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THE SUMMER MONSOON ONSET PROCESS OVER SOUTH ASIA AND AN OBJECTIVE METHOD FOR THE DATE OF MONSOON ONSET OVER KERALA

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ABSTRACT

Eight pentads before the monsoon onset over Kerala (MOK), a spatially large area of deep convection formed near the equator south of the Bay of Bengal, which moved to Southeast Asia marking the onset of the South China Sea monsoon (SCSM) for many years. Three pentads before MOK, a similar area of convection formed near the equator south of the Arabian Sea. This heat source and the associated cross-equatorial low-level jet stream (LLJ) grew steadily in strength while moving north and at MOK the convective heat source passed through Kerala latitudes and the core of a well developed LLJ was located just south of Kerala.

Eight pentads before MOK a warm pool was located over central Bay of Bengal and the area of active convection formed to its south near the equator in the region of large sea surface temperature (SST) gradient. Three pentads before MOK when the Bay of Bengal SST had cooled, a warm pool formed over central Arabian Sea and an active convection area was located south of it, also in the region of large SST gradient.

A three-step method for objectively defining MOK has been developed in this paper. In step 1 of this operationally usable method, the date on which the zonal wind of 850 hPa, averaged over a box bounded by latitudes 5 °N and 10 °N and longitudes 70 °E and 85 °E, reached 6 m/s at 600 hPa is taken as the tentative date of MOK. Steps 2 and 3 checked whether the date thus chosen was a bogus monsoon onset or not and whether on that date there was widespread convection (low OLR) around Kerala, which moved north from the equatorial region.

KEY WORDS: monsoon onset over Kerala (MOK); low-level jet stream; warm pool; outgoing longwave radiation (OLR); pre-monsoon rain peak or bogus monsoon onset; objective method for date of MOK; SST gradient and convection

1. INTRODUCTION

The long-term mean date of monsoon onset over Kerala (MOK), the southern most state of India, is close to 1 June and it has a standard deviation of about 8 days (Ananthakrishnan and Soman, 1988). Joseph *et al.* (1994) has given a critical review of the literature on MOK. The India Meteorological Department (IMD) has determined the date of MOK operationally every year, for more than 100 years. These are subjective estimates based primarily on the daily rainfall reports from raingauge stations of the synoptic network. At MOK, rainfall is found to be widespread spatially over Kerala and persistent for a few days. Accompanying such rainfall, the lower tropospheric westerly wind (the monsoon current) over Kerala is strong and deep and the relative humidity of the air is high from the surface to at least 500 hPa (Rao, 1976). IMD has been taking all these factors into consideration in a subjective way to determine the date of MOK. In this study, we have used the dates of MOK as determined by IMD to understand the monsoon onset process. The IMD'S method of arriving at the date of MOK is considered subjective, as no quantitative thresholds are set for the

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factors used to determine the onset. The factors used are described qualitatively. During the last 100 years, the extreme dates of MOK as derived by IMD are 11 May in 1918 and 18 June in 1972. In this paper, we have also derived an objective method for operationally determining the date of MOK.

Joseph *et al*. (1994) studied the temporal and spatial evolution of the tropical deep convection associated with MOK using composite pentad (5 days) mean maps of outgoing long wave radiation (OLR) data of 10 years, in each of which the date of MOK is very close to 1 June. At MOK, there is a band of deep convection (low OLR) in the east–west direction passing through Kerala, a maximum cloud zone (MCZ) as studied by Sikka and Gadgil (1980). They found that this cloud band passing through Kerala had genesis over the Indian Ocean, three to four pentads before MOK and during the following pentads steadily increased in area and intensity (lower OLR). The axis of lowest OLR moved northwards bringing monsoon rains to Kerala. Prior to MOK, the warmest area of the warm pool of the tropical oceans is centred over southeast Arabian Sea (Joseph, 1990), but the monsoon cloud band that formed three to four pentads before MOK is in an area near the equator with a large meridional gradient in sea surface temperature (SST), about 10° latitude south of the centre of the southeast Arabian sea warm pool (Joseph *et al*., 2003).

Joseph *et al*. (1994) (in their Figure 1) have shown the slow evolution of deep convection over the tropical Indian and west Pacific oceans, with respect to MOK, pentad by pentad, from about 40 days (8 pentads) before MOK, in their 10-year composite. They had found that prior to MOK, at pentad −8 a cloud band formed in the equatorial regions of the Bay of Bengal and this band moved northeastwards to Southeast Asia and the China Sea. After this, the convective region weakened slightly at pentad −4, and the convective cloud band associated with MOK formed in the equatorial area south of the Arabian Sea. It is of interest to study the slow evolution of the atmosphere and also of the tropical Indian and west Pacific Oceans over a much longer period prior to MOK than in the study of Joseph *et al*. (1994). Also, a different method of compositing is adopted in this paper.

Hsu *et al*. (1999) describe the onset of South China Sea monsoon (SCSM) as the first transition of Asian summer monsoon (ASM) causing major changes in both convection and winds. The Indian monsoon onset follows the first transition. Wang and Lin (2002) consider the onset of monsoon over Asia as having two phases, one with a rainfall surge over South China Sea and the other with increased rainfall over India. Wang *et al*. (2004) have derived dates of onset of SCSM for the period 1948 to 2000 using an objective method.

In this paper, we have analysed the OLR as a measure for deep convection. We have also used winds at levels 1000 to 300 hPa and SST data over a 70-day period prior to MOK to understand the slow evolution of the atmosphere and also of the tropical Indian and west Pacific Oceans that lead to MOK (the onset process). This period includes the movement of the MCZ (also called the *inter tropical convergence zone* - (ITCZ)) across the equator from south of the equator to its north, establishment of monsoon over South China Sea and the onset of monsoon over Kerala.

2. DATA AND METHODOLOGY

The data used here are: (1) Daily wind data (U and V components in m/s) of 1000, 925, 850, 700, 600, 500, 400 and 300 hPa and integrated water vapour (IWV) from 1000 to 300 hPa (NCEP/NCAR reanalysis data sets, Kalnay *et al*., 1996) for the period 1971–2003, both of which are on a 2.5° latitude–longitude grid (2) Daily observed OLR (NOAA) data (for the period 1975–2003, except 1978) as given along with NCEP/NCAR reanalysis data sets. These data are in W/m^2 and each value represents the average OLR flux for a $2.5 \times 2.5°$ box (Gruber and Krueger, 1984). (3) TRMM Microwave Imager (TMI) SST data, for the period 1998–2003. Clouds and aerosols do not affect the TMI (Wentz *et al*., 2000) owing to its microwave retrieval, thus making it possible to produce a very reliable SST. Three-day composites of SST are used here which are on a 0.25° latitude–longitude grid. (4) Daily highly reflective clouds (HRC) data by Garcia (1985) with a spatial resolution of $1 \times 1°$ and which extends from 25 °N–25 °S and from 0 to 359 °E. This data is used to identify regions with deep convective clouds and heating in place of OLR, which is unavailable during the year 1978 and for the period 1971–1974.

The dates of MOK used for the composites are as derived by IMD. We have also used those derived by Ananthakrishnan and Soman (1988), who used daily rainfall data of South Kerala only but by an objective

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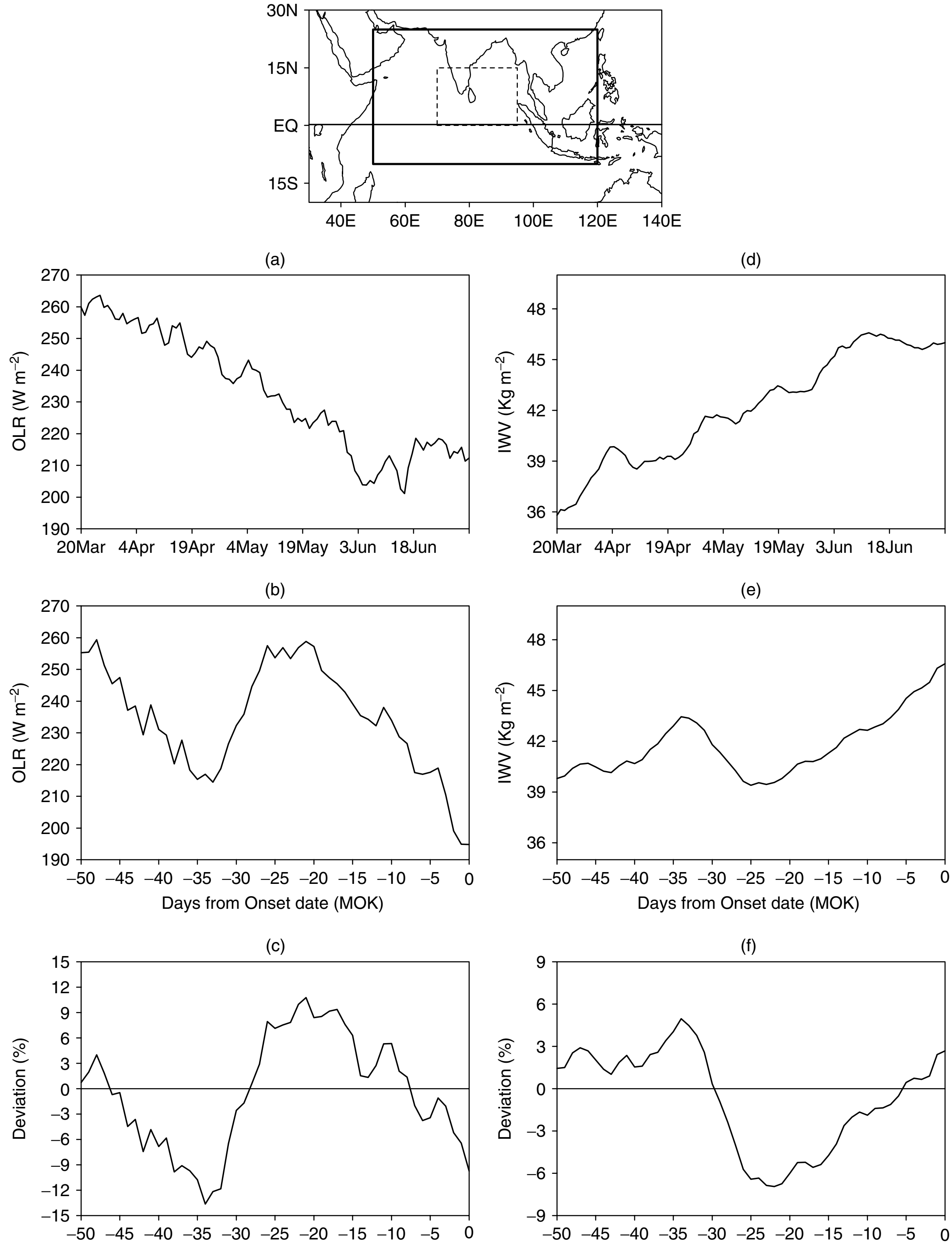

Figure 1. Twenty-year average by calendar date of (a) OLR (in W/m^2) and (d) IWV (in kg/m^2) for 1979–1998 of the inner box (70–95 °E, Eq-15 °N), marked in the inset figure by the dotted lines. Composite mean (b) OLR and (e) IWV of the inner box for the 9 years; 1979, 1982, 1984, 1986, 1987, 1990, 1993, 1995 and 1996 with respect to MOK as 0. Composite percentage departure of (c) OLR and (f) IWV for the above 9 years from the average for 20 years (1979–1998). The outer box marked by thick line is bounded by 50°–120 °E and 10 °S–25 °N

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method. For comparison, we used the dates of monsoon onset over India as derived by Fasullo and Webster (2003), hereafter called FW. For the SCSM onset, we used the dates as derived objectively by Wang *et al.* (2004) using only wind data. The methodology for deriving each of these onset dates is given by the respective authors in their papers and all these dates of monsoon onset are given in Table I.

We examined the daily IWV and OLR averaged over a box shown in Figure 1(top) bounded by latitudes, equator and 15 °N and longitudes, 70 °E and 95 °E (let us call it the inner box) for a 3-month period before MOK for each year of the 20-year period 1979–1998. It is found that in this box IWV is very high and OLR very low on the day of MOK and also several pentads earlier for each year. The periods between the maxima in IWV or minima in OLR varied between 18 and 54 days (except for 1988 and 1989 which had much shorter periods) for this sample of 20 years. Out of these, there were 9 years during which the interval between these two convective episodes was in the range 30–40 days with a mean of 35 days or 7 pentads. These years are 1979, 1982, 1984, 1986, 1987, 1990, 1993, 1995 and 1996. In these 9 years MOK varied between 19 May in 1990 and 13 June in 1979, with a mean of 1 June. From the 10-year composites of Joseph *et al.* (1994) it is seen that in this box convection is maximum at MOK and also about 7 pentads before MOK. We thus find that MOK is associated with an intra-seasonal oscillation (ISO) of period in the range 18–54 days. It may be noted that in the OLR composite of Joseph *et al.* (1994), in the entire 10 years monsoon onset was close to the normal date of MOK. In this study, we have kept the period of ISO (as defined in this paper) nearly constant (i.e. around 35 days). The composites of the mean daily IWV and OLR of the inner box for these 9 years and their departures from the 20-year mean (anomaly) are given in Figure 1 for the period from MOK to 50 days earlier. The calendar day variation of IWV and OLR as averages of the 20 years (1979–1998) for the period from 20 March to 30 June is also given in the same figure from which it is seen that IWV (OLR) of the 20-year average increases (decreases) steadily from March to June. But in the 9-year composite with 0-day as MOK, there are two peaks one at MOK and the other about 35 days (an ISO cycle) earlier.

3. NINE-YEAR COMPOSITE OF OLR AND 850-hPa WIND

We made composites of OLR and 850 hPa wind with the data of 9 years with ISO period close to 35 days for each pentad from MOK (0-pentad) to minus 14 pentad (P − 14), i.e. two ISO cycles before MOK. At (P − 14) (70 days before MOK), we see a strong band of ITCZ convection (low OLR) extending from the Indian Ocean to the western Pacific and south of the equator (Figure 2(a)). By (P − 12) (Figure 2(b)) the ITCZ band moved close to the equator. By P − 10 (Figure 2(c)), this area of convection between longitudes 90 °E and 130 °E has moved north and part of it lies north of the equator. At (P − 8) (Figure 2(d)) a new area of convection has formed near the equator south of the Bay of Bengal between longitudes 70 °E and 110 °E. A strong band of 850 hPa westerlies (Figure 3(a)) is now seen around the equator over this equatorial heat source and to its west covering the whole of the equatorial Indian Ocean. This is as per the Gill (1980) model of wind response to an equatorial convective heat source. Figure 3(a) also shows a pair of cyclonic circulations one to the north of these westerlies and the other to its south, which again is as per the Gill's model. The composite given by Joseph *et al.* (1994) also describes the formation of two cyclonic regions, one on either side of the equator between (P − 8) and (P − 6). At (P − 7) (Figures 2(e) and 3(b)) Kerala experiences rain and wind as at MOK. Rain is particularly heavy in delayed MOK years. This feature was called *pre-monsoon rain peak* (PMRP), a feature occurring every year, by Joseph and Pillai (1988) and Joseph *et al.* (1994), and *bogus monsoon onset*, occurring only in a few years, by Flatau *et al.* (2001).

The large convective area near the equator at (P − 8) moves north and later northeast. By (P − 5) (Figure 2(g)) convection has reached Southeast Asia and South China Sea along with a strong band of low-level monsoon westerlies over these areas (Figure 3(c)). These westerlies replace the easterlies associated with the Western Pacific Subtropical High, seen in earlier pentads. We may consider this phase (P − 5) as the onset of SCSM as studied by several authors – Lau and Yang (1997), Wang and Wu (1997), Lau *et al.* (1998), Hsu *et al.* (1999), Wang and Lin (2002) and Wang *et al.* (2004). With the onset of SCSM the Western Pacific Subtropical High moved eastwards well into the Pacific Ocean, as was shown earlier by Hsu *et al.* (1999).

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Table I. Objectively derived date of onset over Kerala (OBJ–MOK), onset dates as derived by IMD, onset dates over South Kerala as derived by Ananthakrishnan and Soman (1988) and Soman and Krishna Kumar (1993) (denoted by AS (SK)), the dates of monsoon onset over India as derived by FW and SCSM onset dates as determined by Wang *et al*. (2004) are given in columns 3 to 7. Column-2 gives the first stage of deriving OBJ–MOK. Column-3 gives the final OBJ–MOK after applying steps 2 and 3. M and J stand for May and June respectively

Year	Depth and strength of westerlies	OBJ MOK	Date of monsoon onset				FW minus IMD	AS minus IMD	IMD minus SCSM	OBJ MOK minus IMD
			IMD	AS (SK)	FW	SCSM				
1948	–	–	11J	10J	5J	8M	−6	−1	34	–
1949	–	–	23M	13M	1J	28M	9	−10	−5	–
1950	–	–	27M	27M	10J	8M	14	0	19	–
1951	–	–	31M	30M	3J	3M	3	−1	28	–
1952	–	–	20M	20M	6J	13M	17	0	7	–
1953	–	–	7J	6J	12J	8M	5	−1	30	–
1954	–	–	31M	28M	2J	2J	2	−3	−2	–
1955	–	–	29M	17M	6J	23M	8	−12	6	–
1956	–	–	21M	18M	24M	2J	3	−3	−12	–
1957	–	–	1J	18M	3J	7J	2	−14	−6	–
1958	–	–	14J	12J	13J	23M	−1	−2	22	–
1959	–	–	31M	12M	23M	28M	−8	−19	3	–
1960	–	–	14M	14M	20M	28M	6	0	−14	–
1961	–	–	18M	18M	25M	13M	7	0	5	–
1962	–	–	17M	10M	24M	18M	7	−7	−1	–
1963	–	–	31M	5J	1J	28M	1	5	3	–
1964	–	–	6J	5J	12J	18M	6	−1	19	–
1965	–	–	26M	24M	12J	23M	17	−2	3	–
1966	–	–	31M	31M	15J	3M	15	0	28	–
1967	–	–	9J	8J	12J	23M	3	−1	17	–
1968	–	–	8J	7J	11J	17J	3	−1	−9	–
1969	–	–	17M	25M	12J	23M	26	8	−6	–
1970	–	–	26M	25M	30M	7J	4	−1	−12	–
1971	27M	27M	27M	25M	27M	3M	0	−2	24	0
1972	19J	19J	18J	22J	16J	8M	−2	4	41	1
1973	7J, 24J	7J	4J	3J	5J	12J	1	−1	−8	3
1974	23M, 10J	23M	26M	23M	18J	23M	23	−3	3	−3
1975	2J, 11J	2J	31M	1J	7J	2J	7	1	−2	2
1976	27M, 24J	27M	31M	30M	30M	8M	−1	−1	23	−4
1977	15M, 10J	10J	30M	27M	8J	18M	9	−3	12	11
1978	14M, 6J	6J	28M	27M	4J	23M	7	−1	5	9
1979	11M, 13J	13J	13J	11J	13J	13M	0	−2	31	0
1980	4J	4J	1J	31M	1J	13M	0	−1	19	3
1981	21M, 31M	31M	30M	29M	9J	2J	10	−1	−3	1
1982	27M	27M	1J	1J	6J	2J	5	0	−1	−5
1983	6J, 14J, 17J	14J	13J	12J	14J	2J	1	−1	11	1
1984	30M, 17J	30M	31M	1J	31M	23M	0	1	8	−1
1985	23M, 11J	23M	28M	24M	27M	28M	−1	−4	0	−5
1986	7J, 13J	7J	4J	13J	9J	13M	5	9	22	3
1987	1J	1J	2J	1J	2J	7J	0	−1	−5	−1
1988	4J, 16J	4J	26M	2J	7J	23M	12	7	3	9
1989	25M, 4J, 11J, 18J	4J	3J	1J	3J	18M	0	−2	16	1
1990	16M, 25M, 9J	16M	19M	17M	19M	18M	0	−2	1	−3

(*continued overleaf*)

Table I. (*Continued*)

Year	Depth and strength of westerlies	OBJ MOK	Date of monsoon onset				FW minus IMD	AS minus IMD	IMD minus SCSM	OBJ MOK minus IMD
			IMD	AS (SK)	FW	SCSM				
1991	2J, 16J	2J	2J	–	5J	7J	3	–	−5	0
1992	15M, 31M, 6J	6J	5J	–	12J	18M	7	–	18	1
1993	4J, 13J, 22J	4J	28M	–	5J	7J	8	–	−10	7
1994	28M	28M	28M	–	3J	3M	6	–	25	0
1995	6J, 8J	6J	5J	–	11J	13M	6	–	23	1
1996	29M, 11J	11J	3J	–	5J	8M	2	–	26	8
1997	21J	21J	9J	–	20J	18M	11	–	22	12
1998	16M, 3J, 8J, 20J	3J	2J	–	9J	23M	7	–	10	1
1999	22M, 2J	22M	25M	–	12J	28M	18	–	−3	−3
2000	17M, 1J, 11J	1J	1J	–	29M	8M	−3	–	24	0
2001	25M, 5J, 20J	25M	23M	–	–	–	–	–	–	2
2002	16M, 1J, 12J	12J	29M	–	–	–	–	–	–	14
2003	16J	16J	8J	–	–	–	–	–	–	8
Mean	–	3J[a]	30M[b]	28M[c]	5J[d]	21M[d]	5[d]	−1.6[d]	9.2[d]	2.2[a]
SD	–	8.4[a]	7.4[b]	9.7[c]	7.4[d]	11.4[d]	–	–	–	–

[a] 1971–2003.
[b] 1948–2003.
[c] 1948–1990.
[d] 1948–2000.

At P − 3 (Figure 2(i)) a fresh area of convection forms close to the equator in the western Indian Ocean between longitudes 50 °E and 75 °E (south of the Arabian Sea). During the following pentads this convection grows in area and intensity till MOK at pentad P0 (Figure 2(l)). The axis of maximum convection in these longitudes, which is close to the equator at P − 3, moves north and reaches latitude of about 8 °N by P0. During the period P − 3 to P0 a cross-equatorial low-level jet stream (LLJ), as described by Findlater (1969a,b) and Joseph and Raman (1966) crossing the equator near the coast of east Africa and moving over north Indian Ocean, forms and intensifies (Figure 3(d) to (f)). At MOK the axis of LLJ is a few degrees of latitude south of the axis of maximum convection in the north Indian Ocean.

At P − 7 (Figures 2(e) and 3(b)) also, the large area of convection near the equator south of the Bay of Bengal is associated with a strong band of westerly winds at 850 hPa. During this pentad, the trade winds of the south Indian Ocean do not turn into westerlies crossing the equator near the east African coast as in the LLJ described by Findlater (1969a,b). The turning of the trades into westerlies north of the equator at P − 7 occurs further east at longitudes 60–75 °E.

At MOK, rain is widespread and heavy over Kerala and a large area around, as seen in the OLR composite, and the associated westerlies are strong at 850 hPa. Examination of winds at levels up to 500 hPa has shown that the LLJ has deep westerlies also. Figure 4 shows the vertical structure of zonal wind (u) in the box 70–85 °E and 5–10 °N at pentads P − 2, P − 1, P0 and P + 1 of the 9 year composite. At P − 2, the composite monsoon current (westerlies) has a maximum strength of 6 m/s and a depth up to 700 hPa only with the level of maximum wind at 925 hPa. Between P − 1 and P0 the depth of westerlies (monsoon current) has deepened to 400 hPa and the maximum wind has become 10 m/s with the level of maximum wind near 850 hPa. The depth of westerlies has not further increased from P0 to P + 1. It may be noted that the major change in the strength and depth of zonal westerlies has occurred between pentads P − 1 and P0.

At MOK the intense convection extends from the south Arabian Sea to Southeast Asia through the Bay of Bengal. In declaring MOK IMD takes care, although in a subjective way, of the three factors, of rainfall and the strength and depth of the westerly winds (Rao, 1976). Thus MOK, as determined by IMD, is not just the increase in rain in a miniscule part of the erstwhile colonial British empire (Kerala), as described in FW,

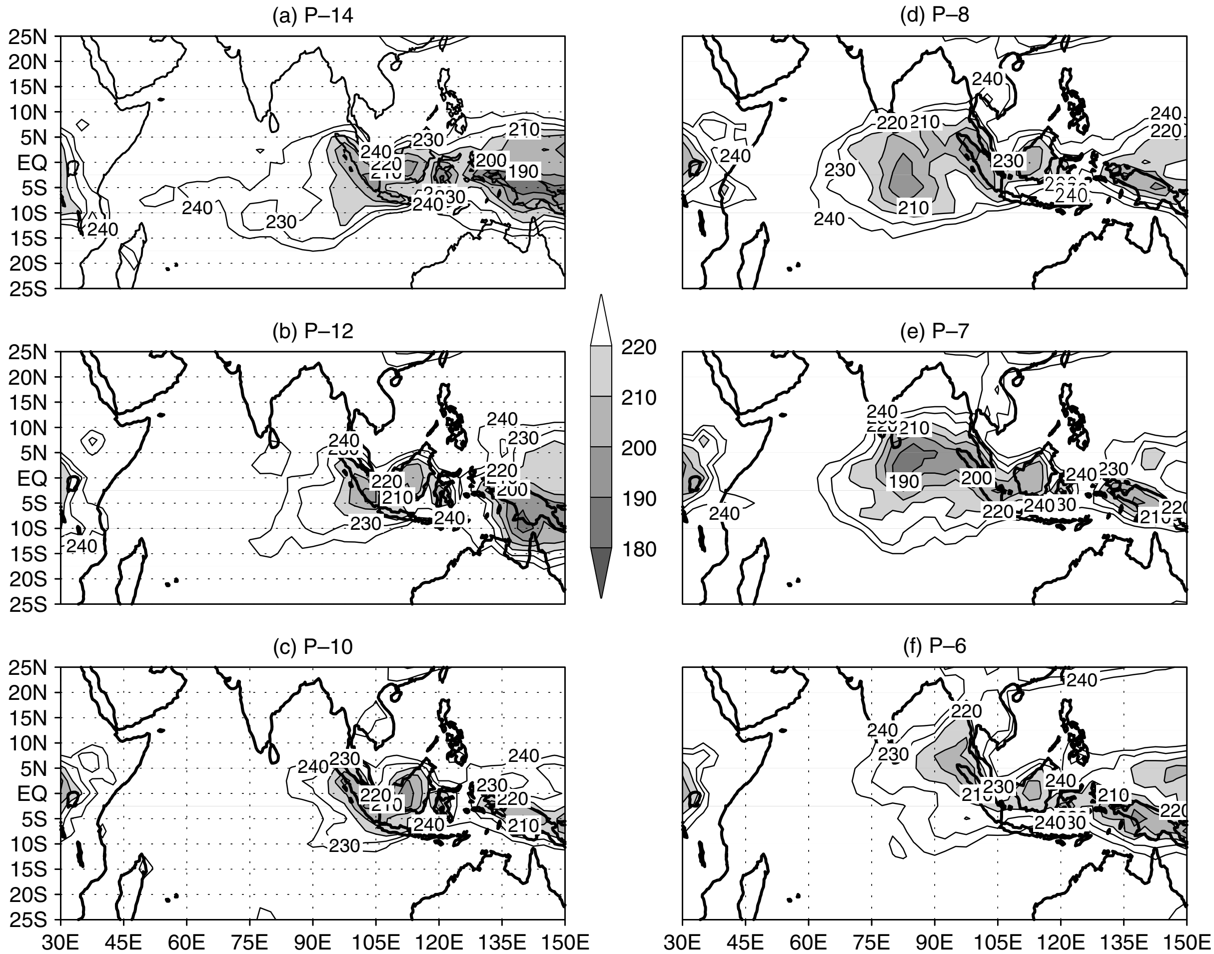

Figure 2. (a–l) Pentad mean OLR in W/m^2 for pentads (P − 14, P − 12, P − 10, P − 8, P − 7, P − 6, P − 5, P − 4, P − 3, P − 2, P − 1 and P0) as a composite of 9 years; 1979, 1982, 1984, 1986, 1987, 1990, 1993, 1995 and 1996. Only contours of 240 W/m^2 and less at intervals of 10 W/m^2 are shown. Contours below 220 W/m^2 are shaded up to 180 W/m^2. MOK is at the middle of 0-Pentad. Pentad number is marked on top of each figure

but it is a large-scale signal associated with a planetary scale feature, the LLJ. Ananthakrishnan and Soman (1988) used only the daily mean rainfall of Kerala for defining monsoon onset.

In the wind composite at P0 (Figure 3(f)) we do not see an onset vortex in the Southeast Arabian Sea but only large shear vorticity north of the LLJ axis. Following the description of an onset vortex in association with the monsoon of the FGGE MONEX year 1979 by Krishnamurti *et al*. (1981), several authors have of late been looking for an onset vortex to trigger a monsoon onset – e.g. Rao and Sivakumar (1999) and Shenoi *et al*. (1999). However, in the 850 hPa wind composite of P − 7, a cyclonic vortex is seen in the Bay of Bengal.

Examination of individual years of the 9-year composite shows that the changes, as described in the composite, are seen broadly in all the individual years of the composite except that in a few years the onset of SCSM did not occur at P − 5. Wang *et al*. (2004) has given the date of SCSM onset for the period 1948–2000 (Table I). The difference between the dates of MOK and the onset of SCSM for these 53 years are also given in the table. The SCSM onset in the mean has occurred about 10 days prior to MOK. The difference between these onsets (IMD minus SCSM) has varied between −14 days and +41 days. From Figure 5(a) and (b) (IMD minus SCSM onsets), it is seen that in many cases the difference is largely negative or positive (−10

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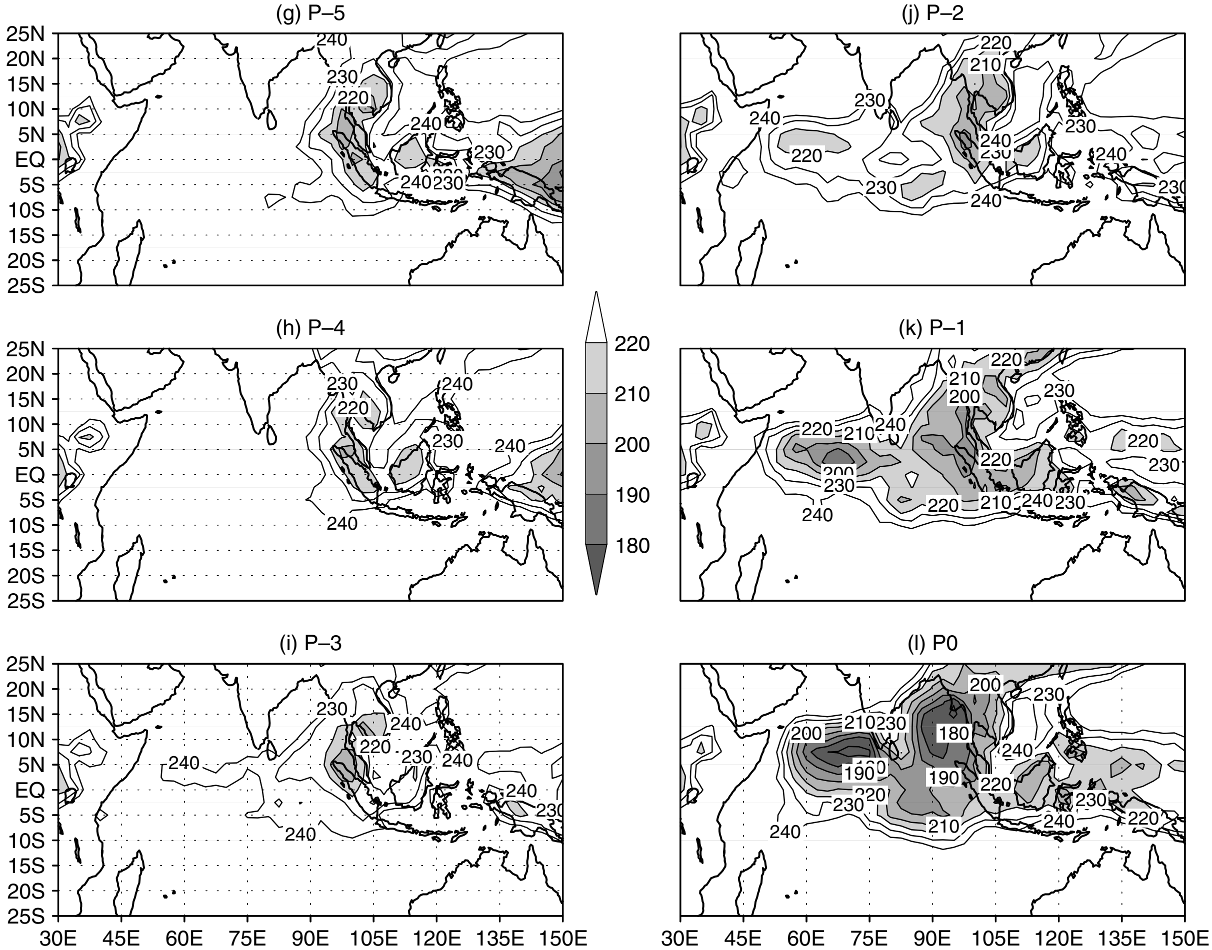

Figure 2. (*Continued*)

to −15 and +20 to +30 days). It is thus not surprising that the correlation between IMD and SCSM onset dates for the period 1948–2000 is low (−0.06). Therefore it is difficult to accept the description of ASM onset as occurring in two stages, the first transition and the second transition related to monsoon onsets over the South China Sea and later over India (Tao and Chen, 1987; Lau and Yang, 1997; Lau *et al*., 1998; Hsu *et al*., 1999). We may, however, say that the onset process has two stages: first and second in terms of the convection in the Bay of Bengal and eastwards (P − 8 to P − 5) and the convection over the Arabian Sea and eastwards (P − 3 to P0).

Composite Hovmuller diagrams of OLR and 850 hPa wind averaged between longitudes 70 °E and 85 °E is shown in Figure 6(a) and (b). Convection (OLR) is large near the equator about 10 days prior to MOK. Convection slowly intensified and the axis of maximum convection (lowest OLR) slowly moved north from 10 days prior to MOK to the MOK. At MOK there is a strong convection covering Kerala latitudes. After MOK, convection moved fast northwards without further intensification. The axis of maximum 850 hPa U-wind followed the movement northwards of convection with its axis a few degrees latitude south of the axis of maximum convection. Convection is induced and maintained by the cyclonic vorticity in the atmospheric boundary layer north of axis of maximum U-wind. Thus it is seen that MOK is a distinct phase in the northward movement of convection and LLJ, both of which are very strong at MOK. Both in the wind and convection there is a temporary weakening soon after MOK. It is also seen that soon after MOK there is a rapid northward movement of both convection and LLJ.

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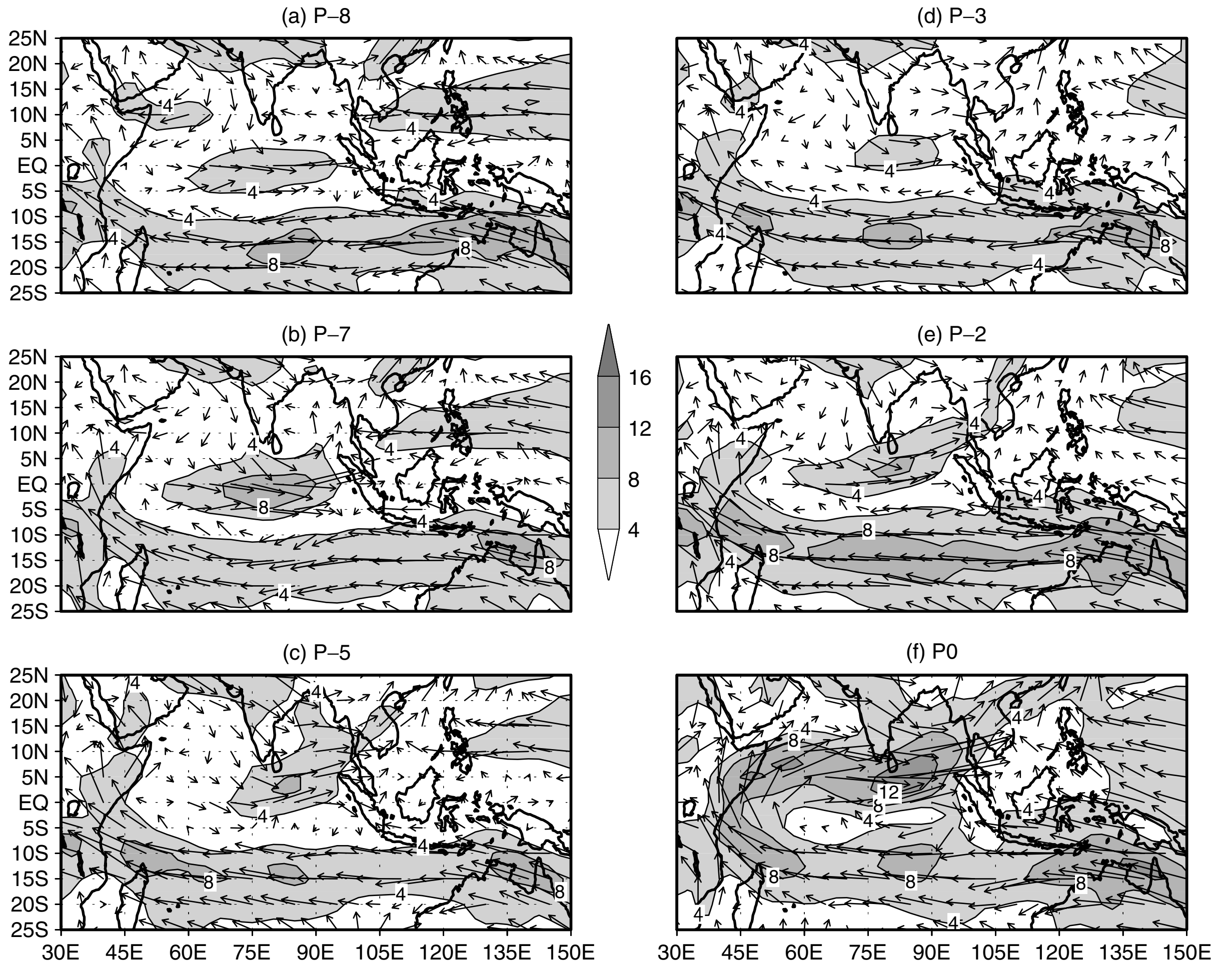

Figure 3. (a–f) Pentad mean 850 hPa wind in m/s for pentads (P − 8, P − 7, P − 5, P − 3, P − 2 and P0) as a composite of 9 years; 1979, 1982, 1984, 1986, 1987, 1990, 1993, 1995 and 1996. Only contours of 4 m/s and above, at intervals of 4 m/s are shown with shading. MOK is at the middle of 0-Pentad. Pentad number is marked on top of each figure

A similar study was done for the period 1998–2003 having TRMM data of SST. In 1998 the period of ISO was very short, nearly 20 days as may be seen from the OLR variation of the inner box (please see Figure 7). The OLR of this box is low at MOK and also about 20 days earlier. That year was studied separately in Section 6. The mean ISO period 1999–2003 was close to 40 days and a composite study was made for these 5 years in 850 hPa wind and OLR. Results are similar to that of the 9-year composite.

4. MONSOON ONSET BY FASULLO AND WEBSTER

MOK as given in the 9-year composite described in Section 3 occurs when a fully developed cross-equatorial LLJ has reached almost the southern tip of India, when the cyclonic vorticity to the north of the LLJ axis generated widespread and persistent rainfall over Kerala and to its east and west. Thus, MOK as defined by IMD is a planetary scale phenomenon. Mean difference between the FW onset date for Indian Summer Monsoon and the IMD onset date for Kerala is 3 days for the 9 years of the composite described in Section 3. The difference (date of FW onset minus IMD onset) varied between 0 and +8 days for these 9 years. The composites of OLR and 850 hPa wind for the FW onset pentad for these 9 years (figures not given) is very similar to the composite

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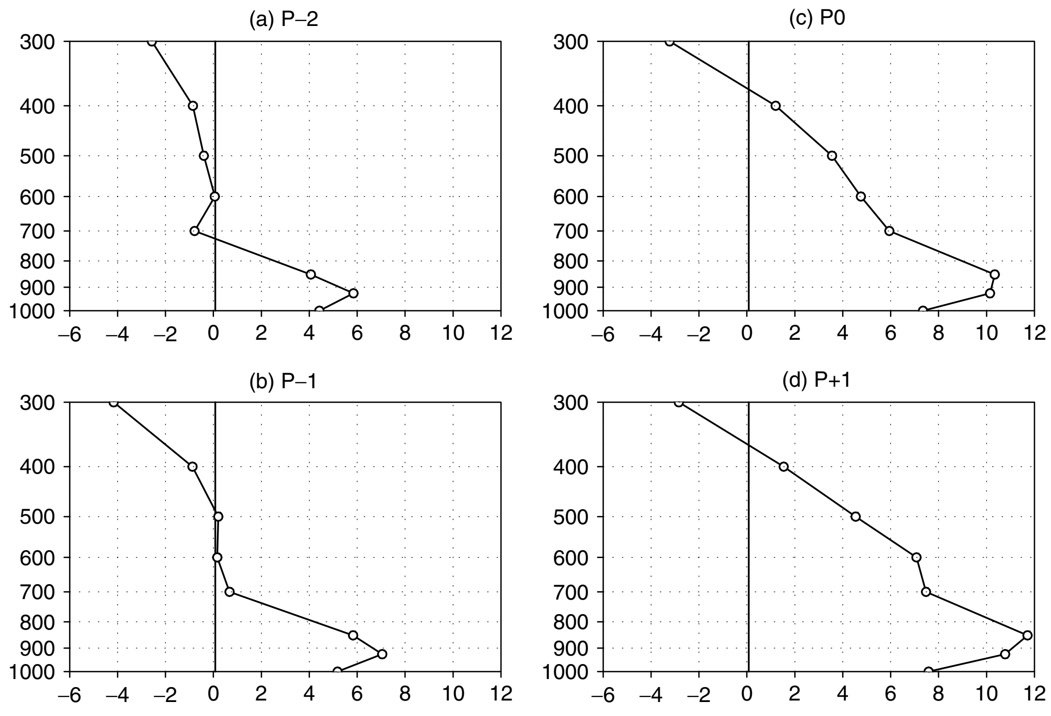

Figure 4. Nine-year composite vertical structure of U-wind in the box 70–85 °E and 5°–10 °N for (a) P − 2, (b) P − 1, (c) P0 and (d) P + 1

of P0 for the 9-year composite using IMD onset dates. At FW onset, there is incursion of monsoon winds to peninsular India carrying large quantities of moisture across it. The structures important in FW onset are the same LLJ and the band of convection. As there is a difference of 3 days between the 9-year composites of IMD onset and FW onset, moisture transport through peninsular India is likely to be slightly stronger at FW onset.

IMD onset dates and the FW onset dates (as given in Table I) for the full period 1948–2000 are compared in Figure 8. FW onset occurs in most of the years after IMD onset over Kerala (Figure 8(b)). It is seen from Figure 8(a) that the maximum frequency of occurrence of FW onset is in the range 0–6 days after MOK. There are many years in which FW onset occurs 7–20 days after MOK (IMD). The correlation coefficient between the two onset dates (IMD and FW) for the period 1948–2000 is 0.59. It may be emphasized here that MOK (IMD) is characterized by the first day of a fully developed cross-equatorial LLJ that continues to prevail over south Asia during the ASM lasting till September with its active–break cycles as described in Joseph and Sijikumar (2004).

5. MONSOON ONSET OF 2002

The onset process of the 2002 monsoon followed the time evolution as in the 9-year composite discussed in Section 3 both in convection (OLR) and 850 hPa wind (figures not shown). There was a large area of convection in the Bay of Bengal in early May (PMRP or Bogus Onset) as discussed in Flatau *et al.* (2003). By following the pentad-to-pentad evolution of OLR and 850hPa wind up to mid-May of that year, the monsoon onset was forecast by the first author (Joseph) to be delayed by about 2 weeks assuming an ISO period of 35 days. Flatau *et al.* (2003) in their study of the monsoon onset of 2002 has pointed out that the onset dates as derived by them agreed well with the onset predicted by Joseph. IMD declared monsoon onset on 29 May in 2002. The IMD onset was associated with feeble convection in a small area over the Southeast Arabian Sea. This feeble convective area was possibly generated by pre-monsoon thunderstorm

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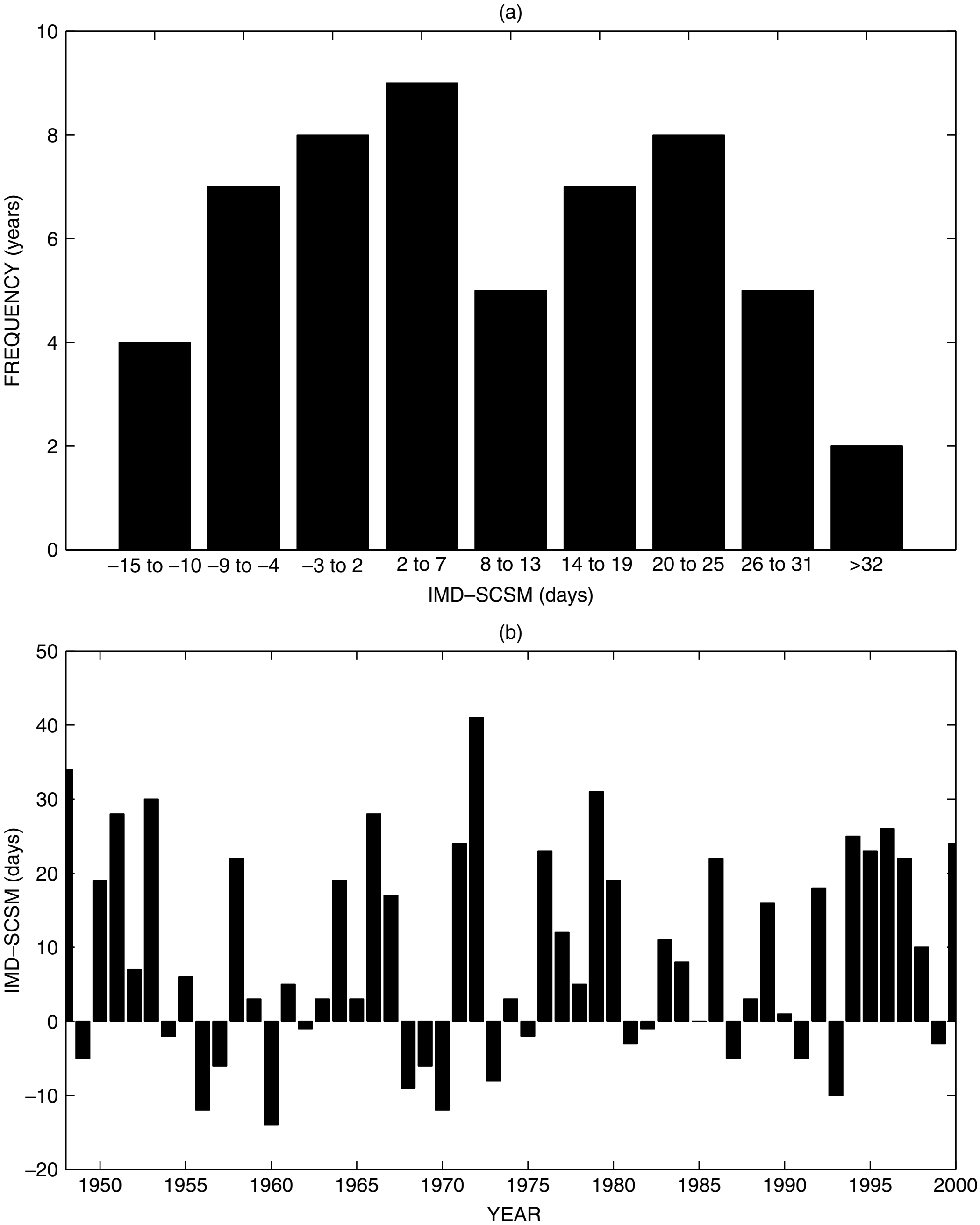

Figure 5. Dates of MOK as determined by IMD and the dates of SCSM onset by Wang *et al*. 2004 are compared in (a) and (b)

activity as discussed in Flatau *et al*. (2003). Figure 9(a) and (b) gives, respectively, the Hovmuller diagrams of the time variation with latitude of OLR and the 850-hPa zonal wind (both averaged over longitude belt 70°E to 85°E). These figures clearly show that the convection associated with the IMD onset date was short lived and the corresponding wind was very weak. The figures further show the slow and steady strengthening of convection and the 850 hPa wind prior to the predicted onset date beginning from the equatorial areas and moving north. Both the convection and wind were found to develop rapidly in intensity, only after 10 June. Daily data showed that the rain in Kerala around 29 May was temporary and it was followed by a dry spell

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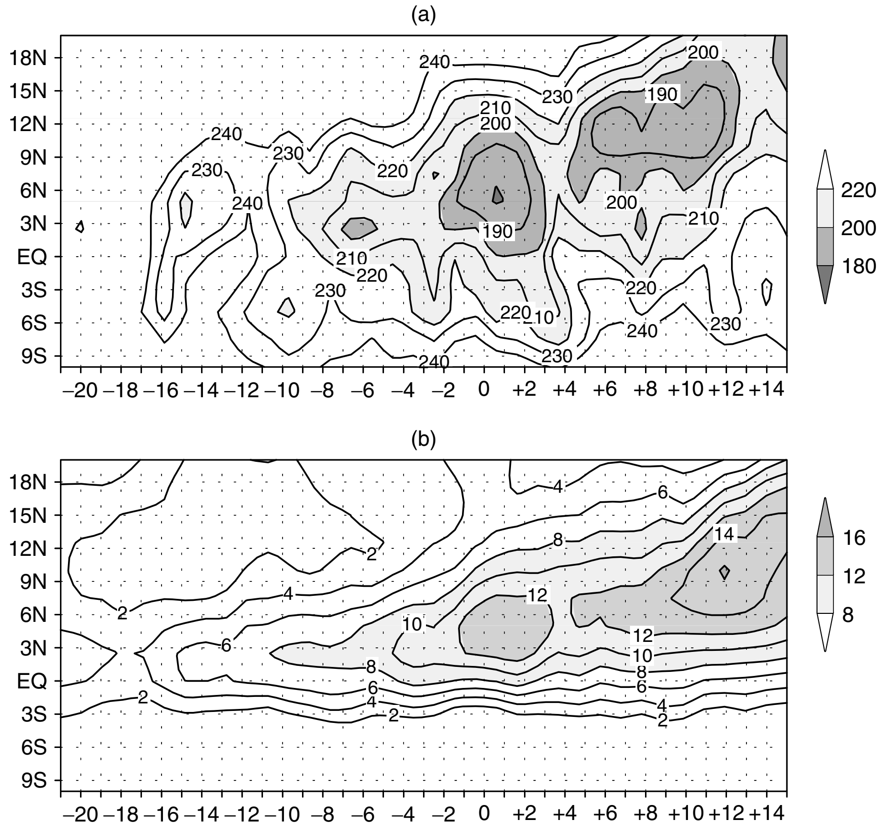

Figure 6. Composite (9-year) Hovmuller diagrams of (a) OLR in W/m^2 and (b) 850 hPa zonal wind in m/s, both averaged over the longitudes 70°–85 °E. The 9 years are 1979, 1982, 1984, 1986, 1987, 1990, 1993, 1995 and 1996. In (a) only contours of 240 W/m^2 and less at intervals of 10 W/m^2 are shown. Contours below 220 W/m^2 are shaded up to 180 W/m^2. In (b) only contours of 2 m/s and above, at intervals of 2 m/s are shown. Contours above 8 m/s are shaded

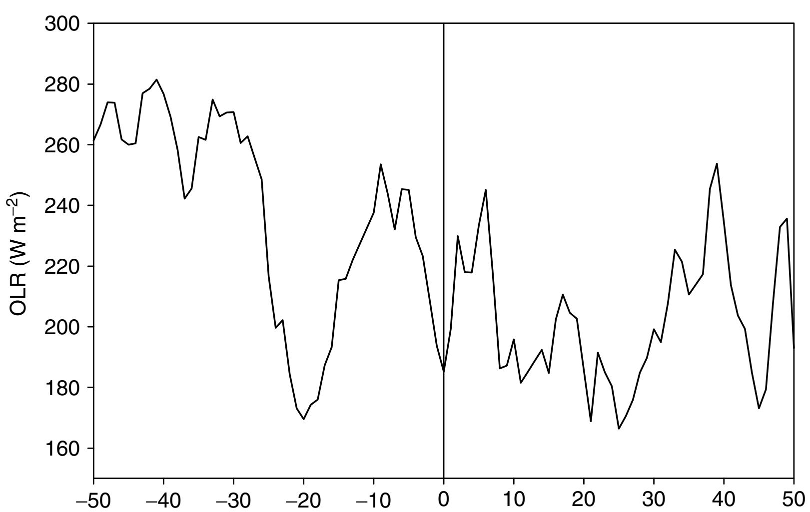

Figure 7. Daily mean OLR in the box 70–95 °E, Eq-15 °N for 1998 with respect to the date of MOK

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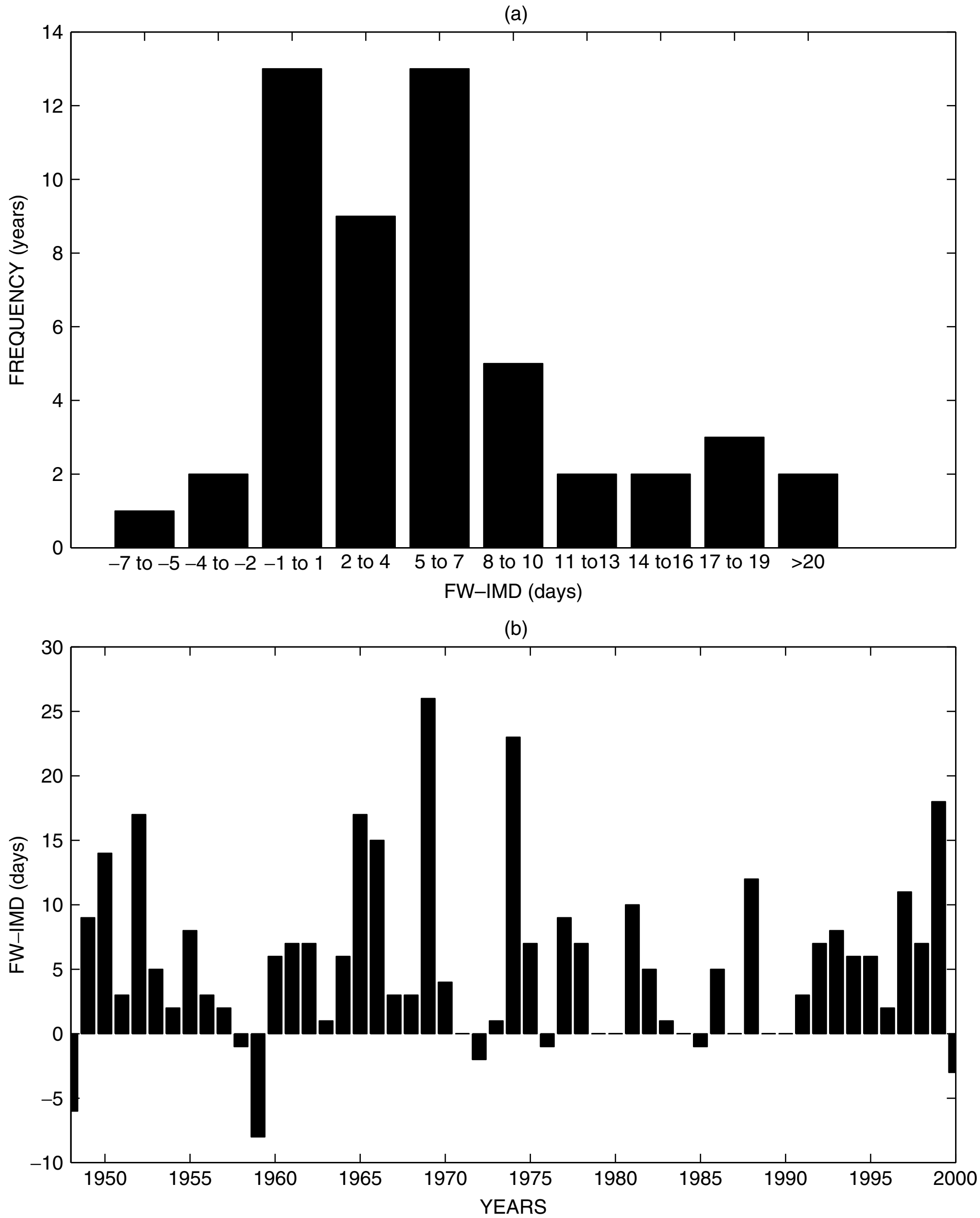

Figure 8. Dates of MOK as determined by IMD and the dates of onset over India by FW are compared in (a) and (b)

for 2 weeks. A 850 hPa wind data has shown that there was a strong LLJ around 13 June in contrast with the feeble winds around the IMD date of onset of 29 May.

6. MONSOON ONSET OF 1998

It is seen that the changes in convection and 850 hPa wind from P − 8 to P0 in the case of the 9-year composite had taken place in 1998 also, but in a shorter period of 20 days. MOK in 1998 as determined by IMD was

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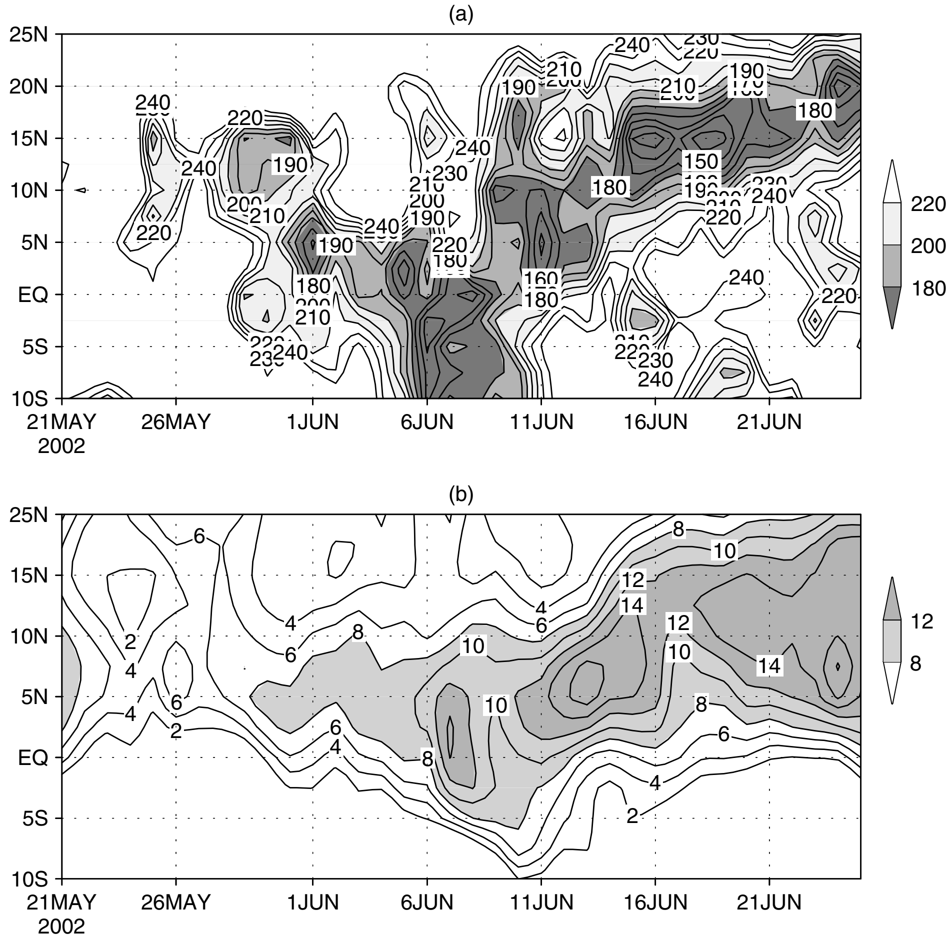

Figure 9. Hovmuller diagram for 2002 of (a) OLR in W/m^2 and (b) 850 hPa zonal wind in m/s, averaged over the longitudes 70°–85 °E. In (a) only contours of 240 W/m^2 and less at intervals of 10 W/m^2 are shown. Contours below 220 W/m^2 are shaded up to 180 W/m^2. In (b) only contours of 2 m/s and above at intervals of 2 m/s are shown. Contours above 8 m/s are shaded

on 2 June. PMRP was 20 days earlier on 13 May when there was an active convection near the equator south of the Bay of Bengal, as may be seen from Figure 7. This area of convection moved northeastwards and caused SCSM onset after 5–10 days. The SCSM onset as determined by Wang *et al*. (2004) was on 23 May 1998. Figure 10 gives the pentad averages of 850 hPa wind in 1998 at P − 4 (Figure 10(a)), P − 3 (Figure 10(b)) and P − 1 (Figure 10(c)) and also at P0 (Figure 10(d)). At P − 4 the wind flow with a cyclonic circulation over southwest Bay of Bengal is similar to the wind pattern at P − 8 or P − 7 of the 9-year composite (Figure 3(a) and (b)). At P − 4 in 1998 trade winds from the Pacific prevail over Southeast Asia which is replaced by the monsoon westerlies at P − 3 (Figure 10(b)), similar to P − 5 of the 9-year composite (Figure 3(c)). Figure 10(c) and (d) shows the LLJ associated with MOK in 1998.

7. THE MONSOON ONSET PROCESSES OVER SOUTH ASIA

From the preceding sections, it is clear that prior to MOK systematic changes have taken place in the atmosphere over a large area in and around south Asia and over the Indian Ocean. There is an active ocean–atmosphere interaction prior to MOK. We discuss here the changes in the parameters IWV, SST and LLJ and also about ISO period.

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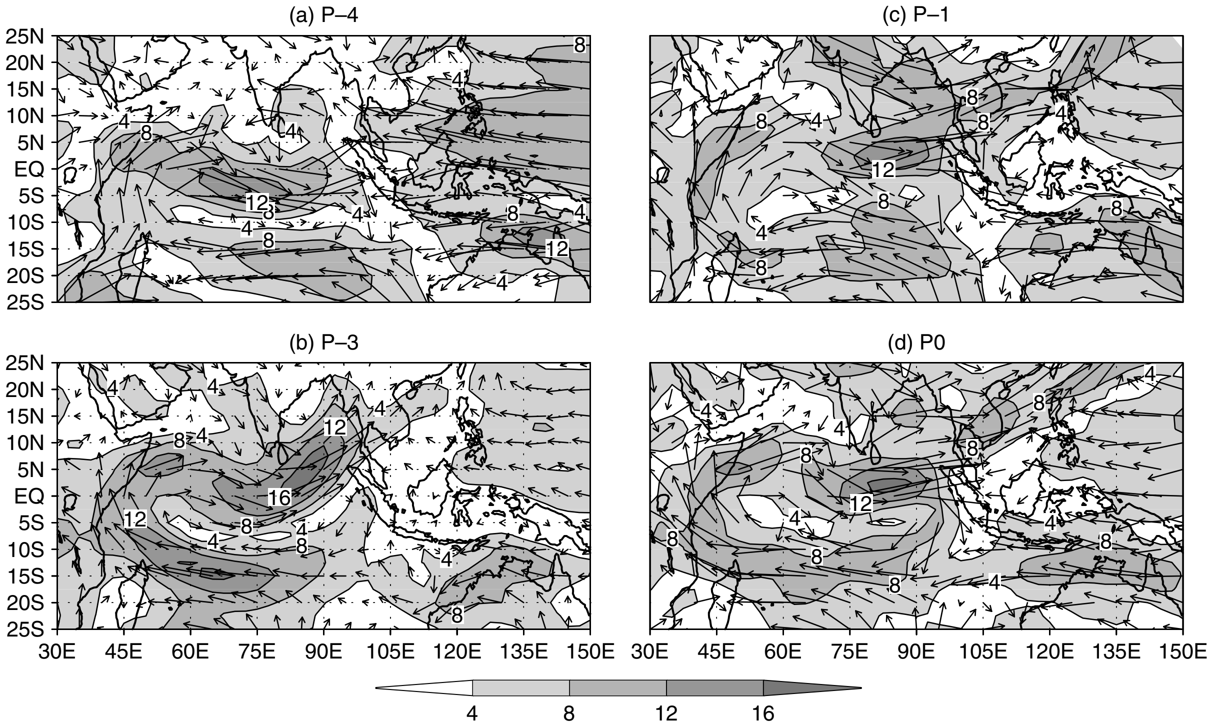

Figure 10. Pentad mean 850 hPa wind (in m/s) of 1998 for pentads P − 4, P − 3, P − 1 and P0. Only contours of 4 m/s and above at intervals of 4 m/s are shown with shading. MOK is at the middle of 0-Pentad. Pentad number is marked on top of each figure

7.1. Integrated water vapour (IWV)

The changes of OLR and IWV in the inner box around Kerala were shown in Figure 1. The changes in IWV are due to the pumping up of moisture by the convection in this box (the inner box of Figure 1). The outer box shown there covers a much larger area, at different parts of which convection occurred during the 14 pentads prior to MOK as shown in Figure 2. We have averaged the IWV over this large area bounded by latitudes 10 °S and 25 °N and longitudes 50 °E and 120 °E from P − 14 to P0 and composited for the same 9 years (Section 3), and its variation is shown in Figure 11. It is seen that IWV of the outer box steadily grows and reaches very large values at MOK of the order of 45 kg/m^2. This steady growth of IWV to large values in the outer box (the monsoon area) is needed for organizing MOK, in which convection and wind are strong covering very large areas (on the planetary scale). A similar picture emerged from the study of monsoon onset by Pearce and Mohanty (1984) who discussed the moisture build up in the monsoon area during a period of a few weeks prior to MOK during the 4 years 1979 to 1982. Our study agrees with their finding of a positive feedback between convection and monsoon current during the period P − 3 to P0, when the growth of IWV is very rapid.

7.2. Warm pool SST

It is found using TMI SST of the years 1999–2003 that the centre of a warm pool is located in the Bay of Bengal during P − 8 to P − 6 with SST of the order of 32 °C. At this time Arabian Sea SST is much lower. A large area of convection formed around P − 8 near the equator south of the centre of the Bay of Bengal warm pool in each of these years where SSTs are only of the order of 29 °C, but SST gradient in the north–south direction is large. The origin of this convection is likely to be by the mechanism suggested by Lindzen and Nigam (1987), which is particularly effective in low latitudes. Such a mechanism has been suggested by Vecchi and Harrison (2002) and by Joseph *et al.* (2005) to explain the convection in the Bay

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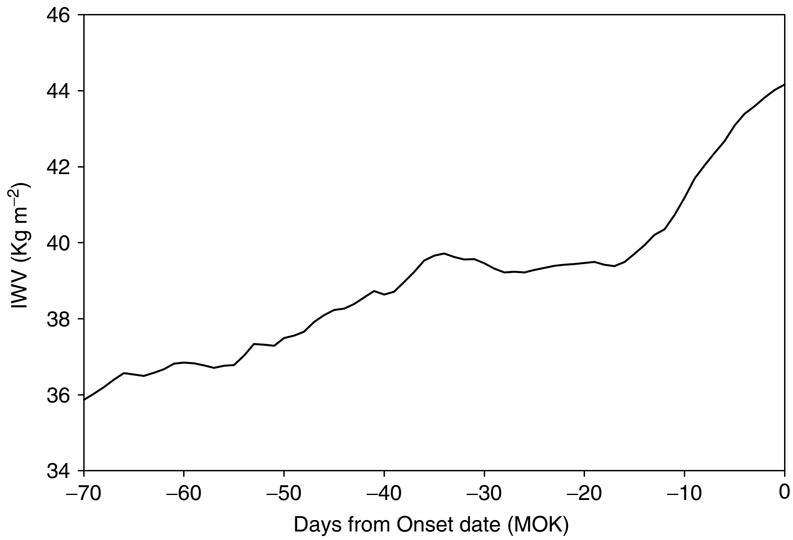

Figure 11. Composite mean IWV in the outer box 50–120 °E, 10 °S–25 °N for the 9 years; 1979, 1982, 1984, 1986, 1987, 1990, 1993, 1995 and 1996. (The area called the outer box is marked in the inset figure of Figure 1 by thick lines)

of Bengal associated with the active–break cycle of the monsoon. This area of convection moves from the equatorial areas to Southeast Asia by P − 5. The convective clouds and the associated strong westerly wind in the boundary layer cool the Bay of Bengal destroying the warm pool there. Such changes in association with the monsoon onset of 2002 have been pointed out by Flatau *et al*. (2003). In the meantime, Arabian Sea SST steadily increases due to solar radiation. The warm pool of the Arabian Sea reaches maximum development by P − 2. At P − 2, a large area of convection forms near the equator in the region of high SST gradient, south of the centre of the Arabian Sea warm pool. This area of convection moves north resulting in MOK. Figure 12(a) and (b) shows the variation of SST for 1998 and 2003 over the Bay of Bengal and the Arabian Sea boxes marked in the inset. It is seen from the figure that for 2003, about 35 days earlier to MOK the warmest area is in the Bay of Bengal, while at 10 days prior to MOK, it is in the Arabian Sea. In 1998, where ISO had a period of only 20 days, the warm pool is in the Bay of Bengal about 20 days before MOK and in the Arabian Sea 5 days prior to MOK.

7.3. Low-level jet stream

From the preceding sections, it is clear that MOK is accompanied by an extensive area of intense convection extending from the southeast Arabian Sea through the Bay of Bengal to Southeast Asia and a strong and deep LLJ with its axis passing just south of Kerala. The band of intense convection is on the cyclonic shear side of the LLJ. For MOK to occur, intense convection is needed in the east Arabian Sea. It is clear from our study that MOK occurs on the first day of a well-developed strong, and deep LLJ as described in Findlater (1969a,b) and Joseph and Sijikumar (2004). Such an LLJ, which is a planetary scale phenomenon, has its genesis at the time of MOK.

7.4. ISO period

A study by Joseph *et al*. (2004) of the daily mean monsoon rainfall of south Kerala for the period 1901–1995 has shown that the ISO of south Kerala rainfall varied between 23 and 64 days. From our study of a composite with mean ISO period of 35 days and a year with the period close to 20 days (i.e. 1998), it is seen that the durations of the different phases of the onset process are dependant on the period of ISO. We may be able to predict the date of MOK following the pentad-to-pentad evolution of OLR and 850 hPa wind if we have prior knowledge of the period of this ISO. More work is needed in this direction.

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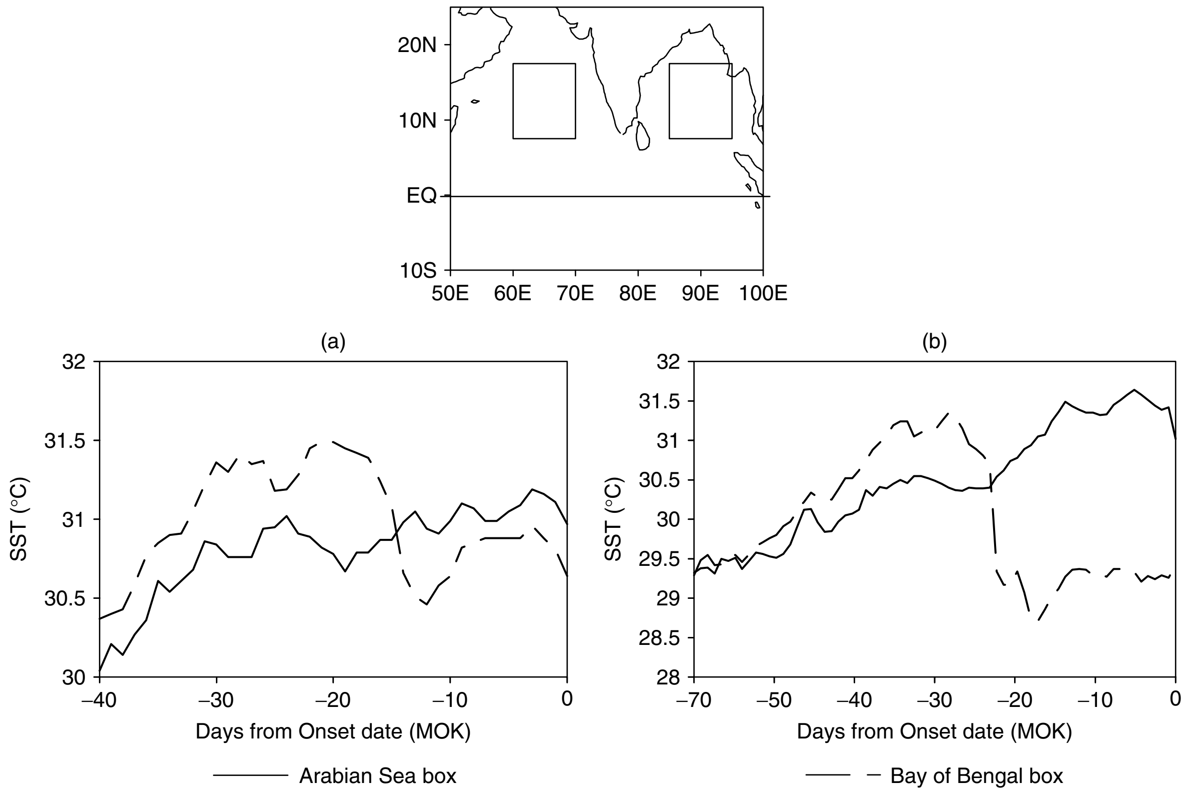

Figure 12. Daily mean TMI SST in °C for (a) 1998 and (b) 2003 over Arabian Sea box (7.5–17.5 °N, 60–70 °E) and Bay of Bengal box (7.5–17.5 °N, 85–95 °E) for the periods 40 days prior to MOK for 1998 and 70 days prior to MOK for 2003. The areas are marked in the inset figure

The ISO discussed in this paper is not the Madden–Julian oscillation (Madden and Julian, 1994). It is more like the active–break cycle of the monsoon or the Sikka and Gadgil (1980) type of oscillation where there is an active ocean–atmosphere interaction as shown by Vecchi and Harrison (2002) and by Joseph *et al*. (2005).

8. AN OBJECTIVE METHOD FOR DATE OF MONSOON ONSET OVER KERALA

The method in use by IMD to determine the date of MOK is a subjective one. An objective method for deriving date of MOK was given by Ananthakrishnan and Soman (1988). They used only one parameter, which is the daily mean rainfall of south and north Kerala. Monsoon onset as seen from earlier sections is a large-scale (spatial) phenomenon and defining it using the rainfall of a small area like Kerala may not be proper. This was pointed out by FW. The correlation coefficient between IMD onset and AS onset is 0.81 (for the period 1901–1990). For the same period, the mean onset dates (AS and IMD) differed by only 2 days. There are, however, several years in which the two onsets differed by more than 10 days. In this context, it is of interest to investigate the possibilities of defining MOK objectively bearing in mind the large spatial structures in convection and wind associated with MOK and the temporal evolution of these two fields during the period of about 2 months prior to MOK. An attempt is made to see whether an objective method can be derived using readily available atmospheric parameters covering a large area around Kerala, which can be used operationally.

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8.1. Parameters for objectively defining date of MOK

The results presented in Section 3 described the changes prior to MOK. This consisted of (1) a steady increase of convection over an area bounded by latitudes 0 and 15 °N and longitudes east of about 60 °E during the period P − 3 to PO (2) a steady acceleration of the cross-equatorial Findlater (1969a) type LLJ in response to this heat source (3) an increase in the depth of westerlies in the LLJ just prior to MOK and (4) a movement of the axes of the area of deep convection and LLJ from the equatorial region of the Arabian Sea at P − 3 to higher latitudes at P0. The effect of increase in the speed of LLJ is twofold: (1) the cross-equatorial flow (V-wind) increases around the east African coast and (2) the U-wind and the cyclonic shear associated with the LLJ (north of the LLJ axis) increases. Rainfall is associated with the cyclonic shear of LLJ, which induces vertical motion of the moist monsoon air mass in the atmospheric boundary layer. Thus, there are several factors of large spatial extent associated with MOK. We studied all of them and examined the possibility of choosing a few of these for deriving an objective method for defining the date of MOK. The chosen parameters are discussed in the following paragraphs. The dates derived objectively using the three steps described here are hereafter referred to as OBJ–MOK.

8.1.1. Step-1: check for depth and strength of monsoon westerlies. The strength and depth of the monsoon westerlies increase rapidly just prior to MOK as seen from the 9-year composite vertical structure (see Figure 4) of the U-wind averaged daily over the box bounded by longitudes 70 °E and 85 °E and latitudes 5 °N and 10 °N. It has been shown that from P − 1 to P0 the depth of westerlies has deepened to 400 hPa. The increase in depth and strength of the lower tropospheric westerlies are two of the features already known to occur at the time of monsoon onset (Rao, 1976). From our study it is seen that the depth of the westerlies has not further increased from P0 to P + 1 (Figure 4). We analysed the daily variation of the depth and strength of the monsoon westerlies for the period 5 May to 25 June of each year of the 33-year period 1971–2003. The 6 m/s box mean U-wind in the vertical section should cross 600 hPa level is chosen arbitrarily as a criteria to define the date of MOK. This criteria of 6 m/s was chosen so that the dates of MOK so determined are close to the dates subjectively determined by IMD.

In 1972, (Figure 13) westerlies of 6 m/s are observed to reach 600 hPa on 19 June. We have taken this date as the objective date of MOK for 1972 by step-1. In 1972, MOK as determined by IMD was 18 June. In 1979, (Figure 13), there were two possible choices for MOK, one on 11 May and another on 13 June (IMD onset was 13 June). In 1987 (a case of normal onset by IMD) the MOK by step-1 is 1 June. The possible choices for MOK in 1990 are 6 May, 16 May, 25 May and 9 June by the objective criteria of step-1.

We have tabulated the possible choices for the dates of MOK by step-1 in the second column of Table I. Examination of the table shows that in many years, the westerlies are found to deepen in early May itself. The early May deepening and strengthening may be due to the occurrence of PMRP or bogus onset as described earlier. For getting the correct onset dates for such years, we performed the second test (step-2).

8.1.2. Step-2: check for PMRP (bogus onset) using 850 hPa wind and OLR. It is seen from the 9-year composite (discussed in Section 3) that at MOK (P0), wind flow is of the Findlater type, with the flow crossing equator over the East African coast and accompanying it there is a big area of convection in Southeast Arabian Sea, east of 60 °E, whereas at PMRP there is very little convection in the Arabian Sea and Findlater type of jet does not form. Instead wind flow crosses equator east of longitude 60 °E. These we have used as the criteria for differentiating MOK from PMRP. Pentad mean OLR is used for the years after 1974 only (with exception of 1978). For the years 1971–1974 and 1978, HRC data was used as a proxy for convection. For those years in which the step-1 was satisfied during the period 5 May to 25 May, the second criteria (step-2) was applied to eliminate PMRP.

In 1972 (Figure 13), the westerlies strengthened and deepened only on 19 June and checking for PMRP was not needed. In 1979 (Figure 13) there were two possible choices for MOK, 11 May and 13 June. Figure 14(a) and (b) shows the OLR and 850 hPa wind for the pentad centred on 11 May. It is seen from this figure that convection is south of the Bay of Bengal and the wind flow is not of the Findlater jet type. We find strong westerlies east of longitude 70 °E and this was maintained by flow from the north and south hemispheres east of longitude 60 °E. Figure 14(c) and (d) gives the OLR and 850 hPa wind for the pentad centred around

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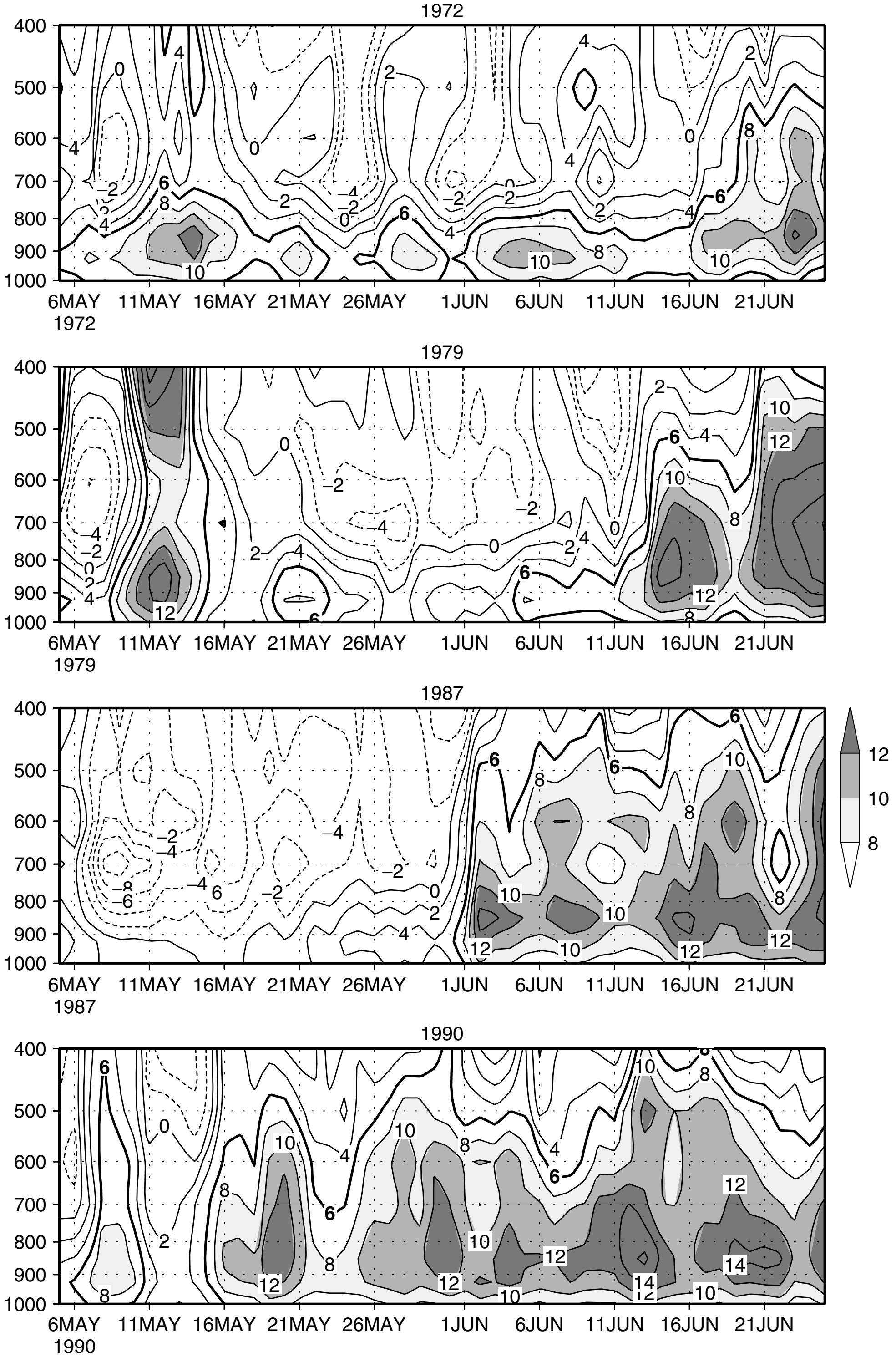

Figure 13. Vertical variation of the U-wind averaged daily over the box bounded by longitudes 70 °E and 85 °E and latitudes 5 °N and 10 °N. The contours are drawn at an interval of 2 m/s. Thick line represents the 6 m/s contours. The contours above 8 m/s are shaded

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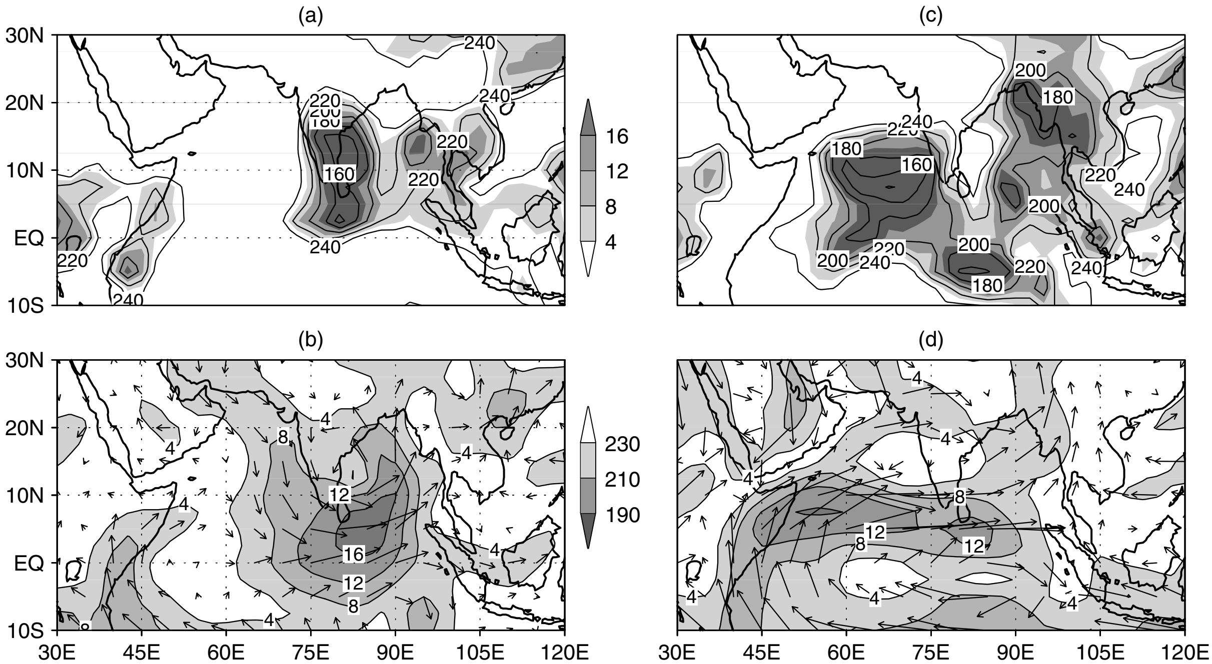

Figure 14. Pentad mean OLR for (a) 9–13 May 1979 and (c) 11–15 June, 1979. Contours less than 240 W/m^2 at intervals of 20 W/m^2 are shown in (a) and (c) and are shaded from 190 to 230 W/m^2. Pentad mean 850 hPa wind (m/s) for (b) 9–13 May 1979 and for (d) 11–15 June 1979. Contours in (b) and (d) are drawn at intervals of 4 m/s and those above 4 m/s are shaded

13 June. In this case, the low OLR pattern is found to extend eastwards from 60 °E and 850 hPa wind flow is of the Findlater type. The choice of MOK as 11 May for 1979 is not possible. It was a case of PMRP.

In 1987, there was only 1 day (i.e. 1 June) on which step-1 was satisfied. This possible date of OBJ–MOK is after 25 May, hence the test for PMRP is not needed. In 1990, the dates determined by step-1 are 6 May, 16 May, 25 May and 9 June. Of these 6 May, 16 May and 25 May are between 5 May and 25 May and so a check with the step-2 is needed. The spatial pattern of 850 hPa wind flow shows that on 6 May the wind flow is not of Findlater jet type whereas around 16 May and 25 May, it crosses the east African coast like the Findlater LLJ. The spatial pattern of OLR for the pentad centred on 6 May showed that the maximum convection lay east of 75 °E thus ruling out the possibility of taking it as MOK, whereas in the case of 16 May and 25 May OLR is low eastward of 60 °E. The date of MOK derived by this method will be further checked by step-3.

8.1.3. Step-3: check for widespread rain in and around Kerala at MOK. The Hovmuller diagrams of daily OLR, averaged between longitudes 65 °E and 80 °E, describes the development of convection in the equatorial region south of Arabian Sea and its strengthening and slow northward movement reaching Kerala latitudes resulting in MOK. The above pattern as observed in the Hovmuller, is chosen as the third and the final criteria for fixing the date of OBJ–MOK. We examined the Hovumuller diagrams of daily OLR. For 1979, the probable date after applying steps 1 and 2 is 13 June. The Hovmuller pattern of OLR for this year (Figure 15(a)) showed that the convection developed in the equatorial region about 1 June and moved slowly northwards bringing rainfall along the Kerala latitudes close to 13 June. Similarly for 1987 the probable date is 1 June by steps 1 and 2. Convection is found to develop in the equatorial region by about 22 May (Figure 15(b)) and moving slowly northward reached the Kerala latitudes around 1 June. For 1979 OBJ–MOK is fixed as 13 June and for 1987 it is 1 June. For 1990, the probable OBJ–MOK dates are 16 May and 25 May, after applying step 1 and 2. Convection is found to develop in the equatorial latitudes around 11 May. This

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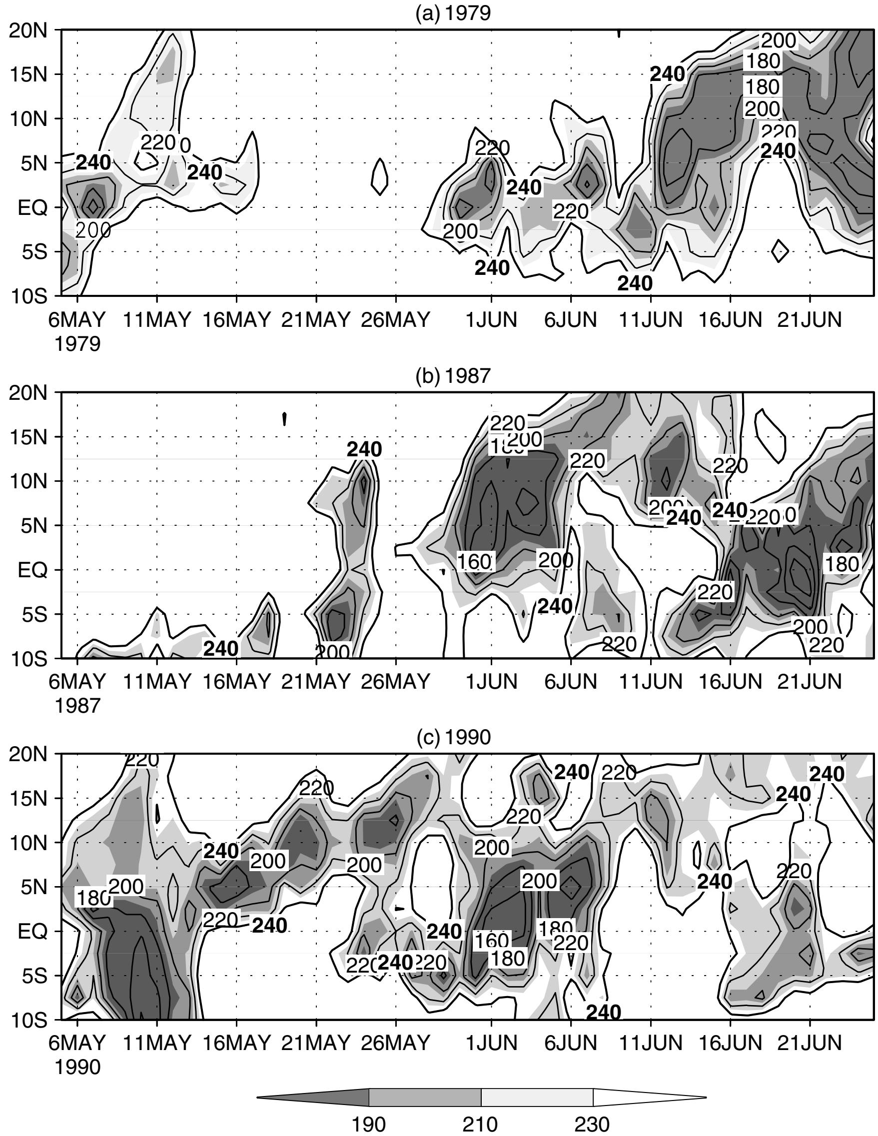

Figure 15. Hovmuller of OLR averaged along the longitudes 65 °E–80 °E. Contours less than 240 W/m^2 at intervals of 20 W/m^2 are shown. Contours are shaded from 190 to 230 W/m^2. Thick line represents the 240 W/m^2 contours

is observed (Figure 15(c)) to move northwards reaching the Kerala latitudes around 16 May. So we have chosen the date of OBJ–MOK for 1990 as 16 May.

Following the criteria given in steps 1 to 3, the dates of OBJ–MOK were fixed for each year of the period 1971–2003. The dates derived corresponding to step-1 and the finally chosen dates of OBJ–MOK are presented in Table I, in columns 2 and 3.

Examination of the table shows that large differences (more than 5 days) between IMD and OBJ–MOK occurred in 1977, 1978, 1988, 1993, 1996, 1997, 2002 and 2003. In the remaining years of the period 1971–2003, onset dates as fixed by the 3-step objective method (OBJ–MOK) have shown only minor differences from IMD onset dates. The case for 2002 was discussed earlier. The correlation between dates of OBJ–MOK and IMD onset for the period 1971–2003 is 0.80.

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9. SUMMARY AND CONCLUSIONS

We find that two ISO cycles (with a total duration of about 70 days or 14 pentads in many of the years) are needed for the ASM onset processes. During this period large-scale organized convection occurs systematically at different locations of a big area (10 °S–25 °N, 50–120 °E) in which the vertically IWV up to 300 hPa pumped up by convection increases steadily and reaches nearly 45 kg/m^2 around the date of MOK. Strong air–sea interaction occurs over north Indian Ocean during the second ISO. During the second ISO cycle an SST warm pool first forms in the Bay of Bengal. Convection, which gets organized by this warm pool in the low latitude area of large SST gradient to its south and the associated strong winds cools the SST of the Bay of Bengal warm pool. The Arabian Sea warm pool forms 2–3 pentads later and the large area of organized convection that forms to its south, pulls across the equator an LLJ of the Findlater (1969a) type. The two together move north from very low latitudes to Kerala latitudes and brings about MOK.

An objective method for operationally determining the date of MOK has been developed. The three steps of this method are:

Step-1: The daily depth and strength of the monsoon current's westerly (zonal) component in a box just south of Kerala bounded by latitudes 5 °N and 10 °N and longitudes 70 °E and 85 °E is to be monitored daily beginning on 5 May. At MOK this area mean wind should reach 6 m/s at 600 hPa.

Step-2: If a possible MOK is found by the first step during the period 5 May to 25 May, we check whether it is MOK or the PMRP (bogus monsoon onset) by examining the spatial pattern of OLR and 850 hPa wind field.

Step-3: The slow and steady movement of organized convection and rainfall from the equatorial area to the latitudes of Kerala to bring about MOK is checked in a Hovmuller diagram averaging OLR between longitudes 65 °E and 80 °E to confirm that the date chosen is the real MOK.

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