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On the onset of summer monsoon over India in relation to interactions of the monsoon stationary wave with transient baroclinic waves leading to monsoon cyclogenesis

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सार - भारत में ग्रीष्मकालीन मानसून के शीघ्र अथवा विलम्ब से आने की महत्वपूर्ण समस्या का इसमें अध्ययन किया गया है और यह देखा गया है कि स्थल-समुद्र तापीय विषमता के कारण उस क्षेत्र में बनने वाली अप्रगामी मानसून तरंगावलि की संरचना और व्यवहार से इसका संबंध है। यह अप्रगामी मानसून तरंगावलि एशिया के उपोष्ण क्षेत्र से चलने वाली पश्चिमी और पूर्वी हवाओं में उत्पन्न होने वाले विक्षोभ के साथ अन्योन्यक्रिया करती है। भारत में मानसून का शीघ्र अथवा विलम्ब से आना इस प्रकार से एक दूसरे को प्रभावित करने वाली इन मानसून हवाओं के परस्पर मिलने अथवा इनके न मिल पाने पर निर्भर करता है। चूँकि उत्तराभिमुखी मानसून हवाओं में बनने वाले अवदाबों के कारण मानसून शीघ्र आ जाता है अतः इस अध्ययन में ऐसे विक्षोभों को उत्पन्न करने वाली पारस्परिक क्रिया और विक्षोभों के विकास और उनकी गति का विस्तृत विश्लेषण किया गया है।

ABSTRACT. The important problem of the early or late onset of summer monsoon over India is addressed in the present study and found to be related to the structure and behaviour of a monsoon stationary wave that forms over the region due to land-sea thermal contrast and interacts with travelling wave disturbances in the westerlies and the easterlies associated with the subtropical belt over Asia. Depending upon the type of coupling and decoupling that occurs between the interacting waves, monsoon advances towards India either slowly or speedily. Since northward–propagating monsoon depressions are found to accelerate the onset processes, the study carries out a detailed analysis of the interaction processes which give rise to such disturbances and determine their development and movement.

Key words — Onset of summer monsoon, Tropical-mid latitude interactions, Developments and movement of monsoon depression.

1. Introduction

Monsoon rainfall is vitally important for crop production in India and other countries of Southeast Asia. However, as records testify (*e.g.*, Ananthakrishnan *et al.*, 1968; Rao, 1976; Mooley and Shukla, 1987), the coming of monsoon at a place in any year is seldom at the expected normal date of onset worked out by the India Meteorological Department (IMD, 1943) on the basis of the rainfall record of that place. In fact, the actual date may vary from the normal date by several days or weeks. For example, in 1996, monsoon arrived before normal date over the northwestern parts of the country, was more or less on time over the Arabian sea and the west coast of India but arrived nearly two weeks late over the Bay of Bengal and adjoining northeastern parts of India (Fig. 1). The dates were estimated mainly on the basis of the first burst or incidence of sustained rainfall of the season, though other associated features, such as sudden drop in air temperature and increase in humidity at surface and appearance of thick cloud bands overhead as observed by satellites were also taken into consideration.

Little definite is known or documented regarding the factor(s) that might be responsible for early or late onset of monsoon , though it is generally believed that monsoon is ushered into India by the northward advance of the equatorial trough of low pressure or its associated upper-tropospheric ridge of high pressure, which generally follows the seasonal movement of the sun. Direct or

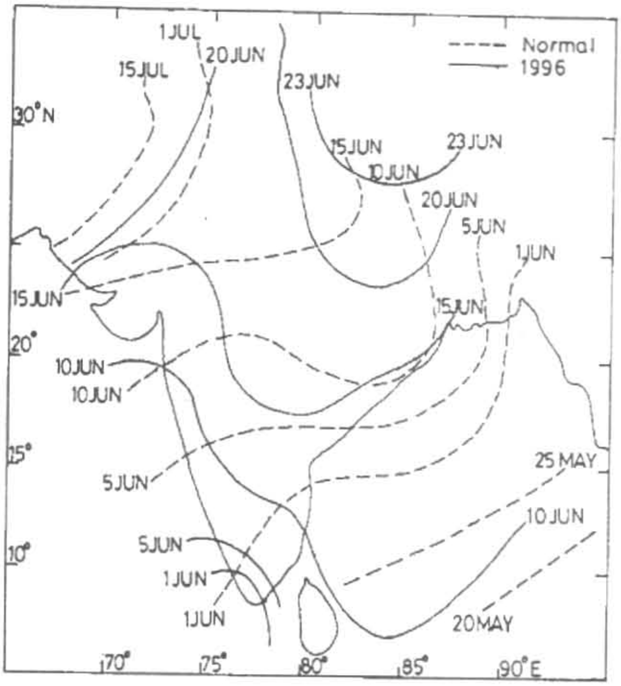


Fig. 1. Isolines of dates of onset of summer monsoon over India Normal (- - -), 1996 (—)

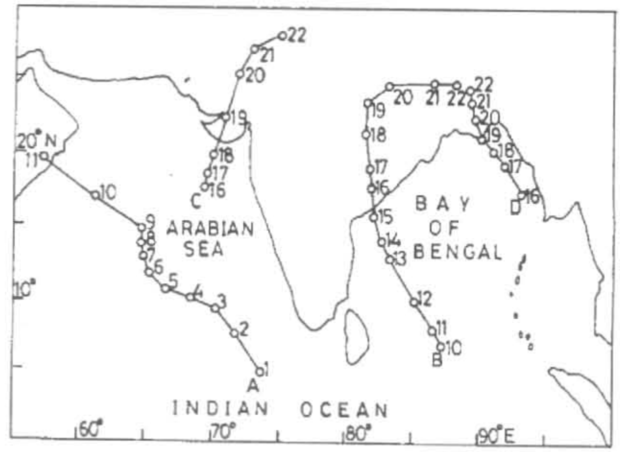
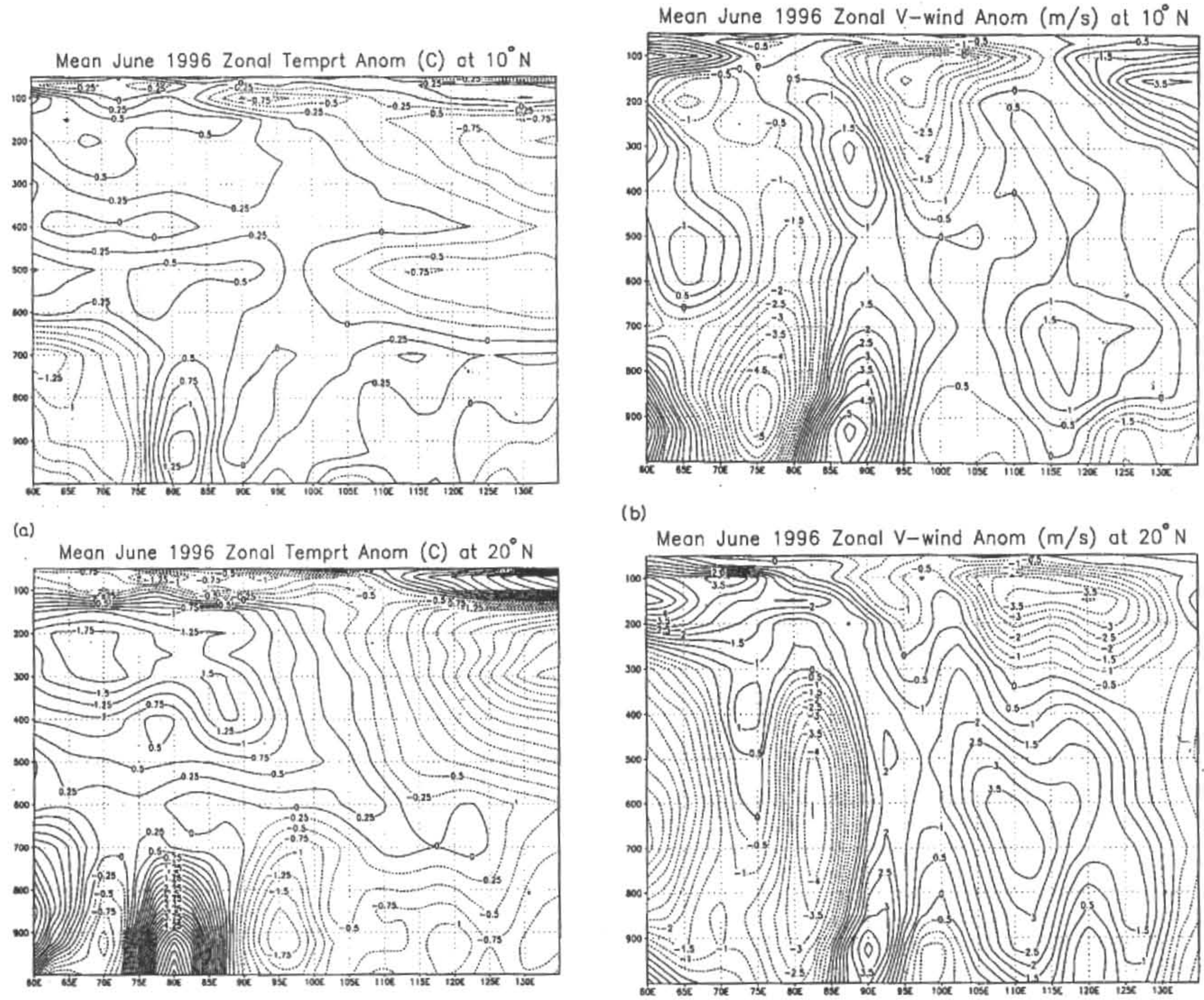


Fig. 2. Tracks of monsoon depressions (A-D) over the Indian seas, showing daily locations of their centres at MSL at 1200 UTC, 1-22 June 1996

indirect influences of several global and/or regional factors, such as El-Nino/ Southern Oscillation (ENSO) in the Pacific ocean (*e. g*., Joseph *et al*., 1994), large-scale snow cover on the mountains (Dey and Bhanukumar, 1982: Ropelewski *et al*., 1984), interhemispheric influences from across the equator (Sikka, 1980; Sikka and Gray, 1981), latitudinal movement of the subtropical ridge over India (*e.g*., Banerjee *et al*. , 1978; Mooley *et al*., 1986), prior moisture build-up over the Arabian sea (Pearce and Mohanty, 1984), have been suggested. The observed deviations from the normal date are obviously due to the different rates of northward advance of the monsoon in different years. In some years, the advance is accelerated (delayed) by the early (late) formation and movement of monsoon depressions. However, an onset due to the movement of monsoon depressions occurring too early in the season, *i.e*., much before the normal date, may not last long and monsoon may revert back to its original location soon after the disturbances fill up. In some years, monsoon may stagnate or its advance retarded by continued westerly wave activity over India (Biswas *et al*., 1998). In 1996, monsoon advanced over India in association with as many as four depressions/cyclonic storms which formed over the northern Indian ocean and moved initially NNW-ward but later recurved northward or even NNE-ward. The daily locations of the centres of these disturbances as estimated from available meteorological data and INSAT satellite cloud imagery are shown in Fig.2.

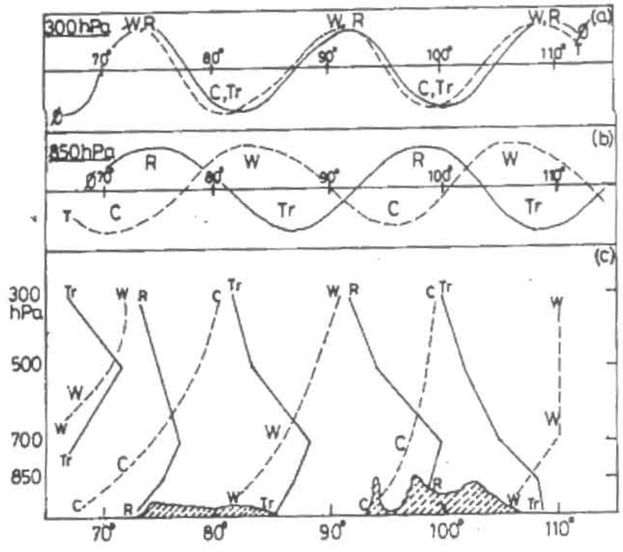
Since the onset of monsoon is intimately linked with the movement of the equatorial trough of low pressure and/or the disturbances that may occur in it, the object of the present study is to address the following questions: (*i*) Is there any basic structural pattern in which monsoon advances over land and sea? (*ii*) Why do monsoon disturbances tend to form in some preferred locations, usually the wave trough zones? (*iii*) What causes the observed fluctuations in the intensity of a disturbance during its lifetime? and (*iv*) What determines the direction of movement of monsoon depressions? These are fundamental questions which plague the minds of every weather forecaster and to which no satisfactory answers are yet available. It is well-known (*e.g*., Fu *et al*., 1983; Saha and Chang, 1983; Saha and Saha, 1996) that a stationary wave develops along the southern periphery of a giant 'heat low' at surface over Asia and adjoining Indian ocean due to land-sea thermal contrast during the northern summer. There is sufficient synoptic evidence to suggest that most of the monsoon depressions originate in the trough zones of stationary wave. Attention is, therefore, directed to examine how the structure and properties of this stationary wave existing at about the time of onset of summer monsoon reacts to the passage of the transient waves travelling in the westerlies and the easterlies along the northern and the southern boundaries respectively of the subtropical belt, the underlying idea being that the factors responsible for early or late onset of monsoon may, perhaps, arise as a result of these interactions. Attempts will be made to identify the specific types of interactions that would normally be associated with formation, development and movement of monsoon depressions, using the data for the year 1996 in detail. The conclusions reached and the mechanisms suggested by the study of 1996 onset will be tested in some other years, especially 1979, 1997 and 1998.



Figs. 3 (a&b). Zonal-vertical sections along 10° N and 20° N showing the distributions of zonal anomaly (deviation from zonal mean) of (a) temperature (° C) and (b) the meridional component of the wind ($m\ s^{-1}$)

2. Data and analysis

Data used for the study were obtained from two main sources. These are: (*i*) the National Centre for Environmental Prediction (NCEP), Washington, D. C., USA and (*ii*) the India Meteorological Department (IMD) at New Delhi. Data from source (*i*) include the basic 0000 and 1200 UTC daily winds and temperatures at surface and standard pressure surfaces 850, 700, 500, 300, 200 and 100 hPa over an area bounded by the equator and 50 ° N and longitudes 40°E and 120°E during the period 25 May through 24 June 1996. The authors also obtained from the same source the daily 0000 and 1200 UTC analyses of winds, temperatures and humidity-mixing-ratios, as well as computed values (in graphical form) of wind divergence, vertical velocity and vertically-integrated thermal advection for the same period and over the same region in 1996 and the daily 1200 UTC analyses of winds and temperatures for June 1997 and 1998 over the same region. From source (*ii*) the authors obtained synoptic data at 0000 and 1200 UTC daily at surface and 850 hPa over a period of six days (7 to 12 June) over the Indian ocean region. From the same source they also obtained daily satellite cloud imageries (INSAT pictures) and rainfall data as plotted on special rainfall maps for close monitoring of the onset process. The authors' independent manual analyses of basic data *i.e.*, winds and temperatures were available to compare with the NCEP analyses. They found that the latter were quite reliable over the tropics in general, except over data-void oceans.



Figs. 4 (a-c). Trough-ridge system of the monsoon stationary wave in relation to temperature wave at (a) 300 hPa and (b) 850 hPa and (c) in a zonal-vertical section along 20° N over India (After Saha and Saha, 1996). ϕ- geopotential, T – temperature, C– cold. W – warm, R – ridge and Tr– trough

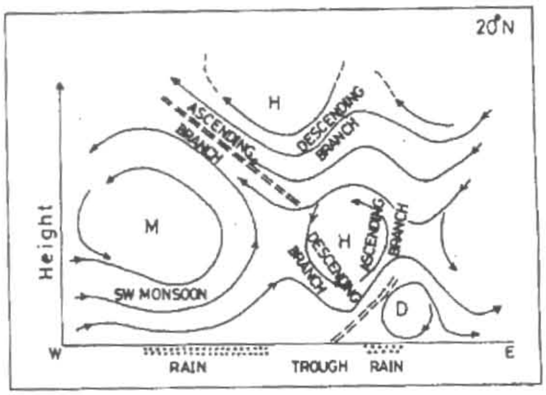


Fig. 5. Schematic showing on the zonal-vertical plane along 20° N projections of the two segments of the monsoon trough (double-dashed) and their associated circulation and weather (cloud and rain) zones(dotted). Symbols M stands for monsoon, D for depression-forming cell and H for elevated Hadley cell associated with D and M

3. Structure and properties of the disturbances

(a) *Monsoon stationary wave*

The monsoon stationary wave referred to in section 1, which is generated and maintained by land-sea thermal contrast over India, starts forming up over the southern parts of the peninsula early in summer, say from April onward, with low pressure over the warm land and high pressures over the relatively cool seas to both west and east, in the lower troposphere. However, due to vertical reversal of the horizontal pressure field, a low (high) in the lower troposphere is capped by a high (low) in the upper troposphere, whereas the horizontal temperature field remains more or less invariant with height. Thus, in the monsoon stationary wave, a 'warm high' is located above a 'warm low' and a 'cold low' above a 'cold high'. It is important to recognize this vertical structure that binds the lower to the upper troposphere in the monsoon stationary wave and controls the observed zonal circulation over the region, westerlies in the lower troposphere and easterlies above. Till about mid-May or early June, the monsoon stationary wave remains more or less stationary over the extreme southern part of India with its lower tropospheric trough along about 10° N and upper tropospheric ridge along about 15° N. However, by the middle of third week of June, the lower tropospheric trough moves to a latitude of about 20°-25° N, bringing up the monsoon westerlies over most parts of southern India. However, as already mentioned, the rate at which the monsoon advances is highly variable from year to year and from place to place. It will be shown in subsequent sections that the movement of the monsoon stationary wave depends crucially on its interaction with transient waves in subtropical westerlies which move eastward across northern India during this period.

Some recent studies (*e.g.* , Fu *et al.* ,1983; Saha and Chang, 1983; Saha and Saha, 1996) have thrown light on the detailed structure and the properties of the monsoon stationary wave and stressed its importance in the context of the observed weather and climate over the region. The existence of this wave in temperature and wind field is testified by Figs. 3(a & b) which show the zonal anomaly of the monthly mean values of these parameters in zonal-vertical sections along 10°N and 20° N respectively. According to Saha and Saha (1996), the trough ridge system of the stationary wave tilts eastward with height in the lower troposphere where the prevailing wind is mainly westerly and westward with height in the upper troposphere where the prevailing wind is easterly. Also, there appears to be a phase difference between the geopotential and the temperature fields with the temperature field lagging behind the geopotential field, looking downstream, in both the lower and the upper tropospheres (Fig. 4, taken from Saha and Saha, 1996). Further, it is well known that in addition to the zonal tilt, the monsoon trough over India tilts equatorward with height. A projection of the circulations associated with the monsoon trough on the zonal vertical plane, found by Saha and Saha, (1996), is shown schemetically in Fig. 5 which indicates the main areas of cloud and rainfall

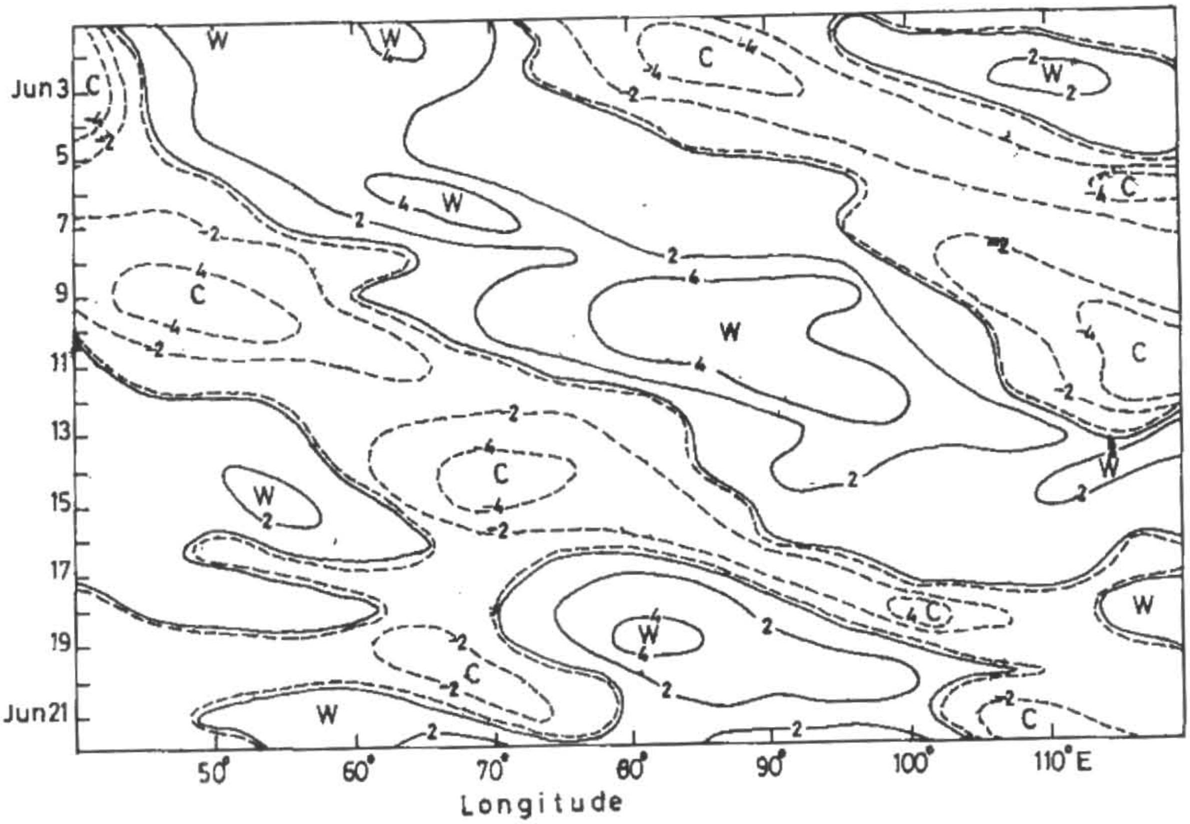
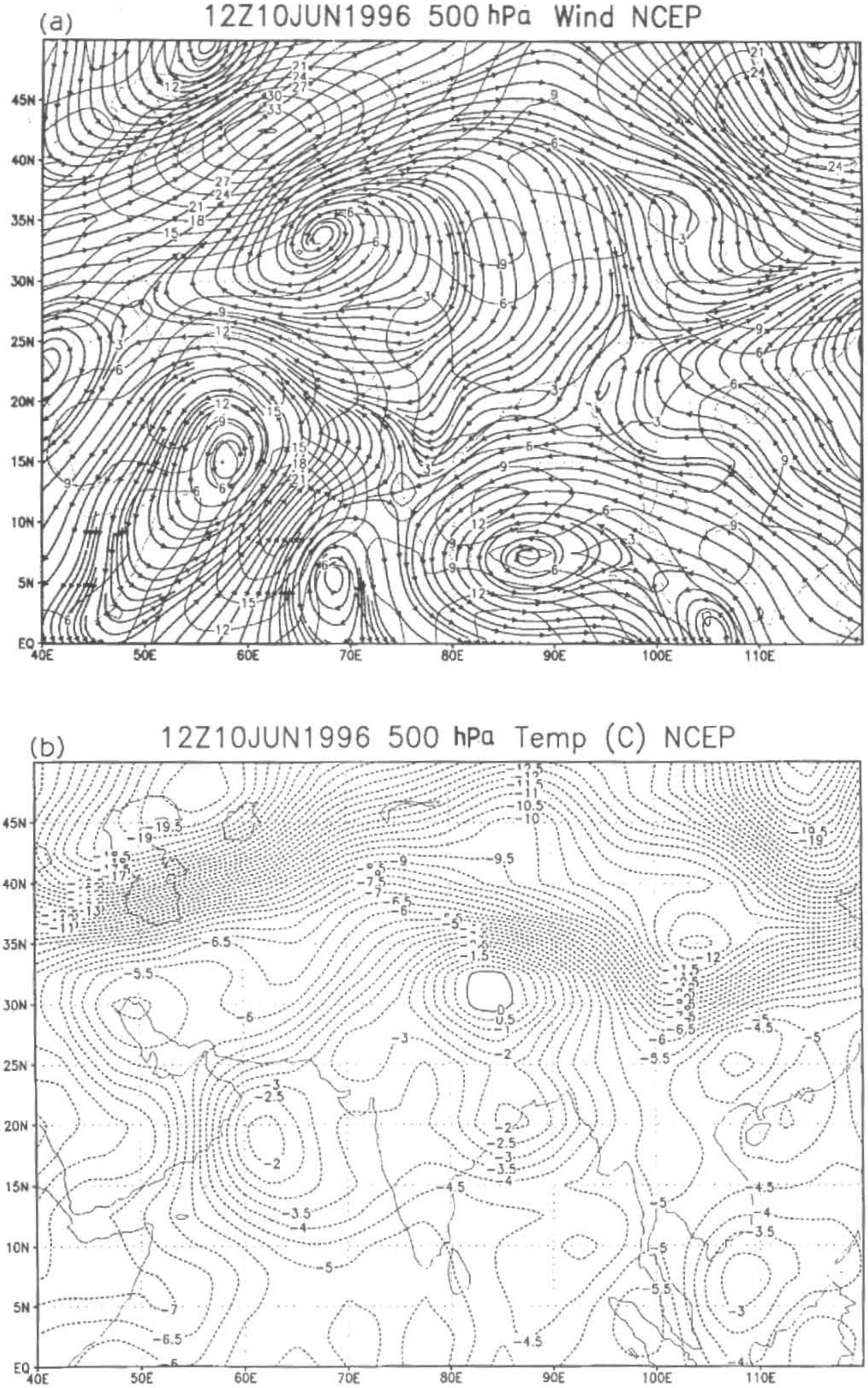


Fig. 6. Time-longitude diagram showing distribution of zonal anomaly of temperature (°C) at 500 hPa along 45° N daily during the period 1 through 22 June 1996. W – warm, C – cold

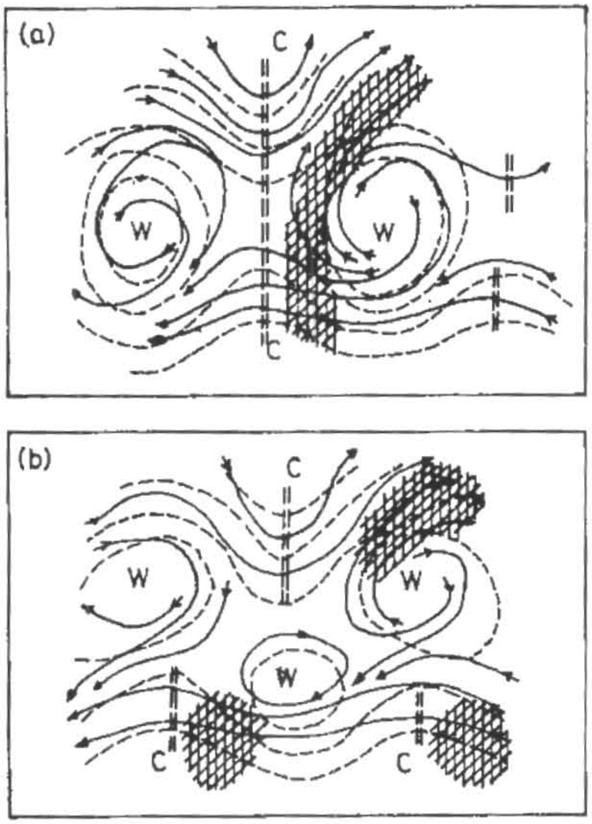
relative to the surface location of the trough which appears to have a rainfall minimum. The idealized circulations and the distributions of cloud and rain shown in Fig. 5 would appear to be consistent with the satellite-observed cloud distribution and the computed field of vertical motion relative to the centre of a Bay of Bengal monsoon depression over a coastal belt, reported by Sanders (1984) and several others.

(b) *Waves in the easterlies*

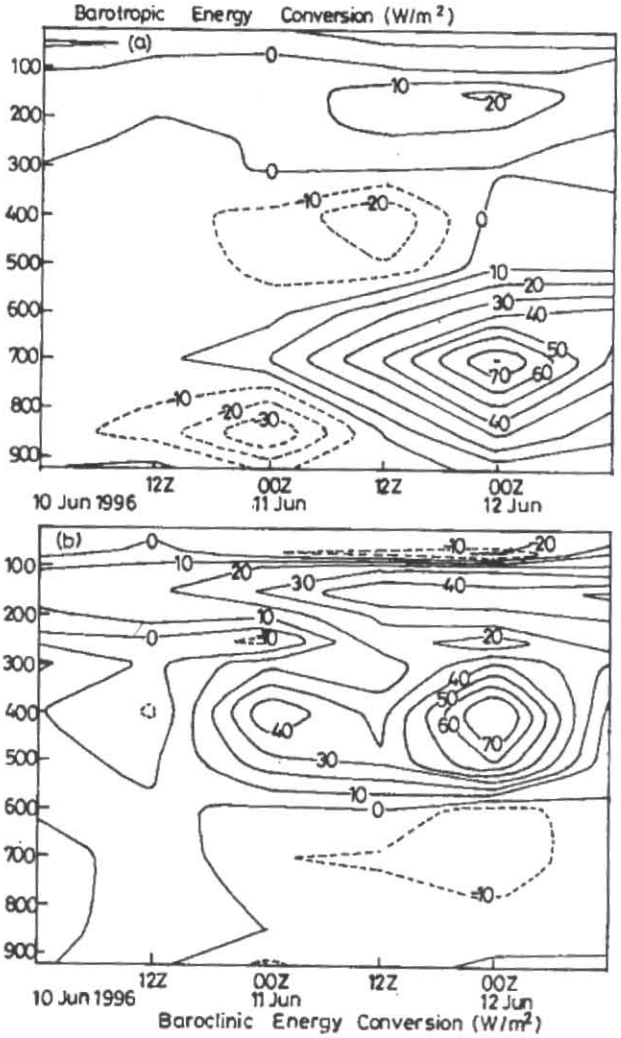
It is well known that the easterly thermal wind over the Indian region sustains a vertical wind profile in which the low-level westerlies decrease with height and give way to easterlies the speed of which increases with height to reach a maximum at the level of tropical easterly jet stream at about 150 hPa over southern India. For such a vertical profile of the zonal wind, Riehl (1954) who made an extensive study of the structure and properties of easterly waves over different parts of the tropics, found that the zonal-vertical tilt of the trough of these waves that moved from a region where the speed of the easterlies decreased with height to a region where it increased with height changed from eastward to westward with height. Reed and Recker(1971) who studied the structure and the properties of synoptic-scale disturbances in equatorial western Pacific also found a similar change in the zonal-vertical tilt of the troughs of these disturbances in the easterlies as they moved from the western Pacific towards the Asian monsoon region. These studies also showed that a change in the zonal-vertical tilt of the axis of the wave trough from eastward to westward was accompanied by a corresponding change in the distribution of cloud and rain from the east to the west of the surface location of the trough. These findings would appear to provide strong support to the structure and properties of the monsoon stationary wave in which the zonal-vertical tilt of the wave trough in the easterlies over the Indian region was found to be westward with height (Fig. 4). Since most of the easterly waves that affect the Asian monsoon drift from the far east and the western Pacific, it appears reasonable



Figs. 7 (a&b). NCEP analysis of (a) wind (ms $^{-1}$) and (b) temperature (° C) at 500 hPa at 1200 UTC on 10 June 1996 over the Asian monsoon region



Figs. 8 (a&b). Schematic showing typical circulation patterns (—) and isotherms(- - -) at about 500 hPa in an (a) In-phase and (b)out-of-phase interaction between a monsoon trough/depression and its mid-latitude counterpart. Associated cloud and rain zones are shown by hatching. W – warm, C – cold



Figs. 9 (a&b). Vertical distributions of barotropic and baroclinic energy conversion (unit : $10^{-2}Wm^{-2}$) at 12-hourly intervals from 0000 UTC 10 June through 1200 UTC 12 June 1996 : (a) barotropic and (b) baroclinic

to assume that on entering the Asian monsoon region they have the structure and properties similar to those found in the monsoon stationary wave.

(c) *Waves in baroclinic westerlies*

The structure and properties of waves in subtropical or mid-latitude westerlies have been documented in several publications (*e. g.* , Palmen and Newton, 1969; Holton, 1979). These wave disturbances form over a latitudinal belt in which the thermal wind is westerly and are associated with warm and cold sectors, with the cold sector generally lying to the west of the wave-trough and the warm sector to the east, a zonal arrangement quite opposite to that in the monsoon stationary wave or monsoon disturbances. In consequence of this arrangement, the trough-ridge system of the waves in the baroclinic westerlies tilts westward with height and a developing wave has usually a phase difference between the geopotential and the temperature fields with the temperature field lagging behind the geopotential field, looking downstream, in the lower troposphere. The phase difference leads to warm advection and upward motion to the east of the trough and cold advection and downward motion to the west. The trough-ridge system generally moves eastward in the prevailing westerlies, as shown in Fig. 6 which is a time-longitude diagram of daily distribution of zonal anomaly of temperature at 500 hPa along 45° N latitude during June 1996.

Some of the important differences in the structure and properties of waves in baroclinic westerlies and their monsoon counterparts have recently been summarized by

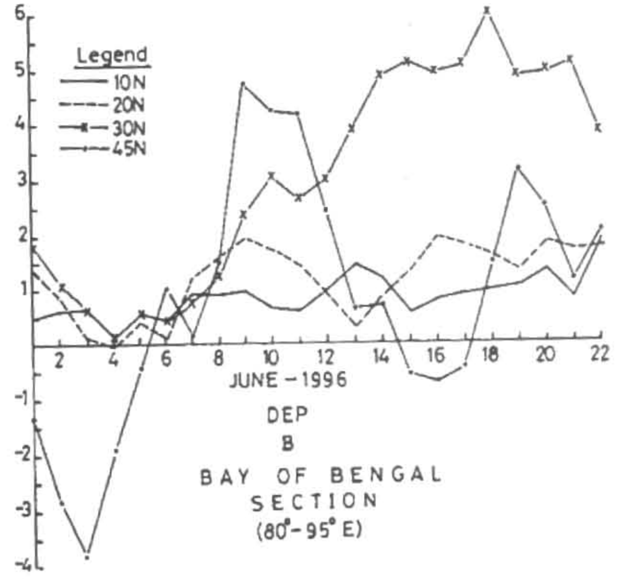


Fig.10. Daily distribution of mean zonal anomaly of temperature (°C) at 500 hPa, averaged over the longitude band (80°E–95°E) (Bay of Bengal) sector along 10°N (—), 20°N (- - -), 30°N (-x-) and 45°N (- · -) during the period 1 through 22 June 1996

Saha and Saha (1996). For example, the average wavelength, temperature amplitude and speed of movement of a wave in the westerlies over the Asian region are about 5000 km, 5° C and 5-10 ms^{-1} respectively, whereas the corresponding figures in respect of a monsoon disturbance are about 1500-3000 km, 1-2°C and 2-5 ms^{-1}.

4. Interaction between disturbances of high and low latitudes

Over the non-monsoon regions of the globe, such as the Pacific and the Atlantic oceans, waves in subtropical/mid-latitude westerlies and tropical/equatorial easterlies moving in their respective latitudinal belts in opposite directions, often interact directly across the latitudes when they approach a common longitude, producing what are known as extended troughs and ridges. Such interactions often lead to amplification of the waves and birth of a new tropical disturbance (*e.g.* ,Riehl, 1954). Over the monsoon region, such direct interactions seldom occur. Here, the interactions are almost always with the monsoon stationary wave that exists over the region. Normally, the stationary wave may interact with one of the wave trains at a time but occasionally it may involve both. Such an interaction with either of the moving wave trains effectively means that, on arriving at or near a common longitude, the warm (cold) sector of the moving wave may be superimposed, though temporarily, on the warm (cold) sector of the stationary wave and in the case of an interaction with a disturbance in the subtropical westerlies, this superimposition may occur despite known differences in their structure and properties especially in regard to their wavelength and amplitude. When the warm (cold) sector of one wave is superimposed upon the warm (cold) sector of the other, one may call it 'in-phase' interaction. When the interaction is in the opposite phase, *i. e.*, when the warm (cold) sector of one wave is superimposed upon the cold (warm) sector of the other, it will be called an 'out-of-phase' interaction. In the case of an in-phase interaction, an extended trough-ridge system may form between the two latitudinal belts. An example of such an interaction of the monsoon stationary trough with a mid-latitude/subtropical disturbance is presented in Fig. 7 which shows the NCEP analyses of (a) temperature and (b) wind fields at 500 hPa at 1200 UTC on 10 June 1996. A schematic showing the manner in which the circulation and the associated thermal patterns may organize themselves in an (a) in-phase and (b) an out-of-phase interaction between the disturbances of low and mid-latitudes in the upper troposphere is presented in Fig. 8.

5. Development of monsoon troughs/depressions

By development of a trough of low pressure, one really means its deepening or intensification as given by the expression, $\dfrac{\partial^2}{\partial x^2}\left(\dfrac{\partial p}{\partial t}\right)$, where p is the pressure at the trough axis, t is time and x is a coordinate axis perpendicular to the trough line. If the pressure system is a low or depression , and p is pressure at the centre, the intensification is given by the expression, ∇^2 $(\partial p/\partial t)$, where $\partial p/\partial t$ the pressure tendency is given by the approximate relation:

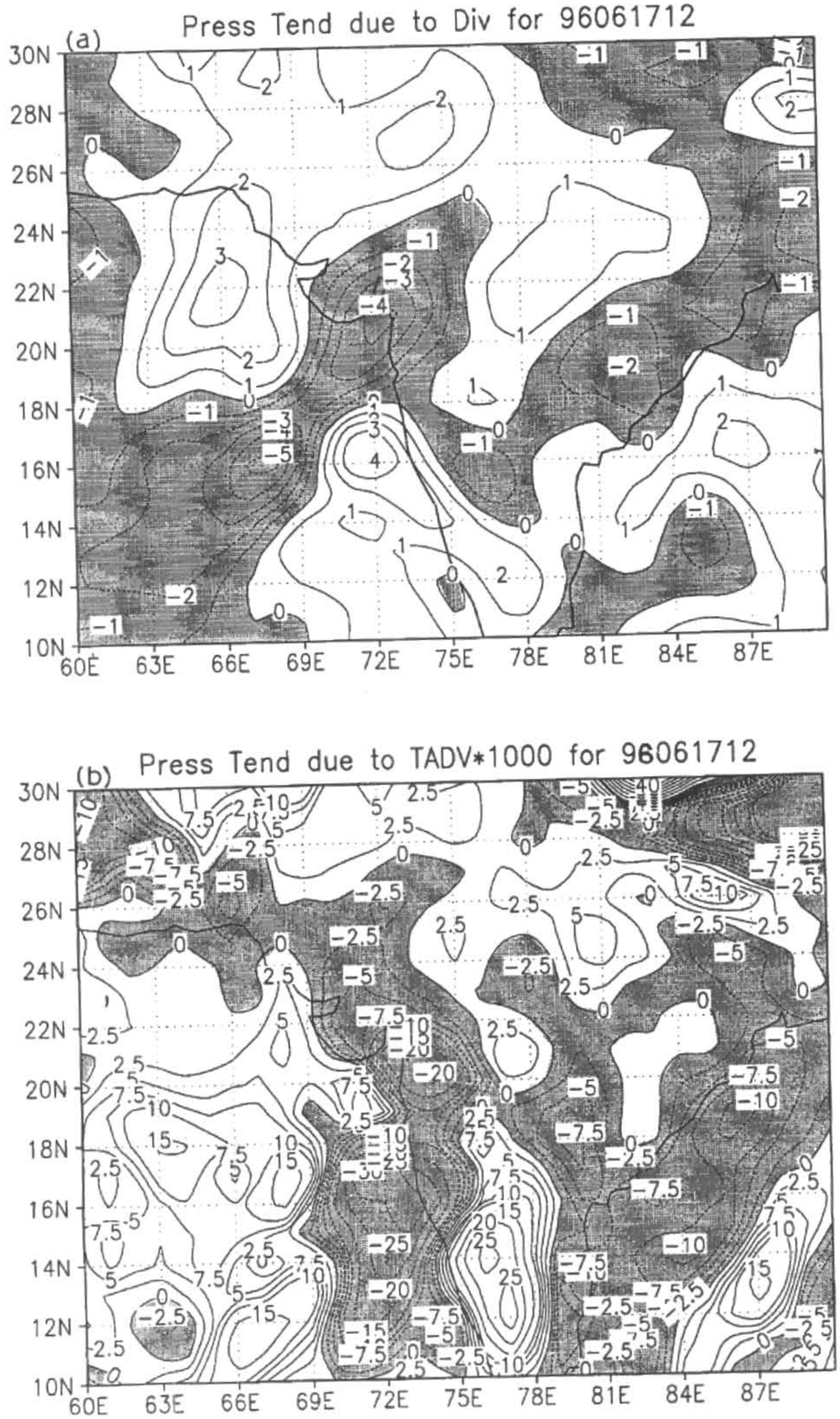
$$\frac{\partial p}{\partial t} = -\int_0^{p_0} \left[\nabla_p \vec{V} - \left(\vec{V} \bullet \nabla_p T\right)/T\right] \delta p \qquad (1)$$

where p_0 is pressure at the earth's surface,

$\vec{V}$ is the wind vector at the p-surface with components, (u,v) positive towards east and north respectively,

and T temperature (°A).

The above kinematic relationship, which is derived from the hydrostatic equation after neglecting the vertical



Figs.11 (a&b). Fields of pressure tendency (Pa s^{-1}) due to vertically-integrated (a) divergence and (b) thermal advection at 1200 UTC on 17 June 1996 velocity at the lower boundary, incorporates the effects of both divergence of the wind and thermal advection on the development process.

In the past, three plausible mechanisms have been suggested for development of tropical disturbances. These are: barotropic instability of the flow arising from the horizontal shear of the wind (*e.g.*, Nitta and Masuda, 1981; Krishnamurti *et al.* , 1981), baroclinic instability of the flow due to vertical shear of the wind (*e.g.*, Mak, 1975; Brode and Mak, 1978; Mishra and Salvekar, 1980) and conditional instability of the second kind (CISK) brought about by condensational heating (Charney and Eliassen, 1964). Though extensive literature exists on all the three mechanisms and some (*e. g.*,Shukla, 1978) have even suggested the combined effects of all the three mechanisms in the formation of a monsoon depression or cyclone, the relative contribution of each of them to the over-all growth rate at various stages of development is yet to be worked out and no unified theory incorporating the possible effects of all the three mechanisms has yet been presented. In the present study, the authors make an appraisal of the relative importance of the barotropic and the baroclinic energy conversion processes separately in the case of a Bay of Bengal monsoon depression (marked B in Fig. 2) during its formative stage, by using the following expressions (after Lorenz, 1967):

Barotropic energy conversion,

$$\langle [K] \bullet K' \rangle = -\left(\frac{1}{g}\right) \int \{ \; [u'v'] \frac{\partial}{\partial y}[u] + [u'w'] \frac{\partial}{\partial p}[u] + [v'v'] \frac{\partial}{\partial y}[v] + [v'w'] \frac{\partial}{\partial p}[v] \; \} \partial p \qquad (2)$$

Baroclinic energy conversion,

$$<P' \, . \, K'> = -(\, R/g \,) \int \left\{ \left(\frac{\overline{w'T'}}{\mathrm{p}} \right) \right\} \delta \mathrm{p} \qquad (3)$$

Where, K, K' and P' are zonal kinetic energy, eddy kinetic energy and eddy available potential energy respectively over a closed domain, the prime denotes a deviation from the zonal average [′], and the two terms within the angular brackets denote conversions from the first to the second, R is gas constant for dry air and the other terms have their usual meanings. Results of the computations are presented in Fig. 9, which shows that at the formative stage of the depression, the baroclinic energy conversion was all-important but after the formation both the processes became active with barotropic conversion dominating in the lower troposphere and baroclinic in the upper troposphere. Ramanathan (1980) who computed the energetics of an onset vortex/depression over the Arabian sea during MONEX-1979 also found a similar result, *i e.*, the dominance of the barotropic process in the lower levels and baroclinic process in the upper levels.

CISK visualizes a mutually co-operative mechanism between condensational heating by small scale cumulus clouds and synoptic scale boundary layer convergence in the field of a depression. However, its applicability to intensification of a monsoon depression which can explain warming of the atmosphere and lowering of pressure near its centre when major condensation occurs over its southwest quadrant, far away from the centre, is yet to be demonstrated. Observational studies, such as those of Dixit and Jones, (1965), Ramage (1971) and Saha and Saha (1993a) appear to support CISK hypothesis, though the exact manner in which the mechanism operates to create warming and lowering of pressure near the centre needs to be identified. Saha and Saha (1993a) found that in the field of a westnorthwest-ward moving monsoon depression over the Arabian sea, maximum upward motion and diabatic heating due to condensation occurred in the southwest quadrant while downward motion and diabatic cooling occurred over the northwest quadrant. The authors are of the view that in all probability the CISK mechanism in a monsoon depression may operate *via* the elevated Hadley cell circulation (Fig. 5), the ascending branch of which represents condensational heating and the descending branch adiabatic warming and lowering of pressure near the centre of the depression.

Following an in-phase interaction (Fig. 8), when warm advection from the extended warm ridge to the southern part of the extended trough to its west is maximized, conditions become favourable for development of a depression in the low level trough zone of the stationary wave. However, as the interacting waves separate and the depression moves from an in-phase to an out-of-phase interaction, the depression may weaken for a while before starting to intensify again when it returns to an in-phase interaction with a new wave in the westerlies. Thus, the intensity of a westward-propagating depression would seem to fluctuate as it moves from an in-phase to an out-of-phase interaction, or *vice versa*, with an eastward-moving wave in the subtropical/mid-latitude westerlies. This would seem to be substantiated by Fig. 10, which shows the daily distribution of the mean zonal anomaly of temperature at 500 hPa along four latitudes, *viz.*,10° N, 20° N, 30°N and 45° N, averaged over the longitude band, 80° E-95° E, which lies over the Bay of Bengal during the period 1 through 22 June 1996. It appears to bring out that during the first week of the month, there was a strong cold anomaly along 45°N and a mild warm anomaly along 10° N but after about 8 June a strong warm anomaly developed along all the latitude belts to the north of the Bay, suggesting an in-phase interaction of the stationary wave with a subtropical/mid-latitude baroclinic wave. This interaction led to the formation of a depression over the south Bay on 10 June. Similar development of a monsoon depression and fluctuations in its intensity may be expected to occur when a westward-propagating easterly wave may interact with the monsoon stationary wave. Koteswaram and George (1958) and Koteswaram *et al.*, (1987) hypothesized that a low-level monsoon trough may develop into a depression when the trough of an upper-level easterly wave gets superimposed on it. The finding of the present study which requires the warm ridge of the easterly wave to be superimposed on the low-level trough for development would appear to be at variance with their conclusion.

6. Movement

There are several aspects of the movement of a monsoon depression which remain unclear. Why is it that sometimes it moves at a crawling speed and at other time simply races? Why is it that sometimes it fills up shortly after birth, say in a couple of days, and at other times is able to survive over a long period and cover a long track, say from south China sea to Bay of Bengal or from Bay of Bengal to Arabian sea? Why is it that some times it moves westward but at other times recurves northward or even northeastward? A mass-weighted steering current has often been mentioned in the literature but it is difficult to see how such a simplistic concept can explain such a diverse character of the movement, as mentioned above.

According to kinematic considerations (*e.g.*, Petterssen, 1956), a depression or a cyclonic storm moves in the direction of the isallobaric gradient across its centre with a velocity $\vec{C}$ given by :

$$\vec{C} = -\nabla (\partial p/ \partial t)/ \nabla^2 p \qquad (4)$$

where $\partial p/\partial t$ is the pressure tendency given by relation (1). To test the validity of relation (4), the authors computed the values of vertically integrated divergence and thermal advection daily for a period of 6 days, *i. e.*, from 15 through 20 June 1996 in the case of Arabian sea depression (marked C in Fig. 2). The contributions of the two terms in equation (1) were calculated separately, since

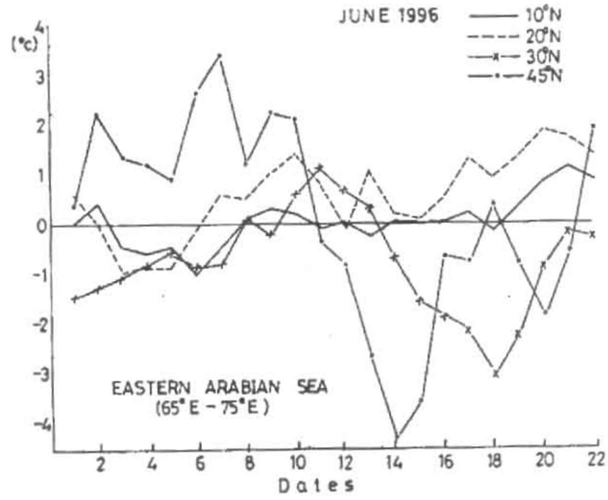


Fig.12. Distribution of daily mean zonal anomaly of temperature at 500 hPa, averaged over the longitude band (65°E–75°E) (Arabian sea sector), along latitudes 45°N, 30°N, 20°N and 10°N, during the period 1 through 22 June 1996

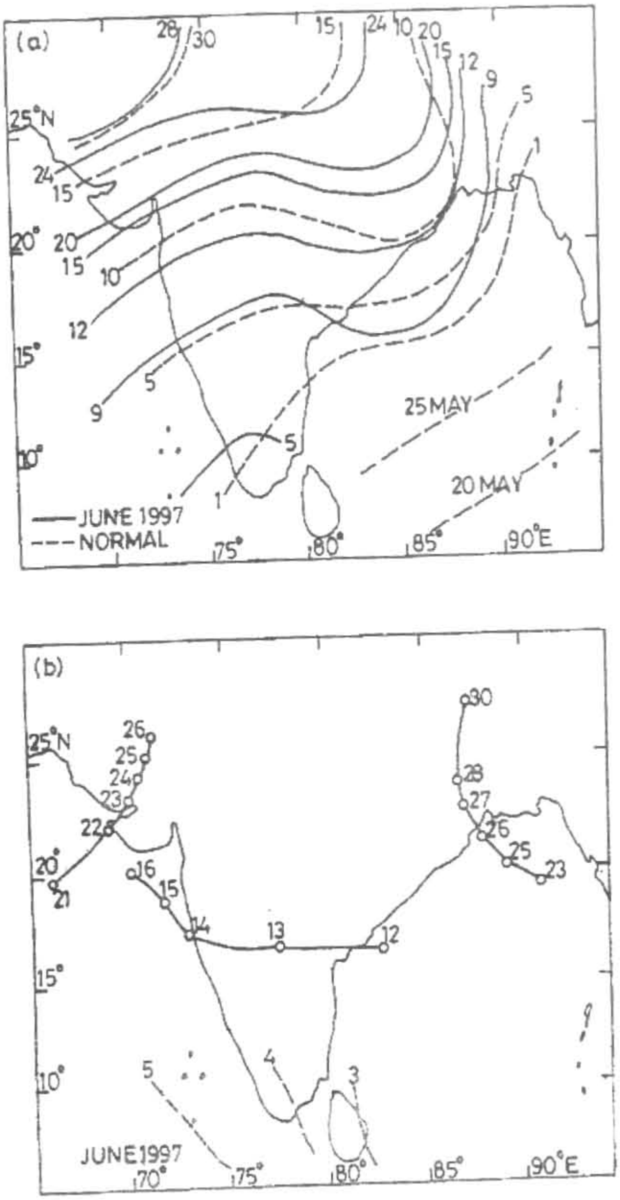
it was found that while the term involving thermal advection yielded pressure tendency of the right order of magnitude when compared with observed values which seldom exceed (+/–) 10 hPa per day, that due to divergence turned out to be nearly three orders of magnitude larger. An example of the computed field is presented in Fig. 11 which shows the contribution to the pressure tendency separately by (a) divergence and (b) thermal advection at 1200 UTC on 17 June 1996 when the depression was centred near 19° N, 70° E. Separately, the isallobaric gradient across the centre in both would seem to suggest a northward movement of the centre, as actually observed. A westward movement of the depression was prevented by the rising pressure to the west due to cold air advection from a westerly trough, as evidenced by Fig. 12 which presents the daily mean zonal anomaly of temperature at 500 hPa for the longitudinal section, 65° E – 75° E (Arabian sea section), for June 1996.

7. Onset in some other years

The authors looked into the observed anomalies in the date of onset of monsoon in several other years, but would concentrate, for lack of space, on their findings in three years only, *viz.*, 1979, 1997 and 1998. Yearwise, the findings are as follows:

(a) *1979*

This was the year of Summer Monsoon Experiment (SMONEX) over the Indian ocean and its programme included, inter alia, a study of the onset of monsoon over India and formation of monsoon depressions. The onset



Figs.13(a & b). (a) Dates of onset of monsoon, vis-à-vis the normal date, in June 1997, (b) Tracks of monsoon depressions, showing daily locations of their centres, June 1997. The dashed line denotes a trough of low pressure

was brought about by a northnorthwestward moving disturbance which later developed into a severe cyclonic storm over the mid-Arabian sea. A rapid northward advance of the monsoon occurred along the west coast of India between 10 and 20 June in association with the movement of this disturbance but the advance slowed down as the disturbance moved away westward. Several meteorologists have written regarding the formation and development of this disturbance (*e. g.*, Krishnamurti *et al.*, 1981; Ramanathan, 1980; Saha and Saha, 1993 a). Saha and Saha (1993a) showed that the formation of this disturbance was due to an in-phase interaction of the monsoon stationary wave with a deep, large-amplitude trough in the subtropical westerlies over the southeastern part of the Arabian sea on or around 14 June. Its initial northnorthwestward movement was also forced by the activity of this w'ly trough. However, between 16 and 18 June, it came to have another in-phase interaction with a second w'ly trough approaching northern Arabian sea from the west and it was this later in-phase interaction that led to the rapid intensification of the disturbance into a severe cyclonic storm on 17 June.

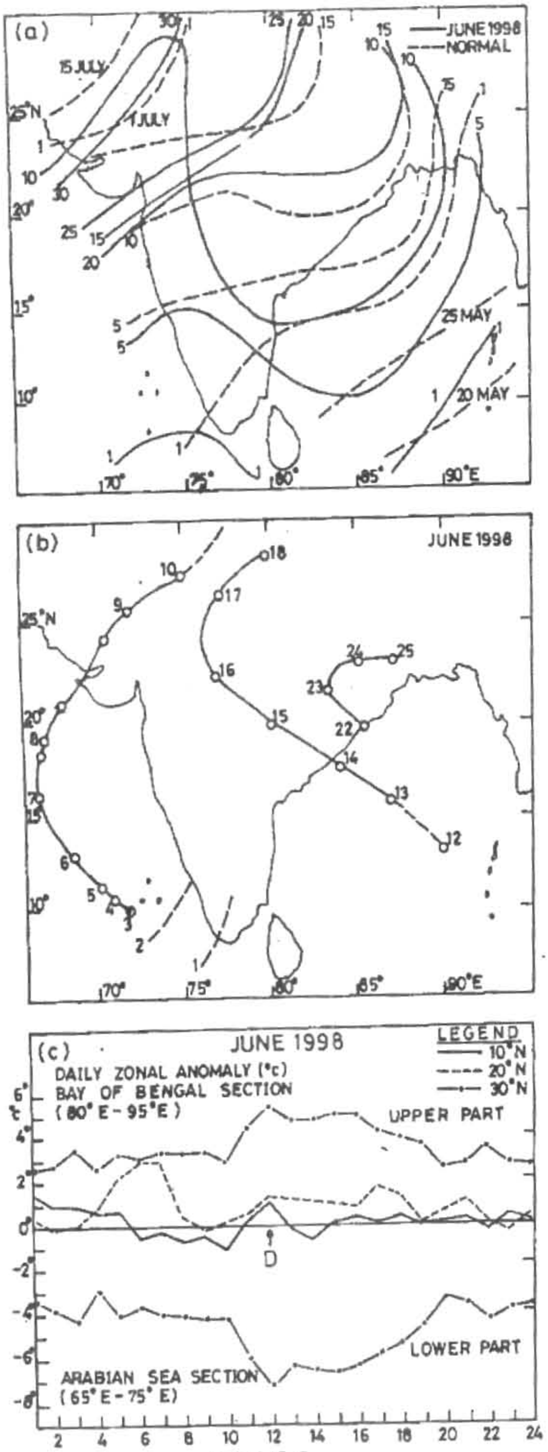
The onset of monsoon over the Bay of Bengal and the east coast of India was delayed by nearly another 10 days but the delay was offset by the rapid development of a depression that formed over mid-Bay on or about 20 June and moved first northwestward and then westward. The depression intensified on 27 June on entering the northeasten corner of the Arabian sea when it interacted in-phase with a subtropical w'ly trough but it died soon after when it came under the influence of the cold sector of the w'ly trough (Saha and Saha, 1993b). Under the influence of this depression, the monsoon advanced over the whole of southern and eastern parts of India by 25 June.

A third depression formed over the northeastern corner of the Head Bay of Bengal on or about 27 June and moved almost northward but it filled up over northeastern India by 30 June. Monsoon covered the whole of the country by 30 June. It is, therefore, evident that the onset of monsoon in 1979 was strongly influenced by the formation, development and movement of monsoon depressions.

(b) *1997*

The dates of onset of monsoon over India and the disturbances that formed over the ocean in June 1997 are presented in Figs. 13 (a & b). It may be seen that the onset was delayed over both the Arabian sea and the Bay of Bengal sectors but the delay was made up along the west coast of India by 12 June and along east coast by about 15 June.

In the first week of the month, a deep cold trough in the subtropical westerlies at 500 hPa extended equatorward to about 10° N over the Arabian sea and lay almost diagonally across peninsular India in a NE-SW orientation. The 'warm high' associated with this westerly trough covered most of the Bay of Bengal and in the south interacted with the warm sector of the monsoon stationary wave which at this time existed near Sri Lanka and gave rise to a trough of low pressure at low levels which



Figs.14 (a-c). (a) & (b) same as Fig. 13, but for June 1998, (c) Daily distribution of mean zonal anomaly of temperature (° C) at 500 hPa, over the longitude band (80° E–95°E) (Bay of Bengal sector), along latitudes 30°N, 20°N and 10°N and the longitude band (65°E–75°E) (Arabian sea sector) along 30°N during June 1998. Scale of temperature for 30°N is at left and that for 20°N and 10°N is at right

eventually moved westward during the following two days (Fig. 13b). The northward advance of the monsoon was delayed by the presence of the above-mentioned w'ly trough but as soon as the trough withdrew northeastward towards the end of the week, there was a rapid northward surge of the monsoon over the western part of the peninsula and the delay in onset in that sector was made up by 12 June. A depression formed over the Bay of Bengal as a result of an in-phase interaction of the warm sector of the stationary wave with the warm sector of a new subtropical w'ly wave. The depression after formation moved almost westward during the following three days and emerged over the northeastern corner of the Arabian sea where it filled up on 16 June.

Again, it was an in-phase interaction between the monsoon stationary wave and the subtropical w'ly trough that led towards the end of the month to the formation of two monsoon depressions, one over the Bay of Bengal and the other over the Arabian sea. Both the depressions after formation on or about 22 June were captured by the w'ly wave and moved to a northerly direction.

(c) *1998*

The year provided a real test case for the validity of the hypotheses advanced in the present study. Several diverse features of the monsoon onset process mentioned earlier were revealed. These would be evident from Figs. 14 (a-c). Figs 14 (a & b) are self-explanatory, while Fig. 14 (c) gives the values of the longitudinally-averaged zonal temperature anomaly at 500 hPa over the Bay of Bengal sector (80° E-95° E) along the three latitudes 30° N, 20° N and 10° N (the upper part) and over the Arabian sea sector (65° E- 75° E) along 30° N (the lower part) daily during the period 1 through 24 June.

Monsoon onset in 1998 was effected in two distinct phases : The first was an accelerated temporary advance by an Arabian sea severe cyclonic storm which originated first as a trough of low pressure near Sri Lanka on or around 1 June due to an in-phase interaction of the monsoon stationary wave with a well marked w'ly wave and then moving northwestward intensified into a deep depression/ cyclonic storm on 5 June. It intensified further into a severe cyclonic storm between 6 and 7 June over mid-Arabian sea and its track gradually recurved through north to a northnortheasterly direction under influence of a deep w'ly trough affecting the northwestern part of India from the west. Moving at an unprecedented speed of about 15 ms^{-1}, it crossed the Gujarat coast between 8 and 9 June and caused heavy loss of life and property in the coastal belt. However, monsoon onset effected by this cyclone was short-lived and northern limit of monsoon reverted back to a position near about 20° N over the peninsula.

A second phase of monsoon advance occurred after the formation of a monsoon depression over the Bay of Bengal on or around 12 June and its movement first in a northwestward direction which later veered to northward and then northnortheastward. The recurvature of the track of this depression was due to the presence of the cold sector of a subtropical w'ly wave to the west, as would be evident from Fig. 14 (c) which shows the marked temperature contrast between the Bay of Bengal sector (80°E-95°E) and the Arabian sea sector (65°E-75°E) along 30° N. Under the influence of the Bay depression, summer monsoon advanced over most of the country by the end of June. Another depression occurred near Head Bay towards the end of June but its role in the onset of monsoon was limited.

8. Findings and conclusion

The findings of the present study may be summarized as follows:

(*i*) A monsoon stationary wave which owes its existence to land-sea thermal contrast and resides at the southern boundary of the subtropical belt over southern Asia appears to have been involved in the onset and advance of monsoon over India in 1996 and some other years.

(*ii*) The observed deviation of the actual date of onset from the normal date in all the years appears to have been caused by early or late arrival of monsoon depressions/ cyclonic storms. The onset process was accelerated by a northward movement of these disturbances.

(*iii*) An in-phase interaction between the monsoon stationary wave and a transient baroclinic disturbance in which the warm (cold) sector of one is superimposed on the warm (cold) sector of the other in mid and upper-troposphere, appears to have provided the right condition for breeding of a disturbance in the trough zone of the stationary wave.

(*iv*) Development of a monsoon disturbance and fluctuations in its intensity appear to depend on the type of interaction between the stationary and the transient waves, *i.e.*, whether the interaction is in-phase or out-of-phase. It is the transition from an out-of-phase to an in-phase interaction that leads to rapid development.

(*v*) Recurvature and northward movement of a monsoon depression appears to take place when it moves from an out-of-phase to an in-phase interaction with a w'ly wave. The isallobaric gradient in such a situation gradually veers from westward to northward. Its further recurvature to northeastward often follows change in interaction from in-phase to out-of-phase. The fact that a monsoon depression usually recurves when a w'ly wave approaches it from the west is used by operational forecasters in their work.

(*vi*) A baroclinic energy conversion process appears to initiate the formation of a monsoon disturbance. However, after development, both the baroclinic and the barotropic processes appear to be important, barotropic in the lower troposphere and baroclinic in the upper troposphere.

(*vii*) CISK appears to be a valid mechanism for intensification of a monsoon depression. The mechanism appears to operate *via* the elevated Hadley circulation the ascending branch of which represents condensational heating in the southwest quadrant of a westnorthwestward-propagating depression and the descending branch adiabatic warming and lowering of pressure in the northwest quadrant near the centre of the depression.

In conclusion, it should be stated that because of the pivotal role played by the monsoon stationary wave in the onset process and distribution of monsoon cloud and rain, its structure and behaviour especially in relation to its interaction with travelling wave disturbances deserve to be studied with greater attention than hitherto. The interaction with w'ly waves in the Indian region is observed more clearly in the middle and upper troposphere, because of the presence of high mountain ranges to the north of India. At the lower levels, the monsoon stationary wave is often affected by cross-equatorial flow of cold air from southern-hemispheric mid-latitude baroclinic disturbances (Sikka and Gray, 1981). Hence, it would seem to be mandatory on the part of the tropical forecaster to maintain a close watch on the movement of wave disturbances in both the hemispheres and critically assess their likely interaction with the monsoon stationary wave.

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References

Ananathakrishnan, R., Srinivasan, V., Ramakrishnan, A.R. and Jambunathan, R., 1968, " Synoptic features associated with onset of southwest monsoon over Kerala", IMD, FMU. Rep. – IV-18.2.

Banerjee, A.K., Sen, P.N. and Raman, C.R.V., 1978, " On foreshadowing southwest monsoon rainfall over India with mid-tropospheric circulation anomaly of April", *Indian J. Met. & Geophys.*, **29**, 425-431.

Biswas, N.C., De, U.S.and Sikka, D.R., 1998, "The role of Himalayan Massif - Tibetan plateau and the mid-tropospheric sub-tropical ridge over north India during the advancing phase of the southwest monsoon", *Mausam*, **49**, 3, 285-300.

Brode, R.W. and Mak, M., 1978, " On the mechanism of the monsoonal mid-tropospheric cyclone formation", *J.Atmos. Sci.*, **35**, 1473-1484.

Charney, J.G. and Eliassen,A., 1964, " On the growth of the hurricane depression ", *J. Atmos. Sci.* , **21**, 68-75.

Dey, B. and Bhanukumar, O.S.R.U., 1982, " An apparent relationship between Eurasian snow cover and the advance period of the Indian summer monsoon", *J. Appl. Meteor.*, **21**, 1929-1932.

Dixit, C.M. and Jones, D.R., 1965, " A kinematic and dynamical study of active and weak monsoon conditions over India during June and July 1964", Int. Met. Centre, Bombay (pre-published).

Fu, C., Fletcher, J. and Slutz, R., 1983, " The structure of the Asian monsoon surface wind field over the ocean", *J. Climatol. and Appl. Meteor.*, **22**, 1242-1252.

Holton, J.R., 1979, An Introduction to Dynamic Meteorology (second edition), Academic Press, p 391.

India Meteorological Department, 1943, Climatological atlas for airmen, IMD, p 3.

Joseph, P.V., Eischeid, J.K. and Pyle, R.J., 1994, " Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El-Nino and sea surface temperature anomalies", *J. Climate*, **7**, 81-105.

Koteswaram, P. and George, C.A., 1958, " On the formation of monsoon depressions in the Bay of Bengal", *Indian J. Met & Geophys.*, **9**, 9-22.

Koteswaram, P., Rao, C.P. and Krishnamurthy, M., 1987, "Formation and structure of a monsoon revival depression over the Bay of Bengal during a break monsoon period", *Mausam*, **38**, 1, 29-42.

Krishnamurti, T.N., Ardanuy, P., Ramanathan, Y.and Pasch, R., 1981, " On the onset vortex of the summer monsoons", *Mon. Weath. Rev.*, **109**, 344-363.

Lorenz, E.N., 1967, "The nature and theory of the general circulation of the atmosphere", World Meteorological Organization, 1-161.

Mak, M., 1975, " Monsoonal mid-tropospheric cyclogenesis", *J. Atmos. Sci.*, **32**, 2246-2253.

Mishra, S.K. and Salvekar, P.S., 1980, " Role of baroclinic instability in the development of monsoon disturbances", *J. Atmos. Sci.*, **37**, 383-394.

Mooley, D. A., Parthasarthy, B. and Pant, G.B., 1986, "Relationship between all-India summer monsoon rainfall and location of ridge at 500 hPa level along 75° E", *J. Climatol. and App. Meteor.*, **25**, 633-640.

Mooley, D.A. and Shukla, J., 1987, " Variability and forecasting of the summer monsoon rainfall over India", Monsoon Meteorology (ed: Chang and Krishnamurti), Oxford Univ. Press, New York, 26-59.

Nitta, T. and Masuda, K., 1981, " Observational study of monsoon depression developed over the Bay of Bengal during summer MONEX", *J. Meteor. Soc., Japan*, **59**, 572-582.

Palmen, E. and Newton, C.W., 1969, Atmospheric Circulation Systems, Academic Press, New York.

Pearce, R.P. and Mohanty, U.C., 1984, " Onsets of the Asian summer monsoon, 1979-1982", *J. Atmos. Sci.*, **41**, 1620-1639.

Petterssen, S., 1956, Weather Analysis and Forecasting (second edition), Vol. **1**, Motion and motion systems, McGraw-Hill Book Co. New York and London.

Ramage, C.S., 1971, Monsoon Meteorology, Academic Press, New York, p 296.

Ramanathan, Y., 1980, " Onset of the monsoon in the Arabian sea during 1979", Int. Conf. on Early Results of FGGE and large scale aspects of its monsoon experiments", condensed papers and meeting report, Tallahassee, Florida, U.S.A.

Rao, Y.P., 1976, Southwest Monsoon, Met. Monograph-Synoptic Meteorology No. 1/1976, IMD, Pune.

Reed, R.J. and Recker, E.E., 1971, " Structure and properties of synoptic-scale disturbances in the equatorial western Pacific", *J. Atmos. Sci.*, **28**, 1117-1133.

Riehl, H., 1954, Tropical Meteorology, McGraw-Hill Book Co., New York, p 392.

Ropelewski, C.F., Robock, A. and Matson, M., 1984, Comments on "An apparent relationship between Eurasian snow cover and the advance period of the Indian summer monsoon" , *J. Climatol. and Appl. Meteor.*, **23**, 341-342.

Saha, K.R. and Chang, C.P., 1983, " The baroclinic process of monsoon depressions", *Mon. Weath. Rev.*, **111**, 1506-1514.

Saha, K.R. and Saha, S., 1993a, " A diagnostic analysis of MONEX-1979 onset vortex over the Arabian sea", *Mausam*, **44**, 4, 321-328.

Saha, K.R. and Saha, S., 1993b, " Variations in intensity and structure of a westward-propagating monsoon depression", *Mausam*, **44**, 3, 231-238.

Saha, S. and Saha, K.R., 1996, " Structure and properties of summer monsoon stationary wave over southern Asia – an observational study ", *Mausam*, **47**, 2, 133-144.

Sanders, F., 1984, "Quasi-geostrophic diagnosis of the monsoon depression of 5-8 July 1979", *J. Atmos. Sci.*, **41**, 538-552.

Sikka, D.R., 1980, " Southern hemispheric influences and the onset of southwest monsoon of 1979", FGGE Operations Report, 9(B), 23-26.

Sikka,D.R. and Gray, W.M., 1981, " On the linkage of the genesis of the monsoon disturbances and cyclones in the north Indian ocean with the passage of baroclinic waves across the south Indian ocean', Int. Conf. on The scientific results of the monsoon experiment, Extended abstracts, Denpasar, Bali, Indonesia.

Shukla, J., 1978, "CISK- barotropic-baroclinic instability and the growth of monsoon depressions", *J. Atmos. Sc.*, **35**, 495-508.