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ONSET CHARACTERISTICS OF THE SOUTHWEST MONSOON OVER INDIA

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ABSTRACT

Dynamic and thermodynamic characteristics of the Asian summer monsoon during the onset phase over the Indian Peninsula (Kerala coast) and its variability are examined with reanalysis data sets. For this study, daily averaged (0000 and 1200 UTC) reanalysis data sets of National Centre for Environmental Prediction–National Centre for Atmospheric Research for the period 1948–99 are used.

Based on 52 years of onset dates of the Indian summer monsoon, we categorized pre-onset, onset and post-onset periods (each averaged 5 days) to investigate the mean circulation characteristics and the large-scale energetics of the Asian summer monsoon. It is found that the strength of the low-level Somali jet and upper tropospheric tropical easterly jet increase rapidly during the time of evolution of the summer monsoon over India. Over the Bay of Bengal and the Arabian Sea, predominant changes are noticed in the large-scale balances of kinetic energy, heat and moisture from the pre-onset to the post-onset periods. Prior to the onset of the summer monsoon over India, a zone of flux convergence of heat and moisture is noticed over the eastern sector of the Bay of Bengal and this intensifies in the onset and post-onset periods. During onset of the monsoon over India, the horizontal flux convergence of heat and moisture, as well as diabatic heating, are enhanced over the Arabian Sea. These subsequently increase with the evolution and advancement of the monsoon over India.

Further, the dynamics of the evolution processes (15 days before and 30 days after the onset date of the monsoon over Kerala for each annual cycle) are studied over various sectors, such as the Arabian Sea, Bay of Bengal and Indian Peninsula region. The study reveals that the low-level kinetic energy, vertically integrated generation of kinetic energy and net tropospheric moisture over Arabian Sea can be used as potential predictors for the prediction of the possible onset date of the summer monsoon over the Indian Peninsula. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: Indian summer monsoon onset; NCEP–NCAR reanalysis; kinetic energy; heat; moisture

1. INTRODUCTION

The Indian summer monsoon is characterized with rainfall regimes, onset/withdrawal dates, active/break phases and synoptic disturbances. The basic forcing of the Asian summer monsoon is provided by the annual cycle of solar radiation interacting with different heat capacities of the tropical ocean and land areas (Li and Yanai, 1996) and their respective geographical arrangements. The monsoon flow represents much more than a giant sea breeze circulation. Strong heating in spring creates a thermal low over the northern Indian subcontinent, before the onset of the monsoonal southwesterly flow.

The evolution, advancement (active/break or stagnation aspects) and retreat are the most important epochs associated with the summer monsoon over India, as they essentially decide the duration of the summer monsoon and the quantity of rainfall over different parts of the country. The arrival of the summer monsoon over India is also of great importance, occurring towards the end of May or in early June over the southern tip of the Indian (Kerala) coast. Although, there is no precise definition of the onset of the monsoon, Indian meteorologists conventionally identify the date of onset over the Kerala coast based on a sharp increase and

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characteristic persistency of the rainfall (Ananthakrishnan *et al.*, 1968). In addition to the importance of the strength of the overall monsoon in a particular year, forecasting of the onset and the subseasonal variability (active/break periods) are of significant relevance for the Indian economy. A late or early onset of the monsoon and break periods in the monsoon rainfall may have devastating effects on agriculture, even if the mean rainfall in the monsoon season as a whole is normal. As a result, understanding the dynamical mechanisms of the monsoon variability on time scales ranging from weeks to months is an issue of considerable importance.

It is well recognized that the onset of the summer monsoon is accompanied by distinct changes in the large-scale circulation and rainfall distribution over the Indian landmass and surrounding oceanic regions. These include the northward displacement of upper tropospheric westerly flow to the north of the Himalayas, establishment of the upper tropical easterly jet (TEJ) stream (Koteswaram, 1958) and lower tropospheric westerly jet (Somali jet) over the Arabian Sea (Findlater, 1969). The intensification of the monsoon flow is mainly dictated by the release of convective instability and tropospheric diabatic heating (Krishnamurti and Ramanathan, 1982; Mohanty *et al.*, 1983; Pearce and Mohanty, 1984; Rao and Aksakal, 1994). Studies by Ananthakrishnan and Soman (1988, 1989) and Soman and Krishnakumar (1993) documented the climatological structure of the meteorological fields associated with the onset phase of the summer monsoon. Murakami and Ding (1982) compared the large-scale circulation and temperature fields before and after the onset of the 1979 Indian summer monsoon. They found that the maximum warming took place over the Afghanistan–western Tibetan plateau region and over the east China Sea–Japan region. They emphasized the importance of diabatic heating over the Eurasian continent as a whole in establishing the summer monsoon circulation. Hsu *et al.* (1999) elucidated the circulation changes and heating associated with the first transition of the Asian summer monsoon. The significant features include the development of a low-level cyclonic circulation and an upper level anticyclone in south Asia, as well as strong convection in the Bay of Bengal. However, these studies used only a limited number of onset events; therefore, it is difficult to generalize essential features of the onset phenomenon over India. Also, the variability of rainfall at Kerala during the onset phase results from both local synoptic variability and large-scale dynamics of the summer monsoon, and their relationship is not well known (Fasullo and Webster, 2003).

In this study, an attempt is made to examine the mean circulation features and energetics associated with onset of summer monsoon seasons over India for a period of 52 years from 1948 to 1999. The data and methodology are briefly described in Section 2, followed by the results and discussion of mean circulation features and energetics during onset of the southwest monsoon over India in section 3. Finally, a summary of the results are presented in Section 4.

2. DATA AND METHODOLOGY

The National Center for Environmental Prediction (NCEP) reanalysis project (Kalnay *et al.*, 1996) is based on an advanced Global Data Assimilation System (GDAS), which utilized data from diverse sources for the period 1948 to 1999. The use of delayed observations along with a state-of-the art assimilation system provides an enhanced reliability to the products of the NCEP. In general, the 52 year NCEP reanalysis provides a consistent and reliable data set for investigating weather and short-term climate phenomena. It provides for the first time a unique database to examine the climate variability of circulation features and the energetics of a monsoon. The twice-daily (00 and 12 UTC) reanalysis data sets produced at the NCEP with a horizontal resolution of 2.5° on a regular latitude–longitude grid are processed for the Asian summer monsoon domain (30–120 °E, 15 °S–45 °N). Based on onset dates of the Indian summer monsoon over the southwest Kerala coast (Ananthakrishnan and Soman, 1988), we have categorized the onset phase into three subphases, viz. pre-onset, onset and post-onset periods in each annual cycle. The onset period is considered as 2 days before and 2 days after the reported date of onset (5 days). Pre-onset and post-onset periods are considered respectively for 5 days before and 5 days after the onset period. The basic meteorological fields considered for the study include geopotential height Z, horizontal wind u and v, temperature T and specific humidity q at 12 pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150 and 100 hPa). In order to avoid the problems with divergent wind, the vertical velocity fields in this study have been computed from horizontal wind components (u and v) by using the kinematic method as suggested by O'Brien (1970). In this technique, the divergence is adjusted to its vertically integrated zero value in the entire column of the atmosphere. The vertical velocity distribution obtained from the kinematic method delineates realistic Hadley circulation over the monsoon domain, compared with the archived field.

The comprehensive analysis of dynamical features associated with the evolution of the Asian summer monsoon and its variability are carried out through the study of large-scale balances of kinetic energy, heat and moisture. The budget equations are obtained from the prognostic and diagnostic equations of an atmospheric model based on simple mathematical transformations and represented in flux form with pressure as the vertical coordinate (Raju *et al.*, 2002). In this study, the time-mean large-scale balance equations are bifurcated into stable mean and transient eddy parts. The primary focus is on the mean component of the budgets, as the tropical circulations are dominated by the mean component of flow.

All budget terms at each regular latitude and longitude grid point are averaged, both in zonal and meridional directions, over various sectors/zones and integrated vertically from 1000 to 100 hPa. Thus, the volume integral of any variable $F(\lambda, \varphi, p)$ for the limited region bounded by meridians λ_1 and λ_2, latitude circle φ_1 and φ_2 and isobaric surfaces P_1 and P_2 may be written as

$$\overline{F} = \frac{1}{g}\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\int_{P_1}^{P_2} Fa^2 \cos\varphi \, \mathrm{d}\lambda \, \mathrm{d}\varphi \, \mathrm{d}P$$

where a is the average radius of the Earth.

The vertical integration of the budget equation with the boundary condition that vertical motion ($\omega = 0$) vanishes at the bottom and the top of the atmosphere leads to the elimination of all the terms representing vertical flux divergences of various quantities. Although we evaluated all the budget equations, the discussions in this paper are restricted to the terms that contribute significantly to the budgets and which are thus largely responsible for the maintenance of the summer monsoon circulation.

3. RESULTS AND DISCUSSION

Using the rainfall from a dense network of raingauge stations over south and north Kerala, the dates of the onset of the summer monsoon have been derived on the basis of subjective criteria used by the Indian Meteorological Department (IMD) on an operational basis. Figure 1 shows the interannual variability of onset date of the summer monsoon over India. The onset dates are taken from material published by the IMD. During the 52 year period (1948–99), the mean onset date is 1 June with a standard deviation of 8 days. The earliest and most delayed onset dates of the summer monsoon over Indian during the last 52 years are 17 May (1962) and 18 June (1972) respectively. Based on an analysis of sea-surface temperature fields, Joseph *et al.* (1994) hypothesized that the delay of monsoon onset is due to warm anomalies over the equatorial central Pacific Ocean causing a delay in the shifting of convection from the equatorial western Pacific to the north Indian Ocean.

3.1. Circulation characteristics

During the onset of the monsoon over India, significant changes occur in the large-scale atmospheric structure over the Asian monsoon region. Some of the well-known features are a rapid increase of daily precipitation, vertically integrated moisture and an increase in the kinetic energy in the lower levels (Mohanty *et al.*, 1983). In this section, the circulation features of the Asian summer monsoon have been studied with composites of the three different pentads during the evolution of the monsoon over India. The basic features of the monsoon flow during pre-onset, onset and post-onset periods can be seen in the climatology (1948–99) of wind (Figure 2) at 850 hPa (left panels) and 150 hPa (right panels). The circulation features at 850 and 150 hPa clearly demonstrate a very rapid intensification of flow from the pre-onset to post-onset periods. The lower tropospheric flow depicts the strengthening of the flow and establishment of the Somali jet, strong

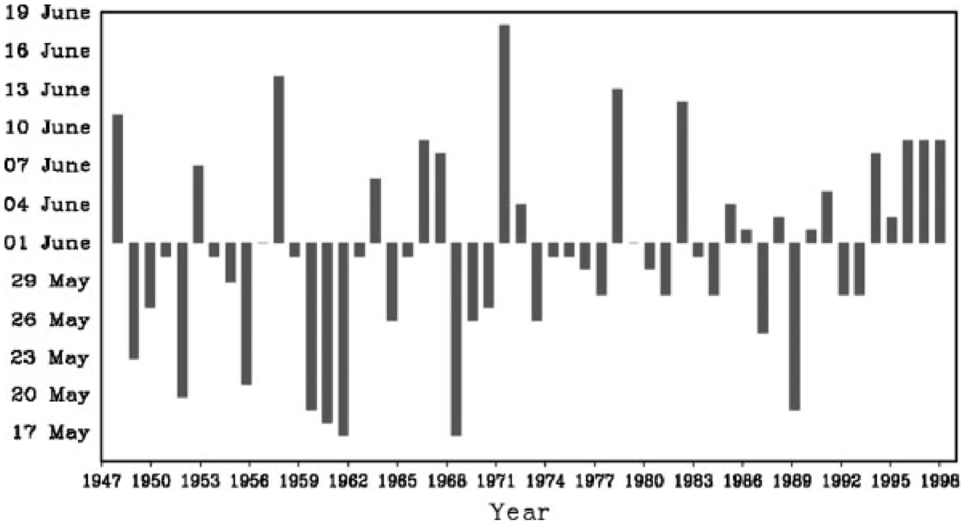


Figure 1. Interannual variability of onset dates of summer monsoon over India (Kerala)

cross-equatorial flow and northward propagation from the pre-onset phase to the post-onset phase. The main cross-equatorial flow takes place to the north of the equator between 40 and 60 °E. The prominent features of the upper tropospheric flow (150 hPa) illustrate that the TEJ develops during the onset phase with a maximum of around 20 m s^{-1} close to the equator between 65 and 95 °E and gradually expands northwards over the equatorial Indian Ocean in the post-onset phase. It also gains strength during the post-onset period. The subtropical westerly jet over the northern latitudes is gradually shifted northwards (not shown in the figure). The composite time series of wind speed over the Somali jet and the TEJ regions are presented in Figure 2(d) and (h). The Somali jet region shows a sharp increase at the time of the onset over India. In contrast, over the TEJ region, a gradual increase of wind speed is noticed 2 weeks before the onset date over India.

The vertical velocity for pre-onset, onset and post-onset periods is depicted in Figure 3. The vertical velocity field at the 850 hPa level (left panel) shows a strong rising motion over the entire Indo-Gangetic plains along the monsoon trough zone and extending into the South China Sea across Mayanmar. It is interesting to note that another zone of rising motion over the north Arabian Sea is built up only during the onset period and intensifies further in the post-onset period. A zone of sinking motion is noticed over northwestern India and the adjoining Pakistan–Afghanistan, which is built up before onset and maintained after onset of the monsoon. The sinking motion is also noticed over the southeast peninsula and equatorial zones. The sectorial mean pressure–latitude structure of the vertical velocity fields (right panels) depicts the whole monsoon regime as being characterized by a rising motion. An interesting feature noticed during the pre-onset period is that there are two maxima of rising motions, one over 500 hPa at 5 °S and another at 400 hPa at 5 °N. However, during the onset and post-onset periods, the maxima over the Southern Hemisphere weaken and the Northern Hemispheric maxima shift further north and establish at 15 °N. A sinking motion maximum is noticed over the extratropics around 35 to 40 °N. In the Southern Hemisphere, a region of sinking motion is noticed south of 15 °S. Thus, an intense Hadley cell is set up in the post-onset phase around 16–17 °N. The sinking arms of the Hadley cell are close to 35–40 °N and 15 °S or further south. Also, another sinking motion region in the lower troposphere is noticed between the equator and 5 °N. This sinking motion may be due to the cross-equatorial flow becoming anticyclonic flow after crossing the equator, which is usually confined up to 600–700 hPa in the lower troposphere.

3.2. *Kinetic energy budget*

The maintenance and intensity of the general circulation of the atmosphere depend on the balance between generation and dissipation of kinetic energy. The kinetic energy of the atmosphere is created through the

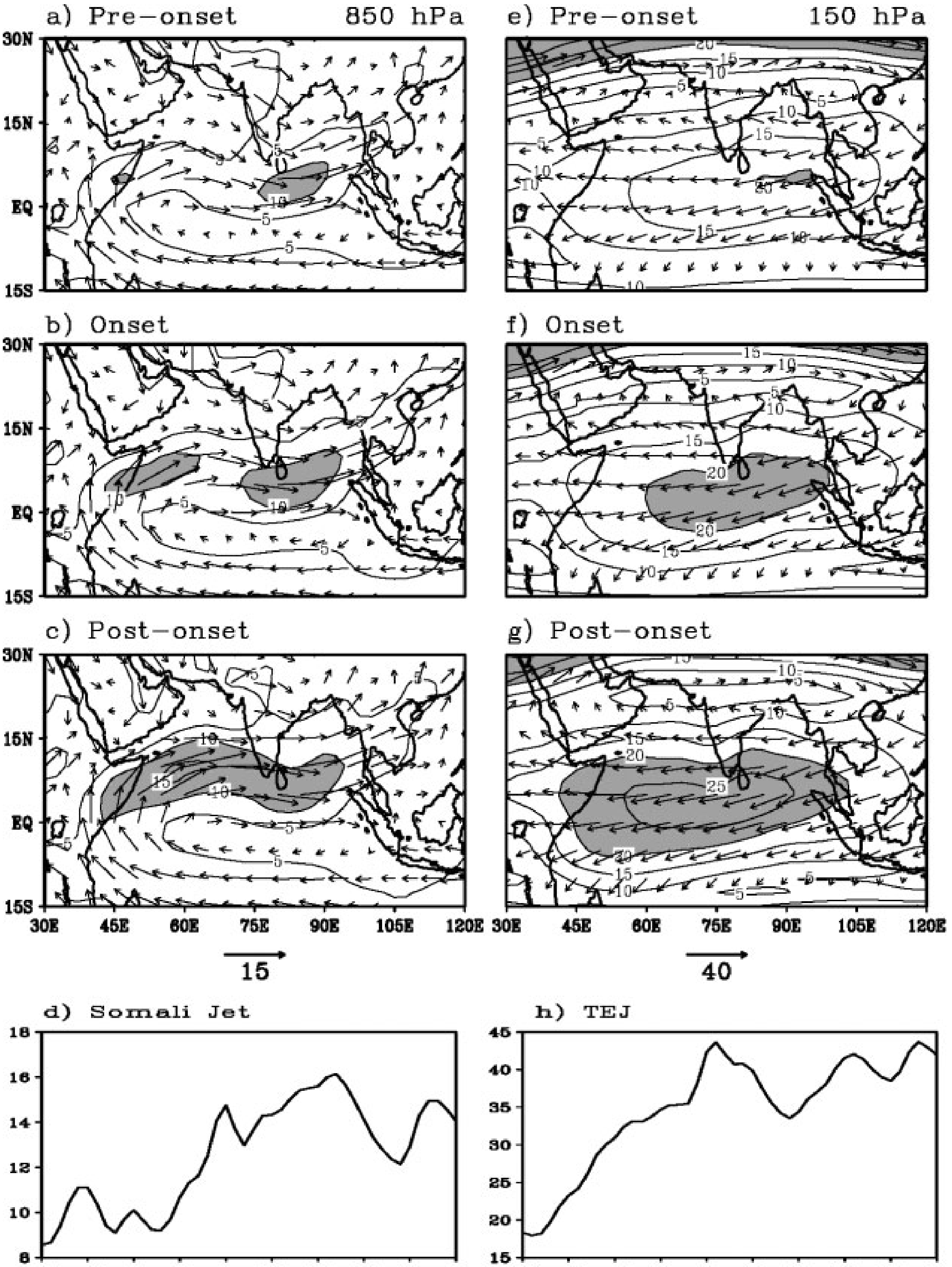


Figure 2. Climatology of wind (m s^{-1}) for 850 hPa (left panels) (a) pre-onset, (b) onset, (c) post-onset, (d) variation of wind over the region of Somali jet and for 150 hPa (right panels) (e) pre-onset, (f) onset, (g) post-onset, (h) variation of wind over the region of TEJ

conversion of available potential energy and is eventually dissipated through irreversible frictional processes. The local balance of kinetic energy is governed by three significant terms, namely horizontal flux, and generation and dissipation of kinetic energy. The horizontal flux divergence of kinetic energy (850 hPa and 150 hPa) is depicted in Figure 4. There are substantial variations between pre-onset, onset and post-onset

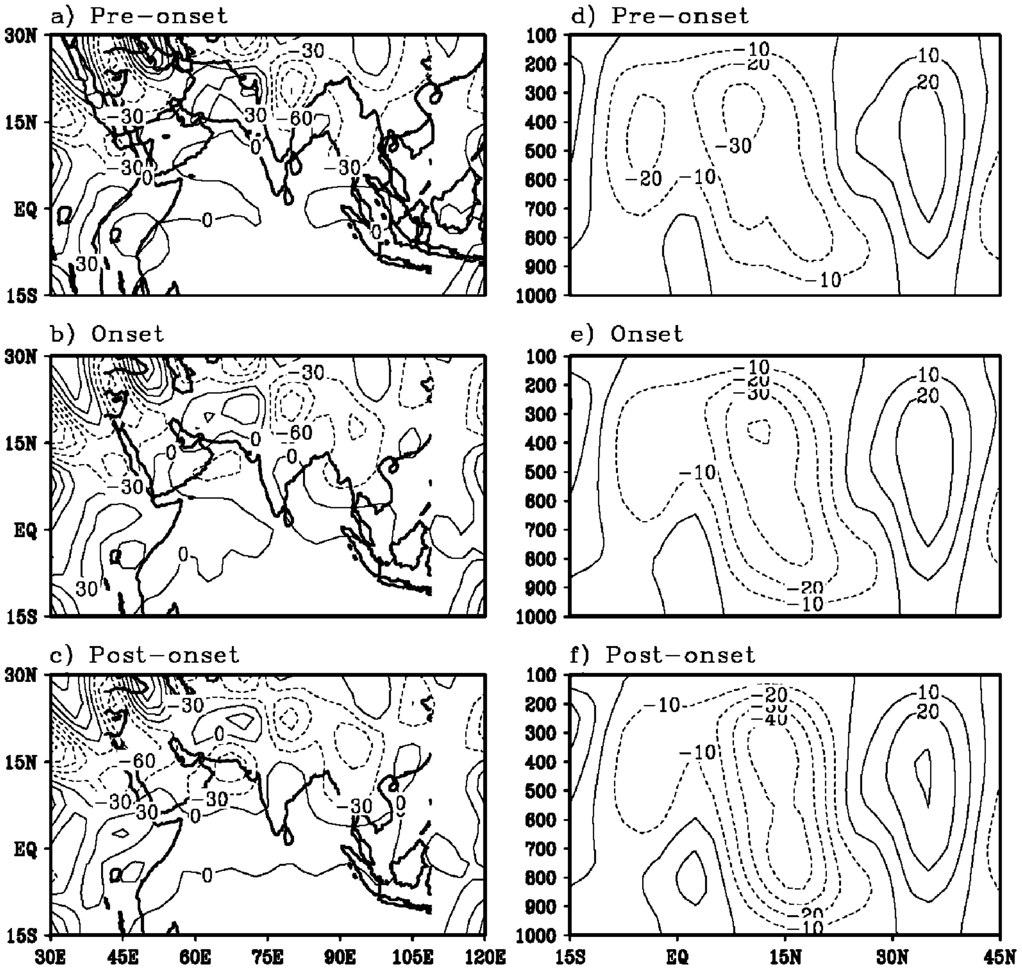


Figure 3. Climatology of vertical velocity (10^{-3} Pa s^{-1}) for geographical distributions (left panels) (a) pre-onset, (b) onset, (c) post-onset and sectorial mean cross-sections (right panels) (d) pre-onset, (e) onset, (f) post-onset

phases at lower and upper levels. The lower tropospheric features show that flux divergence is present over the Somali coast and southwest Sri Lanka during the pre-onset phase. This increases during the onset phase. The zone over the Somali coast intensifies and extends to the Arabian Sea in the post-onset period. A convergence flux of kinetic energy is noticed over the southeast Bay of Bengal prior to the onset of the Indian summer monsoon and the zone of flux convergence is maintained during the onset and northward progress of the summer monsoon over India. Another zone of horizontal flux convergence of kinetic energy is noticed over the central Arabian Sea. During the onset period, a large increase of this zone is observed with maxima shifted towards the east Arabian Sea and extended into the Indian Peninsula. The upper level features of divergence flux of kinetic energy are shown in Figure 4(d)–(f). The flux divergence is noticed over the southeast Bay of Bengal during the pre-onset period. Further, it increases during the onset and post-onset periods. The flux convergence of kinetic energy is noticed over the East African region during the onset phase and it is strengthened further in the post-onset period. Also, there is strong flux divergence noticed over the south Arabian Sea. One interesting aspect is that a convergence of kinetic energy is found over the Indian peninsular region. Thus, the initiation of the onset of the summer monsoon is accompanied by a low-level convergence over the Arabian Sea and upper level divergence in the Bay of Bengal. Also, over the Somali coast, flux divergence at low levels and flux convergence at upper levels are the characteristic features in the evolution of the summer monsoon over India.

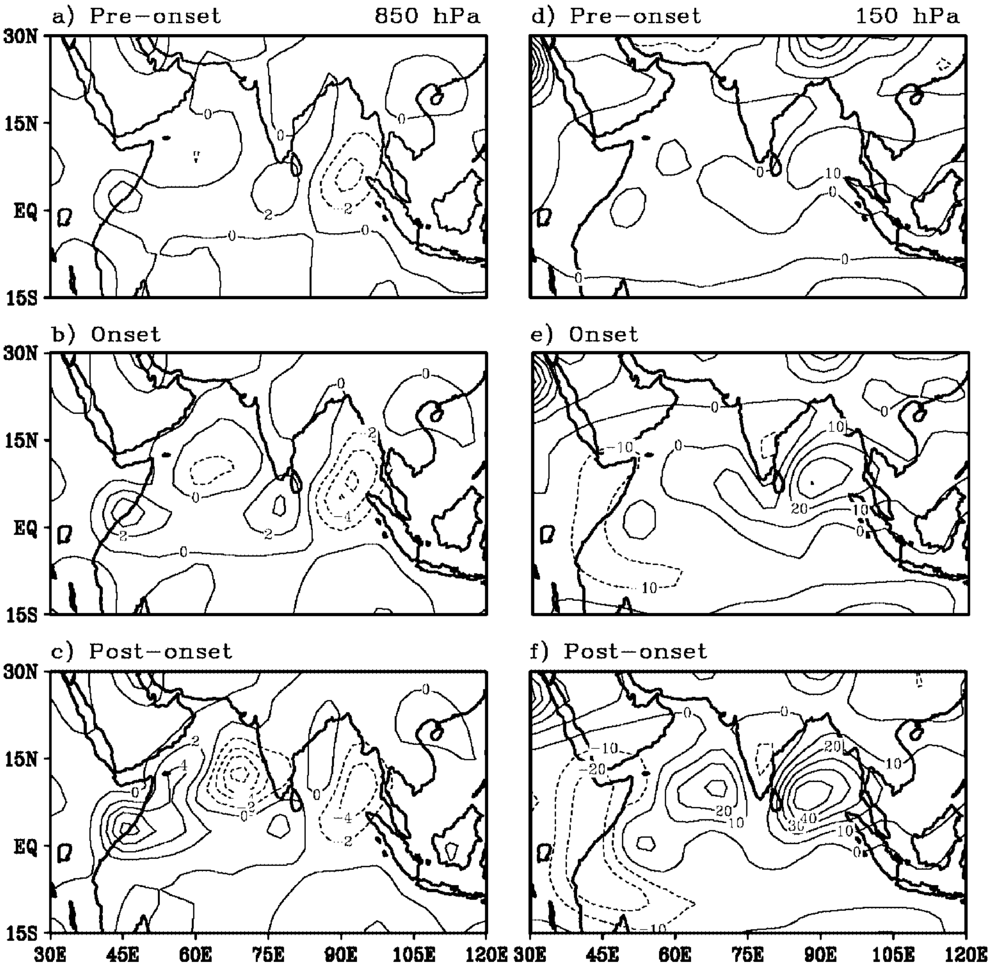


Figure 4. Geographical distribution of horizontal divergence flux of kinetic energy (10^{-4} kg^{-1}) for 850 hPa (left panels) (a) pre-onset, (b) onset, (c) post-onset and 150 hPa (right panels) (d) pre-onset, (e) onset, (f) post-onset

The kinetic energy is basically produced by the ageostropic component of the flow. Positive magnitudes signify the generation of kinetic energy from the available potential energy and the negative magnitudes denote the destruction of kinetic energy, i.e. transformation of kinetic energy back to the available potential energy. The areas characterized by the flux divergence of kinetic energy are the regions of strong kinetic energy production, and the regions of flux convergence are characterized by destruction/weak production of kinetic energy. Such a nature of kinetic energy production is, in fact, necessary to maintain the strong outflow/inflow of energy at the entrance/exit regimes of the TEJ in the upper troposphere. The adiabatic generation of kinetic energy is depicted in Figure 5. The lower tropospheric features (left panels) show that there is generation of kinetic energy over the Somali coast during the pre-onset period. This is further strengthened during the onset and post-onset periods. A small negative value of kinetic energy generation is noticed over the eastern Bay of Bengal during pre-onset and maintained almost constant during the onset and post-onset periods. The distribution of mean adiabatic generation of kinetic energy (Figure 5) at 150 hPa (right panels) over the summer monsoon region shows that three is generation of kinetic energy over the Bay of Bengal and the adjoining Indonesian regions, as in the pre-onset periods. However, the production of kinetic energy increases and extends over the south Asian region covering from the west Pacific to the eastern Arabian Sea, with maxima generation situated over the Bay of Bengal and the eastern Arabian Sea respectively during the post-onset period. There is negative generation over the North African region. These zones of kinetic energy

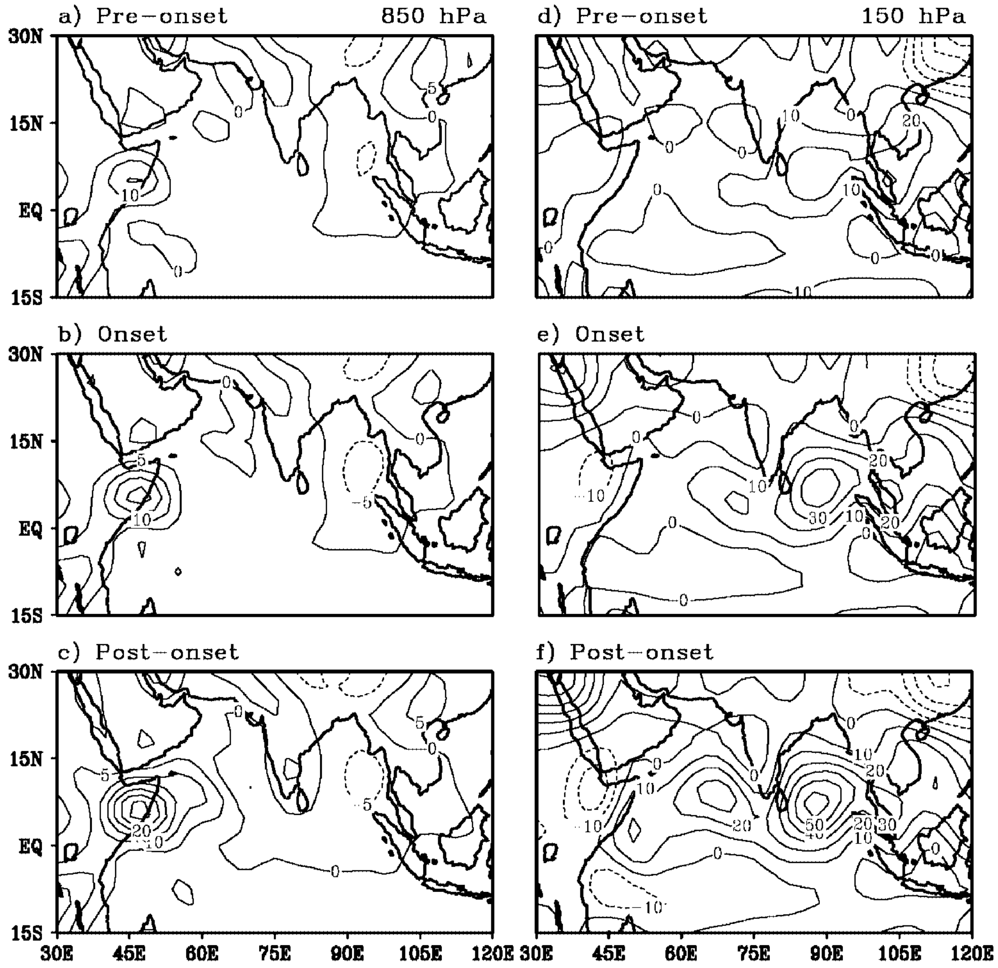


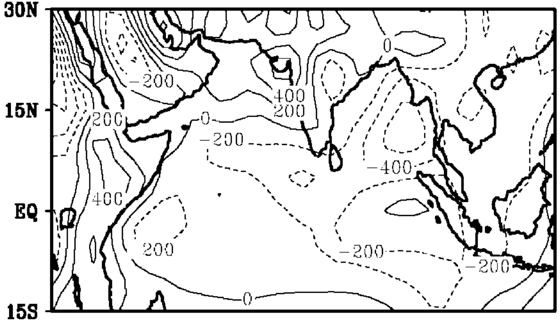
Figure 5. Geographical distribution of adiabatic generation of kinetic energy (10^{-4} W kg^{-1}) for 850 hPa (left panels) (a) pre-onset, (b) onset, (c) post-onset and 150 hPa (right panels) (d) pre-onset, (e) onset, (f) post-onset

production (destruction) are situated at the respective entrance (exit) regions of the TEJ. In general, the zonal component contributes for generation in the extratropics and dissipation in the tropics, and vice versa for the meridional component (Kung, 1971). However, the interesting feature delineated by these two components over the monsoon domain is that both contribute for generation.

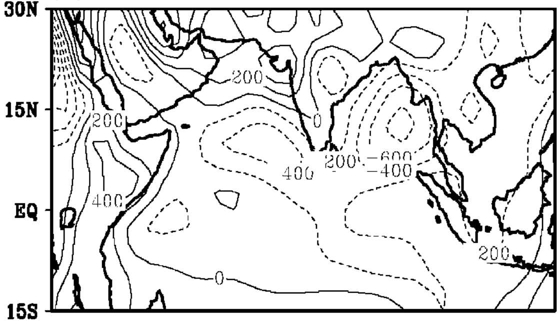
3.3. Heat and moisture budget

The thermodynamic characteristics of the summer monsoon during the onset phase over India are examined with heat and moisture budgets. The vertically integrated horizontal flux divergence of heat for pre-onset, onset and post-onset is presented in Figure 6 The significant features noticed are the increasing flux convergence over the eastern Bay of Bengal from the pre-onset period. These zones are intensified in the onset and post-onset periods. The strong heat flux convergence is developed during the onset period and is strengthened further in the post-onset period. In the southeast Arabian Sea, the horizontal flux convergence increases from 200 to 600 W m^{-2} from the pre-onset phase to the post-onset phase. The geographical distribution of the diabatic heating pattern is presented in Figure 7. The diabatic heating pattern shows that excess heating is noticed over the eastern Bay of Bengal in the pre-onset period. This is intensified further in the onset and post-onset periods. This is consistent with the earlier study by Hsu *et al.* (1996), who stated that the warming of

(a) Pre-onset



(b) Onset



(c) Post-onset

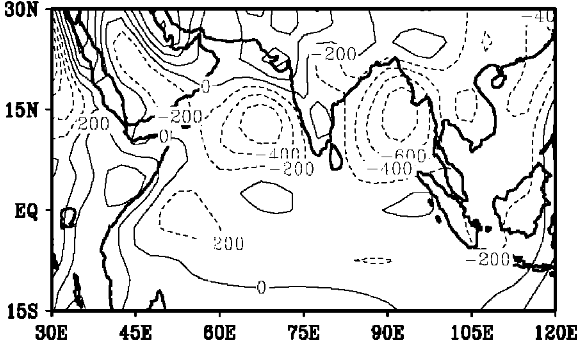
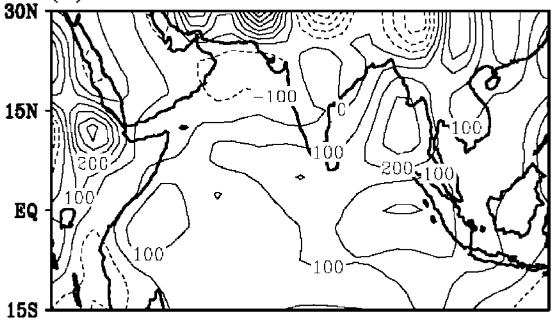
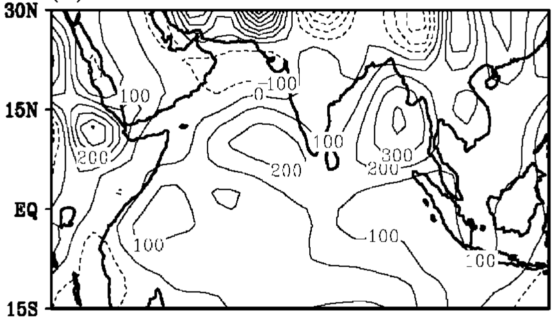


Figure 6. Geographical distribution of vertically integrated horizontal divergence flux of heat (W m^{-1}): (a) pre-onset, (b) onset, (c) post-onset

the Bay of Bengal takes place during the first transition of the Asian summer monsoon. Also, diabatic heating is developed in the southeast Arabian Sea during the onset period and increases in the post-onset period. A decreasing diabatic heating trend is noticed over the Arabian Peninsula. The diabatic heating dominates mainly due to the release of latent heat over this region. The strong moisture influx coupled with an intense rising motion and release of latent heat are the essential factors in sustaining the diabatic heat source, thus giving a positive feedback that maintains the summer monsoon circulation. The zones of diabatic heating pattern over the Asian summer monsoon regions over the Bay of Bengal and the Arabian Sea during pre-onset, onset and post-onset periods are characterized by a horizontal flux convergence of moisture (Figure 8). A flux divergence of moisture is noticed over East Africa in the pre-onset, onset and post-onset periods. The differential heating between the south Asian continent and the adjoining tropical Indian Ocean necessitates cross-equatorial flow off East Africa. This flow is primarily responsible for the transport of mass and moisture from the oceanic regions.


(a) Pre-onset


(b) Onset

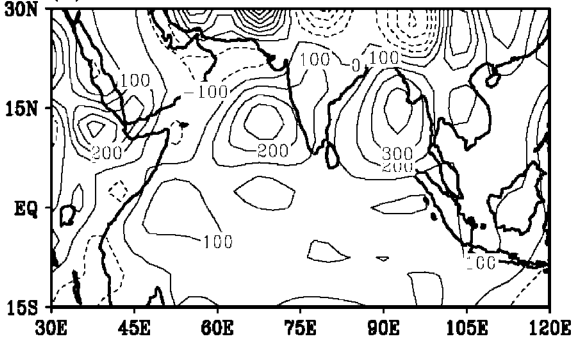

(c) Post-onset

Figure 7. Geographical distribution of vertically integrated diabatic heating (W m^{-1}): (a) pre-onset, (b) onset, (c) post-onset

3.4. *Evolution of summer monsoon*

The evolution of the monsoon onset processes is characterized by intensification of low-level circulation, particularly the cross-equatorial flow off the East Africa coast, in response to the heating over the Arabian Peninsula, Pakistan and northwest India, and formation of low pressure over northwest India. With the increase of the low-level wind over the Indian Ocean there is an increase in surface moisture flux. Consequently, the moisture content of the air increases and reaches a level sufficient to produce deep cumulus convection and latent heat release. This provides an additional heat source and the whole circulation continues to intensify through positive moisture feedback, leading to the onset of the monsoon over the Indian subcontinent, which is characterized by a deep convection over the Arabian Sea, extending in to the Bay of Bengal and across peninsular India. Therefore, a detailed study over the Indian seas and peninsular India is crucial in understanding the physical mechanisms involved in the onset and advancement of the summer monsoon. In this section, time–latitude cross-section aspects are examined with the 52 year NCEP reanalysis data over the various sectors during the evolution processes of the summer monsoon in relation to onset over the south

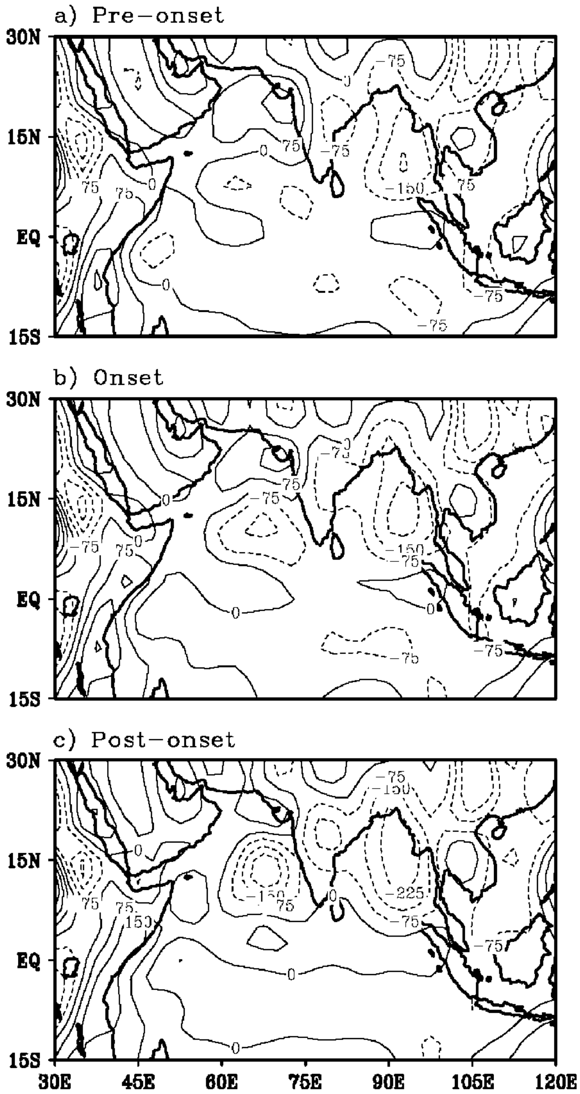


Figure 8. Geographical distribution of vertically integrated horizontal divergence flux of moisture (W m^{-1}): (a) pre-onset, (b) onset, (c) post-onset

Kerala coast. It is worth emphasizing here that we examined the evolution processes for each annual cycle (15 days before onset and 30 days after the onset date which was reported over south Kerala coast). Figure 9 (left panels) shows the time–latitudinal variations of the low-level kinetic energy (850 hPa). The low-level kinetic energy in Figure 9 (left panels) is the average in the 50–70 °E, 70–85 °E and 85–100 °E longitudinal belts, representing the Arabian Sea, Indian Peninsula and the Bay of Bengal respectively. It is seen from the time–latitudinal evolution of the kinetic energy in Figure 9 that, in the Arabian Sea, a magnitude of 40 m^2 s^{-2} of kinetic energy takes place at the equator to 15 °N before the onset of monsoon over the Kerala coast. This gradually increases with the advancement of the monsoon, which is due to the strengthening of westerlies over this region. In the 70–85 °E and 85–100 °E belts the pattern is similar to 50–70 °E, but the intensity of low-level kinetic energy is weaker than for the Arabian Sea belt. In the 70–85 °E belt the kinetic energy slowly extends north up to 25 °N with the advancement of the monsoon over India. The vertically integrated adiabatic generation of kinetic energy is averaged in the three longitudinal belt representing the Arabian Sea,

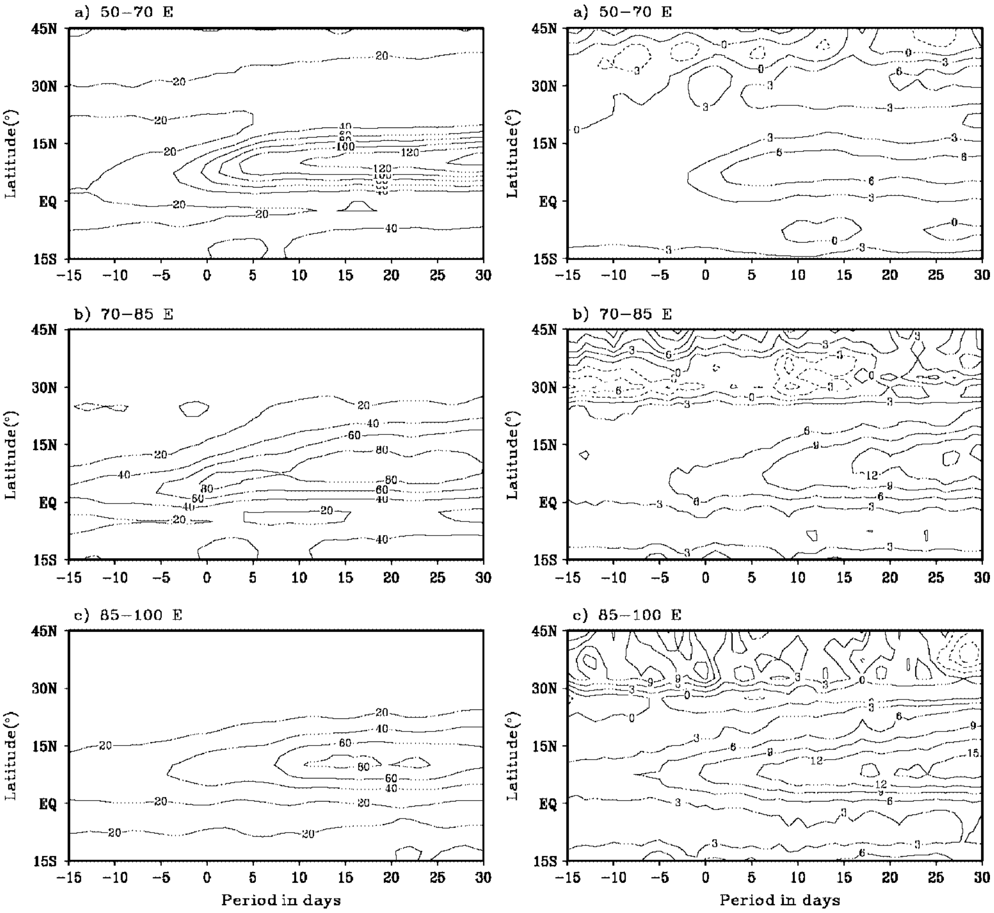


Figure 9. Time–latitude variations of kinetic energy at 850 hPa (m^{-2} s^{-2}) (left panels) vertically integrated generation of kinetic energy (W m^{-2}) (right panels) for (a) Arabian Sea, (b) Indian Peninsula and (c) Bay of Bengal

Indian Peninsula and Bay of Bengal presented in Figure 9 (right panels). It indicates that the generation of kinetic energy increases from the date of onset over the southern tip of India in the longitudinal belts. However, the Indian Peninsula and the Bay of Bengal show higher generations of kinetic energy compared with the Arabian Sea with the advance of the monsoon over India. The generation changes are significantly larger in the belt from the equator to 15 °N. As discussed earlier, the large generation of kinetic energy over the Bay of Bengal is due to the outflow of the TEJ.

The evolution of the onset processes of the summer monsoon are examined by considering time- and area-averages over the various regions, i.e. Arabian Sea (50–72.5 °E, 5–15 °N), Bay of Bengal (82.5–97.5 °E, 5–15 °N), Indian landmass (72.5–82.5 °E, 5–15 °N). The daily variations of low-level kinetic energy (850 hPa) are presented in Figure 10 (left panels). In Figures 10 and 12 the '+' symbol gives the bounds in one standard deviation below and above the mean values. It can be seen that, during the onset of summer monsoon in India (southwest Kerala), rapid intensification of low-level kinetic energy takes place over the Arabian Sea. This varies between 25 and 65 m^2 s^{-1}. Also, the kinetic energy increases at the lower levels over the Bay of Bengal and the Indian peninsular region during the onset phase. This is in good agreement with the findings of earlier results (Krishnamurti and Ramanathan, 1982; Pearce and Mohanty, 1984; Ramesh *et al.*, 1996). Although, significant changes are noticed over these regions, the Arabian Sea region has a higher magnitude of kinetic energy following the onset of the monsoon. It appears that attaining a magnitude of 40 m^2 s^{-2} and then a sharp rise of kinetic energy at 850 hPa is an appropriate time to declare the onset

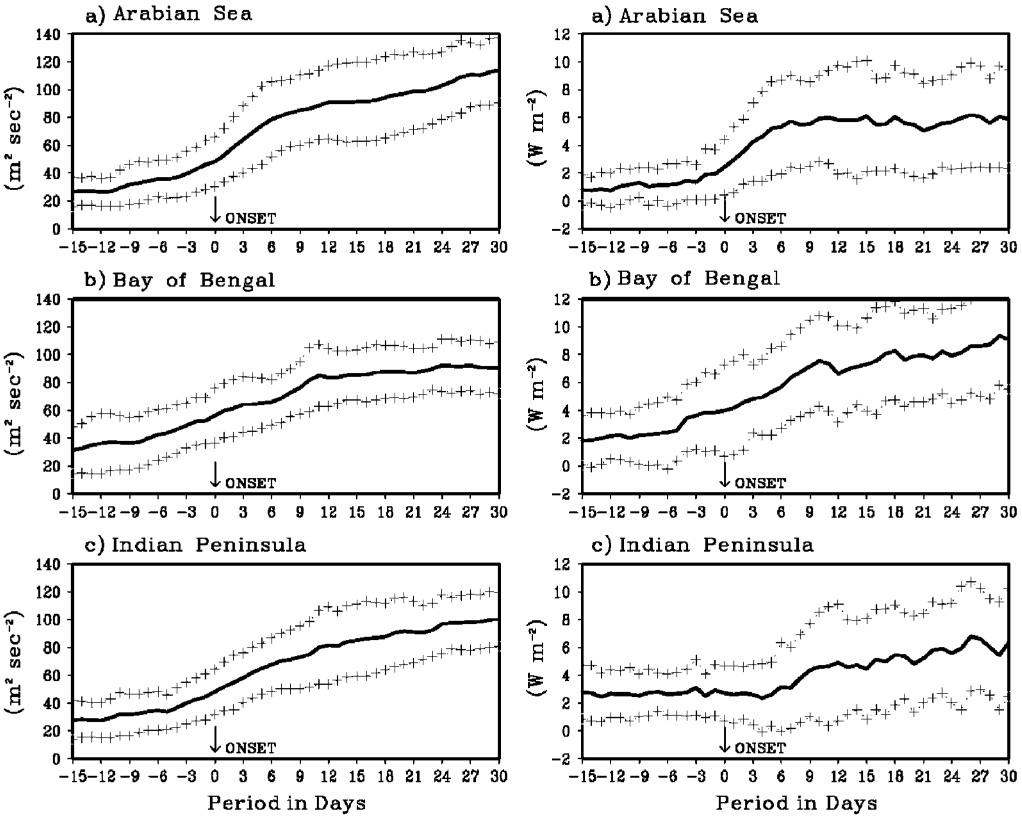


Figure 10. Evolution of kinetic energy at 850 hPa (m^2 s^{-2}) (left panels) and volume-integrated generation of kinetic energy (W m^{-2}) (right panels) during the onset phase over Kerala for (a) Arabian Sea, (b) Bay of Bengal, (c) Indian Peninsula (the + symbols represents the upper and lower bounds of standard deviation from the mean value)

of the summer monsoon over India. The day-to-day variation of generation of kinetic energy (Figure 10, right panels) shows a sudden increase over the Arabian Sea. The Bay of Bengal region shows a gradual increase in the onset process. The Indian peninsular region shows little increase in generation of kinetic energy.

The time–latitude structure of the net tropospheric moisture and diabatic heating are averaged over the three longitudinal belts representing the Arabian Sea, Indian Peninsula and Bay of Bengal is shown in Figure 11. The Arabian Sea ((figure 11(a)) belt shows a higher net tropospheric moisture between the equator and 15 °N during the onset of the summer monsoon over the Kerala coast. The Indian Peninsula belt shows a maximum in moisture between 10 and 35 °N after 1 week of onset of the monsoon over Kerala (figure 11(b)). Further, net moisture increases with the advancement of the summer monsoon over India. The Bay of Bengal (figure 11(c)) sector shows a higher net moisture between 15 and 40 °N. This higher magnitude appears to be the result of the topography of the northeast region. The time–latitude structure of the vertically integrated diabatic heating over three longitudinal belts is presented in Figure 11 (right panels). In the Arabian Sea belt, diabatic heating is present between 10 °S and 15 °N and cooling is present between 15 °N and 45 °N. The vertically integrated diabatic heating over peninsular India averaged over the longitudinal belt of 70 to 85 °E is presented in Figure 11(b). This indicates that heating in the lower latitudes between 10 °S and 15 °N and cooling in the higher latitudes between 15 °N and 35 °N, with a maximum cooling of 200 W m^{-2} before the onset of the monsoon over the Kerala coast. Thereafter, the diabatic cooling decreases with the advance of the monsoon. The slope of the maximum diabatic heating indicates the convection shifting northwards at the advancement of the monsoon over Kerala. In the Bay of Bengal sector (85–100 °E), the entire region exhibits diabatic heating up to 30 °N, with a maximum of

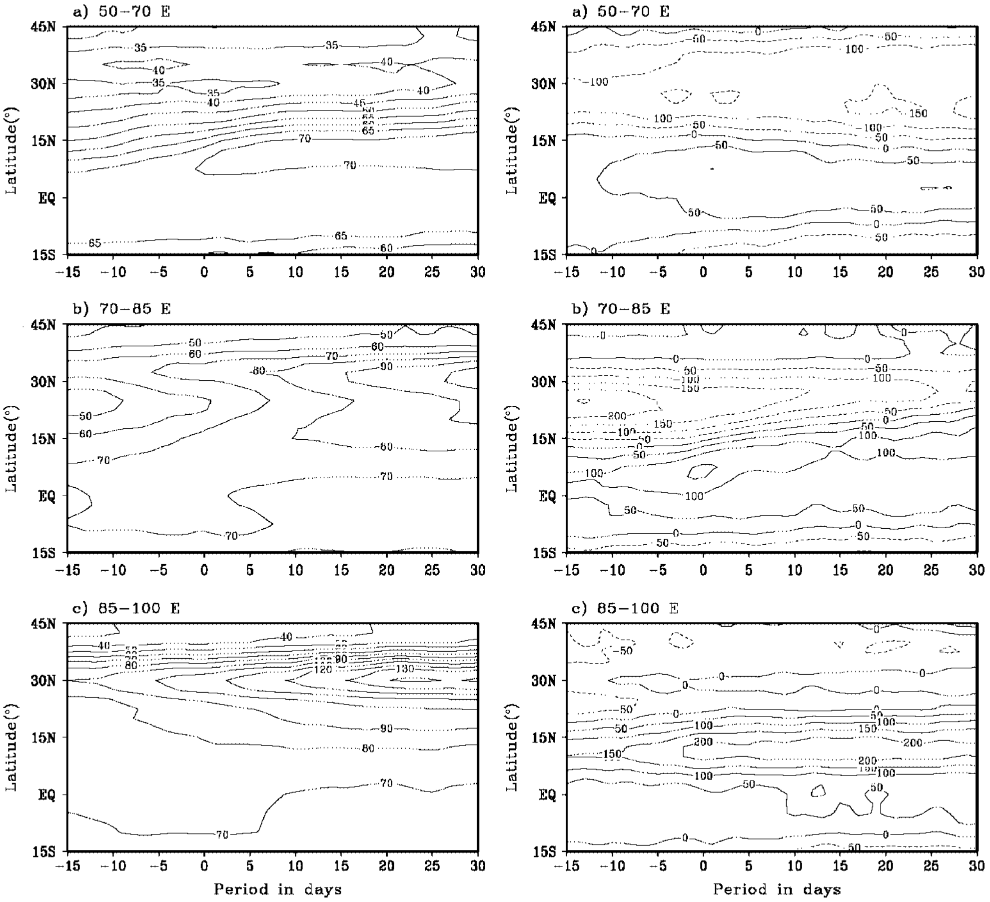


Figure 11. Time–latitude variations of net tropospheric moisture (mm) (left panels) and vertically integrated diabatic heating (W m^{-2}) (right panels) for (a) Arabian Sea, (b) Indian Peninsula and (c) Bay of Bengal

200 W m^{-2} at 10 °N during onset, and this is maintained with the advancement of the monsoon over India. The diabatic cooling is replaced by heating between 20 and 45 °N 5 days before the onset of the monsoon over India.

The daily variations of net tropospheric moisture and diabatic heating are presented in Figure 12. The net tropospheric moisture (Figure 12, left panels) builds up and can be clearly noticed 10 days before the onset of the monsoon in Kerala, and it advances further over the Arabian Sea, Bay of Bengal and the Indian landmass. However, the net moisture build up over the Arabian Sea is accompanied by a fall/no change in net moisture after a certain amount of increase in net moisture (43 mm). This characteristic decrease in net moisture is due to the transient convective activity that is organized and developed in association with local meso/synoptic-scale systems (Krishnamurti and Ramanathan, 1982; Pearce and Mohanty, 1984). The diabatic heating pattern shows an increase in convective activity during the onset phase over the Arabian Sea, Bay of Bengal and Indian landmass. The diabatic heating (Figure 12, right panels) over the Arabian Sea decreases gradually after reaching a certain amount of heat, which is due to the large amount of evaporation over the Arabian Sea. The strong heating enhances the low-level cross-equatorial flow, and this may be augmented further by precipitation and latent heat release over the Arabian Sea. These characteristics indicate the complexity of the diabatic forcing and the additional role of dynamic factors that influence summer monsoon. The Bay of Bengal sector exhibits a gradual increase of diabatic heating with the advance of monsoon over India.

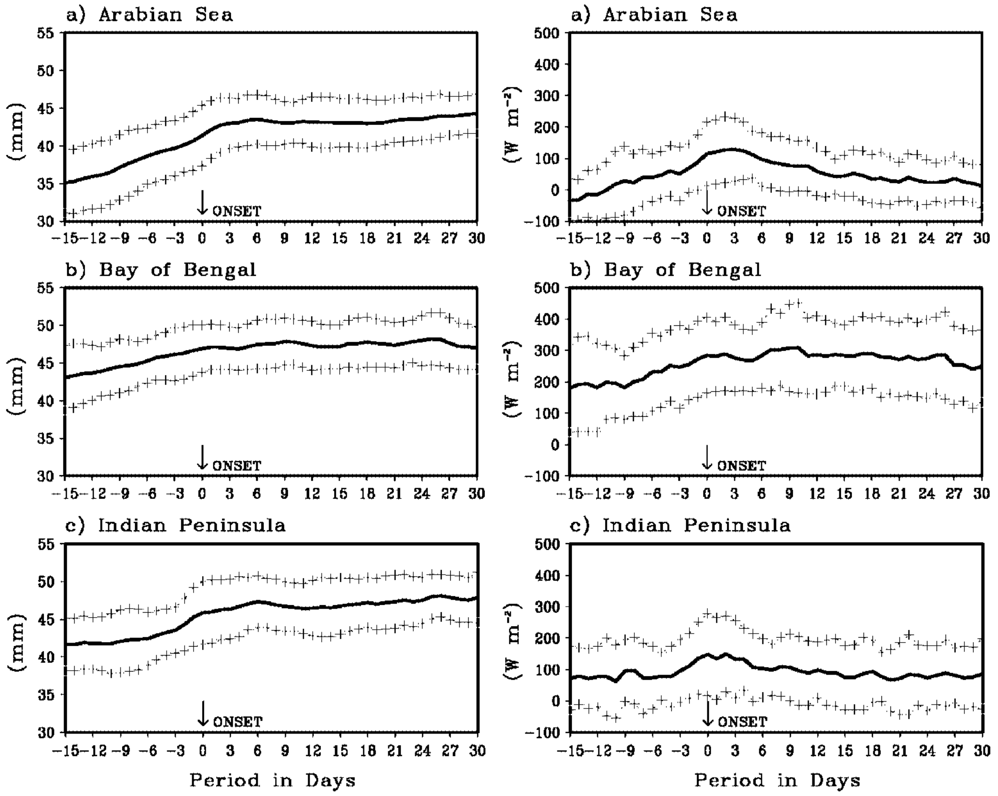


Figure 12. Evolution of net tropospheric moisture (mm) (left panels) and volume-integrated diabatic heating (W m^{-2}) (right panels) during the onset phase over Kerala for (a) Arabian Sea, (b) Bay of Bengal, (c) Indian Peninsula (the + symbols represents the upper and lower bounds of standard deviation from the mean value)

4. CONCLUSIONS

The mean circulation features, dynamics and energetics of the Asian summer monsoon are discussed during its evolution over India. Strong cross-equatorial flow and intense westerlies over the Arabian Sea are the characteristic low-level features in the evolution process of the summer monsoon over India. On the other hand, the westerly jet migrates towards the north, and the TEJ is strengthened during the onset period and it is intensified in the post-onset period. Further, there is a strong rising motion over the tropics and a sinking motion over the extratropics from the pre-onset period to the post-onset period.

The flux divergence of kinetic energy over the Somali coast at the low levels intensifies with the evolution of the monsoon over India. The flux convergence zone is developed over the central Arabian Sea in the onset period, and it is strengthened and extends over the Indian Peninsula during the post-onset period. The upper level feature delineates the flux divergence over the Bay of Bengal and flux convergence over East Africa, the western Indian Ocean and south Arabia during the onset period, and these intensify further with the advance of the summer monsoon over India. These zones of kinetic energy flux transport maxima (minima) are situated at the respective entrance (exit) regions of the TEJ.

In the Arabian Sea region, the low-level kinetic energy (850 hPa) and vertically integrated generation of kinetic energy show large difference in the pre-onset, onset and post-onset periods. It appears that attaining a magnitude of 40 m^{-2} s^{-2} and then a sharp rise of kinetic energy at 850 hPa is an appropriate time to declare the onset of the summer monsoon over India. The horizontal flux convergence of kinetic energy over the Arabian Sea and Indian Peninsula is transported from the southwest equatorial Indian Ocean. On the other hand, the flux divergence of kinetic energy over the southeast equatorial Indian Ocean is shifted to the Bay of Bengal region during the onset phase over India (Kerala coast).

The large-scale balances of heat and moisture illustrate some interesting features. Prior to the onset of the summer monsoon, the east Bay of Bengal exhibited flux convergence of heat, moisture convergence and large convective activity, which further intensified in the onset and post-onset periods. Once the monsoon sets over India, the flux convergence of heat, diabatic heating and moisture convergence developed in the onset period over south Arabia and subsequently strengthened in the post-onset period.

The study shows that, in addition to a sufficient level of net tropospheric moisture (above 40 mm), a minimum strength of low-level flow is needed to trigger convective activity over the Arabian Sea and Bay of Bengal. The present study reveals that the low-level kinetic energy, generation of kinetic energy and net tropospheric moisture can be used as potential predictors for the possible onset of the summer monsoon over India.

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