Space–Time Evolution of Meteorological Features Associated with the Onset of Indian Summer Monsoon

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ABSTRACT

To study the climatological structure of the atmospheric fields during the onset phase of the Indian summer monsoon, a composite analysis of different meteorological parameters over Indian stations is carried out. The composites are constructed relative to a uniform set of onset dates over south Kerala. Over the peninsular Indian stations, the rainfall composites show sudden and sharp increases with onset except in the case of east coast stations, where rainfall does not substantially change with the onset of the summer monsoon. The composite wind analysis demonstrates how the upper-tropospheric subtropical westerlies weaken and shift poleward and the tropical easterlies strengthen and spread north with the onset of the monsoon. The onset vortex that takes the monsoon northward along the west coast in many years is clearly discernible between 600 and 400 hPa in the composite streamline charts. The relative humidity builds up suddenly in the vertical a few days before the onset at the respective stations. The vertically integrated zonal moisture transport at individual stations over the peninsula increases sharply with respect to the south Kerala onset, with appropriate lag in time. The composite outgoing longwave radiation fields over the north Indian Ocean show rapid buildup of convective activity over the southeast Arabian Sea and east Bay of Bengal with the approach of the monsoon.

1. Introduction

The onset of the southwest monsoon over Kerala marks the beginning of the principal rainy season for India, during which the country receives the bulk of its annual rainfall. The remarkable punctuality of the monsoon's arrival over the Kerala coast around the end of May/beginning of June is well known. The mean date of onset over Kerala is 1 June, with a standard deviation of eight days. The monsoon rains take about six weeks from the time of onset over Kerala to cover the entire country (Fig. 1, adopted from IMD 1943). Although no objective criterion exists for fixing the date of onset, the primary indicator from the early days of Indian meteorology has been a sharp and sustained increase in rainfall at a group of adjacent stations (Ananthakrishnan et al. 1967). The increase in rainfall is also associated with changes in circulation and moisture distribution in the vertical. Since the 1960s, satellite cloud imagery has also been a valuable aid for identifying the monsoon onset.

A large number of studies have been made on the synoptic features of the onset phase of the southwest monsoon, which were summarized by Ananthakrishnan et al. (1968) and Rao (1976). After the Monsoon Experiment 1979 (MONEX-79) some studies using First Global GARP (Global Atmospheric Research Program) Experiment (FGGE) datasets have addressed the diagnostic and prognostic aspects of the monsoon onset (Krishnamurti et al. 1981; Krishnamurti and Ramanathan 1982; Pearce and Mohanty 1984; Kershaw 1988; Slingo et al. 1988).

The main circulation features of the onset that emerge from the above studies, based on the data for individual years, can be summarized as follows; (i) formation and northward movement of a cyclonic circulation (onset vortex) in the southeast Arabian Sea in many years; (ii) strengthening and deepening of westerlies in the lower troposphere and organization and strengthening of easterlies in the upper troposphere over peninsular India; (iii) the subtropical westerly jet over north India tending to break up and shift northward; and (iv) persistent heavy cloudiness over the southeast Arabian Sea.

Preparation of a century-long homogeneous time series of the onset dates must use rainfall as the sole criterion, since the upper-air observations started only about 40 years ago. Ananthakrishnan and Soman (1988, 1989) made an attempt in this direction, using the daily rainfall data at 44 raingage stations in south Kerala and 31 raingage stations in north Kerala, and prepared a time series of the date of onset during 1891–1980. The daily area-averaged rainfall series of south and north Kerala show spells of light and heavy rain of varying durations. Light rain spells form a feature of the premonsoon months, which dramatically give

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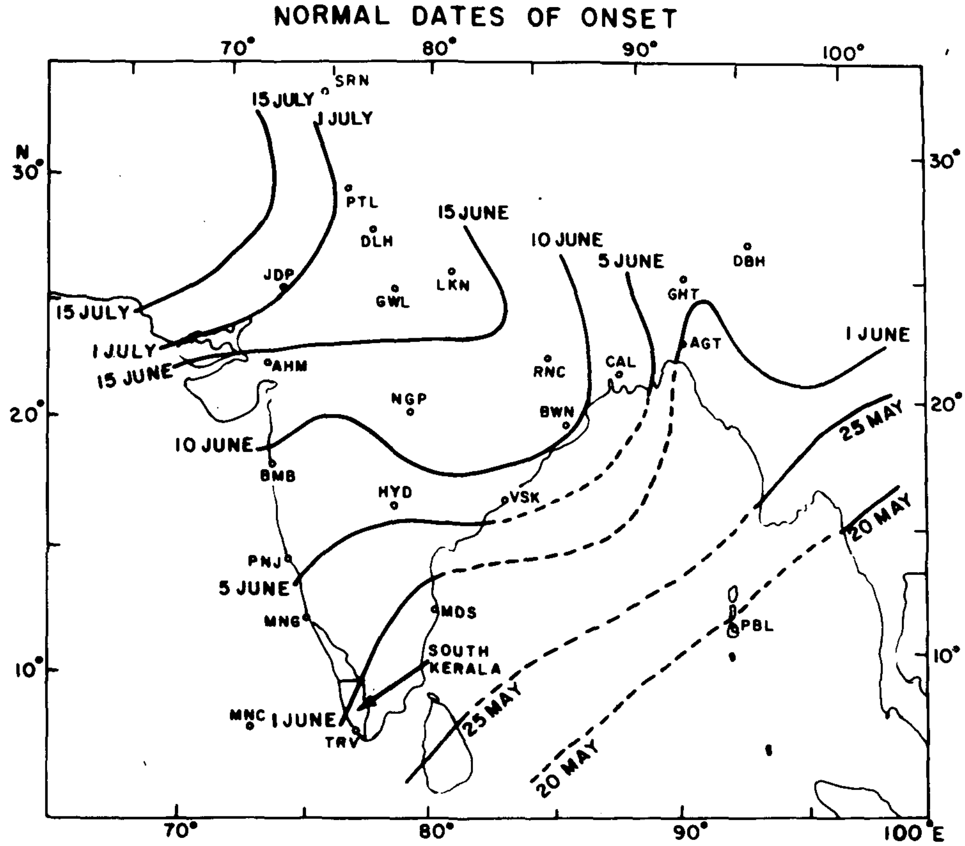


FIG. 1. Normal onset dates of the southwest monsoon over India. The location of aerological stations and south Kerala are also shown (India Meteorological Department 1943).

way to heavy rain spells heralding the onset of the southwest monsoon. The transition is sharp and abrupt. The date of monsoon onset is taken as the first day of the transition from the light to heavy rainfall category, with the proviso that the average daily rainfall during the first 5 days after the transition should not be less than 10 mm. The time series of onset dates has been extended up to 1990 in the present study, using the same rainfall criterion. The mean date of onset of the southwest monsoon over south Kerala is found to be 31 May, with a standard deviation of 8.5 days during 1891–1990. The extreme dates of onset during this period were 7 May 1918 and 22 June 1972.

The synoptic features during the onset phase of the monsoon have broad similarities with superimposed interannual variations. The present study attempts to bring out the similarities by making a composite study of some meteorological features during the onset phase, taking the date of onset over south Kerala as the key date. Similar study on the onset phase of Australian summer monsoon has been made by Hendon and Liebmann (1990), taking the date of onset over Darwin as the key date for compositing various parameters.

2. Data and methodology

The meteorological parameters composited to study the evolution of the monsoon onset are rainfall, wind, relative humidity, vertically integrated moisture transport, and the outgoing longwave radiation (OLR). Data for the stations in Table 1 are utilized in the study. The locations of the stations are also shown in Fig. 1.

The rainfall composites are prepared using daily data for the 80-yr period 1901–80. The wind- and moisture-related parameters are taken from the daily aerological data of 0000 UTC for the periods listed in Table 1. The data from the surface to 100 hPa with 50-hPa intervals have been considered for wind-related parameters and up to 300 hPa for humidity-related parameters. The OLR data prepared by the National Oceanic and Atmospheric Administration for the period 1974–87 are utilized to examine the convective activity over the north Indian Ocean during the onset phase of the monsoon. The details of the OLR dataset are given by Gruber and Krueger (1984). The OLR data, however, are not available for the year 1978. The onset dates of the summer monsoon over south Kerala that are uti-

TABLE 1. Locations of stations considered in the study and the record length of aerological data used for compositing.

Station	Abbreviation	Latitude (N)	Longitude (E)	Elevation (m MSL)	Data period
Port Blair	PBL	11°40′	92°43′	79	1971–85
Minicoy	MNC	8°18′	73°00′	2	1971–85
Trivandrum	TRV	8°29′	76°57′	64	1971–85
Mangalore	MNG	12°55′	74°53′	102	1975–85
Madras	MDS	13°00′	80°11′	16	1971–85
Panjim (Goa)	PNJ	15°29′	73°49′	55	1971–85
Hyderabad	HYD	17°21′	78°28′	545	1972–85
Visakhapatnam	VSK	17°43′	83°14′	3	1971–85
Bombay	BMB	19°07′	72°51′	14	1971–85
Bhubaneswar	BWN	20°15′	85°50′	46	1971–85
Nagpur	NGP	21°06′	79°03′	310	1971–85
Calcutta	CAL	22°39′	88°27′	6	1971–85
Agartala	AGT	23°53′	91°15′	16	1978–85
Ranchi	RNC	23°45′	85°23′	606	1978–85
Ahmedabad	AHM	23°04′	72°38′	55	1971–85
Gauhati	GHT	26°06′	91°35′	54	1971–85
Lucknow	LKN	26°45′	80°53′	138	1971–85
Gwalior	GWL	26°14′	78°15′	207	1978–85
Jodhpur	JDP	26°18′	73°01′	224	1971–85
Dibrugarh	DBH	27°29′	95°01′	111	1978–85
New Delhi	DLH	28°35′	77°12′	216	1971–85
Patiala	PTL	30°20′	76°28′	250	1977–85
Srinagar	SRN	34°05′	74°05′	1587	1971–85

lized for compositing the meteorological parameters are listed in Table 2.

Centered on the onset date over south Kerala, the aforementioned meteorological parameters have been composited from 20 days before to 20 days after the date of onset.

3. Results

a. Rainfall

The normal daily or pentad (5-day) rainfall at stations on the west coast of India shows a gradual increase in rainfall from the end of May to the beginning of June. This gradual increase in rainfall is because of the spread of the dates of onset in individual years. Superposed epoch analysis of area-averaged rainfall of south and north Kerala relative to the onset date showed a sharp and spectacular increase of rainfall heralding the monsoon onset (Ananthakrishnan and Soman 1988). In the present study, similar analysis has been made of the daily rainfall of some stations well spread over India, relative to the onset over south Kerala, to see whether there is an abrupt increase with respect to onset over Kerala with an appropriate lag corresponding to the normal advance of the monsoon over the country. The composite daily rainfall of six such representative stations (Trivandrum, Madras, Bombay, Port Blair, Calcutta, and Gauhati) are presented in Fig. 2a, and 2b.

At Trivandrum (TRV, south Kerala), the daily rainfall shoots up from about 5 mm to more than 25 mm with the onset. Over the bay island station Port Blair (PBL), where the normal date of onset according to Fig. 1 is 10 days prior to the onset over south Kerala, a small increase in rainfall can be noticed around −11 days, but a more sustained increase occurs with the Kerala onset. However, the increase in rainfall at PBL relative to the onset over Kerala is not very distinct, because the premonsoon rainfall at this station is also

TABLE 2. Onset dates of the southwest monsoon over south Kerala (1971–1990).

Year	Date
1971	25 May
1972	22 June
1973	3 June
1974	23 May
1975	1 June
1976	30 May
1977	27 May
1978	27 May
1979	11 June
1980	31 May
1981	29 May
1982	1 June
1983	12 June
1984	1 June
1985	24 May
1986	13 June
1987	1 June
1988	2 June
1989	1 June
1990	17 May

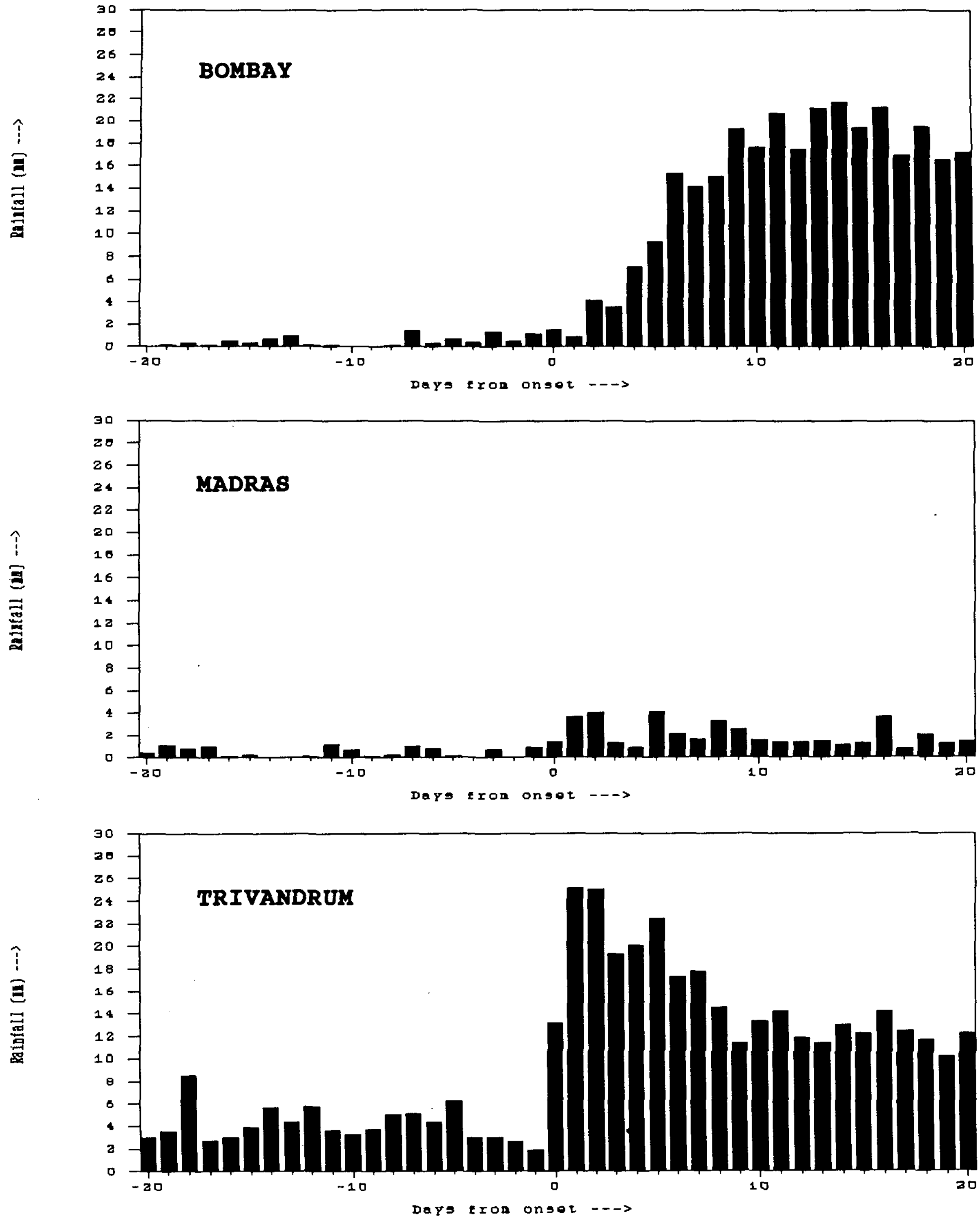


FIG. 2a. Composite daily rainfall (mm) relative to onset over south Kerala at Trivandrum, Madras, and Bombay.

quite heavy. At Bombay and Calcutta, the composite analysis of rainfall shows a sharp increase around 5 and 8 days, respectively, after the onset over south Kerala.

Almost all the stations show distinct increases in rainfall with respect to the south Kerala onset. However, for stations away from Kerala, the increase in rainfall with the normal lag after the onset over Kerala

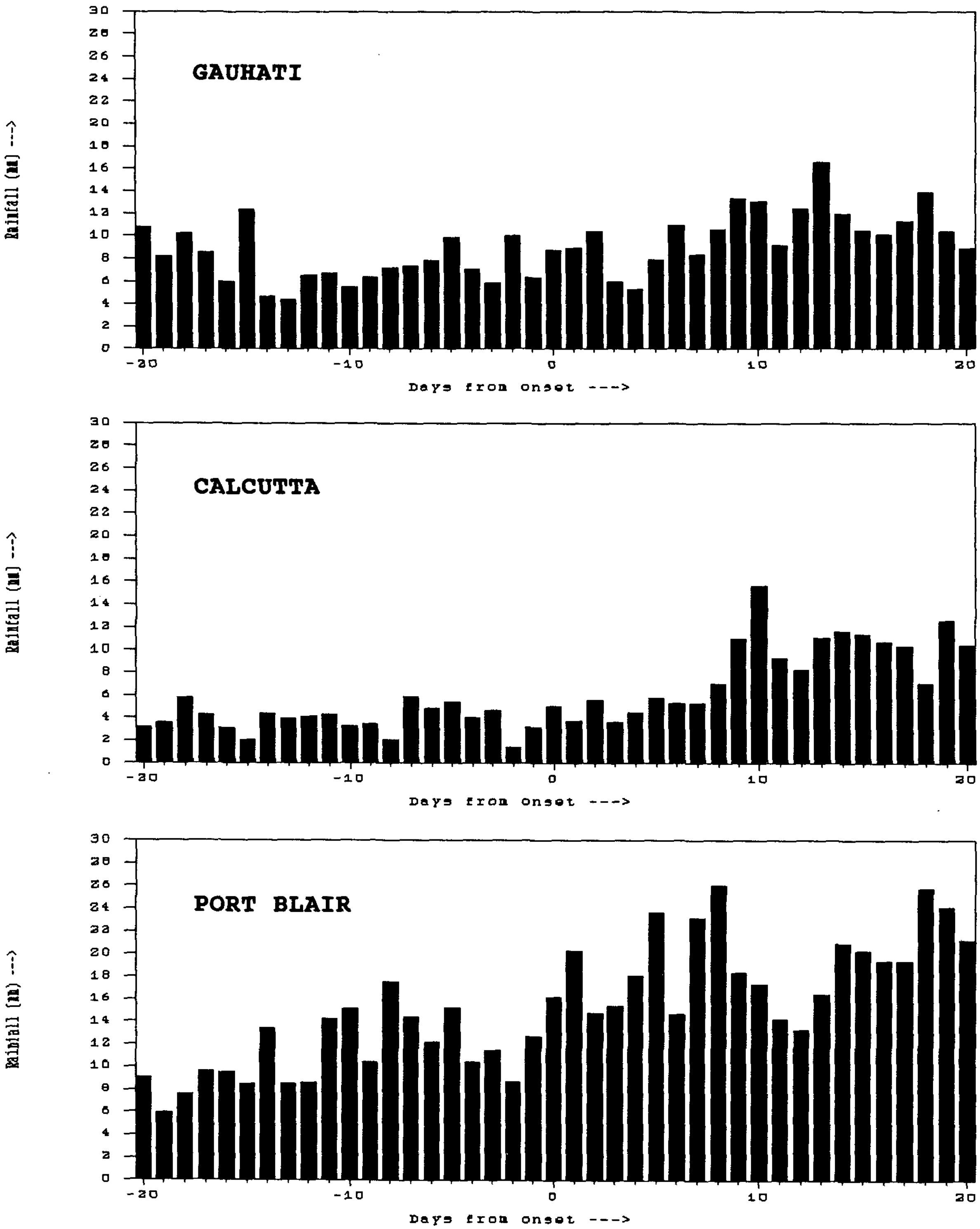
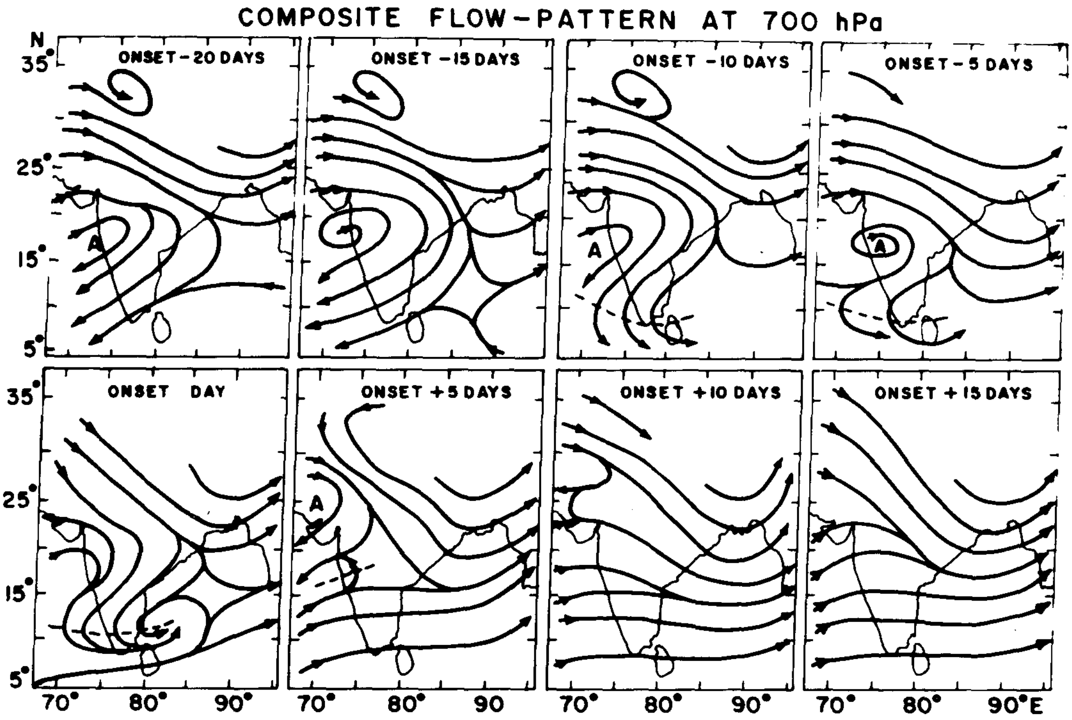
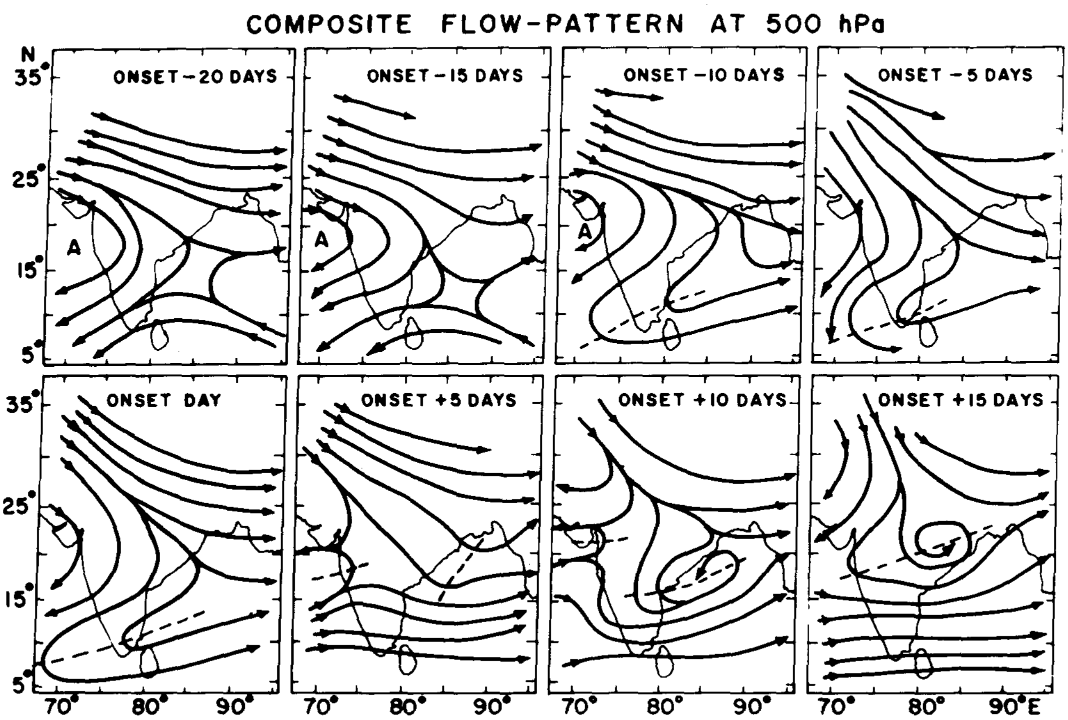


FIG. 2b. Composite daily rainfall (mm) relative to onset over south Kerala at Port Blair, Calcutta, and Gauhati.

is not very sharp as the lag varies in individual years. Also, for some stations in the rain-shadow region of western Ghats, rainfall alone may not be sufficient to fix the onset; changes in wind regime and vertical extent of moisture are more important. Over northeast India (e.g., Gauhati) the premonsoon rainfall is very heavy



(a)



(b)

FIG. 3. (a) Composite flow pattern relative to onset over south Kerala at 700 hPa for selected days. (b) Composite flow pattern relative to onset over south Kerala at 500 hPa for selected days.

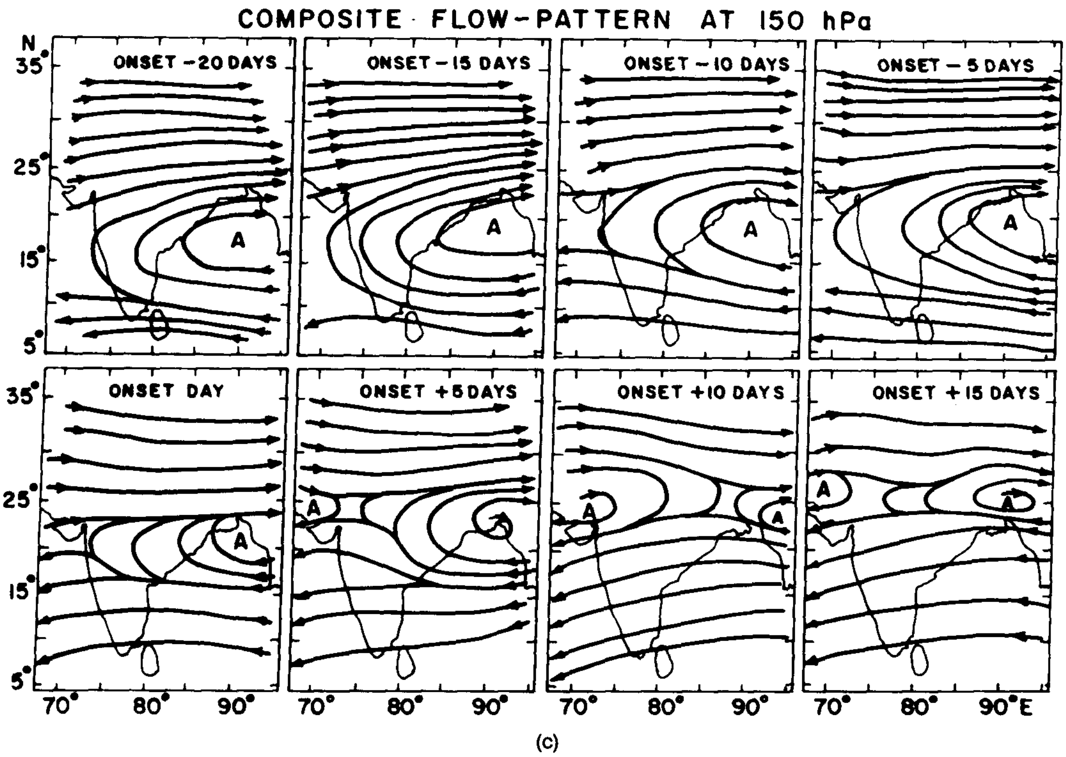


FIG. 3c. Composite flow pattern relative to onset over south Kerala at 150 hPa for selected days.

and the onset of the southwest monsoon brings only a marginal increase in rainfall.

b. Circulation

Changes in wind circulation with the onset of the monsoon have been studied by superposing the following aspects with reference to the date of onset over south Kerala, for the period 1971–85: (i) streamline patterns at selected levels; (ii) meridional cross sections along 75°E of u and v components of wind for selected days relative to onset; and (iii) spatial patterns of zonal kinetic energy at lower, middle, and upper troposphere. The important features of these composites are described in the following subsections.

1) COMPOSITE STREAMLINE PATTERNS

The composite streamline charts have been prepared for all levels, but are presented here only for three representative levels, namely, 700, 500, and 150 hPa (Fig. 3a–c), from −20 days to +15 days at intervals of 5 days.

At 700 hPa (Fig. 3a), 20 days before the onset, the wind flow is westerly over north India and easterly over the south peninsula, separated by a ridge line at 17°N. Up to 15 days before the onset, the circulation remains the same. Around 10 days before the onset, a trough line appears near the tip of the peninsula, which along with the ridge mentioned earlier remains more or less stationary until the onset day. On the onset day the trough line, which is the manifestation of the intertropical convergence zone, is seen around 10°N. Under the influence of the ridge and trough, the wind flow over most of the peninsula is predominantly northerly on the day of the onset. In the next 5 days the ridge and trough at 700 hPa move rapidly northward and disappear afterward. By 10 days after the onset over south Kerala, the monsoon current extends farther north and merges with the prevailing subtropical westerlies of north India.

The northward progress of the trough line in the flow field is more evident at 500 hPa (Fig. 3b). At this level, the trough near the west coast is visible during the first 10 days after the onset. It moves from 10° to 22°N during this period. This trough line in the composite may be associated with the onset-vortex-type circulation described by Krishnamurti et al. (1981), who observed that in the majority of years a cyclonic circulation–trough moves rapidly from about 10° to about 20°N with the advance of the monsoon. The onset vortex during MONEX-79 appeared first at the 300-hPa level and descended to the surface. In the initial stages it resembled a midtropospheric cyclonic circulation (Fein and Kuettner 1980). It is possible that the trough line gets masked at the 700-hPa level in the composite picture because the onset vortex generally forms at the midtropospheric levels and is better or-

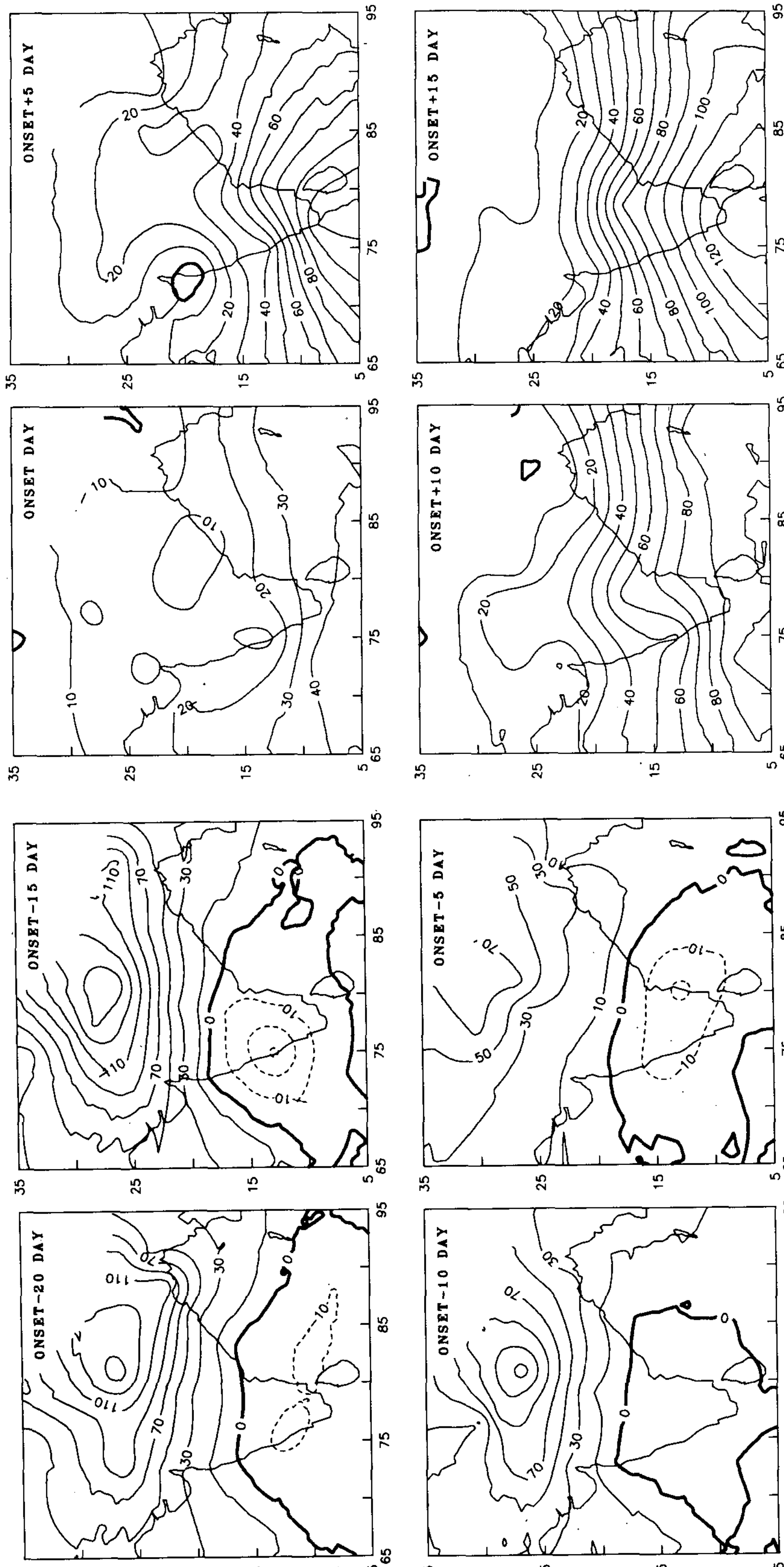


FIG. 4a. Composite mean ZKE (J kg^{-1}) relative to onset over south Kerala in the 1000–700-hPa layer for selected days.

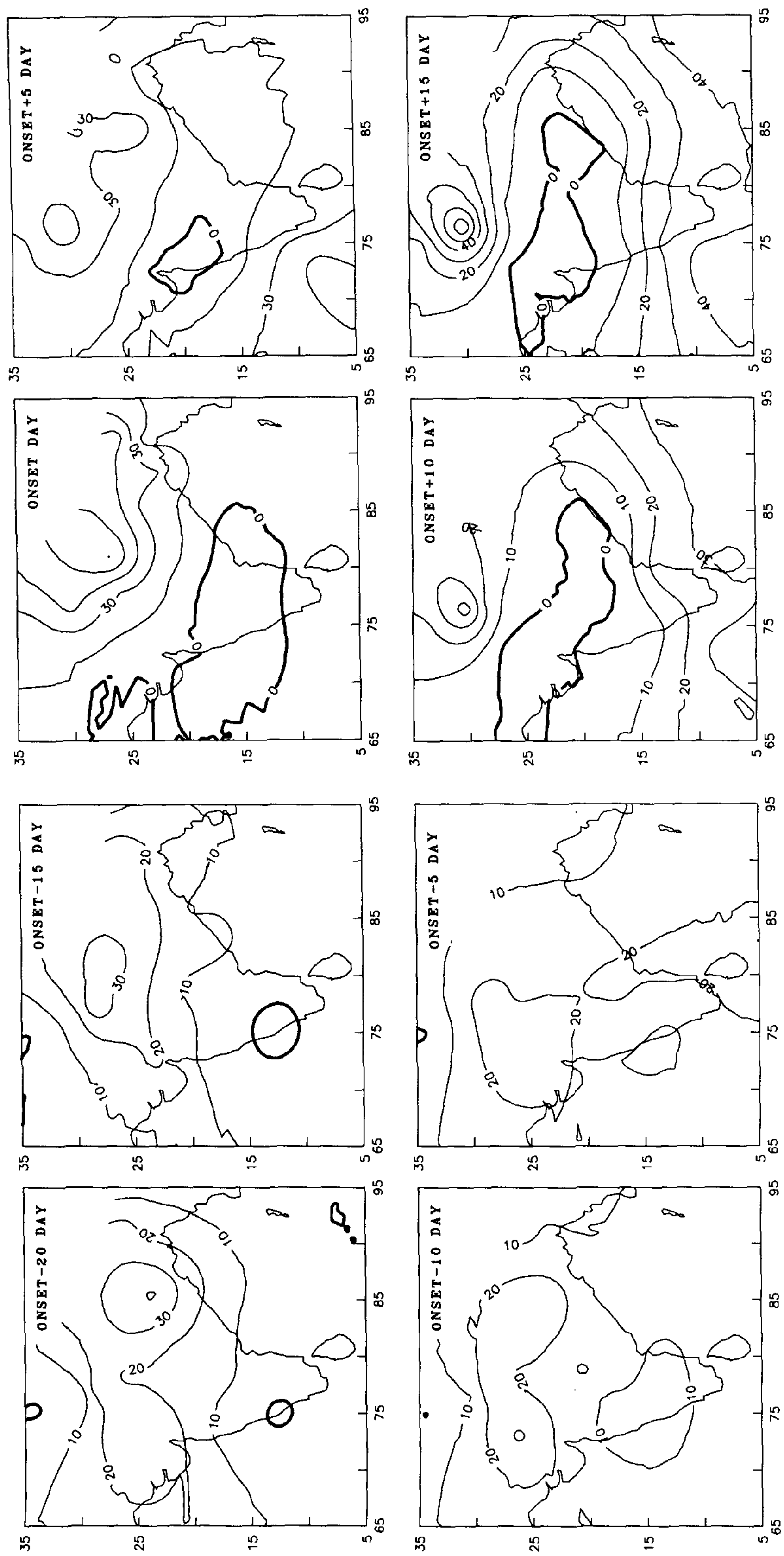


FIG. 4b. Composite mean ZKE ($J\ kg^{-1}$) relative to onset over south Kerala in the 600–400-hPa layer for selected days.

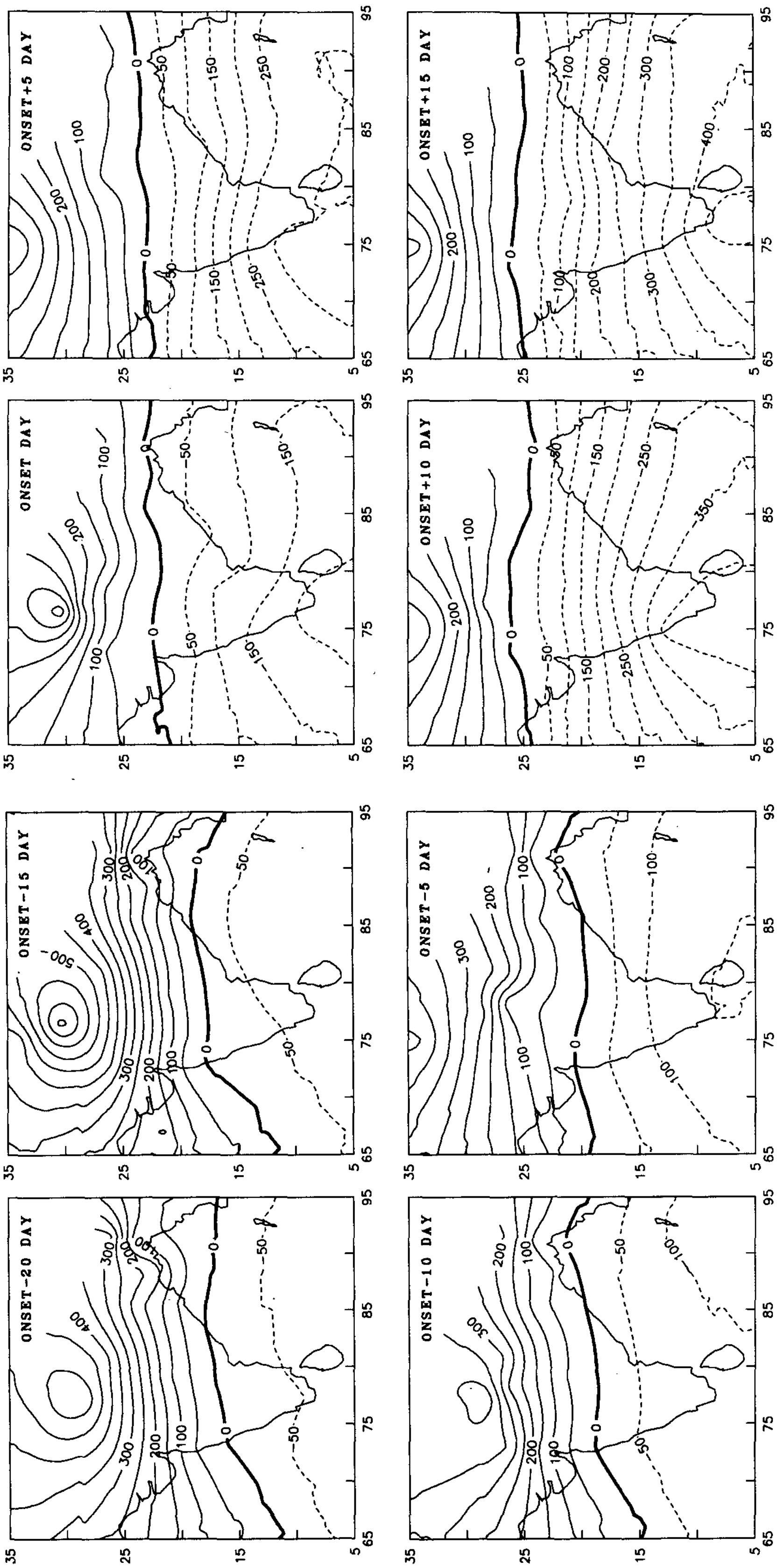


FIG. 4c. Composite mean ZKE (J kg^{-1}) relative to onset over south Kerala in the 300–100-hPa layer for selected days.

ganized there. In fact, the composite charts of the 600- and 400-hPa levels also show the northward movement of the same trough. In addition to the trough associated with the onset vortex on the west coast, a trough in the lower-level westerlies is also seen on the composite 500-hPa chart (Fig. 3b) over the Bay of Bengal 5 days after the Kerala onset and organizes as a cyclonic circulation by +10 days. Under the influence of this cyclonic circulation, the composite winds at Nagpur, Hyderabad, Vishakhapatnam, and Bhubaneswar become northerly or northeasterly. This circulation is seen over the eastern side of the peninsula with a slow northwestward movement. It may again be noted that this circulation is not seen in the composite charts of the 700-hPa level. This trough–cyclonic circulation may be responsible for advancing the monsoon northward along the east coast of India.

At 150 hPa (Fig. 3c), the shift of the subtropical ridge from about 17°N on day −20 to about 26°N on day +15 is clearly visible in the composite chart. There is hardly any change in the location of the ridge line until the onset of the monsoon over Kerala. The rapid shift of the subtropical ridge occurs only after the onset. The easterlies at 150 hPa spread northward with the shifting of the ridge.

2) ZONAL KINETIC ENERGY

The change in the strength of the winds over India, as represented by zonal kinetic energy (ZKE), 20 days before to 20 days after the onset over south Kerala has been computed at each station at 50-hPa intervals from the surface to the 100-hPa level. The spatial distribution of average ZKE for three layers, namely, 1000–700, 600–400, and 300–100 hPa are shown in Figs. 4a–c for (onset − 20) day to (onset + 15) day, at intervals of 5 days. ZKE associated with easterly winds is represented by dashed lines in the figures.

The ZKE changes associated with the monsoon onset first appear in the upper troposphere over peninsular India south of 15°N. This is associated with tropical easterlies in the upper troposphere at least 20 days before the onset (Fig. 4c). In a span of 20 days the average ZKE in the layer 300–100 hPa over this area increases from 50 to 200 J kg^{-1} by the time of the onset. After the onset the ZKE increases rapidly and attains a value of about 400 J kg^{-1} by (onset + 10) day. The weakening and shrinking of the westerlies over north India during the onset phase is clearly shown in Fig. 4c.

The ZKE at the lower levels between 1000 and 700 hPa (Fig. 4a) does not show any appreciable change during the 20 days preceding the monsoon onset over Kerala. On the onset day, the ZKE associated with the lower-level westerlies increases to about 30 J kg^{-1}. It increases rapidly after the onset and the 30 J kg^{-1} isoline moves northward covering 10° latitude in 10 days. The highest ZKE in the lower levels, attained 15 days after the onset, is about 120 J kg^{-1} at the tip of the peninsula which corresponds to an average westerly wind of about 15 m s^{-1} in the 1000–700-hPa layer.

The ZKE over the southern peninsula in the midtroposphere (600–400 hPa) before the onset is of the order of 10–20 J kg^{-1} (associated with easterly winds) and does not show much change before the onset (Fig. 4b). However, the ZKE in the layer associated with the westerlies over north India gradually diminishes as the onset approaches. After the onset, the easterlies over the peninsular region are replaced by westerlies and the ZKE increases to about 30 J kg^{-1} by onset + 15 day.

Examination of the composite data at individual stations and levels shows a sharp increase, with an appropriate lag relative to the onset, in ZKE in the lower levels at all stations over the peninsula. At these stations, the low-level westerlies deepen from 850 to 400 hPa in a time span of 1–2 days during the onset phase. Strengthening of the lower-level westerlies along the west and east coasts occurs simultaneously, though the east coast stations do not show as much increase in rainfall with the onset as over the west coast.

3) MERIDIONAL CROSS SECTION OF u AND v COMPONENTS OF WIND

The latitude–height cross section of the wind components from Trivandrum in the south to Srinagar in the north are prepared using data of nine stations lying roughly along 75°E for −15, 0, and +15 days relative to the onset date (Fig. 5). This analysis is useful to study the location and strength of the tropical easterly and subtropical westerly jet stream over India during the onset phase.

The subtropical westerly jet with zonal wind velocity more than 30 m s^{-1} is seen at the 200-hPa level along 30°N 15 days before the onset. The upper-tropospheric easterlies are seen south of 17°N, with a maximum strength of 10 m s^{-1} at 100 hPa. Light westerlies prevail from the surface to 800 hPa along the west coast. At the time of the monsoon onset over south Kerala, the lower-level westerlies deepen to 400 hPa. Compared to (onset − 15) day, the westerlies in the upper troposphere over north India decrease by about 10 m s^{-1} and the easterlies over south India increase by same magnitude. However, the ridge line separating southern easterlies and northern westerlies above the 700-hPa level remains at almost the same latitude. By (onset + 15) day, the low-level monsoon westerlies spread northward up to 23°N and merge with the subtropical westerlies. In the composite, the low-level monsoon westerly wind has a maximum strength of about 14 m s^{-1} between 800 and 700 hPa. The core of westerlies in the upper troposphere shifts northward. The ridge line, which was stagnant up to the onset day, moves

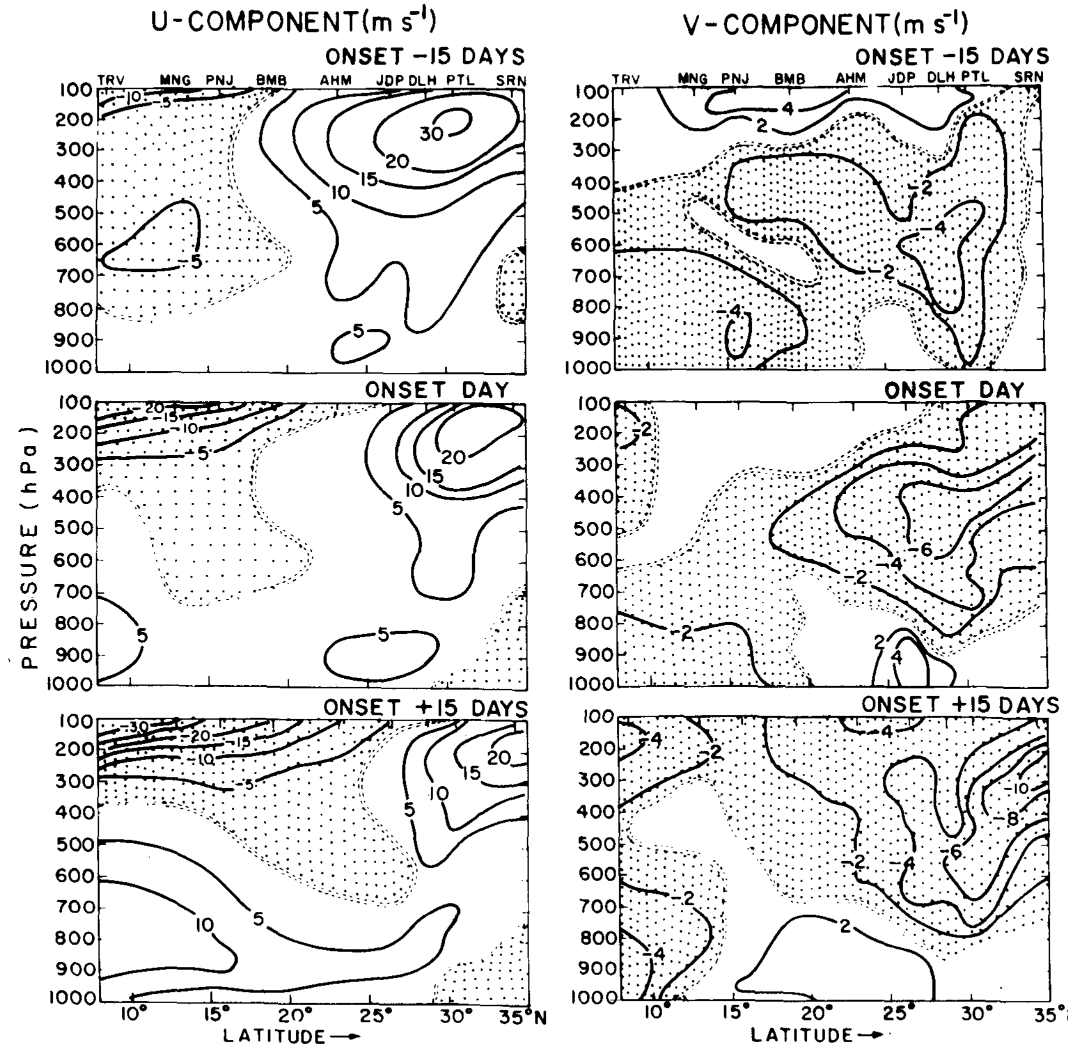


FIG. 5. Composite meridional cross section along 75°E of u and v components (m s^{-1}) of the wind.

rapidly northward after onset. Consequently tropical easterlies move farther north and attain jet magnitude of more than 30 m s^{-1}.

The changes in the cross section of the meridional component of wind (Fig. 5) are more subtle. The northerlies in the midtroposphere strengthen with the onset, and there is a definite strengthening of southerlies in the lower levels north of 15°N after the onset. The change in the wind regime from southerlies to northerlies in the upper troposphere with the onset of the summer monsoon indicates the setting in of the reverse Hadley circulation over the Indian subcontinent.

As India is situated in the tropical region, the changes in the meridional temperature gradients in the troposphere during the onset phase of the summer monsoon are not as prominent as the wind and precipitation changes. However there is a definite change in the direction of the temperature gradient with the onset of the monsoon especially in the middle and upper troposphere. The temperature gradients represented by the temperature difference between two pairs of stations, namely, New Delhi–Bombay and Bombay–Trivandrum, at different levels are given in Table 3 for (onset − 15) day, onset day, and (onset + 15) day. The meridional separation of these two pairs of stations is about 10° latitude. It can be seen that in the midtropospheric levels over the areas south of Bombay, the gradient reverses during the onset. The weak temperature gradients over the peninsular region before and at the time of the onset are consistent with the zonal wind over this region, which shows only a small vertical variation. The gradient turns strongly positive by 15 days after the onset, by which time the lower-level westerlies and upper-level easterlies also develop considerably, indicating strong easterly thermal wind. Over areas north of 20°N, the negative temperature

TABLE 3. Temperature difference (°C) between pairs of stations New Delhi–Bombay and Bombay–Trivandrum in the vertical.

Level (hPa)	Onset −15 days		Onset day		Onset +15 days	
	DLH–BMB	BMB–TRV	DLH–BMB	BMB–TRV	DLH–BMB	BMB–TRV
100	3.4	2.0	2.1	1.7	1.8	1.6
200	−0.2	1.2	1.4	1.7	0.0	4.4
300	−3.7	−1.2	−1.3	1.3	−1.4	5.2
400	−5.4	−1.3	−3.0	0.3	−0.5	3.7
500	−4.4	−0.1	−3.3	0.3	−1.0	3.6
600	−2.5	−0.7	−1.7	0.0	−1.7	3.7
700	−2.7	1.2	−0.3	1.8	0.1	3.7
800	−1.8	3.6	2.0	2.8	2.8	3.1
900	2.8	2.0	5.6	1.7	4.3	2.5

gradient weakens slightly at the time of the onset and almost disappears over areas between 20° and 30°N by two weeks after the onset.

c. *Relative humidity and moisture transport*

The relative humidity composites from the surface to 300 hPa are presented in Figs. 6a and 6b for 12 selected stations. A common feature is that the humid layer deepens sharply a few days before the local onset date. At all the stations except Port Blair, the 60% humidity line rises sharply by about 200–300 hPa in the vertical. With this deepening of the moist layer many stations experience premonsoon thunderstorm activity prior to the onset of the southwest monsoon. Pearce and Mohanty (1984) also noticed similar large-scale moisture buildup, particularly over the Arabian Sea prior to the onset in the years 1979 and 1982. This indicates that the intensification of the monsoon flow is preceded by moisture buildup and release of convective instability not only over the Arabian Sea but also over the Indian landmass. In the composite the moisture buildup over the southern peninsula south of 15°N occurs about one week before the onset. After the onset, with the rapid shift and weakening of the anticyclone over the central peninsula (Fig. 3a), the moist layer at most of the stations in north India deepens rapidly. The humidity layer over stations in northeast India (not presented) extends to higher levels much before the onset and so there is no appreciable increase prior to the onset.

Another noteworthy feature in the humidity field is the distinct maximum in relative humidity between 700 and 500 hPa at most of the stations north of 15°N, which disappear with the onset (Figs. 6a,b). This maximum in the midlevels may be a manifestation of the drying up of the lower atmosphere below 700 hPa due to the anticyclone present over the peninsula above this level (see Figs. 3a,b). With the onset of the monsoon, this anticyclone shifts rapidly northward and becomes unimportant; and as a consequence the dryness over the lower atmosphere also disappears.

The composite daily moisture transport integrated from the surface to 300 hPa across a 1-m-wide area normal to the wind flow have been computed at all the stations. These are shown as vectors at individual stations in Fig. 7 from (onset − 20) day to (onset + 15) day at intervals of 5 days. The moisture transport at the stations gives the combined effect of the wind and humidity changes during the onset.

The direction of the composite moisture transport in Fig. 7 is essentially the same as the direction of the winds at 700 hPa (Fig. 3a), as the maximum contribution to the total moisture transport comes from the lower levels because of the substantially higher moisture content at these levels. The stronger westerly winds transport more moisture at north Indian stations before the onset of the monsoon. Over peninsular India the transports are much smaller and are either northerly or northeasterly under the influence of the anticyclonic flow over this region in the lower and middle troposphere. The moisture transport across Port Blair in the Bay of Bengal increases 15 days before the onset over Kerala and becomes westerly from southerly within 5 days. On the day of the onset the composite moisture transport across Minicoy and Trivandrum is more than 500 kg m^{-1} s^{-1} westerly, while across other stations over the peninsula it is still very small and not westerly. By (onset + 5) day, the strong westerly transport moves up to 15°N with Bombay still showing a small easterly transport. In the next few days, the moisture transport across the whole peninsula increases substantially with simultaneous decrease in transport across stations in north India.

The three west coast stations, Mangalore, Panjim, and Bombay, show rapid increases in the transport with the onset, with an appropriate lag. Among them the southernmost station, Mangalore, shows north-northeasterly transport until the onset day, under the influence of the anticyclone present over the peninsula (Figs. 3a,b). As shown earlier, after the onset over Kerala, this anticyclone moves northward and temporarily reverses the direction of the moisture transport across Bombay for one or two days. After (onset + 5) day

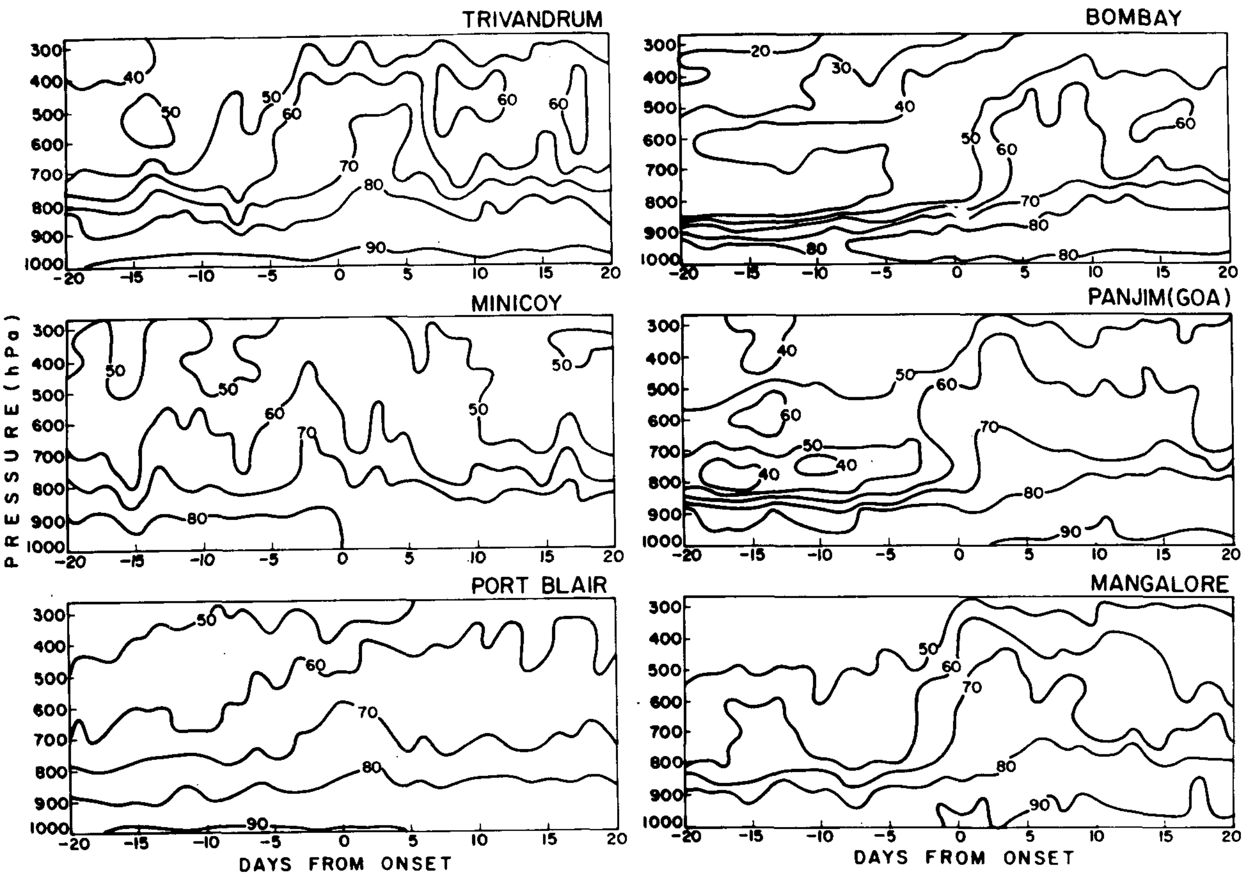


FIG. 6a. Composite daily relative humidity (%) relative to onset over south Kerala at Port Blair, Minicoy, Trivandrum, Mangalore, Panjim, and Bombay.

the composite moisture transport across Bombay turns about 180° and increases sharply; the coincidence with the composite rainfall increase (Fig. 2a) is quite striking.

The increase in moisture transport at Madras during the onset is comparable with that at Trivandrum and Mangalore on the west coast. However, there is no perceptible increase in rainfall at this station because it is situated in the rain-shadow region of the western Ghats. A similar situation is noticed at Hyderabad. On the other hand, at Nagpur the increase in moisture transport is not very spectacular, but as this station is not situated in the rain-shadow region, it shows a substantial increase in rainfall about 12 days after the south Kerala onset.

d. Composite OLR over the north Indian Ocean

The convective activity over the Arabian Sea and Bay of Bengal increases with the advance of the southwest monsoon. The time evolution of this convective activity in a domain extending from 10°S to 30°N and 60° to 100°E is examined using OLR data composites, at 2.5° × 2.5° latitude–longitude grids, relative to the onset dates over south Kerala. The composite OLR fields from (onset − 20) day to (onset + 15) day with an interval of 5 days are presented in Fig. 8. The isolines in the figure represent OLR departures from 240 W m^{-2}. Kripalani et al. (1991), using the same OLR data, have determined the probabilities of rainfall greater than 2.5 mm day^{-1} over India during the summer monsoon season for various OLR threshold values. According to them, the OLR values 220–240 W m^{-2} are associated with rainfall probability 0.7–0.8 and OLR $\leqslant$ 180 W m^{-2} indicate probability of rainfall greater than 0.9. As such, the zero isoline in Fig. 8 can be considered as the periphery of the precipitating clouds and a value of −60 will indicate deep convection.

The main convective area two weeks before the onset is over the northeast Indian Ocean (Fig. 8). By (onset − 10) day, the −20 isoline covers most parts of central and east Bay of Bengal. The convection over the Arabian Sea becomes prominent only after (onset − 10) day. Five days before the onset, the convective area represented by the −40 line (OLR < 200 W m^{-2}) is seen over the Arabian Sea north of the equator at about 70°E. The convection over southeast Bay of Bengal

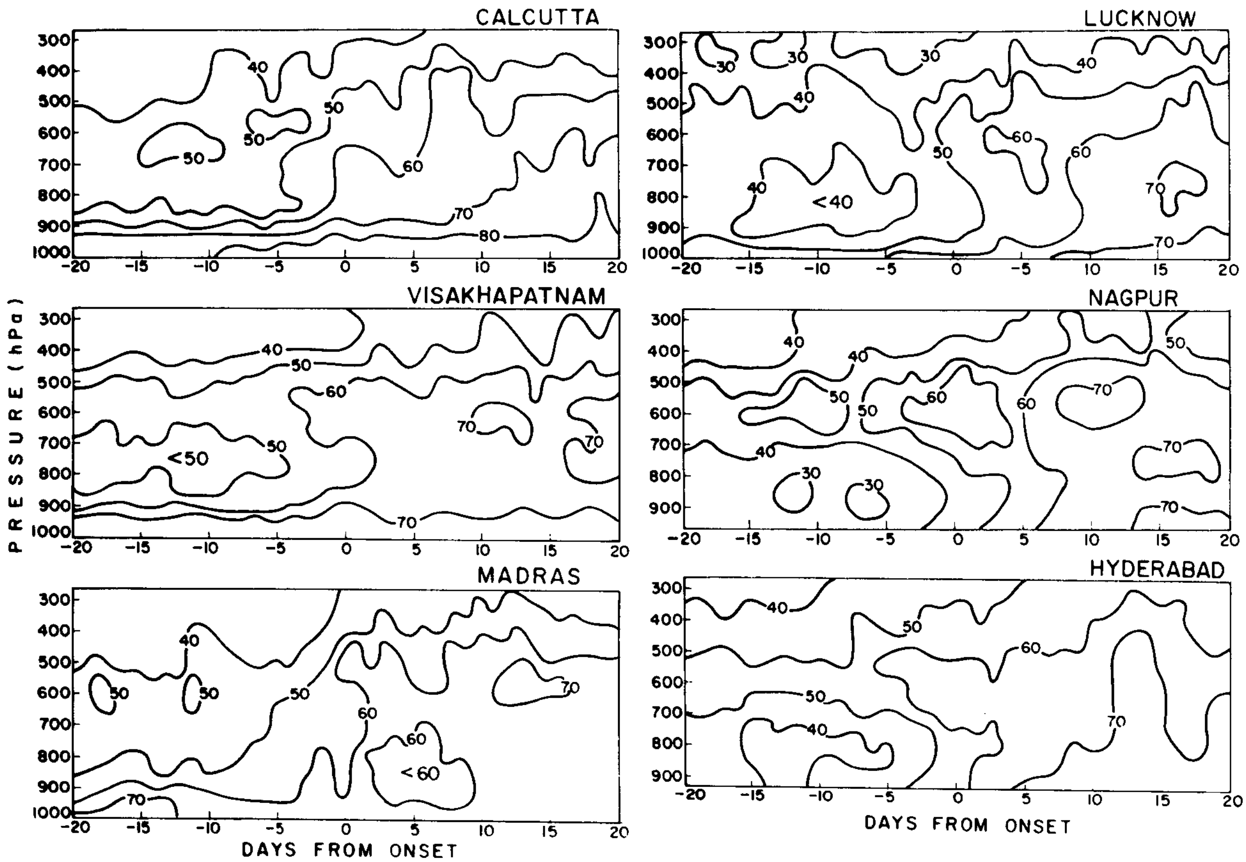


FIG. 6b. Composite daily relative humidity (%) relative to onset over south Kerala at Madras, Visakhapatnam, Calcutta, Hyderabad, Nagpur, and Lucknow.

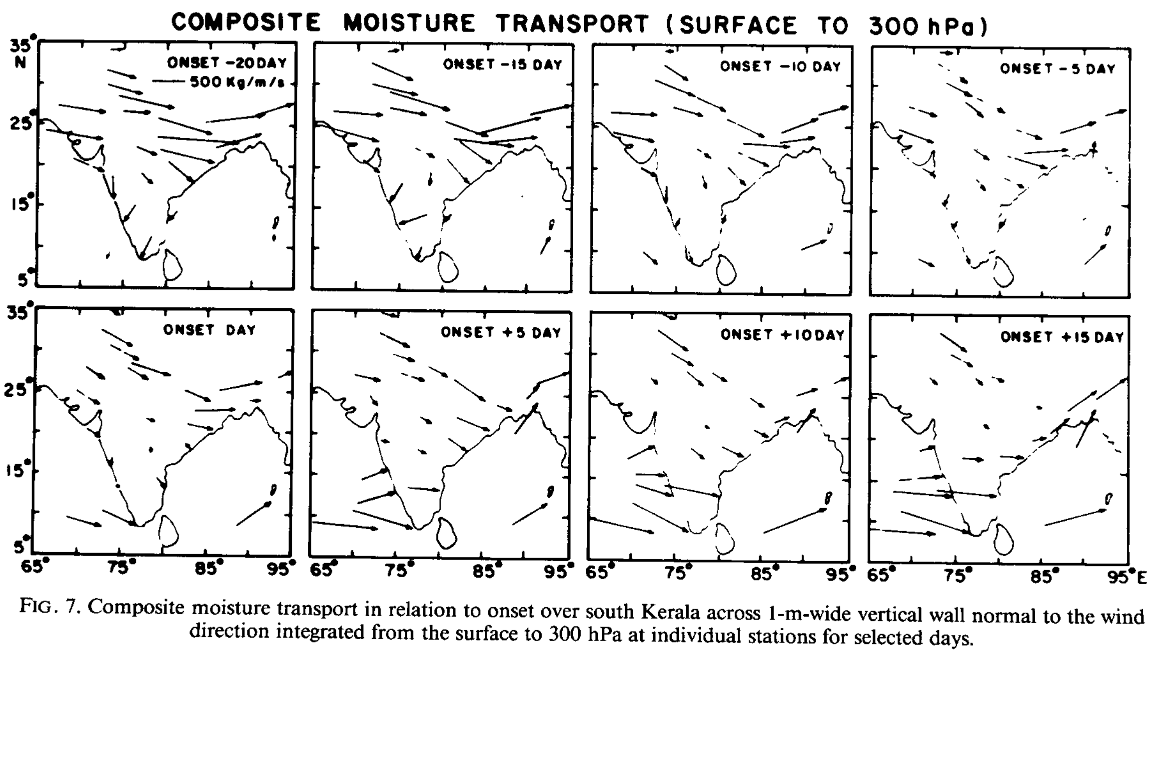


FIG. 7. Composite moisture transport in relation to onset over south Kerala across 1-m-wide vertical wall normal to the wind direction integrated from the surface to 300 hPa at individual stations for selected days.

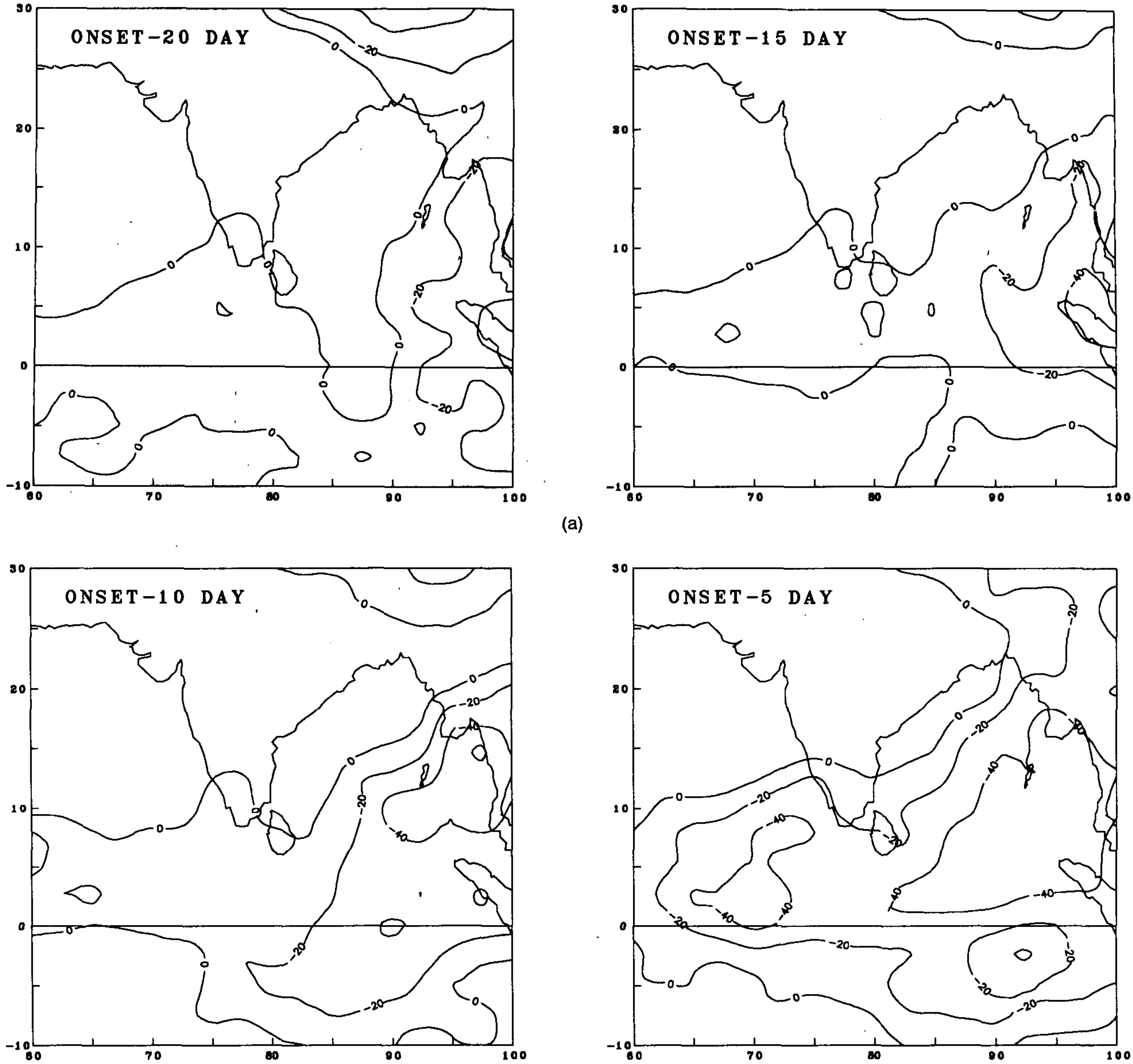
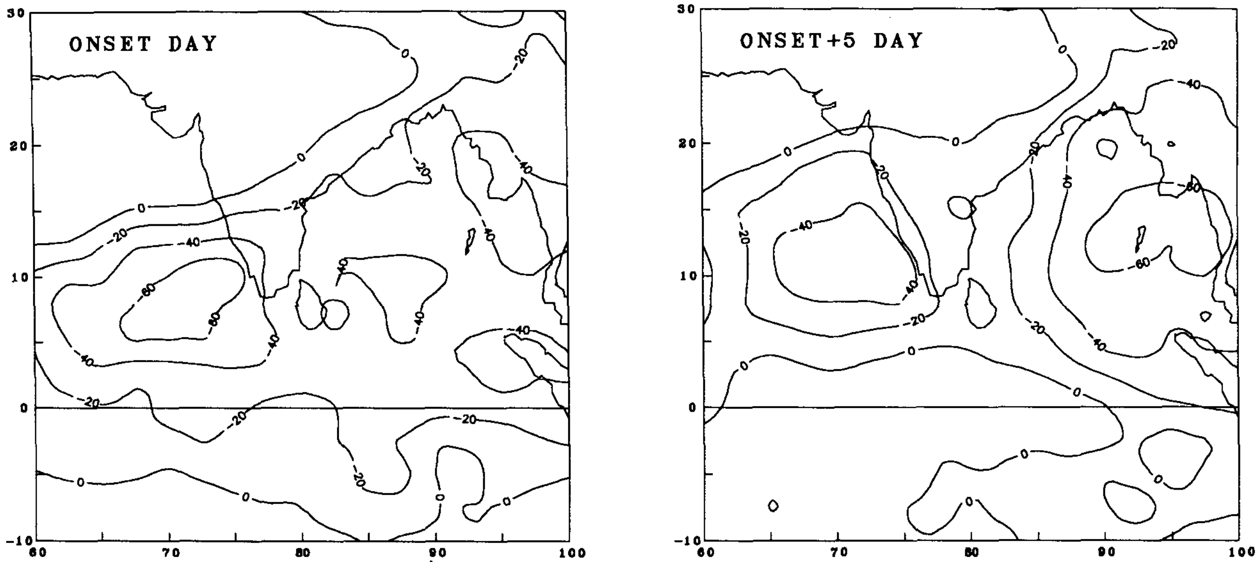


FIG. 8. Composite OLR fields in relation to onset over south Kerala, over north Indian Ocean for selected days. The isolines represent deviations from 240 W m^{-2}.

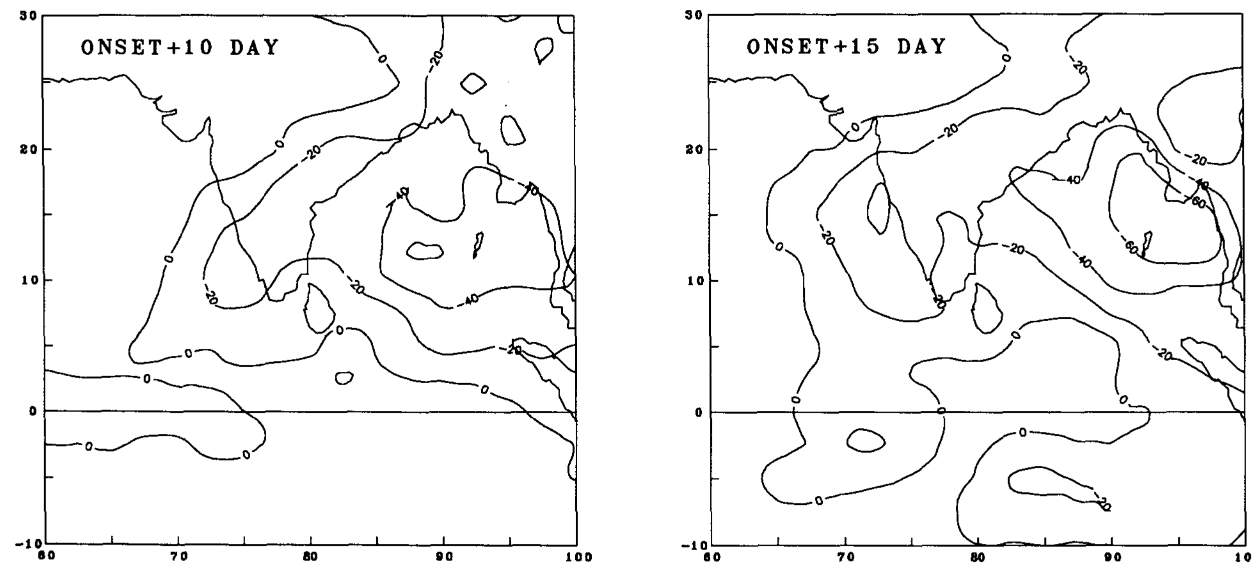
also increases simultaneously. The convective area over the Arabian Sea moves northward rapidly and intensifies further in the next five days. On the onset day, deep convective clouds (OLR $\leqslant$ 180 W m^{-2}) can be seen off the Kerala coast. During the next five days the cloud mass over the Arabian Sea moves northward along the west coast. The deep convective activity shifts to east Bay of Bengal after the onset. The convective activity over the Arabian Sea decreases by (onset + 10) day while it increases over the northeast Bay of Bengal. The OLR over the whole of peninsular and eastern India becomes less than 220 W m^{-2} by 15 days after the onset over south Kerala.

4. Discussion and conclusions

Circulation and moisture changes associated with the onset of the southwest monsoon over south Kerala were examined using a composite approach. The composites were prepared with reference to a uniform set of onset dates for south Kerala based on a criterion involving only rainfall.



(c)



(d)

FIG. 8. (*Continued*)

The rainfall composites show sharp increases over stations along the west coast with progressive lag from south to north. Stations like Calcutta and Nagpur whose normal onset dates are within 20 days of the Kerala onset also show this increase. However, for stations on the southeast coast of India, the important factor for declaring the onset of the southwest monsoon is circulation rather than rainfall.

The first change with the approach of the monsoon is the gradual strengthening of the equatorial easterlies in the upper troposphere. They strengthen, descend downward, and spread northward. The easterlies attain a strength of 20 m s^{-1} in the layer between 300 and 100 hPa over the tip of the peninsula at the time of the onset over south Kerala. The ZKE associated with the easterlies in the layer increase rapidly after the onset and attain a value of about 400 J kg^{-1} by (onset + 10) day. The subtropical westerlies in the upper troposphere over north India start weakening from about 30 to 20 m s^{-1}, slowly at first and more rapidly as the onset date approaches. However, the ridge line separating the easterlies and westerlies above the 700-hPa level at about 17°N does not move northward until the onset. After the onset over Kerala it moves rapidly northward but the core of the westerlies retains the strength of about 20 m s^{-1} for about two weeks.

At lower levels (1000–700 hPa) over the Indian peninsula, the ZKE does not show any appreciable change from −20 days to the onset day. The surface westerlies rapidly deepen to about the 400-hPa level with the onset. The strength also increases to 10–15 m s^{-1} between 800 and 700 hPa. A stationary east-west trough line appears about ten days before the onset at the tip of the peninsula from 700 to 400 hPa in the composite flowcharts (Figs. 3a,b). Careful examination of the first appearance of this trough line in relation to the onset in a number of years may lead to some useful insight that can be of help in medium-range forecasting of monsoon onset over Kerala. After the onset the trough line moves rapidly northward along the west coast to about 22°N taking the monsoon along with it. This trough in the composite may be regarded as the manifestation of the onset vortex noticed in some years over the eastern Arabian Sea during the onset. The study indicates that the onset vortex is more prominent between 600 and 400 hPa.

Vertical distribution of relative humidity shows rapid deepening of the moist layer a few days before the onset (Fig. 6) at the respective stations. In the composite, this moisture buildup occurs in two epochs: (i) over the southern peninsula about a week before the onset and (ii) over the rest of the country, except the northeastern parts, immediately after the onset. The present study brings out the large-scale increase in atmospheric moisture content over the Indian landmass before the strengthening of the monsoon flow, similar to the increase noticed over the Arabian Sea. The composite vertically integrated transport of moisture also shows rapid increase with the onset over peninsular India. In the composite, the transport across Bombay shows 180° turning from easterly to westerly on the sixth day after the onset over south Kerala, which lends support to the increase in rainfall at this station six days after the Kerala onset (Fig. 2). This indicates that the normal onset date for Bombay is 6 June rather than 10 June as shown in Fig. 1. Comparison of moisture transport over Madras and Mangalore, which are located at practically the same latitude, shows simultaneous increase in the transport suggesting a simultaneous onset over both these stations, although the rainfall at Madras shows hardly any increase as against the large increase at Mangalore.

The rapid development of convective activity over the southeast Arabian Sea and west coast and its northward movement as seen from the OLR composites (Fig. 8) confirm the conclusions from the land-based data. The main convective area before the monsoon onset is over the northeast Indian Ocean. A convective area develops near the equator in the vicinity of 70°E about five days before the onset over south Kerala. The intensification and northward movement of this convection brings the first monsoon rains over Kerala. After the onset over Kerala, deep convection again shifts to north-central and eastern Bay of Bengal.

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