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EVALUATION OF BROAD SCALE VERTICAL CIRCULATION AND THERMAL INDICES IN RELATION TO THE ONSET OF INDIAN SUMMER MONSOON

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ABSTRACT

The onset of the Indian summer monsoon over Kerala for an individual year of delayed (1997), early (1999) and normal onset (2000) was examined in relation to the intensity of vertical circulation and thermal indices during the pre-monsoon months (April and May). The study showed that in the delayed monsoon onset year (1997) negative anomalies of vertical zonal index dominated over the north Indian Ocean during pre-monsoon months, particularly in April. In contrast, in the early onset year (1999) the positive anomalies of this index over the north Indian Ocean during the pre-monsoon months were considerably stronger (April and May). However, the meridional vertical index did not show any appreciable difference. The gradient of the vertical thermal index anomalies over the Tibetan Plateau in the month of April was prominently stronger during the years of early and normal onset (1999 and 2000). The anomalies of geopotential height at 200 hPa over the Tibetan Plateau in the pre-monsoon months were significantly lower in the year of delayed onset (1997). The precipitable water content was found to be another major feature, which grew rapidly over the equatorial belt of the Indian Ocean extending up to the Arabian Sea and Bay of Bengal during the two weeks prior to onset. Most of these features were observed very distinctly in the month of April, well before the monsoon onset, and promise to provide important predictive signals for the onset over Kerala. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: Indian summer monsoon; vertical zonal and meridional index; vertical thermal index; precipitable water content; monsoon onset

1. INTRODUCTION

The onset of rain from the Indian summer monsoon is an important event influencing the agriculture of the region. The date of the monsoon onset over Kerala, the extreme southern part of Peninsular India, has been determined operationally each year by the India Meteorological Department (IMD) for the past 100 years. These are subjective estimates based primarily on the nature of daily rainfall reported by the observatory stations of Kerala (Anantakrishnan and Soman, 1988). The date of monsoon onset over Kerala has a large interannual variability. During the last 100 years, the monsoon onset over Kerala has occurred between 7 May and 22 June, with a mean close to 1 June (known as the normal date of onset) and a standard deviation of 8 days.

The general circulation over Asia undergoes abrupt changes during early summer. Various studies have focused on the changes in the atmosphere around the time of onset (Pearce and Mohanty, 1984; He *et al.*, 1987; Kurshaw, 1988; Krishnamurti *et al.*, 1990; Yanai *et al.*, 1992; Soman and Krishnakumar, 1993; Joseph *et al.*, 1994). Pearce and Mohanty (1984) studied the onset of monsoon over southern Asia for the years 1979 to 1982. They noted that the period prior to onset consists of two main phases: (a) a rapid intensification of the Arabian Sea winds and a substantial increase in latent heat release following (b) a moisture build-up phase over the Arabian Sea during which synoptic and meso-scale transient disturbances develop.

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Soman and Krishnakumar (1993) studied the climatological structure of atmospheric fields during the onset phase (from onset − 20 days to onset + 15 days), making a composite analysis of different meteorological parameters over Indian stations. Joseph *et al*. (1994) studied the temporal and spatial evolution of tropical deep convection associated with the monsoon onset using pentad mean maps of outgoing longwave radiation (OLR).

Webster and Yang (1992) observed that monsoon wind fields possessed a combination of interannual and intraseasonal variation. In the early summer, lower tropospheric winds switch rapidly from weak easterlies to rather strong westerlies and are accompanied by an equally rapid acceleration of the upper tropospheric easterlies. From the evolution of the annual cycle of broad-scale monsoon circulations, averaged over the region 5 to 15 °N and 40 to 100 °E and based on data for the years 1986–89, they noted that the broad-scale monsoon circulations developed explosively from April to May, whereas the phase and amplitude varied considerably from year to year. In their study, a monsoon intensity index based on the magnitude of mean vertical shear in this region was defined and this was shown to be consistent with the broad-scale OLR fields. The use of the circulation as an indicator of the vigour of the broad-scale monsoon is also consistent with the theory of Gill (1980), which related the strength of heating over the south Asian region and the magnitude of the vertical shear.

Following Webster and Yang (1992), more recent studies have used vertical circulation (zonal and meridional) indices to link the performance of the Indian summer monsoon (Li and Yanai, 1996; Krishnamurti and Goswami, 1999; Wang and Zeng, 1999). Li and Yanai (1996) also reported the rapid transition of monsoon circulations during mid May utilizing model analysis data for the years 1979–92. From the time evolution they showed that the monsoon circulation was linked with changes in upper tropospheric temperature. They noted that onset of the monsoon was concurrent with the reversal of the meridional temperature gradient in the upper troposphere south of the Tibetan Plateau. They further defined a thermal index based on vertical temperature differences. The time evolution of these temperature anomalies revealed that anomalies began to change from negative to positive in April over the Tibetan Plateau between 90 and 100 °E.

This paper assess the use of these indices in a predictive mode for the monsoon onset over Kerala, by examining the spatial pattern of these indices during pre-monsoon months (April and May) for an individual year of delayed onset, early onset and normal monsoon onset. The years considered are 1997, 1999 and 2000. The selection of the years is due to consideration of the fact that onset was delayed by 8 days in the year 1997, was early by 7 days during 1999 and was normal in the year 2000. Moreover, 1997 was a strong El Niño year whose intensity was unprecedented that century (Slingo and Annamalai, 2000), and 1999 was a La Niña year. The data used in this study are described in Section 2. The spatial evolution of monthly circulation indices are discussed in Section 3 and thermal indices are discussed in Section 4. The weekly evolution of these indices, as well as the precipitable water content (PWC) during the onset of 2000, are given in Section 5.

2. DATA SOURCES

The primary data used are from the daily analysis fields (at resolution $1^\circ \times 1^\circ$) of IMD's operational forecasting system, known as the Limited Area Analysis and Forecast System (LAFS). The LAFS is a complete system consisting of the real-time processing of data received on the Global Telecommunication System (GTS). Decoding and quality control procedures are handled by AMIGAS software, a 3-D multivariate optimum interpolation scheme for objective analysis and a multi-layer primitive equation model. The first-guess fields for running the analysis scheme are obtained online from the National Center for Medium Range Weather Forecasting (NCMRWF), New Delhi. Monthly anomalies are derived using the climatology data (1979–89) at a resolution of $1^\circ \times 1^\circ$, from the National Center for Environmental Prediction (NCEP), Washington. Precipitable water contents are computed from NOAA polar orbiting spacecraft meteorological observations available as a routine in GTS transmission.

3. VERTICAL CIRCULATION INDICES

In this section the vertical zonal and meridional indices are examined and discussed.

3.1. Vertical zonal index

The vertical zonal index is defined as the intensity of the vertical shear of the zonal wind between 850 and 200 hPa ($u_{850} - u_{200}$). In Figure 1(a) and (b) the anomaly fields of zonal wind components (u) at 850 hPa, 200 hPa and the vertical zonal index for the months of April and May of 1997 are illustrated. In the month of April 1997 (delayed year) negative anomalies (-2 m s^{-1}) of u at 850 hPa dominated over the equatorial belts of the north Indian Ocean. At 200 hPa the u anomalies were near normal. The anomalies of the vertical zonal index over northern parts of the Indian Ocean were negative (-3 to -6 m s^{-1}) but gradually increased southward and became normal over the equatorial belt. In the month of May positive anomalies ($+5$ m s^{-1}) of u at 850 hPa were noticed over the equatorial belt of the Indian Ocean. Anomalies of u at 200 hPa were negative to near normal over the equatorial Indian Ocean. Near-normal or slightly positive anomalies of vertical zonal index continued over the north Indian Ocean and Arabian Sea west of longitude 75 °E. Positive anomalies of zonal index of the order of 5 m s^{-1} were confined over the eastern part of the Indian Ocean and extended northward over the Bay of Bengal.

In April 1999 (early onset year), anomalies of u at 850 hPa over the north Indian Ocean from the equator to the southern parts of the Arabian Sea and Bay of Bengal were observed to be considerably stronger (6 m s^{-1}) (Figure 2(a) and (b)). Anomalies of u at 200 hPa were negative to near normal. The anomalies of vertical zonal index were positive (10 m s^{-1}) over the northern Indian Ocean and extended northwards up to the Bay of Bengal. In the month of May, the east–west-oriented positive belt of anomalies (6 m s^{-1}) of u at 850 hPa shifted northwards over the southern parts of the Arabian Sea and Bay of Bengal, and were found to increase further and were confined along latitude 10 °N. Anomalies of u at 200 hPa continued to be negative to near normal. The anomalies of vertical zonal index were also very strong (10 to 15 m s^{-1}), and were confined over the Arabian Sea and Bay of Bengal along latitude 10 °N and extended over the entire north Indian Ocean.

In April 2000 (normal onset year), anomalies of u at 850 hPa were positive (5 m s^{-1}) over the equatorial belt of the Indian Ocean extending northwards up to the south Arabian Sea and Bay of Bengal (Figure 3(a) and (b)). The anomalies of u at 200 hPa over the north Indian Ocean were near normal. The belt of positive anomalies of vertical zonal index (10 m s^{-1}) over the north Indian Ocean extended from the equator to the south Arabian Sea and Bay of Bengal. During May, a positive belt of u anomalies at 850 hPa shifted northwards and lay along latitude 10 °N centred over the south Arabian Sea. Anomalies of u at 200 hPa were negative over the Indian Ocean. The area of positive anomalies of vertical zonal index (10 m s^{-1}) extended over a larger domain from the equator to the north over the Arabian Sea and Bay of Bengal.

The evolution of the planetary-scale zonal vertical index showed that, during the delayed onset year (1997), the anomalies of u at 850 hPa and the vertical zonal index were negative over the north Indian Ocean during the pre-monsoon months, particularly in April. In contrast, in the early onset year (1999) the positive anomalies of these indices over the north Indian Ocean were considerably stronger in April, and these increased further and migrated northward over the southeast Arabian Sea and southwest Bay of Bengal in May. A similar feature was also noticed in the normal onset year (2000), except that the gradient of the anomalies was relatively weak.

These features are also consistent with the results documented by Webster and Yang (1992), who showed that in El Niño years the lower (upper) tropospheric westerly (easterly) flow is weaker than normal, whereas in La Niña years it tends to be stronger than normal. Again the onset of monsoon over Kerala in 1997 was delayed by 8 days. Thus the delayed (early) onset in the El Niño (La Niña) year of 1997 (1999) may well be connected with the weak (strong) anomalous shear of the zonal wind over the north Indian Ocean. Ju and Slingo (1995) have also noted that the greatest impact of El Niño related to boundary forcing on the strength of the monsoon circulation tended to occur during the onset phase of monsoon. In El Niño years the strength of the monsoon, in general, is influenced by the modulation of the Walker circulation, because of the implied additional subsidence over the west Pacific and Southeast Asia due to systematic eastward shifting of the zone of convection.

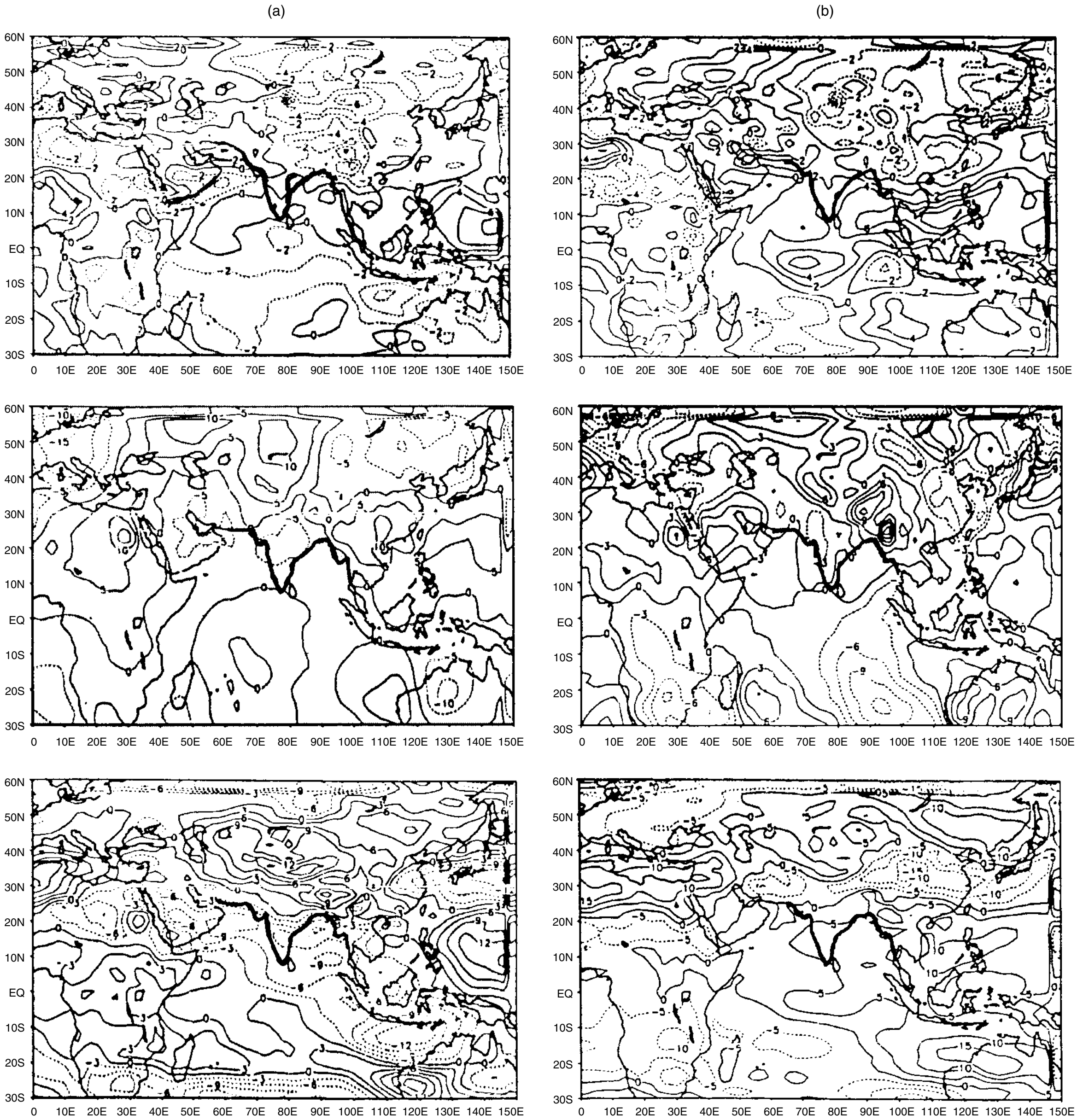

Figure 1. Anomaly fields (m s^{-1}) of u (from top to bottom) at 850 hPa, 200 hPa, and the zonal vertical shear $u_{850} - u_{200}$ for the months of (a) April 1997 and (b) May 1997

3.2. Meridional vertical shear (MHI)

The vertical meridional index is defined as the intensity of the vertical shear of meridional wind between 850 and 200 hPa ($v_{850} - v_{200}$). Figure 4(a)–(f) illustrates the anomalies of the vertical meridional index for the months of April and May during 1997, 1999 and 2000. During April, in all three years, the anomalies were negative to near normal over the Indian Ocean. During May in 1997, positive anomalies of the vertical meridional index were seen over the Indian Ocean east of longitude 80 °E, with maximum values over the south Indian Ocean, and decreasing northward, becoming normal over the north Indian Ocean. In 1999, positive anomalies (3 m s^{-1}) extended over the Indian Ocean from north of latitude 10 °S to the Bay of Bengal. In

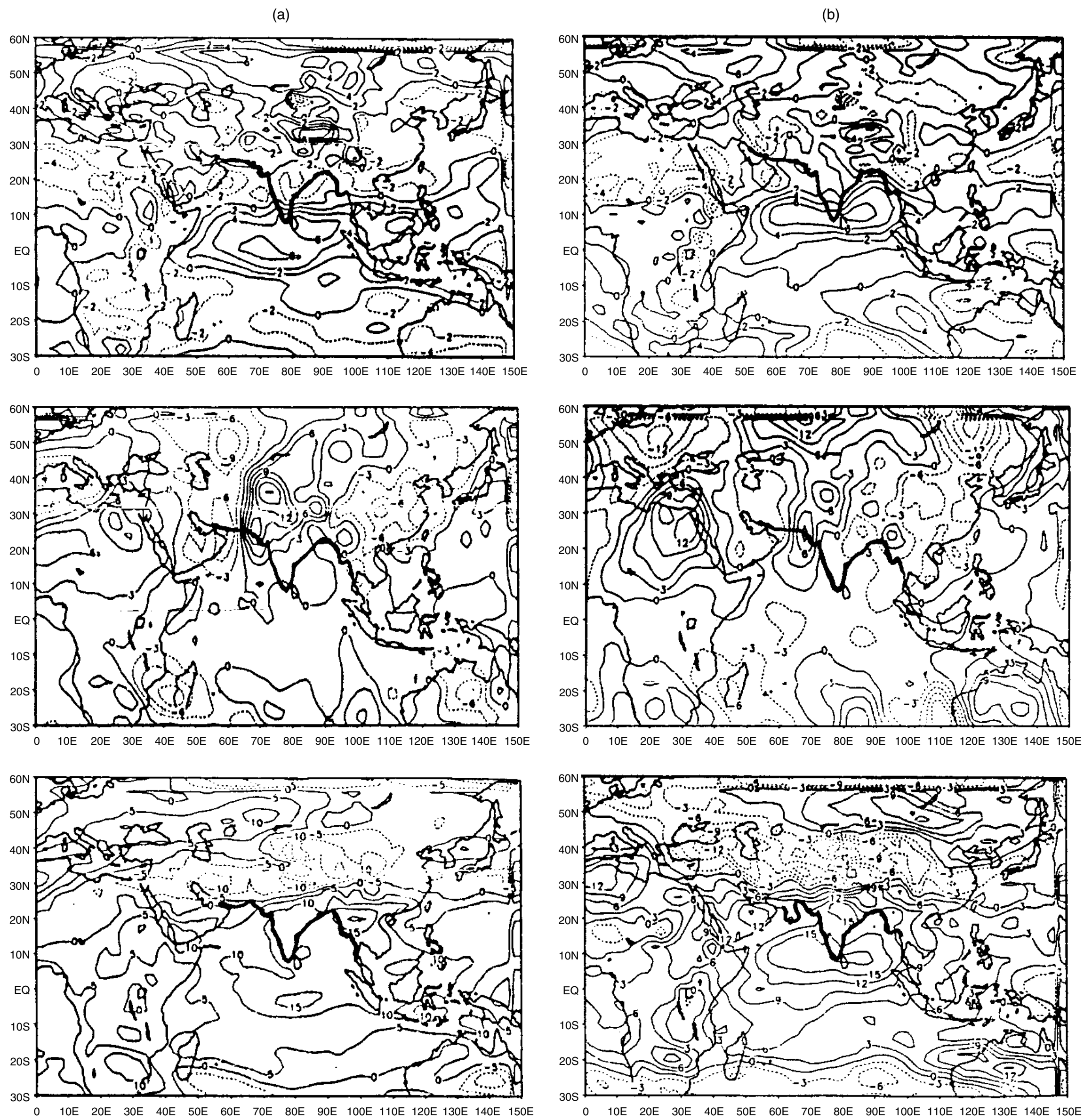

Figure 2. As Figure 1 for the months of (a) April 1999 and (b) May 1999

the year 2000, during May, positive anomalies (6 m s^{-1}) occupied the Indian Ocean east of 80 °E. Thus, no appreciable difference was noticed in the vertical meridional index during pre-monsoon months in these years.

4. THERMAL INDICES

In this section the vertical thermal index and the geopotential height at 200 hPa are examined.

4.1. Vertical thermal index

The vertical thermal index is defined as the vertical difference of temperature between 200 and 500 hPa ($T_{500} - T_{200}$). Figure 5(a)–(f) illustrates the anomalies of meridional vertical thermal index for the months of

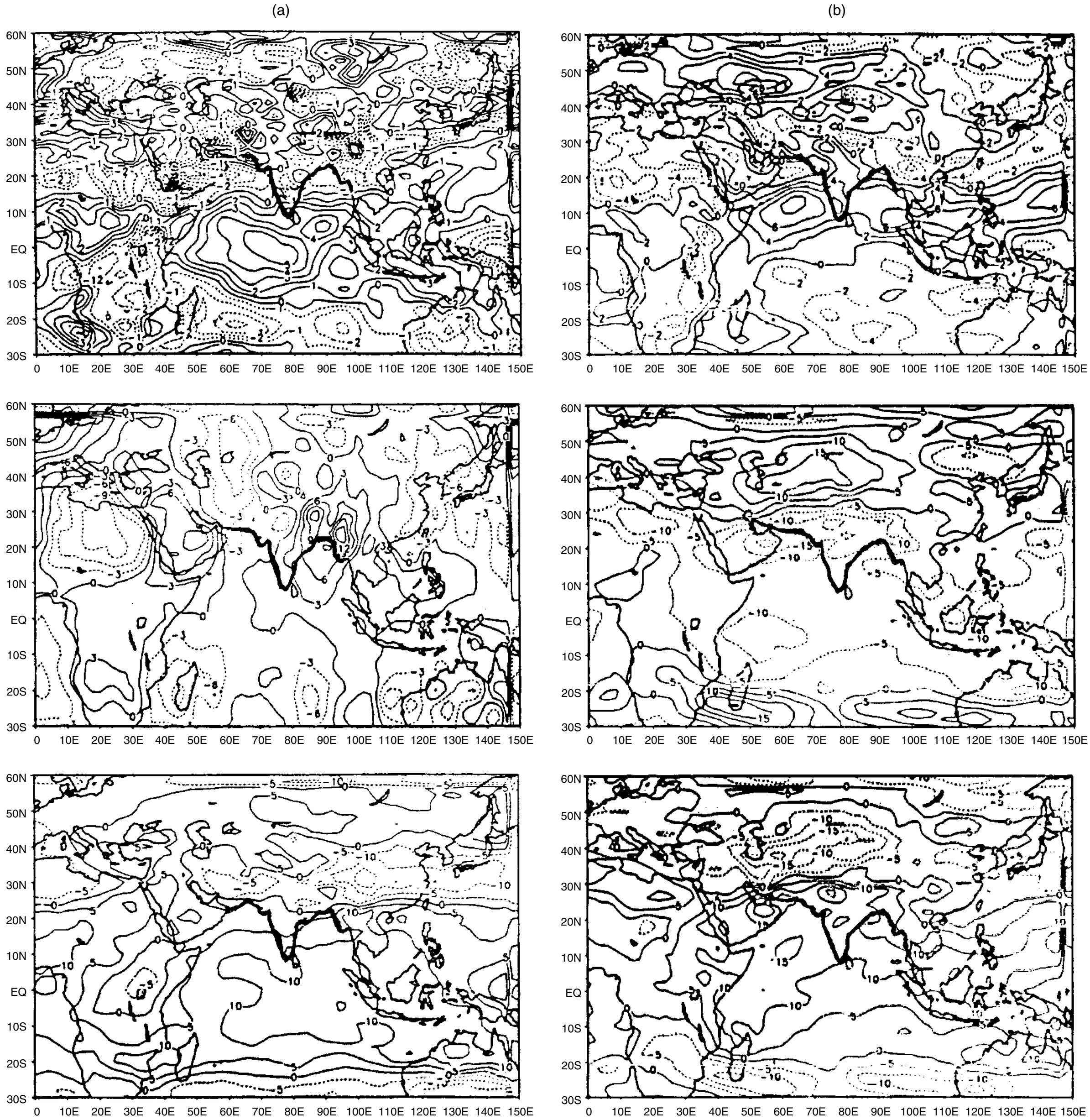

Figure 3. As Figure 1 for the months of (a) April 2000 and (b) May 2000

April and May during 1997, 1999 and 2000. During April 1997, a positive anomaly (2 °C) was seen over the extreme northern parts of India. In 1999, anomalies over the Tibetan Plateau were considerably stronger (6 °C). The anomalies were negative to near normal over the Indian Ocean, resulting in an enhanced meridional thermal gradient. In 2000, considerably strong positive anomalies of the vertical thermal index (6 °C) were found over the Tibetan Plateau and negative anomalies over the Indian Ocean. In May, during all three years, large positive temperature anomalies (2 to 4 °C) covered most of Eurasia between latitude 30 and 40 °N and also covered the Southern Hemisphere south of latitude 20 °S. Negative to normal anomalies prevailed over the tropical belt extending over the Indian Ocean. No appreciable difference in the vertical thermal index during the month of May across all three years was noticed, except that the gradient was weaker in 1997.

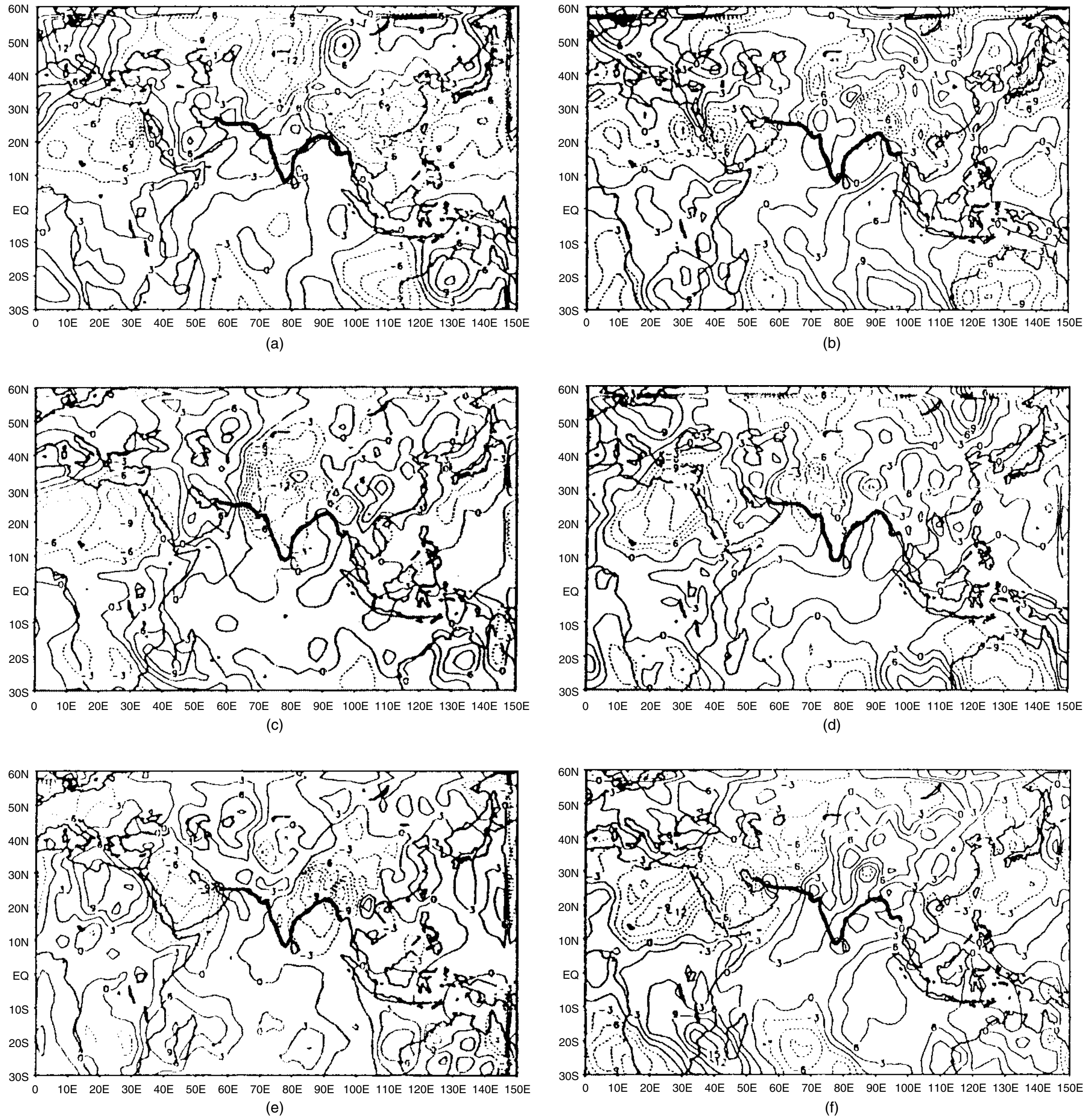

Figure 4. Anomaly fields (m s^{-1}) of meridional vertical shear $v_{850} - v_{200}$ for: (a) April 1997; (b) May 1997; (c) April 1999; (d) May 1999; (e) April 2000; (f) May 2000

The evolution of the vertical difference in temperature anomalies reflects the development of the meridional temperature gradient over the Tibetan Plateau during the month of April in the years of early and normal onset. This also suggests a higher amount of heating during pre-monsoon months on the elevated surface of the Tibetan Plateau and a consequent reversal of the meridional temperature gradient south of latitude 35 °N. This triggered the planetary-scale monsoon system over the Asian region, resulting in an early onset. The Tibetan heat source is mainly produced by sensible heating. It is noticed that latent heat release over the Indian Ocean does not cause an appreciable temperature change over the Indian Ocean because of the compensating effect of adiabatic cooling in May. It is the sensible heating over the Tibetan Plateau in the pre-monsoon months that leads to a reversal of the meridional temperature gradient. Yanai *et al*. (1992) further demonstrated the thermal influence of the Tibetan Plateau as a dominant factor driving the monsoon circulation. This also

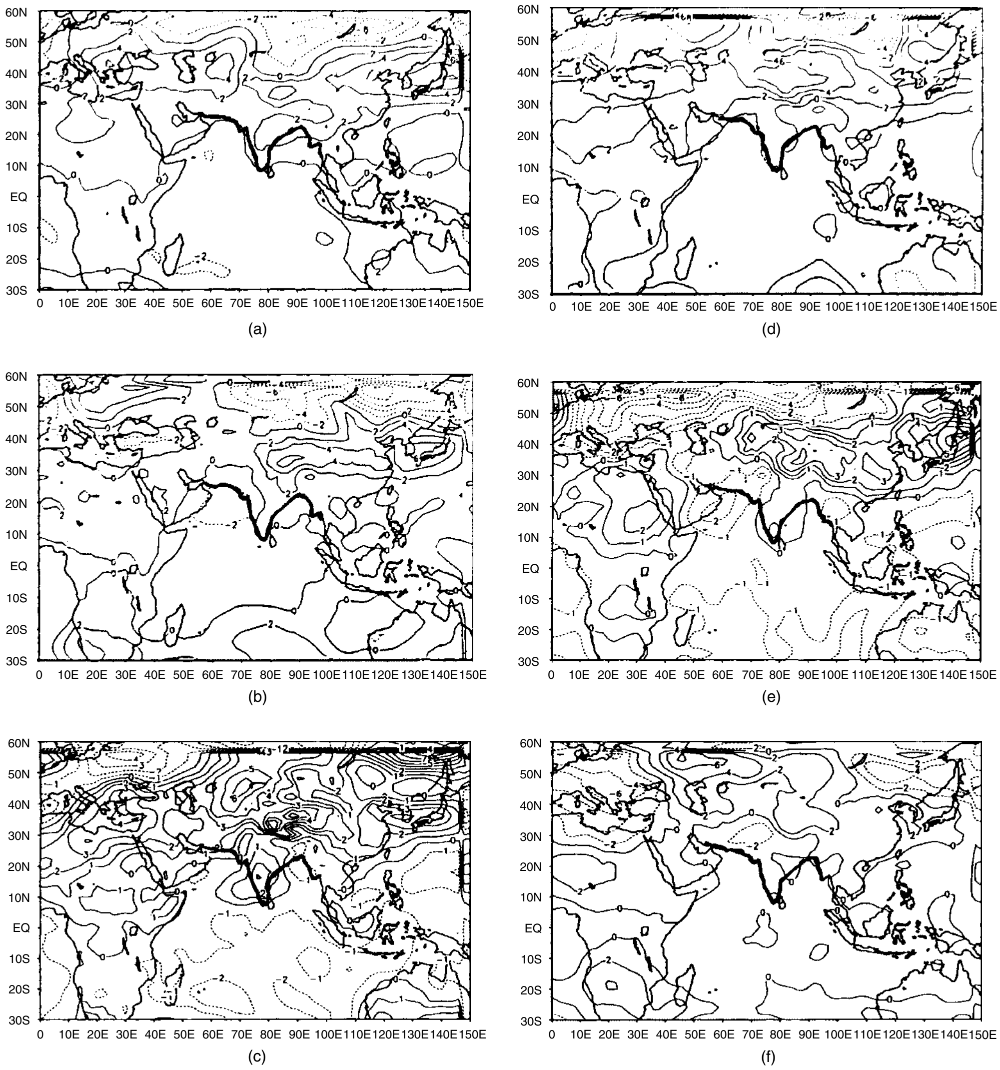

Figure 5. As Figure 4, except for anomaly fields of vertical thermal (°C) gradient $T_{500} - T_{200}$

supports the conclusion by Vernekar *et al.* (1995), that excessive Eurasian snow cover may lead to a weaker and delayed summer monsoon.

4.2. The 200 hPa geopotential height anomaly

Figure 6(a)–(f) illustrates the anomalies of geopotential height at 200 hPa for the months of April and May during 1997, 1999 and 2000. During April 1997, negative anomalies (−100 gpm) were present over the Tibetan Plateau. In contrast, during 1999 the anomalies over this area were considerably stronger (90 hPa) and centred near latitude 30 °N and longitude 80 °E. During April 2000, anomalies over the Tibetan Plateau were 30 gpm. In May 1997 the anomalies became positive (of the order of 40 gpm) and were centred near latitude 35 °N and longitude 110 °E. In 1999 the positive anomalies (of the order of 90 gpm) continued to occupy the same area with a centre near latitude 35 °N and longitude 80 °E. In 2000, the positive anomalies over the Tibetan Plateau had been 120 gpm. Thus, a prominent difference in the 200 hPa geopotential height was noticed in the pre-monsoon months. The lower geopotential height anomaly in the pre-monsoon months appears to be another factor associated with the delay of monsoon onset in 1997.

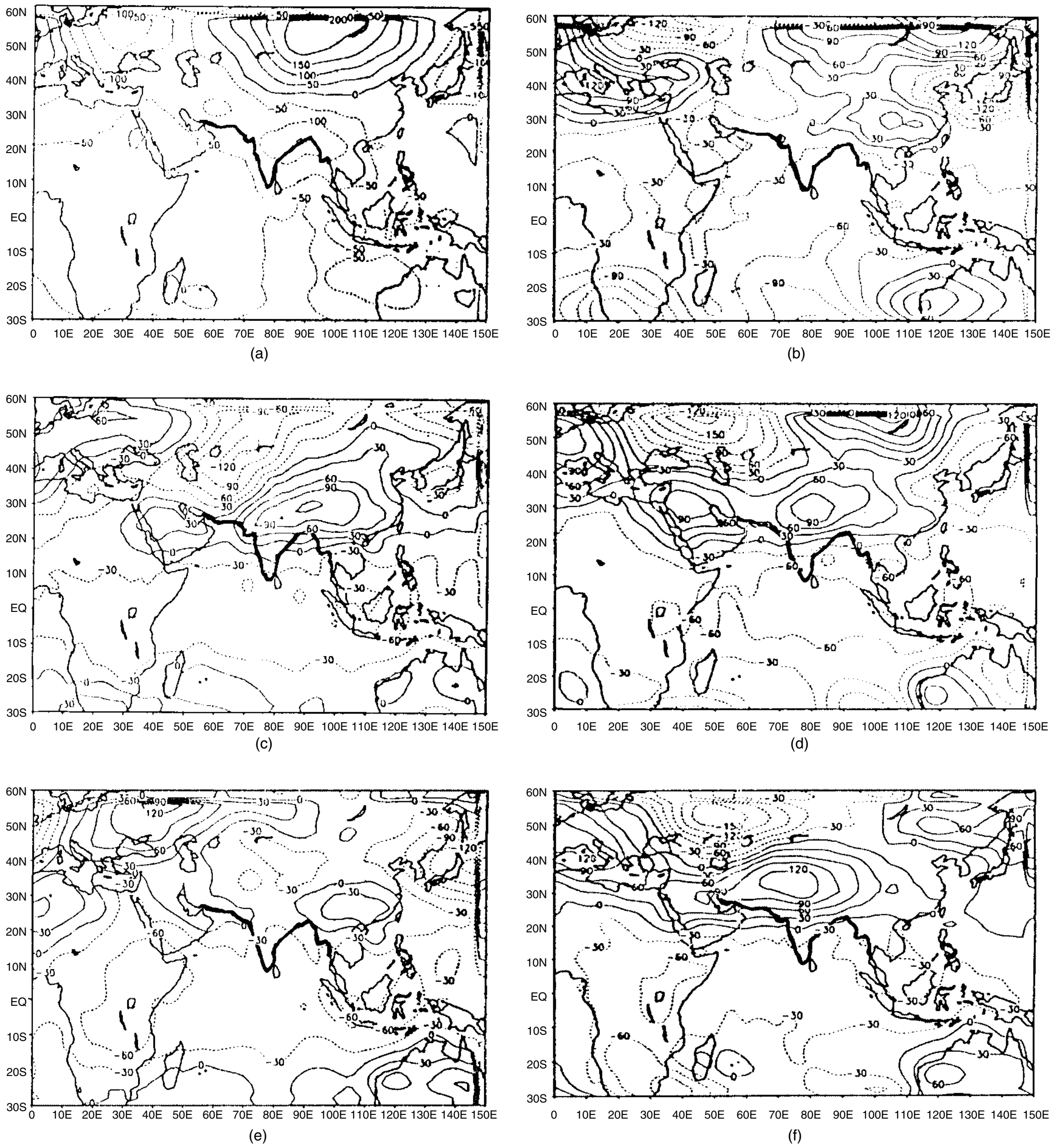

Figure 6. As Figure 4, except for the anomaly fields of geopotential height (gpm) at 200 hPa

5. WEEKLY EVOLUTION DURING ONSET 2000

Monsoon onset over Kerala in the year 2000 took place on the normal date of 1 June. In order to study the nature of the temporal and latitudinal variations of these indices and moisture field over the north Indian Ocean during and prior to monsoon onset, the weekly evolution of these indices and the precipitable water content during the 2 to 3 weeks prior to onset is considered in this section.

5.1. Circulation and thermal indices

The time evolutions of broad-scale circulation and thermal indices are shown (weekly anomalies) for the week ending 7 May 2000 (3 weeks prior to onset; Figure 7(a)), week ending 22 May 2000 (1 week prior to onset; Figure 7(b)) and week ending 7 June 2000 (during onset; Figure 7(c)). During the first week of May, the zonal index over the south Arabian Sea and adjoining north Indian Ocean was of the order of 10 m s^{-1} near the equator at 70 °E longitude. As the season progressed, a clear increase in this index was observed. By the next fortnight the intensity increased rapidly to 20 m s^{-1} and migrated northward with a maximum centred near latitude 10 °N and longitude 70 °E. It increased further to 25 m s^{-1} during the time of onset and was confined over the southeast Arabian Sea. However, the meridional index did not show an appreciable change during the onset phase. The anomalies of thermal index were positive (+3 °C) over the area near latitude 30 °N and longitude 100 °E, and increased slightly and shifted to the west (latitude 35 °N and longitude 85 °E) during the next fortnight. The geopotential height anomaly was 100 gpm near latitude 30 °N and longitude 80 °E during the first week of May, increased to 120 gpm near latitude 25 °N and longitude 75 °E, and then became 100–150 gpm along latitude 30 °N during onset.

5.2. PWC

The time evolution of the PWC for the domain extending from 30 °S to 25 °N and 60 to 100 °E was computed and examined using NOAA temperature and humidity data composited in relation to the onset over Kerala. The weekly mean PWCs for 1 week prior to onset, during onset and 1 week after onset are shown in Figure 8(a)–(c) respectively. A belt of maximum PWC 1 week prior to onset was seen over the equatorial zone over the Indian Ocean. The PWC increased from south to north and the 45 mm (maximum) isoline ran along latitude 10 °S. These features were not seen in the weekly mean map for the week ending 7 May (3 weeks prior to onset). However, a build up of the PWC gradient over the Indian Ocean between latitude 25 and 10 °S was first noticed in the weekly mean map of 2 weeks prior to onset (figure not shown). As the onset phase progressed, the belt of maximum PWC migrated northward to the southeast Arabian Sea and extended over the Bay of Bengal. The 45 mm isoline of PWC covered the area over the Bay of Bengal from the Arabian Sea. A small pocket of 50 mm PWC occupied the northeast Bay of Bengal. At 1 week after the onset the belt of maximum PWC (45 mm isoline) shifted further northward over the Bay of Bengal, with an area of 50 mm over the northern Bay of Bengal.

6. SUMMARY AND CONCLUSIONS

The onset of the Indian summer monsoon for the years of delayed (1997), early (1999) and normal onset (2000) was examined in relation to the intensity of the vertical circulation and the thermal indices during the pre-monsoon months (April and May). The evolution of the broad-scale zonal vertical index showed that during the delayed onset year (1997) the anomalies of u at 850 hPa and the vertical zonal index were negative over the Indian Ocean during the pre-monsoon months, particularly in April. In contrast, during the early onset year (1999), the positive anomalies of these indices over the north Indian Ocean were considerably stronger in April. These increased further and migrated northward over the southeast Arabian Sea and southwest Bay of Bengal in May. A similar feature was also noticed in the normal monsoon onset year (2000), except that the gradient of the anomalies was relatively weak. These features are also in good agreement with the results documented by Webster and Yang (1992); that during an El Niño year (1997) the lower (upper) tropospheric westerly (easterly) flow is weaker than normal, whereas in a La Niña year (1999) it tends to be stronger than normal. In El Niño years the strength of the vertical zonal index over the equatorial Indian Ocean is influenced by the modulation of the Walker circulation because of the implied additional subsidence over the west Pacific and southeast Asia due to a systematic eastward shifting of convection. No appreciable difference was noticed in the vertical meridional index during pre-monsoon months in these years. Roy Bhowmik (2001) noted that the revival of the monsoon during August–September in 1999 was concurrent with a prominent increase of the vertical meridional index over the north Indian Ocean between longitude 70 and 90 °E. Thus, it appears that the vertical meridional index is more dominant during the second (active) phase of the monsoon (August–September) and the zonal index dominates during the onset phase.

The gradient of the vertical thermal index anomalies over the Tibetan Plateau in the month of April was considerably stronger during the year of early onset (1999). This also suggests that a higher amount of heating

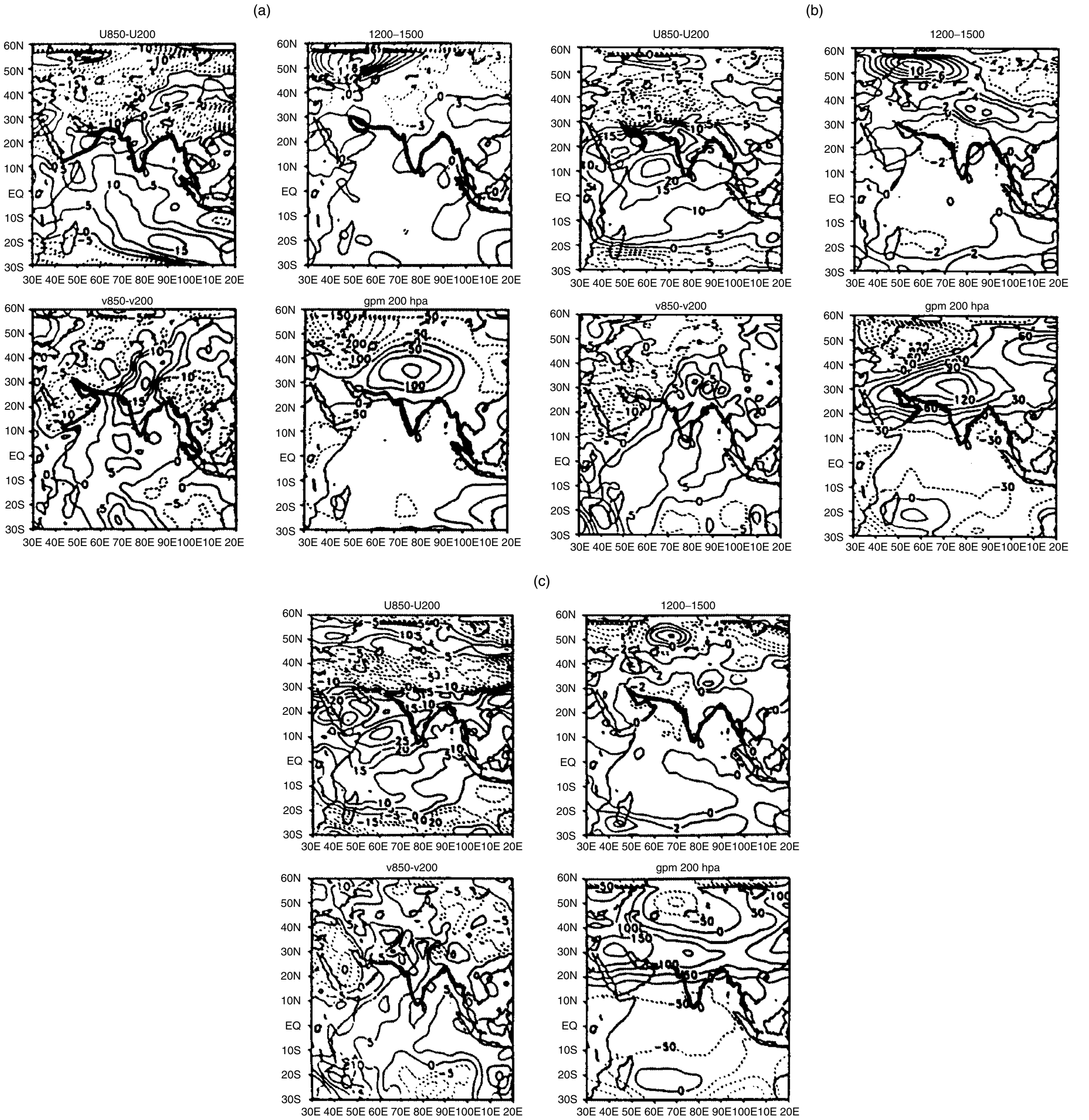

Figure 7. Weekly anomaly fields (m s^{-1}) of $u_{850} - u_{200}$, $v_{850} - v_{200}$, $T_{500} - T_{200}$ in (°C), and 200 hPa geopotential height (gpm): (a) 3 weeks prior to monsoon onset; (b) 2 weeks prior to onset; (c) during onset in 2000

during pre-monsoon months on the elevated surfaces of the Tibetan Plateau and the consequent reversal of the meridional temperature gradient south of latitude 35 °N, trigger the planetary-scale monsoon system over the Asian region. The evolution of the geopotential height anomalies at 200 hPa showed that the anomalies over the Tibetan Plateau were markedly lower in the year of delayed onset (1997). These signals were observed very distinctly in the month of April well before the onset.

The weekly evolution of these indices during the year of 2000 indicates that, like the zonal vertical index, PWC is another major feature that grows rapidly over the equatorial belt of the Indian Ocean and migrates steadily over the Arabian Sea and Bay of Bengal around 2 weeks prior to monsoon onset.

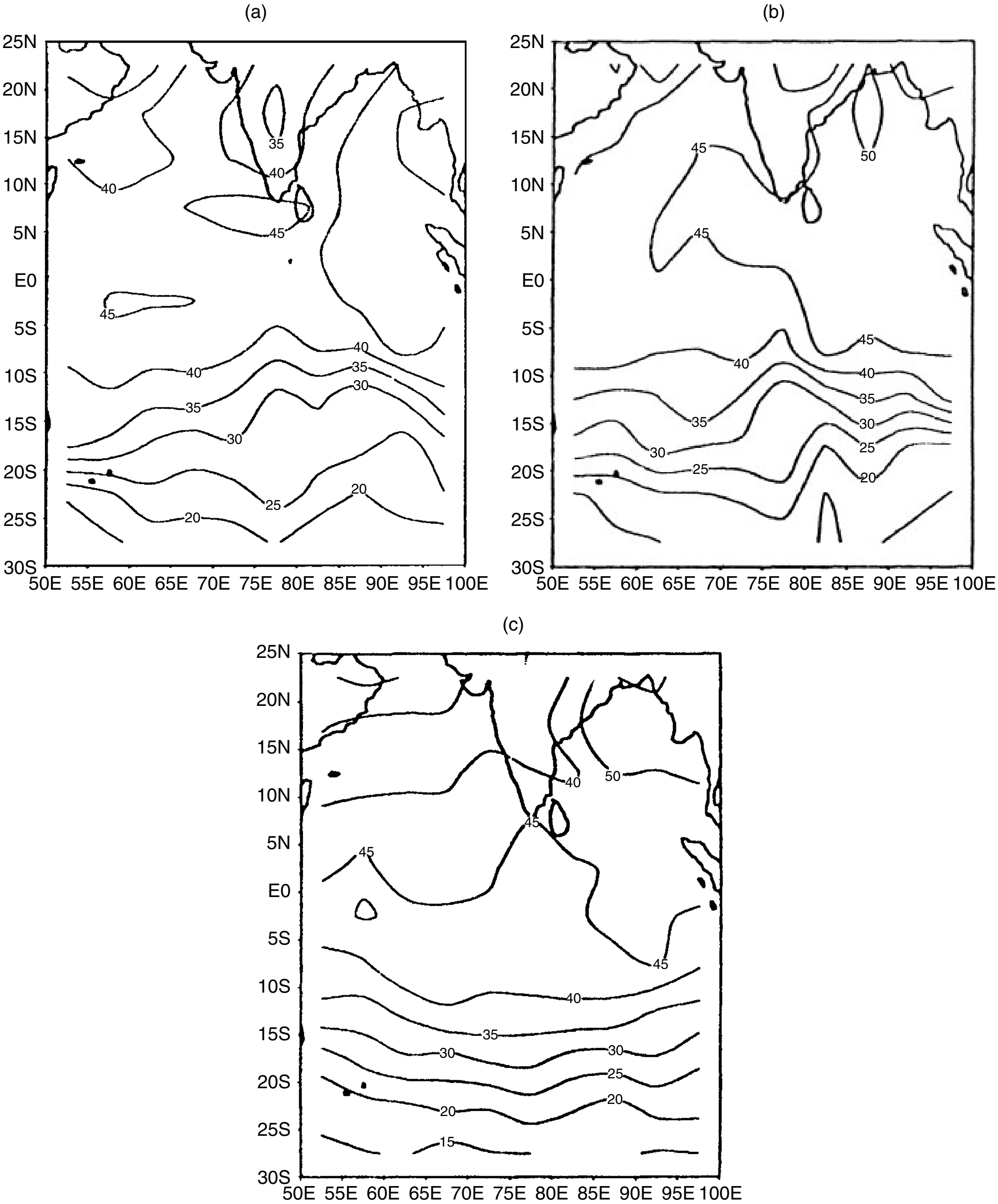

Figure 8. Weekly mean PWC (mm): (a) 1 week prior to monsoon onset; (b) during onset; (c) 1 week after onset in 2000

As the earliest historical date of the monsoon onset over Kerala was 7 May, for operational practices there is a need to derive an objective method for predicting the onset date over Kerala utilizing signals available during April. From the results presented here, it is clear that the predictive signals in the anomaly pattern of the zonal vertical index, vertical thermal index and geopotential height anomalies at 200 hPa may be very useful for assessing the onset date over Kerala. More studies in this direction are needed to decide the critical values of these parameters.

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