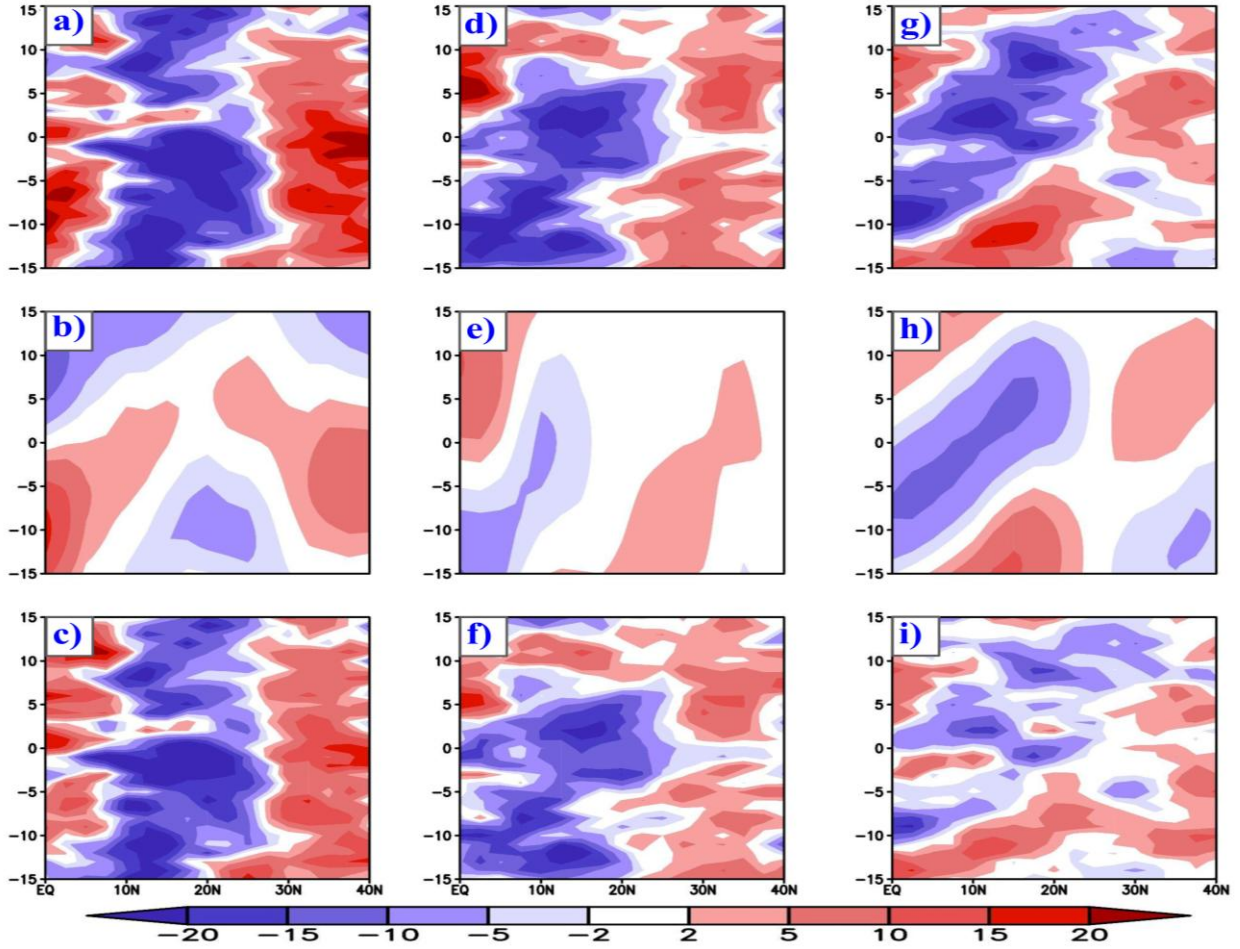


Fig.8- Hovmoller diagrams of Composite OLR anomalies for different monsoon onset categories. Raw anomalies (a, d, g), filtered anomalies (b, e, h), and background anomalies (c, f, i). Columns represent Too Early, Very Early, and Early onset years from left to right.

Figure 8(a-c) represents the Hovmoller diagram of OLR anomalies averaged over 600E-950E, spanning 15 days before to 15 days after the onset date (lag -15 to lead +15) and latitude from equator to 400N, for a) total anomalies, b) MJO filtered anomalies, and c) the residual (Background) component for the too early onset years composite. In this onset case, the total OLR anomaly exhibits northward propagating convection from the equator toward 100-250N from lag -15 through onset (0 day). However, the MJO-filtered anomaly does not show northward propagation during this period, whereas the residual anomaly closely replicates the structure and evolution of the total anomaly. To confirm this, a day 0 composite plot of the total and MJO-filtered anomalies (not shown) indicates the absence of MJO-filtered OLR convection over the Indian region. This result indicates that the early onset is driven by background anomaly rather than MJO activity. Furthermore, this finding supports the previous section's monthly analysis, which identifies La Niña and anomalous upper-level wave activity as key contributors to the background conditions.

Turning to the very early onset years case (figure 8d-e) composite for onset between 20-24 May, the total OLR anomaly similarly shows northward propagation from the equator to 200N from lag -15 to day 0. In this scenario, the MJO filtered anomaly contributes little to the total OLR, whereas the background state plays a significant role. For the early-onset years case (25-29 May), the total anomalous OLR northward propagation starts at a lag of -12 days, originating from the equator and reaching 25°N at day 0. Here, in contrast to the previous two cases, the MJO component plays a key role in propagating the OLR anomaly, while the background state makes a lesser contribution. Consistent with the earlier analysis, the large-scale anomalies in this case are weaker than in the previous two early-onset cases.

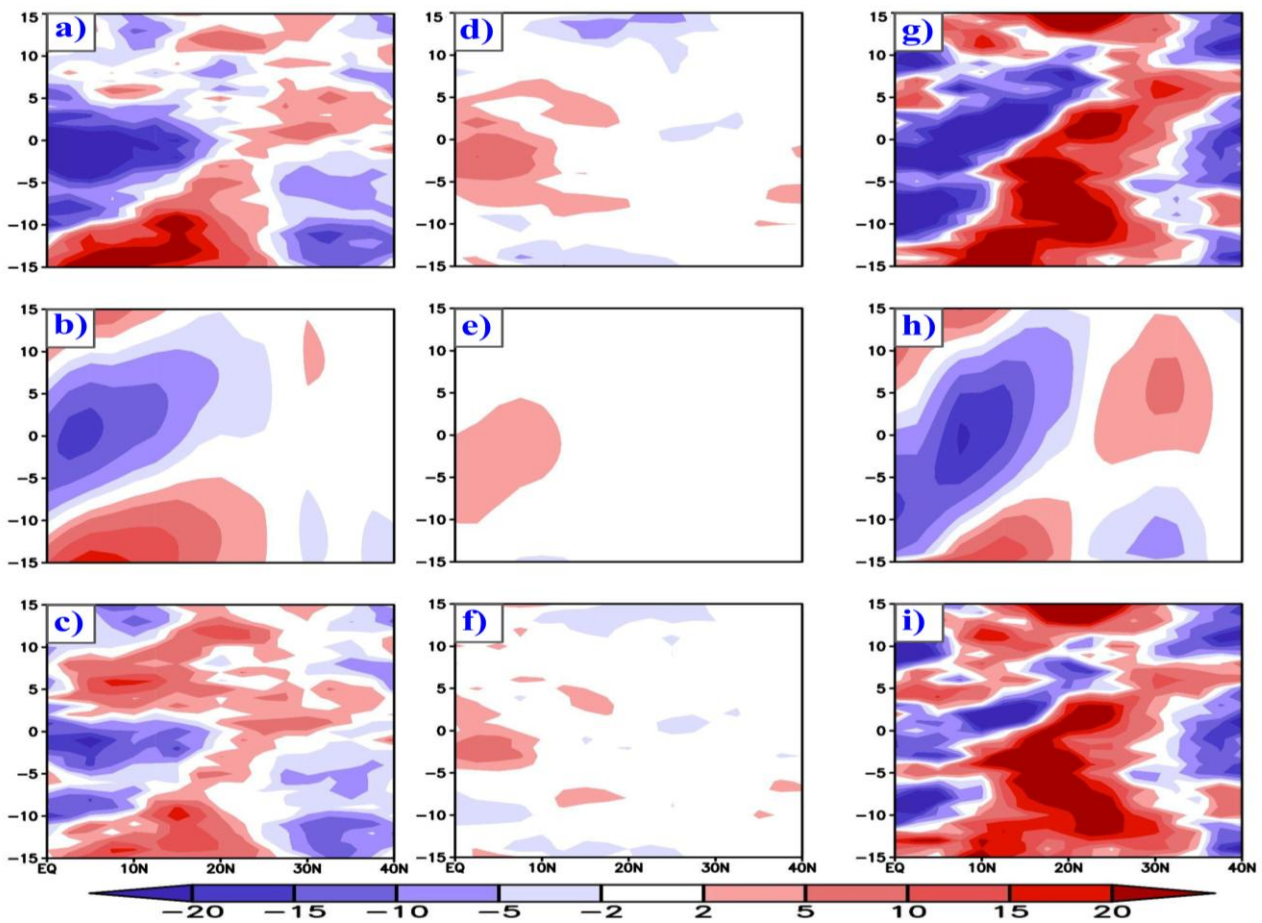


Fig.9- Same as Fig.8. Columns represent Normal, Late and Very Late onset years left to right.

In the normal onset case (figure 9a-c), the anomalous OLR northward propagation starts at lag -10 from the equator to 10°N and further extends to 20°N on the onset day. In this case, the MJO-filtered anomaly plays a significant role compared to the background state. For the late onset case (figure 9d-e), no OLR propagation was observed in the total, MJO filtered and background state. In the very delayed onset year (figure 9f-i), total OLR propagation starts 12 days before onset; MJO-filtered replicates replicate total OLR propagation, whereas the background OLR shows little contribution

438 after the onset day. Joseph et al. (1992) also noted that the movement of the ECCM from the western
439 Pacific Ocean toward the west and northward is delayed during the delayed onset period.

440 Here, the analysis indicates that the background state is stronger for monsoon onset before the 20th
441 of May. This is reflected in both the monthly and ISO-scale analyses. There is no contribution to
442 MJO-related anomalies for the propagation of convection from the equator to the Indian land region.
443 However, in the other two early-onset cases, ISO-range convection propagation is important in setting
444 the onset-related anomalies over the land region. Here, the background-state contribution is weaker
445 and the MJO-scale perturbation contributes positively along with the basic-state modification.
446 However, in the delay-onset case, the MJO plays no role, and the background state is also
447 unfavourable. This is reflected in the evolution figures; the convection is not set on day 0 either. It is
448 interesting to note that, even with a very delayed onset, the ISO plays a significant role in setting the
449 OLR over the monsoon region.

450 **4. Discussion and Conclusion**

451 In the present study, the onset date is defined based on the TT anomalies as described by Xavier and
452 Goswami (2007). Thus, unlike the conventional rainfall-based method, our study accounts for the
453 atmospheric and oceanic conditions that precede the onset of the monsoon. This may lead to some
454 discrepancy in rainfall amounts received on the onset day (day 0) across different categories of onset
455 years. Instead of dividing the years into early, normal and late-onset years, the present study
456 investigated different categories of onset based on the observational data. These categories are based
457 on ISM years with onset before 20th May, between 20th -24th May, between 25th -29th May, 30th
458 May to 2nd June, 3rd -7th June and beyond 7th June. The number of years in the first and last
459 categories is significantly less compared to that in the 30th May and 2nd June categories. However,
460 we analysed ocean-atmosphere parameters that contribute to these categories and understood the roles
461 of intra-seasonal and monthly background states in these processes.

462 It is found that if the onset is very early, earlier than the 20th of May, the pentad SST anomalies
463 remain cool over IO and equatorial western Pacific during all the pentads considered from P-3 to P+3,
464 indicating the existence of a background convection favouring conditions with the presence of
465 cyclonic circulation, precipitable water and moisture convergence well before the onset day. Here, it
466 is given that convection propagates northward from the equatorial IO to north of 30N, aided by the
467 background anomalies. The MJO-scale convective propagation is very weak and does not contribute
468 to total anomalous propagation. The monthly SST and wind patterns during April-May indicated a
469 strong La Niña-like situation in the Pacific, with strong cross-equatorial wind anomalies in the IO.
470 Wave flux activity also indicates anomalous flow converging over the Indian land mass. Thus, the
471 onset before 20th May is primarily driven by background anomalies. This strong seasonal signal is

472 responsible for cool SST, which is associated with existing large-scale precipitation well before day
473 0. This will create the necessary land-sea thermal contrast and northward movement of the mean state
474 for monsoon onset.

475 The North Indian Ocean remains warm up to the onset pentad for the early-onset case from 20th to
476 29th May (2 categories). Here, convection propagates from the equatorial Indian Ocean to the Indian
477 land region, driven by MJO-scale anomalies. Large-scale patterns also favour convection during May
478 under a weak La Niña, while wave flux activity is weak and slightly shifting eastward. Thus,
479 compared to the onset before 20th May, here the MJO component gets a stronger pattern, while large-
480 scale anomalies are weaker. In normal-onset cases, IO remains warmer after the onset date. The PW
481 accumulation begins by day 0 over the western region of IO. The weaker northward propagation of
482 total convective anomalies begins after the normal-onset date associated with the northward
483 propagation of MJO, extending up to 12N. Further, monthly anomalies are weaker for SST, wind and
484 wave-flux activity supporting the weaker northward propagation. However, in late-onset cases, the
485 IO remains warm throughout P-3 to P+3. Northward propagation of the MJO and the mean state is
486 weaker, with little contribution. Simultaneously, the April–May SST pattern indicates El Niño
487 conditions and strong warming in the western Indian Ocean. These warm SSTs warm the entire
488 tropospheric column, weakening the thermal contrast between the Indian Ocean and the Indian
489 landmass. As a result, the propagation of convection remains confined to the Indian Ocean region up
490 to the month of June.

491 The present study provides evidence of how the different scales are interacting to determine the onset
492 of the Indian summer monsoon rainfall. The information is valuable for predicting onset using
493 dynamical models and will be part of future studies.

494

495 **Data availability-**

496 The original, non-processed data sets are downloaded freely from the respective websites of NCEP
497 (<https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>) for atmospheric variables, NOAA
498 (<https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>) for SST and rainfall from
499 IMD (https://imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html). The processed dataset
500 generated during this study are available from the corresponding author on reasonable request.

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504

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507 **Conflict of interest-**

508 The authors declare no conflict of interest.

509 **Credit authorship contribution statement-**

510 Sushant Kokate: Data curation, Formal analysis, Investigation, Methodology, Validation,
511 Visualization, Writing-original draft, Writing-review and editing.

512 Prasanth A Pillai: Conceptualization, Formal analysis, Methodology, Supervision, Writing- review
513 and editing.

514

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