

Study of secondary heat sources over India during southwest monsoon 2002

U. V. BHIDE, S. M. BAWISKAR, V. R. MUJUMDAR, P. V. PURANIK,
S. P. GHANEKAR and A. A. KULKARNI

Indian Institute of Tropical Meteorology, Pashan, Pune – 411 008, India

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e mail : bhide@tropet.res.in

सार – वर्ष 2002 की दक्षिण पश्चिमी मानसून वर्षा के तीन असामान्य लक्षण पाए गए हैं जैसे (i) भारत के सुदूर पश्चिमी भागों में मानसून के पहुँचने में एक महीने का विलम्ब (ii) बंगाल की खाड़ी और अरब सागर में अवदाबों/तूफानों का नहीं बनना और (iii) जुलाई में अखिल भारतीय वर्षा में सामान्य से 51 प्रतिशत की कमी होना। इस शोध पत्र में अंतरामौसमी परिवर्तिता के इन लक्षणों का अध्ययन किया गया है। गौण ऊष्मा स्रोतों की अंतरामौसमी परिवर्तिताओं का समूचे भारत की परिसंचरण और वर्षा की प्रेक्षित अंतरामौसमी परिवर्तिताओं के साथ अध्ययन करने के लिए जून से सितम्बर 2002 तक के दैनिक एन. सी. ई. पी.-पुनः विप्लेषित आँकड़ों का उपयोग करके भारतीय क्षेत्र में ऊष्मा का स्पष्ट स्रोत (Q_1) और आर्द्रता में स्पष्ट कमी (Q_2) का आकलन किया गया है।

जून 2002 में भारत में उर्ध्वाधरीय एकीकृत ऊष्मा स्रोत $\langle Q_1 \rangle$ की घट-बढ़ और आर्द्रता में $\langle Q_2 \rangle$ घट-बढ़ की तीव्रता अधिक वर्षा वाले क्षेत्र के अनुरूप गई है ; जबकि जुलाई 2002 में देश के मध्यवर्ती भागों में $\langle Q_1 \rangle$ की घट-बढ़ और $\langle Q_2 \rangle$ की घट-बढ़ की तीव्रता की तुलना नहीं की जा सकी। इससे पता चलता है कि जुलाई में भारत में संवहनीय वर्षा नहीं हुई और सामान्य ऊष्मा में वृद्धि हुई। 22.5 डिग्री उ. पर 500 हैक्टापास्कल में उष्मण और शुष्कन के अनुपातों के $x-t$ रेखा चित्र से 26 जून के आस - पास पश्चिमी द्रोणी क्षेत्र में 16 डिग्री से. क्रम के दैनिक सकारात्मक उष्मण और शुष्कन बढ़े अनुपातों का पता चला है। इसके परिणामस्वरूप जुलाई में मध्य भारत में निम्न सकारात्मक या नकारात्मक मानों का पता चला है।

500 हैक्टापास्कल पर उर्ध्वाधर वेग के $y-t$ रेखाचित्र से मानसून ऋतु के दौरान लघु हिमालय के क्षेत्रों के पास इसमें बहुत अधिक कमी का पता चला है। इससे बंगाल की खाड़ी और अरब सागर में अवदाबों अथवा तूफानों के बनने की प्रक्रिया पर प्रभाव पड़ा है। क्षोभमंडल में रुद्धोष्म और प्रतिरुद्धोष्म ऊष्मण तथा शुष्कन के कारण जुलाई 2002 में भारत में विरल मानसून की स्थिति उत्पन्न हुई तथा अगस्त और सितम्बर में मानसून का परिसंचरण कमजोर पड़ गया। इस विप्लेषण से दक्षिण-पश्चिमी मानसून 2002 की अंतरामौसमी परिवर्तिता पर उत्तरी गोलार्ध मध्य-अक्षांशीय परिसंचरण के प्रभाव का स्पष्ट पता चला है।

ABSTRACT. The southwest monsoon of 2002 has three unusual features viz., (i) delay in advance over westernmost parts of India by one month, (ii) absence of depressions/storms over Bay of Bengal and Arabian Sea and (iii) -51% departure of all India rainfall in July. These features of intra-seasonal variability have been studied in this paper. Apparent heat source (Q_1) and apparent moisture sink (Q_2) over Indian region have been estimated using daily NCEP-reanalysis data, for June - September 2002 to study the intra-seasonal variations of the secondary heat sources in relation to observed intra-seasonal variations of circulation and rainfall over India.

The intensities of vertically integrated heat source $\langle Q_1 \rangle$ and moisture sink $\langle Q_2 \rangle$ are found to coincide with the excess rainfall zone over India in June 2002, whereas the intensities of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ over central parts of the country in July 2002 are not comparable. This indicates absence of convective rainfall and increased sensible heating over India in July. The $x-t$ diagram of heating and drying rates at 500 hPa along 22.5° N shows large positive heating and drying rates of the order of 16° C per day over the western trough region around 26 June. Following this event, low positive or negative values are observed over central India in July.

The $y-t$ diagram of vertical velocity at 500 hPa shows strong subsidence near the foot hills of Himalayas during the season. This has affected the formation of depressions or storms over Bay of Bengal and Arabian Sea. Adiabatic and diabatic heating as well as drying in the troposphere has led to the break-like situation over India in July 2002 and weaker monsoon circulation during August and September. The analysis has brought out the impact of northern hemispheric mid-latitude circulation on intra-seasonal variability of southwest monsoon 2002 more clearly.

Key words – Break-like situation, Secondary heat source, Subsidence over monsoon trough.

1. Introduction

The rainfall over India during July is very crucial for agricultural activity with respect to the sowing operations of Kharif crops. However, the sowing operations were disturbed in July 2002 over most parts of the country due to deficient or scanty rainfall. The actual seasonal rainfall for 2002 monsoon season was 81% of the normal resulting into a severe drought year for India. Sikka (2003) has diagnosed the factors associated with the drought of 2002 and showed the influence of ENSO warming phase coupled with a quasi-stationary westerly trough around 65° - 70° E. Kalsi *et al.*, (2004) have also investigated the causes for drought of 2002. Daily tropospheric circulation during July 2002 shows many features similar to those observed in monsoon breaks over India, as noted by Ramamurthy (1969) such as shifting of the axis of the monsoon trough to the foot-hills of Himalayas and above normal pressures over most parts of the country. During 2002, an unforeseen delay in the advance of monsoon was observed over westernmost parts of the country. Monsoon activity revived over India during August but the rainfall deficit of July, which was nearly 51% of the monthly normal rainfall, was not compensated in the remaining two months *viz.*, August and September. Formation of any depression was also not observed during the season. In this paper, an effort is made to find out how the monsoon circulation evolved from June to July and August onwards.

The year 1979 had witnessed a monsoon drought. Space and time variation of diabatic heat sources over the monsoon region in the monsoon season of 1979 were studied by Luo and Yanai (1984) and Nitta (1983) using data collected during MONEX-79. He *et al.*, (1987) have also studied the time evolution of the general circulation over Asia during an 80-day period from mid-April to early July 1979 using objectively analyzed FGGE Level IIb data. They have shown that there was continuous heating from the ground surface throughout the analysed period over the Tibetan Plateau. The vertical circulation induced by the Tibetan Plateau coexisted with the northward migrating principal monsoon system. They also identified that adiabatic warming due to large-scale subsidence in the areas surrounding the Plateau increased the mean temperature in the 200-500 hPa layer and led to distinct changes in the general circulation. A diagnostic study of heat sources and moisture sinks over monsoon trough area during active and break phases of monsoon 1979 by Bhide *et al.*, (1997) has shown that on day-to-day scale the apparent heat source (Q_1) and the apparent moisture sink (Q_2) varied coherently with rainfall. The heat sources and moisture sinks propagated westward across the trough area with a period of 10-15 days mode, in association with the propagation of synoptic scale disturbances. Events of

reversal of normal west to east heating gradient, observed in the later part of the active phase were followed by weak/break phases during monsoon 1979. A synoptic climatological analysis of pentad rainfall anomalies using a long period data from 1901 to 1980 for the established phase of southwest monsoon season over India by Bhide *et al.*, (2003) showed that positive heavy rainfall anomalies and the associated development of the heat source over northwest India could cause northward movement of western part of the monsoon trough towards foothills of Himalayas. These studies have brought out adverse effect of the spatial variations of heat sources in the monsoon trough region on monsoon circulation and hence on rainfall over India. An estimation of daily apparent heat source and moisture sink is carried out in this study for the entire monsoon season of 2002 to study the intra-seasonal variations of the secondary heat sources for the season. The data and methodology is given in section 2 of the paper. The rainfall activity and circulation features over India are discussed in section 3. The results are discussed in section 4 and the conclusions are summarized in section 5.

2. Data and methodology

Daily 2.5° Lat. × 2.5° Long. grid point data of zonal and meridional components of wind (u and v respectively), temperature (T) and relative humidity (RH) for ten standard levels between 1000 and 100 hPa from National Centre for Environmental Prediction (NCEP) re-analysis data (Kalnay *et al.*, 1996), over the domain 5° - 35° N and 65° - 100° E, have been used to estimate the apparent heat source (Q_1) and apparent moisture sink (Q_2) for June to September 2002.

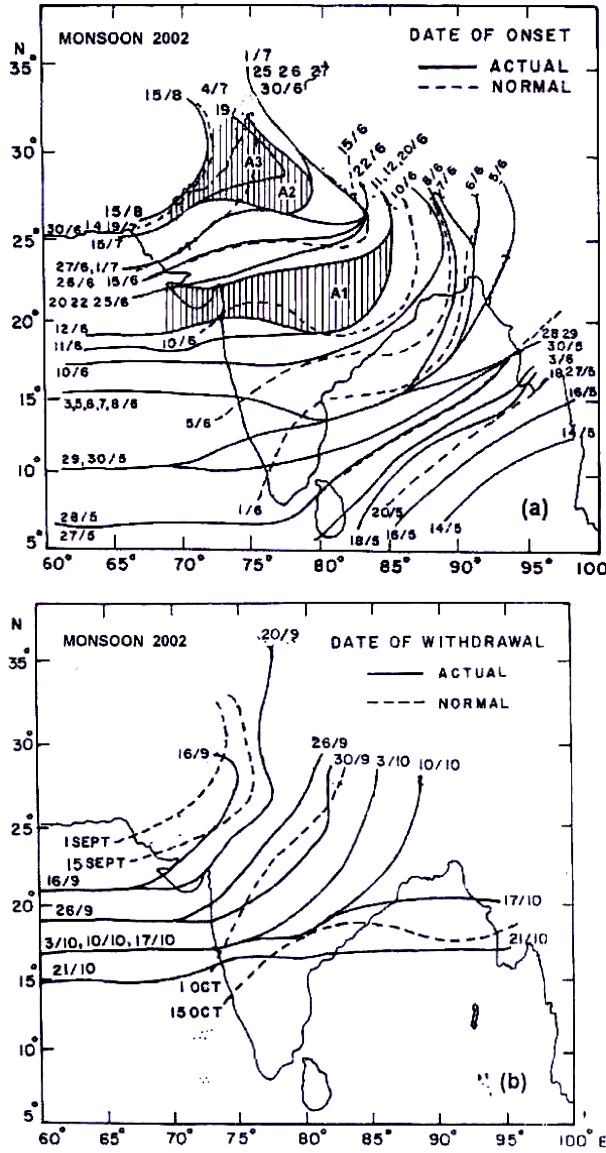
Following Luo and Yanai (1984), the apparent heat source Q_1 and the apparent moisture sink Q_2 are computed with :

$$Q_1 = c_p \left[\frac{\partial T}{\partial t} + v \cdot \nabla T + \left(\frac{p}{p_0} \right)^{R/c_p} \omega \frac{\partial \theta}{\partial p} \right], \quad (1)$$

$$Q_2 = -L \left[\frac{\partial q}{\partial t} + v \cdot \nabla q + \omega \frac{\partial q}{\partial p} \right], \quad (2)$$

(A) (B) (C)

where T is the temperature, θ the potential temperature, q the mixing ratio of water vapor, v the horizontal wind, $\omega = dp/dt$ the vertical velocity in pressure coordinate, R the gas constant, c_p the specific heat at constant pressure of dry air, p the pressure, L the latent heat of condensation and $p_0 = 1000$ hPa. The terms indicated as (A), (B) and (C) of Eqns. (1) and (2) are local



Figs. 1(a&b). Dates of (a) onset and (b) withdrawal of southwest monsoon 2002 over India

change, horizontal and vertical advectations of heat and moisture, respectively.

The computations of local change terms are carried out every 24 hours by the central finite difference scheme. The vertical p -velocity ω has been obtained kinematically by integrating the continuity equation,

$$\frac{\partial u}{a \cos \Phi \partial \lambda} + \frac{\partial v}{a \partial \Phi} + \frac{\partial \omega}{\partial p} = 0, \quad (3)$$

where u and v are the eastward and northward components of horizontal wind, a the radius of earth, Φ the latitude and λ the longitude.

For the surface boundary $\omega = \omega_s$ at $p = p_s$. The suffix s denotes the surface value. The orographically forced vertical velocity ω_s at the surface is calculated by

$$\omega_s = g \rho_s \left(\frac{u_s}{a \cos \Phi} \frac{\partial h}{\partial \lambda} + \frac{v_s}{a} \frac{\partial h}{\partial \Phi} \right) \quad (4)$$

where g is gravity, ρ_s density of surface air and h the terrain height. The quantities u_s , v_s , p_s , and T_s for each grid point at the surface are obtained by extrapolation of the data from the nearest standard level. The smoothed terrain height values are obtained from the Scripps Topography data on a 1° global grid. For the upper boundary, the vertical p -velocity satisfies $\omega = \omega_T$ at $p = 125$ hPa, where :

$$\omega_T = \left(\frac{\frac{\partial \theta}{\partial t} + v \cdot \nabla \theta - \frac{(p_o/p)^{R/c_p}}{c_p} Q_R}{-\frac{\partial \theta}{\partial p}} \right), \quad (5)$$

as suggested by Nitta (1977) and used by Luo and Yanai (1983). Eqn. (5) assumes that there are no heat sources other than the radiative heating in the uppermost layer between 100 and 150 hPa and it is introduced to reduce errors in the computations of the heat source in the upper troposphere. The local time change term for a synoptic time scale at the upper boundary is small compared to the horizontal advection term and is therefore ignored, following Luo and Yanai (1983). Q_R is the radiative heating rate and its values at 125 hPa are taken from Dopplack (1972). The p -velocity is obtained by integrating Eqn. (3) downwards with the boundary conditions, Eqn. (5). The correction to the integrated divergence is found by requiring that $\omega(p_s) = \omega_s$. The estimates of the horizontal divergence at all levels are adjusted by distributing the required correction vertically with more weights at upper levels, following O'Brien (1970).

The computed Q_1 and Q_2 are vertically integrated at each grid point for the troposphere between p_s and 100 hPa for Q_1 and between p_s and 300 hPa for Q_2 by

$$\langle Q_1 \rangle = \frac{1}{g} \int_{100}^{p_s} Q_1 dp \quad \text{and} \quad \langle Q_2 \rangle = \frac{1}{g} \int_{300}^{p_s} Q_2 dp, \quad (6)$$

and are measured in Watts per meter square (Wm^{-2}).

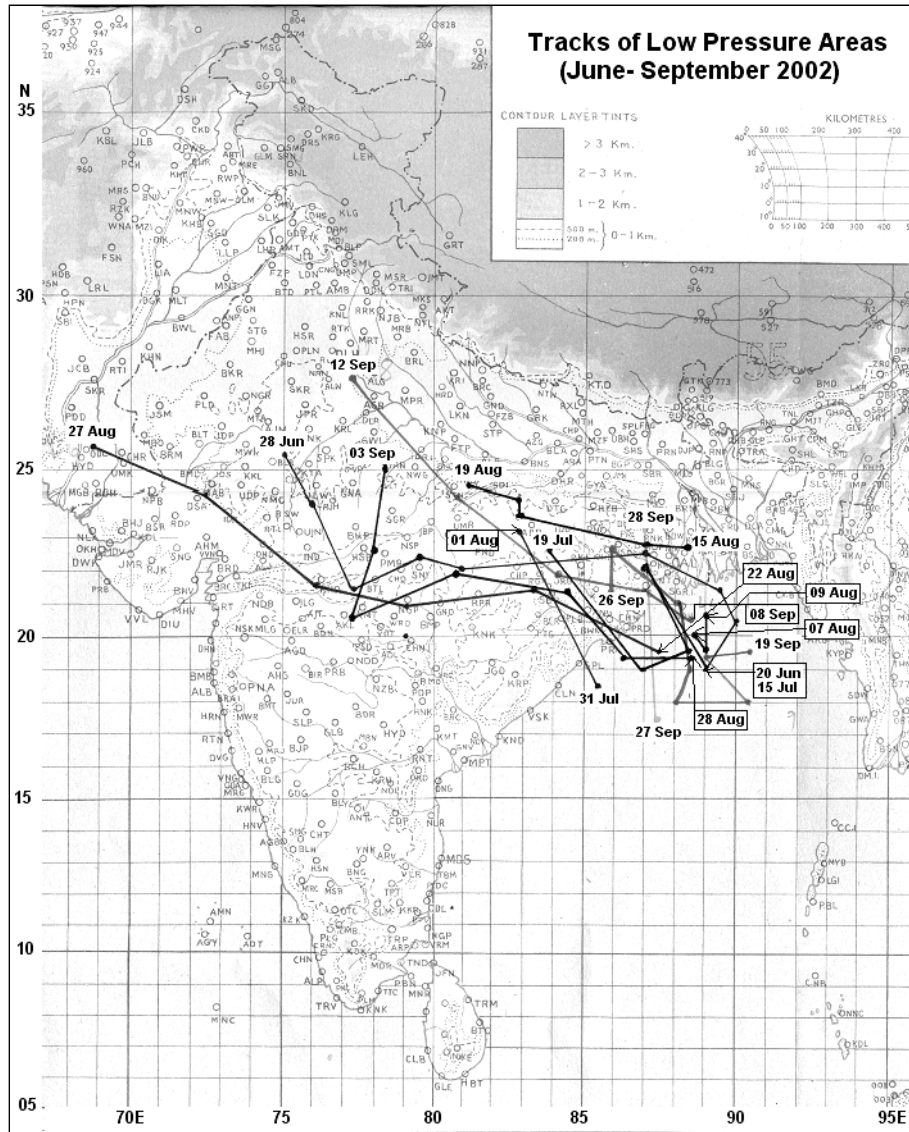


Fig. 2. Approximate path of the low pressure areas (LOWs) during southwest monsoon 2002

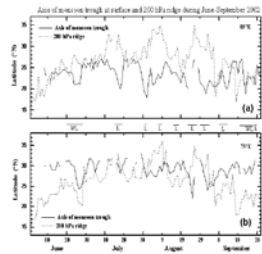
The apparent heating rate (Q_1/c_p) and the apparent drying rate (Q_2/c_p) measured in $^{\circ}\text{C day}^{-1}$ are computed at all grid points for all the levels over the trough area. The Q_2/c_p is termed as the drying rate because the apparent moisture sink (Q_2) results from the drying effect by a compensating downward motion and detrainment of water vapour (Yanai *et al.*, 1973).

3. Circulation and rainfall distribution

3.1.1. Transient Low Pressure Areas (LOWs)

Fig. 1 shows the dates of onset and withdrawal of southwest monsoon 2002 over different parts of India. It

shows that southwest monsoon 2002 set in over Kerala on 29 May and covered the entire country by 15 August Fig. 1(a). The monsoon stagnated over area A1 for more than a week during its advance. The Figure also shows two areas A2 and A3 where it stagnated for more than two weeks. Thus A2 and A3 were deprived of rainfall for a very long period in the early part of the season. Monsoon started withdrawing from Rajasthan and Gujarat region from 16 September and was completely withdrawn by 21 October from regions north of 15°N Fig. 1(b). Monsoon depression, which is the most important synoptic scale disturbance on the monsoon trough, is known to play a vital role in the space and time distribution of rainfall (Sikka, 1977). Generally 24-hourly accumulated rainfall



Figs. 3(a&b). Daily position of axis of the monsoon trough and 200 hPa ridge at (a) 85° and (b) 75° E for June to September 2002

in association with a depression is 10-20 cm. However, isolated falls exceeding 30 cm in 24 hours are also not uncommon. Four to six monsoon depressions are expected to form during July-August. The transient low pressure systems during monsoon season, like low pressure area and well marked low pressure area, which are weaker systems as compared to the depression, cause spatial and temporal variability of monsoon rainfall. Rainfall activity of monsoon 2002 was mainly due to ten Low Pressure Areas (LOWs) which formed over Bay of Bengal. Two of these LOWs in the season became well marked. None of the ten systems intensified into a depression or storm. This is a unique feature of southwest monsoon 2002. Fig. 2 shows the approximate locations of the center of the LOWs formed during monsoon 2002. It can be seen that four LOWs formed over Bay of Bengal on 20 June, 15 July, 31 July, and 7 August, even before monsoon covered the entire country. Three systems of July and August had a very short life and their intensification was suppressed over/near the sea. Three lows formed on 15, 22 and 28 August and one formed on 8 September Fig. 2 had long life spans (between three days and more than a week). These systems distributed good amount of rainfall over different parts of the country. The well-marked low of 19 September remained mostly over the Bay during its

life span, without much westward movement. The last system formed on 27 September was again short-lived and showed a northward movement as is normally observed in other seasons by the end of September. The monthly anomalous pressure pattern of July showed positive pressure anomaly of 3 hPa near 20° N, 70° E and about 1 hPa near northwest Bay region.

During monsoon 2002, sixteen tropical systems formed over west Pacific but most of them remained east of 120°E and recurved northeastwards (Sikka, 2003). Few of them crossed China coast without supporting formation of depression over Bay of Bengal. A large number of induced lows and cyclonic circulations formed over north Pakistan and adjoining Indian region and moved across Jammu and Kashmir area giving excess rainfall over there. Such rainfall was not observed to extend southward of 30° N over India. For July, even Jammu and Kashmir experienced deficient rainfall. Rainfall activity along the west coast of India is associated with the low level westerly jet (LLJ) located along 15° N across Peninsular India and off west coast troughs. Thus, several synoptic features over India during monsoon 2002 indicate that monsoon circulation was weaker than normal over India, particularly during July.

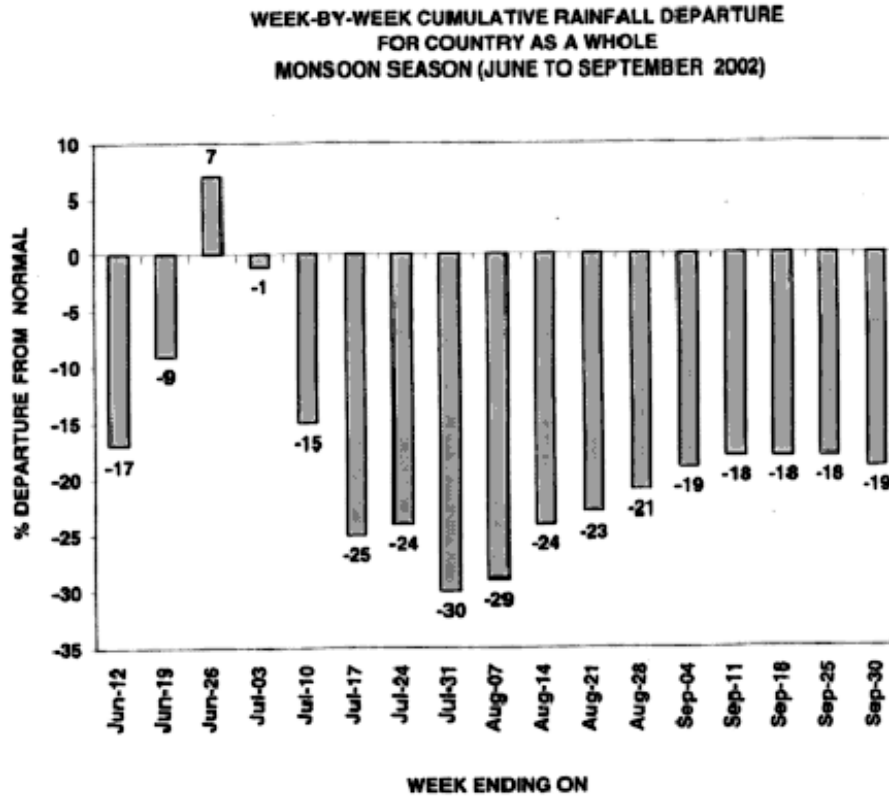


Fig. 4. Weekly cumulative percentage rainfall departures for June to September 2002

3.1.2. Oscillation of monsoon trough

Figs. 3(a&b) shows the latitudinal position of the axis of the trough of low pressure at mean sea level over India and the daily latitudinal location of the 200 hPa ridge at two selected longitudes, 85° and 75° E for the period from 1 June to 30 September 2002. The durations of the ten LOWs are also shown in the Figure. In June and July, the axis of monsoon trough at 85° E remained mostly over north India, except during the formation of lows over Bay of Bengal on 20 June, 15 July and 31 July, when it moved southward. It is remarkable that following the first and the second system the axis of the trough Fig. 3(a) is observed to have moved northward quickly and remained there. The trough axis at 75° E Fig. 3(b) is also seen north of 30° N on many days or is not seen at all on some days. During two epochs in the month of July, the trough axis remained close to the foot hills of Himalayas. Kalsi *et al.*, (2004) have noted that the trough at mean sea level over India remained close to the foot hill of Himalayas from 29 June to 14 July and 18 to 29 July. Thus the two observed epochs of northward shift of the trough adversely affected the daily spatial distribution of rainfall over India during July 2002 and resulted into a deficit in rainfall by 51% on monthly scale.

Sikka (2003) has identified many regional scale circulation features over India for July 2002, like presence of anomalous above normal surface pressure and presence of anomalous anticyclones at 850 and 500 hPa over India. He has also pointed out that India remained under the grip of subsidence in July. An examination of the patterns of temperature (relative humidity) anomalies for July 2002 from the climatological NCEP normal pattern shows that the Indian region was warmer by 0.5 to 2 K (drier by 10%) at 850 and 500 hPa levels (Figures not shown).

The ridge at 200 hPa is normally observed at 25° N in June while at 30° N in July over the Indian region. Around 22 July and 19 August 2002 it was seen near 25° N at 85° E and 75° E [Figs. 3 (a&b) respectively]. Prior to this it was near 35° N, indicating substantial southward shift of the ridge during peak monsoon months of monsoon. The present case shows sequence of events at 75° E [Fig. 3(b)] *viz.*, anomalous southward location of the trough before 28 June 2002 and then shift of the entire axis northward to the foot hills of Himalayas from 29 June till 14 July. This situation changed when the eastern end of the trough dipped in the head Bay region from 15 July and a short lived LOW formed in head Bay. After dissipation of the LOW, the eastern end of the monsoon

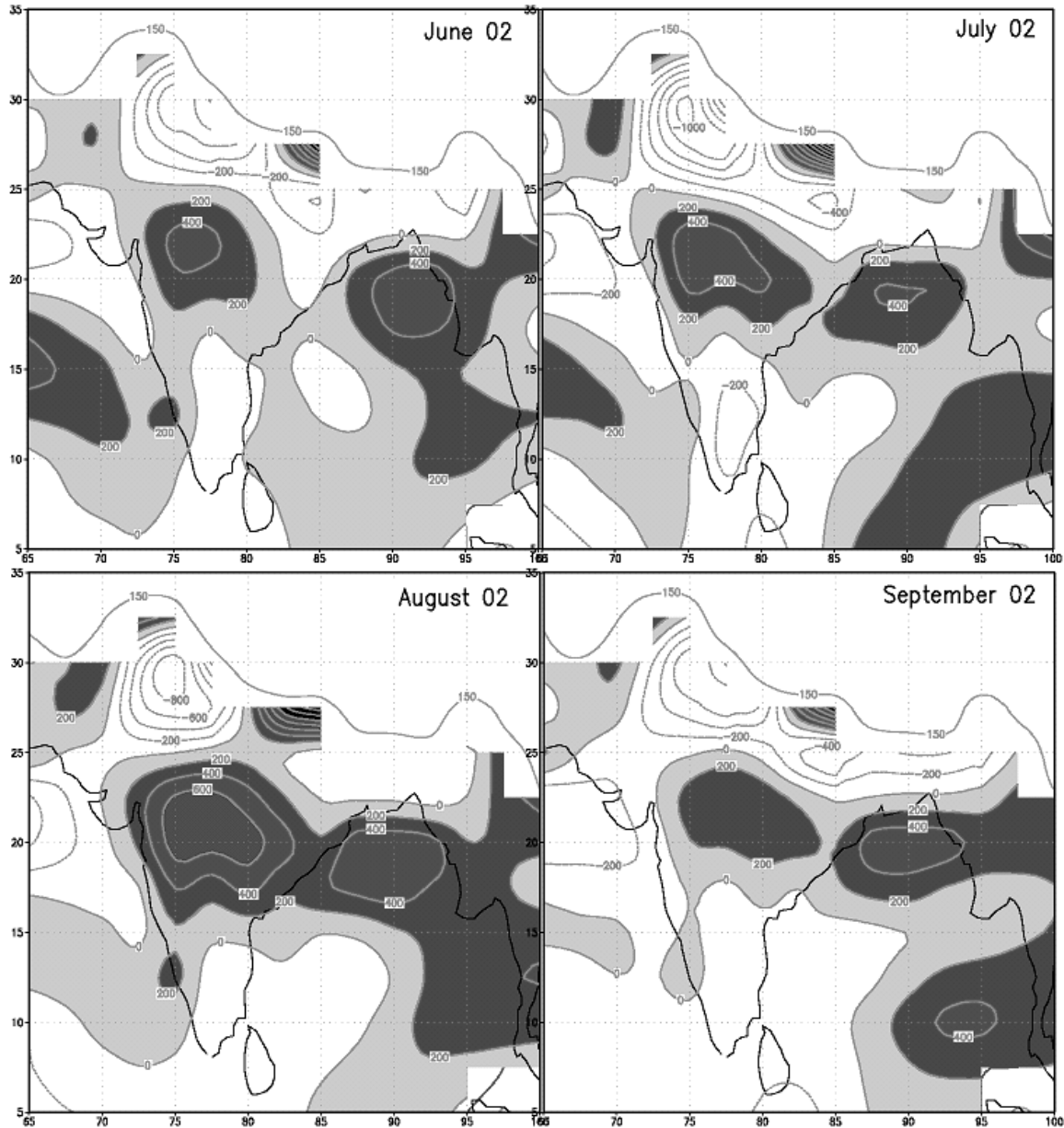


Fig. 5. Vertically integrated heat source $\langle Q_1 \rangle$ over India for June to September 2002 (Wm^{-2})

trough again shifted to the foot hills of Himalayas and led to the second break-like epoch from 20 to 28 July. In the first fortnight of August, at 85°E , the trough remained north of its normal position, more frequently [Fig. 3(a)]. The trough regained its normal position at 85°E on 15 August onwards and four systems formed before 15 September. LOW formed on 22 August moved westward and the trough at 75°E shifted south of at 25°N [Fig. 3(b)]. In the second fortnight of September the trough shifted northward at 75°E but showed significant short north-south oscillations at 85°E .

3.3. Rainfall

Fig. 4 shows the Weekly Cumulative Departure (WCD) of rainfall for India from normal for June to September 2002. The first two weeks of the season ending on 12 and 19 June, when monsoon had covered only peninsular India and northeastern parts of the country, shows WCD as -17% and -9% respectively. The rainfall over India picked up from the next week and exceeded the normal by 7% of for the next week ending on 26 June. In the next week itself WCD value shows a fall [Fig. 4]

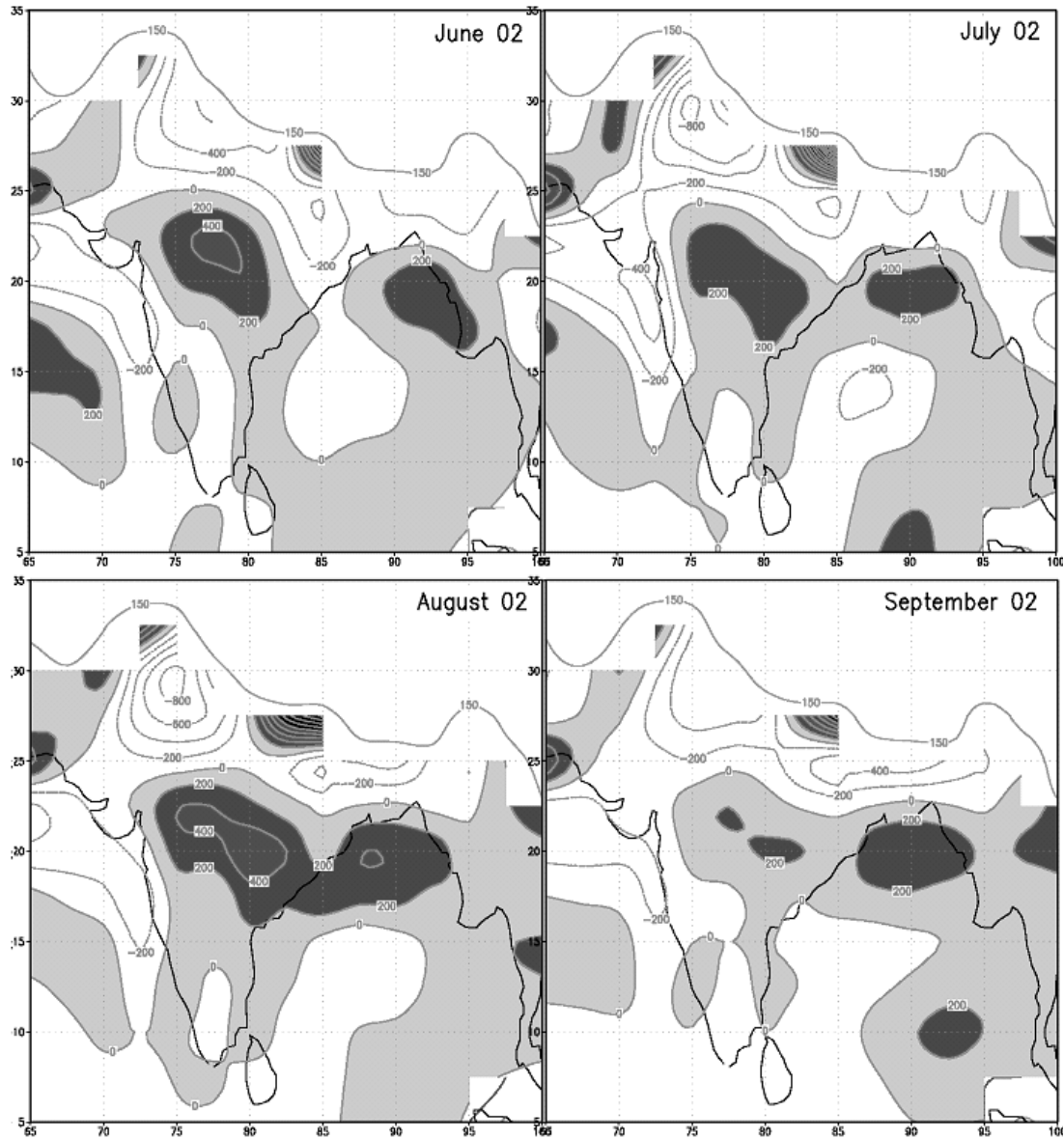


Fig. 6. Vertically integrated moisture sink $\langle Q_2 \rangle$ over India for June to September 2002 (Wm^{-2})

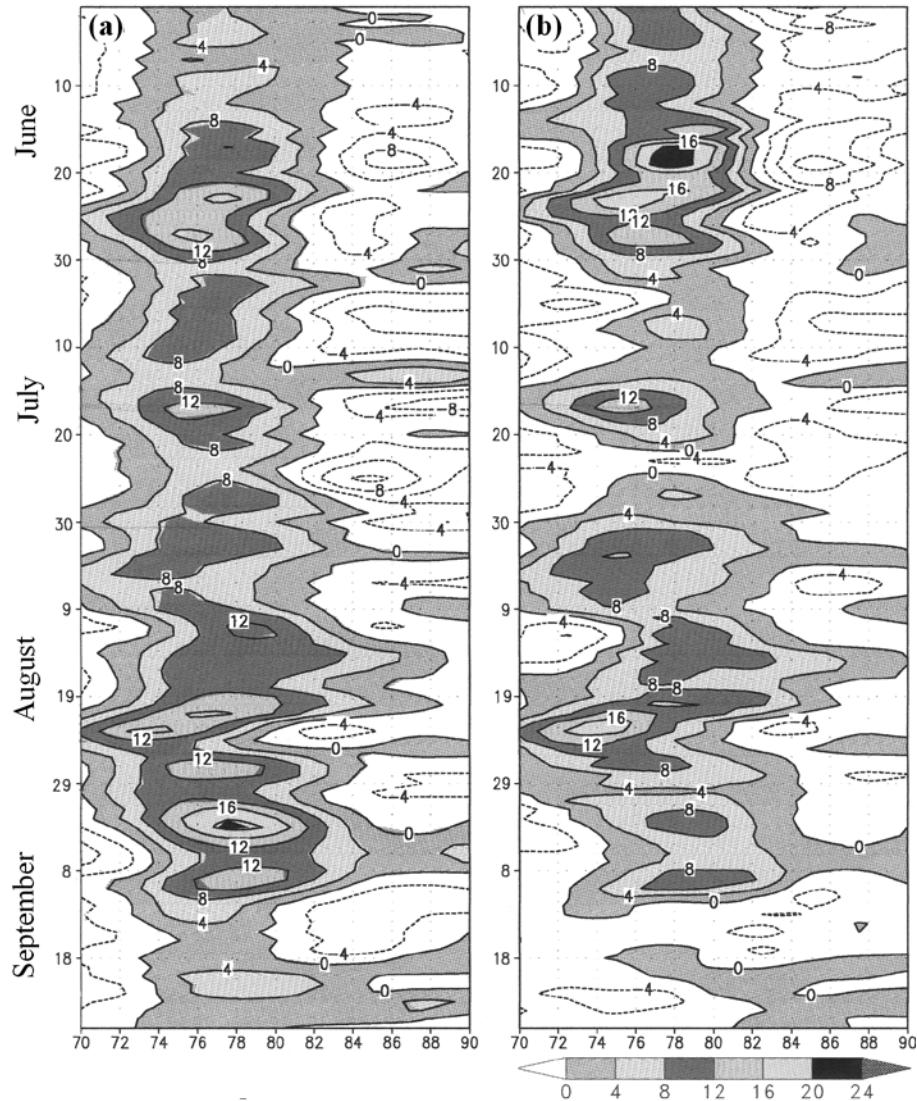
by 8%. The trend was then found to continue till end of July when WCD is -30%. Thus, the WCD series brings out an active – break cycle of monsoon variability in rainfall during June-July 2002.

4. Discussion of results

4.1. Vertically integrated heat source $\langle Q_1 \rangle$ and moisture sink $\langle Q_2 \rangle$

Fig. 5 and Fig. 6 show the distribution of vertically integrated heat source $\langle Q_1 \rangle$ and vertically integrated

moisture sink $\langle Q_2 \rangle$ respectively for June, July, August and September 2002. An intense heat source is observed over India, centered at about $20^\circ - 25^\circ N$ and about $75^\circ E$, in the month of June with $\langle Q_1 \rangle$ value exceeding $400 Wm^{-2}$ [Fig. 5]. The region of positive $\langle Q_1 \rangle$ values is also found to coincide with an area of positive $\langle Q_2 \rangle$ values [Fig. 6] for June. The moisture sink, however, is of lesser intensity as compared to the heat source. The heat source and the moisture sink for June are found to coincide with the area of eight subdivisions having excess rainfall for June 2002. Thus, the vigorous rainfall event of the second fortnight of June has led to development of an intense heat

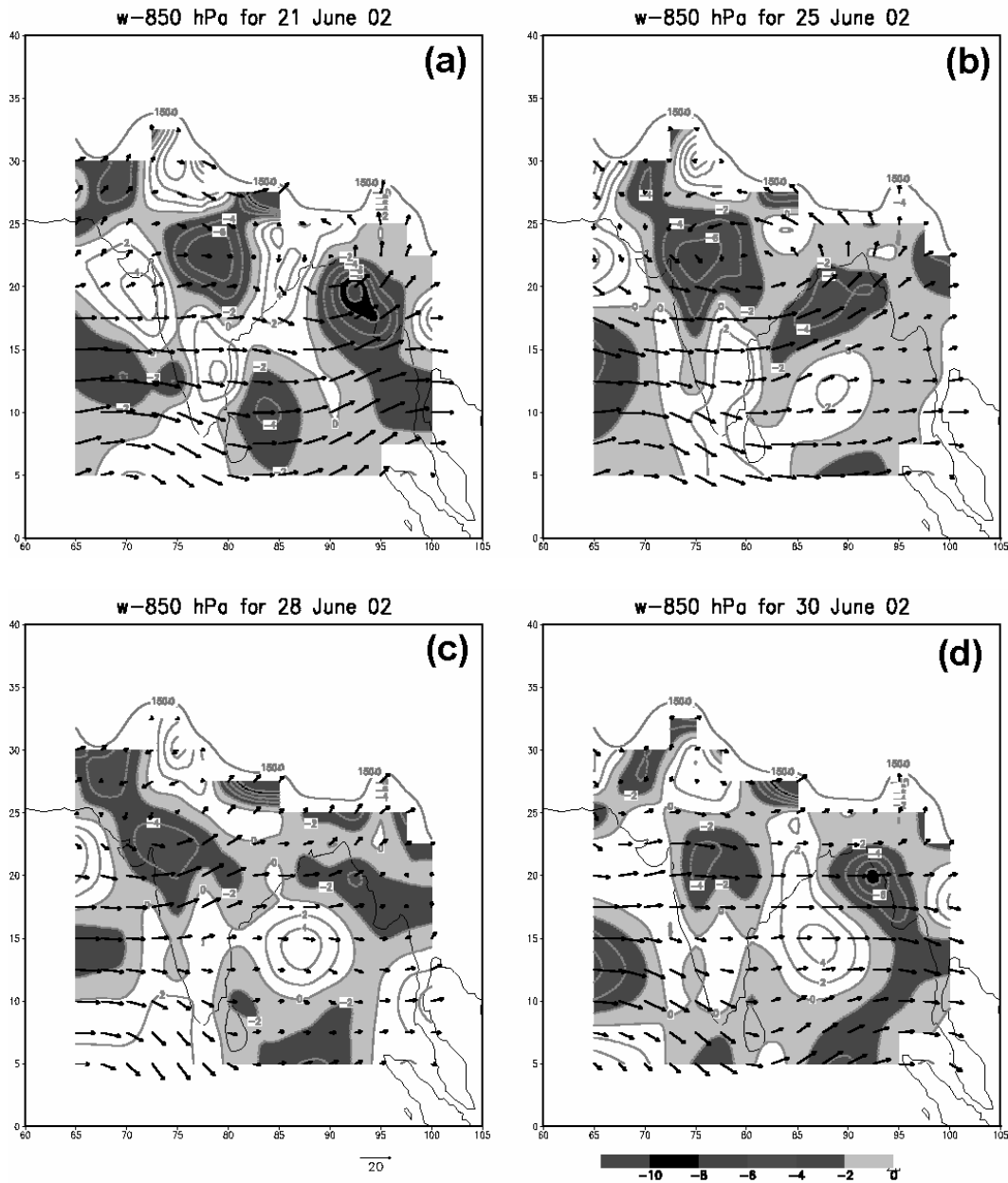


Figs. 7(a&b). $x-t$ diagram of 3-day moving average heating rate ($\langle Q_1 \rangle / C_p$) and drying rate ($\langle Q_2 \rangle / C_p$) ($^{\circ}\text{C}/\text{day}$) for June to September 2002

source in the atmosphere over India. For the next month July the heat source [Fig. 5] and the moisture sink [Fig. 6] have been observed to shrink and their intensity is also found to reduce substantially. This reflects the large deficit in rainfall and absence of organized convection over central India. For the month of August, the centers of the heat source and the moisture sink are coincident but the moisture sink is weaker than the heat source. The distribution of percentage rainfall departures for various subdivisions of India (figure not shown) brings out only normal rainfall for many sub-divisions of India for August. For the month of September the heat source and the moisture sink are found to be intense over north Bay

region only. Sikka (2003) noted a centre of anomalous convergent flow over central India for the months of July to September at 200 hPa which also indicates weaker convective activity over central India. An anomalous divergent flow is observed over Indian region for June 2002 which seems to be in tune with intense heat source and moisture sink Fig. 5 and Fig. 6 respectively and the observed excess rainfall over central and northwest India for June 2002.

Another remarkable feature of these figures is the presence of a heat sink [Fig. 5] and the moisture source [Fig. 6] with negative values $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ in the



Figs. 8(a-d). Synoptic structure of vector wind at 850 hPa over India for (a) 21 June, (b) 25 June, (c) 28 June and (d) 30 June 2002

surrounding area of the land heat source and the moisture sink. Particularly, over northern India the heat sink $\langle Q_1 \rangle$ is as large as -600 Wm^{-2} in June [Fig. 5], which further increased in July. It can be noted that for certain grid points the positive $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ values are very large on the northern side of India in all the four months. This could be partly due to the fact that no special treatment is given for the hilly region. But such high values do indicate intense convective rainfall due to eastward moving systems of the mid latitudes over the belt on monthly

scale. Kalsi *et al.*, (2004) have noted presence of a cyclonic vortex between 600 and 500 hPa centred at 35° N and 85° E for the month of July. They have also noted that the frequency of eastward moving systems in the mid-latitude westerlies was much more than normal in the four months of southwest monsoon 2002. The presence of the belt of heat source [Fig. 5] and moisture sink [Fig. 6] in all the four months reflects the intense convective rainfall due to eastward moving systems on the northern periphery of India.

To the south of land heat source, negative $\langle Q_1 \rangle$ values have appeared over eastern Arabian Sea and western Bay of Bengal [Fig. 5] from June to September. The intensity, however is the largest in June. Negative $\langle Q_2 \rangle$ values indicate presence of moisture source over the areas [Fig. 6] of the heat sink in the different months. This shows reduced convective rainfall over the region in the season.

4.1.1. *x-t diagram of heating and drying rates*

Figs. 7(a&b) shows the *x-t* diagram of 3-day moving average of the heating rate (Q_1/c_p) and drying rate (Q_2/c_p) at 500 hPa along 22.5° N following Bhide *et al.*, (1997) for the longitudinal belt 70° to 90° E during monsoon 2002. It can be seen from the figure that in general large positive (low positive or negative) heating rates [Fig. 7(a)] and drying rates [Fig. 7(b)] are predominant to the west (east) of about 80° E. This is opposite to what was observed by Bhide *et al.*, (1997) for southwest monsoon 1979.

Heating rates upto 4° C / day [Fig. 7(a)] are observed from the beginning of June which increased in the subsequent days. The first epoch of heating rates larger than 12° C / day is seen between 21 to 28 June. This epoch of strong heating rates is associated with large positive drying rates [Fig. 7(b)]. The heating rates decreased after 30 June for about 15 days. In this period smaller positive or even negative drying rates are observed in the entire longitudinal belt. A second very short spell of large heating rates [Fig. 7(a)] and drying rates [Fig. 7(b)] is observed at 75° E around 17 July. This spell seems to be associated with the LOW of 15 July and a cyclonic vortex over northwest India. Following this event, once again, low positive heating rates [Fig. 7(a)] are observed over the western region from 20 July to 20 August. The drying rates are simultaneously low in this period. The third spell of large positive heating rates [Fig. 7(a)] and low positive drying rates [Fig. 7(b)] over the western part started from 20 August. This epoch is broken after 15 September. Bhide *et al.*, (1997) observed three events of east to west movement of centre of large heating and drying rate during the passage of three disturbances *viz.*, one monsoon depression, a LOW and a cyclonic storm during monsoon 1979 in June, July and August respectively. The east to west shift in the large positive heating and drying rates are associated with westward movement of monsoon depressions/storms (LOWS) during 1979.

4.1.2. *Development of break-like circulation over India*

Figs. 8 (a-d) shows synoptic structure of circulation over India at 850 hPa for selected 4 days during the period 20 June 2002 to 30 June 2002. The maps show vector

winds over the region of study for 21, 25, 28 and 30 June and analysis of vertical velocity, ω at the same level. A cyclonic circulation is observed over north Bay of Bengal and neighbouring Indian land area on the eastern part of the monsoon trough on 21 June [Fig. 8(a)] and is observed to move westward on 25 June with its centre approximately at 22.5° N, 77.5° E [Fig. 8(b)]. The cyclonic circulation of the vortex covers the entire trough area on this day. Very strong westerlies of the order of 20 mps are seen south of the centre of the vortex near 17.5° N while easterlies with speeds of the order of 10-15 mps are found to its north. The next map for 28 June shows a northwestward movement of the vortex towards 75° E [Fig. 8(c)]. It suggests that the vortex is linked with the mid-latitude westerly flow when weekly rainfall anomalies increased over Saurashtra and west Rajasthan. The strong easterly winds of 25 June over eastern trough area are replaced by westerly or southwesterly winds on 28 June. The vortex has weaker circulation on 30 June [Fig. 8(d)] and it is also found to move northeastwards as compared to the vortex of 28 June. Westerly flow is found over entire trough region on 30 June. Such spreading of westerlies over monsoon trough region is observed in the break situations in the lower levels. The synoptic structure of wind at 850 hPa from 25 to 30 June shows a pronounced circulation change that took place over India in association with the movement of the well marked LOW. The anomaly anticyclone at 850 hPa for the month of July (Sikka, 2003) seems to have resulted from the persistence of the circulation pattern similar to that observed on 30 June and for a number of days of July 2002 with slight variation from one day to the other.

Fig. 8 also shows the vertical velocity, ω -distribution for the selected days. Small areas or cells having negative and positive ω -values represent upward and downward vertical motion and they are hereafter described as U-cell and D-cell respectively. On 21 June a D-cell extending from Himalayan region towards northwest Bay up to 15° N is observed to separate two U-cells in the monsoon trough region. The U-cell over the Bay region seems to have stronger upward velocity at the center than that over the land cell. Fig. 8(b) shows that on 25 June a U-cell has covered the entire trough region with two centres having negative values of ω , *viz.*, $<-6\text{hPa/hr}$ around 27° N, 75° E over land and $<-4\text{hPa/hr}$ around 20° N, 87° E over head Bay. On 28 June [Fig. 8(c)] the land U-cell is more intense as compared to that for U-cell of 25 June. With the northwestward movement of the vortex on 28 June, a D-cell covered most of the Bay region. This D-cell is found to extend northward and cover the eastern monsoon trough area on 30 June [Fig. 8(d)]. It is remarkable that D-cell prevailed, almost throughout the season, over parts of northwest India, Peninsular India and adjoining oceanic region.

Thus the ω -distributions for selected days show that the well marked low pressure system having strong upward motion was encircled with belts of downward motion. This indicates an isolation of the vortex from its surroundings. The present pattern of evolving ω -distribution shows drying of the atmosphere in the surrounding of a synoptic system and can be related with the large scale subsidence outside the disturbance area. Thus the development of a break-like situation over India occurred after the well marked LOW moved from north Bay towards western trough area, causing high positive weekly rainfall anomalies for different subdivisions of central India. This sequence is similar to what was observed by Bhide *et al.*, (1997) for 1979 drought.

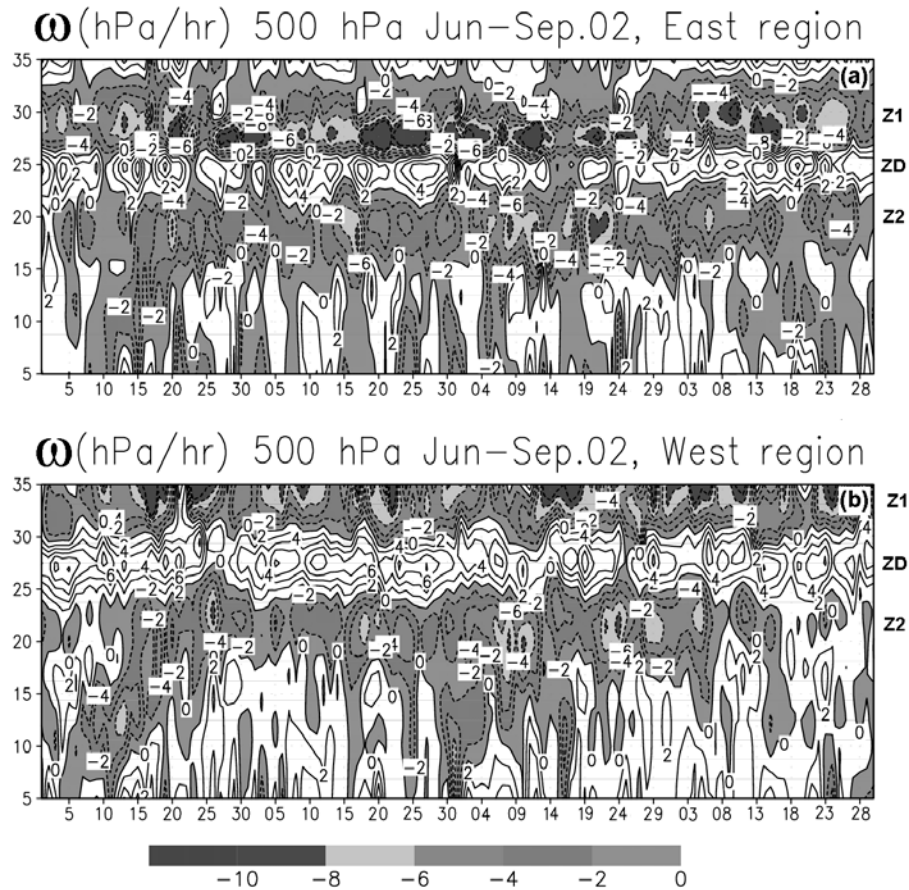
The large scale ω -distribution over Indian region (D-cell) on 28 June seems to behave like a single cloud and its environment envisaged by Yanai *et al.*, (1973) to parameterize the effect of cumulus clouds on the environment. The typical changes in circulation and the D-cells having subsidence outside the vortex, observed on 30 June, indicate that the circulation over India is not conducive for invasion of the mid-latitude troughs over northwest India. Subsidence over north Bay of Bengal region hampers the entrance of the remnant of any western pacific system in the Bay. Similarly, subsidence over south Bay region does not allow the formation of any vortex in the oceanic convergence zone. The observed large scale subsidence in the present case did not provide the moisture convergence in the trough region in July 2002.

4.2. Revival of monsoon activity over India after break-like situation

During the year 2002, monsoon onset occurred over Kerala on 29 May and advanced further northward with the northward propagation of tropical convergence zone (TCZ). The formation and westward movement of the LOW during 20-28 June gave the first active phase of monsoon 2002. Subsequently in July two break-like situations were observed over India intercepted by a weak phase around 15 July. An examination of the cloud imageries from Meteosat-5 showed that during July, bright deep convective cloud cluster covered Bay of Bengal around 15 July and moved westward over land causing rainfall. But the LOW which developed over head Bay on 15 July was short lived. The cloud imageries show organized convective clouds over Indian Ocean south of the equator by end of July. However clouding is less organized and variable over different parts of Bay of Bengal. Convective clouds are seen near foot hills of Himalayas in this period. This indicates that both the oceanic TCZ and continental TCZ in the northern hemisphere remained weak in July. The intraseasonal

variations of the monsoon rainfall over India arise from the space-time variations of the TCZ (Gadgil, 1988). The prominent scales of these variations between active spells and breaks have been identified as the 15-day scale and the 40-day scale. The revival from breaks occurs either by northward propagation of the TCZ over the equatorial Indian Ocean (Sikka and Gadgil, 1980 ; Gadgil and Asha, 1992) or by genesis of a disturbance in the monsoon zone (often as a result of westward propagation of remnants from the west Pacific). The present analysis shows that genesis of low pressure systems occurred over Bay of Bengal on 15 July, 31 July and on 6 August also. But the intensification of these systems did not occur and they had a very short life. The rainfall activity over northwest India and the west coast remained subdued in this period. Gadgil *et al.*, (2002) have pointed that one of the special features of the monsoon season of 2002 was the scarcity of cloud systems over the Arabian Sea and large deficits in rainfall over the west coast of India for the period 1 June to 31 July 2002. This suggests that the genesis over Bay of Bengal did not revive the monsoon activity for the western part of the country till 15 August. Marked subsidence had persisted over northwest and central India during July. From end of July an extensive bright cloud band moved northward from equatorial Indian Ocean towards its continental position over central India and caused the revival of monsoon and its coverage over entire country by 15 August. Well distributed rainfall occurred over central India between 15 August and 15 September due to four low pressure systems which had longer life over land. The cloud imageries indicate that after this period again the continental and the oceanic TCZ remained weak till end of September when the low pressure systems were short lived and the LOW formed on 27 September had a northward movement.

Figs. 9(a&b) shows the $y-t$ sections of vertical velocity (ω), at 500 hPa, for the east and west regions of monsoon trough respectively for monsoon 2002. For this purpose, the values of ω between 80° and 90° E (between 70° and 80° E) are averaged to represent the east (west) regions of India. Two zones of negative ω -values indicate upward vertical motion and are denoted as Z1 and Z2 while the zone ZD, having positive ω -values represents a belt of downward motion for the eastern [Fig. 9(a)] as well as the western [Fig. 9(b)] region. For Z1 (Z2), the magnitude of ω -value is found frequently less than -10 hPa/hr (more than -10 hPa/hr) for the east and the west regions. The latitudes of very strong (weaker) upward motion in Z1 (Z2) seem to represent that the upward motion due to the active eastward moving systems in the mid-latitude westerlies at the northern periphery of India (westward moving disturbances in the normal monsoon trough or in the continental Tropical Convergence Zone).



Figs. 9(a&b). y - t section of daily vertical velocity (hPa/hr) at 500 hPa for (a) east and (b) west region of monsoon trough for June to September 2002

There is a vast difference in the intensity of upward motion in Z1 and Z2 [Fig. 9(a)] in the period between 15 June and 15 August for the east region. It is remarkable that the three systems formed in this period, on 15 July, 31 July and 7 August had rapidly decayed. The LOW that formed on 20 June, however, though remained weak had initially caused vigorous rainfall activity on its way. Between 15 August and 10 September, the weak vertical upward motion in Z1 was associated with passage of monsoon systems having long life over Indian land. The variation in intensity of upward motion over Z1, Z2 and ZD for west and the east regions are similar during 15 June to 10 September [Fig. 9(b)]. But ZD covers a very large latitudinal belt for the west region. It is noted that the subdivisions of northwest India, like west Rajasthan, east Rajasthan etc., which experienced deficit/scanty rainfall during the advancement of monsoon, are located under ZD [Fig. 9(b)]. The epochs of stronger (weaker) upward motion in Z1 are marked with stronger (weaker) downward motion and wider (narrow)

latitudinal belt of ZD for the east and the west regions. This shows that the epochs of active mid-latitude systems hampered the life cycle of monsoon systems on the eastern monsoon trough area through increased subsidence over this region. For the west region such a relationship in Z1 and ZD seems to be responsible for the more southerly path of monsoon systems west of 80° E. For the west region, a zone of upward motion is observed to move from 5° to about 23°N during 5 to 25 June [Fig. 9(b)]. Such northward movement of this zone in June matches well with the advance of monsoon along the west coast of India. It also represents strong upward motion associated with the northward moving TCZ. There is very strong upward motion in Z2 between 25 and 30 June when downward motion in ZD is very weak. Subsequently, the subsidence to the south of Z2 is strong and persistent. Termination of this strong and persistent zone of subsidence over peninsular India in the first half of August indicates revival of monsoon along the west coast.

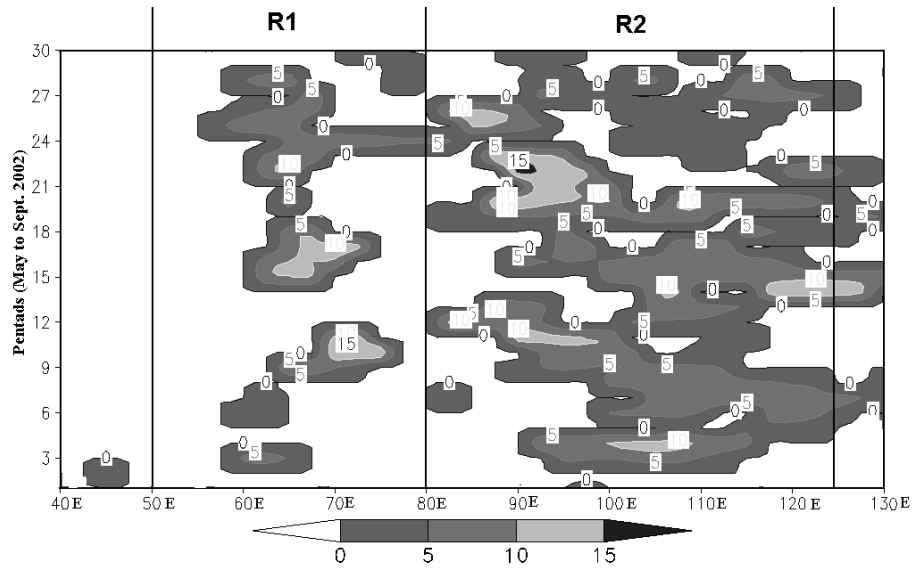


Fig. 10. *x-t* diagram of Pentad mean southwest wind at 850 hPa at 15° N between 40° to 130° E for May to September 2002

4.3. Absence of depressions/storms over Bay of Bengal

Fig. 10 presents an *x-t* diagram of pentad mean of southwest wind at 15° N for the belt 40° to 130° E, following He *et al.*, (1987) for the period May to September 2002. This belt contains two regions, *viz.*, (i) R1- the region 50° - 80° E (Arabian Sea and South India) and (ii) R2 - the region 80° - 125° E (Bay of Bengal - the Philippines). Moderate southwest winds (>5 mps) are seen from the month of May and June respectively over R2 and R1 in association with the onset of monsoon over the respective regions. Subsequently, during pentad 10 and 11 *i.e.*, 15 to 24 June very strong winds (>10 mps) are observed over R1. This is the period when the continental TCZ over India experienced development of transient monsoon systems on western and eastern monsoon trough. Subsequently, till pentad 15 ending on 14 July, the southwest winds are weak over R1. An epoch of strong winds is observed over R1, between 60° and 70° E for pentads 16 and 17 (15 to 24 July). Now for R2, winds are moderate for a long period from pentad 12/13 to 19 (30 June to 3 August). This indicates that the cross equatorial flow was weak during most of the days in July and August over an extended monsoon belt from 40° to 130° E, except for pentads 19 to 23 (29 July to 23 August) when strong winds are observed between 85° and 95° E. Sikka (2003) has noted a positive pressure anomaly of the order of 3 hPa over Arabian Sea off western ghat

during July 2002. It seems to weaken north-south pressure gradient leading to the observed persistent and moderate southwest wind along 15° N on most of the days in July. In the first fortnight of August, winds were still moderate over R1, indicating strong positive pressure anomalies over India. The LOW pressure system formed during this period was short lived and could not revive the monsoon. However, two LOW pressure systems formed on 22 and 29 August remained active over central India and revived the monsoon.

The large positive pressure anomalies observed in the monsoon trough region during July and first fortnight of August indicates filling of the monsoon trough. Chen and Weng (1999) observed that the residual lows of the West Pacific systems lead to an intraseasonal change in formation of monsoon depression in connection with the deepening / filling of the monsoon trough over northern India and Bay of Bengal. The fact that during monsoon 2002, (i) most of the West Pacific systems recurved during July around 140° E and after hitting China coast in August and (ii) the cross equatorial flow over the monsoon region in July and first part of August was weak, indicate that the filling of the trough was not only extended over India but also from Bay of Bengal - Philippines area and beyond. All these factors seem to inhibit the genesis of intense monsoon systems over Bay of Bengal.

5. Concluding remarks

An estimation of the apparent heat source (Q_1) and apparent moisture sink (Q_2) over India has been carried out using daily NCEP-reanalysis data over Indian region for June - September 2002 to study the intraseasonal variations of the secondary heat sources and to find out if the heat sources were responsible for the observed intraseasonal variations of circulation and rainfall over India.

At 850 hPa in the lower troposphere the circulation for July 2002 was dominated by westerly winds throughout the country having very low shears over the monsoon trough area. At 500 hPa, a weak north-south trough was observed with an embedded cyclonic circulation near the head Bay of Bengal. On the western side of this trough, a ridge extended between 20° N and 25° N. This indicated divergence of northwesterly winds from the western side of monsoon trough region in the middle troposphere. At 200 hPa, an anticyclone was over the monsoon trough region with its ridge extending south of 27.5° N over the Indian region. Temperature distribution over India for July 2002 showed that the troposphere over India was warmer as compared to climatological thermal structure. A similar comparison of relative humidity for July over Indian region shows a 10% decrease over different parts as compared to the long term normal values. The vertical velocity at 850 hPa and 500 hPa for July showed a prominent downward motion over northwestern parts of India. A belt of downward motion also was observed from north Arabian Sea to eastern Arabian Sea and adjoining Bay of Bengal region. These circulation features led to the unprecedented below normal rainfall for July which can be described as a break-like situation. The monsoon revived over India due to northward propagation of oceanic TCZ around 15 August.

The $x-t$ diagram showed that events of large diabatic heating rates and drying rates over the western part during June and August were followed by low positive or negative values during July and September respectively. The heat source and moisture sinks coincided with days of very large convective rainfall over the western trough region which led to very large weekly rainfall anomalies for some subdivisions of India. This showed that the development of intense diabatic heat source over western trough region by the end of June led to the break-like situation over India for July. A 60-day mode of variability of pronounced diabatic heating is brought out from the $x-t$ diagram for the western trough region while diabatic heating is low for the eastern trough zone. The $y-t$ diagram of vertical velocity at 500 hPa also showed northward propagation of strong upward vertical motion over

western India in June and August in relation to advance of monsoon along the west coast and revival from the July break-like situation over India respectively.

The analysis has also shown that the mid-latitude circulation over India was responsible for the observed intra-seasonal variability and uniqueness of southwest monsoon 2002 through increased subsidence near foothills of Himalayas on the periphery of the monsoon trough region. This reversed the normal west to east heating gradient over India by the end of June and led to the break-like situation over India in July. For August and September such interaction was weak and monsoon revived but finally resulted into a drought year for India.

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