A diagnostic study on heat sources and moisture sinks in the monsoon trough area during active-break phases of the Indian summer monsoon, 1979

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ABSTRACT

The diabatic heating over the Indian monsoon trough area, along with its thermal structure are studied for the 1979 summer monsoon based on FGGE level-IIIb upper air data of the European Centre for Medium Range Weather Forecasts. The apparent heat source and the apparent moisture sink over the trough area varied coherently with the rainfall over central India. The spatial and temporal variations of the vertically integrated apparent heat source and moisture sink were found to be coincident. These coincidences suggested that diabatic heating was largely contributed by the latent heat released by cumulus convection. During the active periods, the vertical structure of spatially-averaged heating and drying rates above the monsoon trough area showed higher values, as much as 8 K to 11 K day^{-1}, at the mid-tropospheric level (500 hPa), but much smaller and even negative values during break periods. Analyses of the heating and drying rates at 500 hPa level in a x–t diagram revealed that heat sources and moisture sinks propagated westward across the trough area with a period of 10–15 days (often called monsoon mode). The 30–50 day period of fluctuations showed a close link with the two major active/break phases of monsoon during the season. The monsoon mode became a part of the mid-season fluctuation of monsoon activity between the two major active phases. This paper discusses the spatial distribution of rainfall and heat source and moisture sink over the trough area, and the rôle of east–west differential heating in the development of weak/break phases of Indian summer monsoon 1979.

1. Introduction

Since the FGGE Summer Monsoon Experiment in 1979, many investigators have studied the planetary scale aspects of monsoon circulation in relation to the onset, active and weak/break phases of monsoon 1979 by estimating heat and moisture budgets. The rôle of the Tibetan Plateau and the surrounding regions as a heat source on the activity of Asian summer monsoon and on its

evolution was extensively examined. Nitta (1983) has shown that the long period fluctuations of heat sources over the eastern plateau appeared to have a close link with the oscillation of the whole summer monsoon activity of 1979. Later, Luo and Yanai (1984) showed that the heat sources over the plateau are pronounced in the upper troposphere between 200 and 500 hPa, and that the mean heating rate in this layer is as intense as that over Assam-Bengal region. They also identified the principal components of heat sources over the eastern plateau as the surface sensible heat flux and the condensation heating from the

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summer rains, and over the Assam-Bengal region as highly convective monsoon rains.

Recently, Yanai et al. (1992) explored the seasonal changes in the large-scale circulation pattern, and the heat sources and the moisture sinks over the Tibetan Plateau and surrounding areas. They have found that the onset of Asian summer monsoon is an interaction process between the thermally induced vertical circulation over the Tibetan Plateau and the circulation associated with the northward migrating monsoon system. All of these studies had the common objective of understanding the rôle of the Tibetan heat source on the planetary scale monsoon circulation. Very little information, however, could be obtained from these studies on the heat sources in the regional scale over the Indian monsoon region and its relationship with the intraseasonal fluctuation of Indian summer monsoon activity, with which the active-break cycles of monsoon are associated. The purpose of this paper is to fill this gap by studying the temporal and spatial fluctuations of heat source and moisture sink over the monsoon trough area with respect to the oscillation of the summer monsoon activity.

The low-level semi-permanent Indian monsoon trough with its axis stretching from northwest India to the north Bay of Bengal across the Gangetic plains, is characterized by organized convection and vertical motion. During an active monsoon phase, the trough deepens and oscillates around its mean position. At that time, synoptic scale weather systems (which include monsoon lows, monsoon depressions or cyclonic storms) form over the north Bay of Bengal, travel westward along the trough and play a significant rôle in spatial and temporal distribution of rains over central India. Occasional formation of mid-tropospheric cyclones (MTC) over western parts of India the adjoining northeast Arabian Sea (Miller and Keshavamurty, 1968) enhances the rainfall over that part of the country. During the weak/break phases the, monsoon trough moves northward and eventually gets filled up near the foothills of Himalayas. Simultaneously, the rainfall decreases sharply over central India with substantial increase near the foothills. Several studies have documented the differences in the rainfall distribution, the pressure patterns and tropospheric circulation features between the active and weak/break monsoon situations. We refer to a few of the

important works from the past literature. According to the changes in the global circulation at the 500 hPa level during weak/break periods Ramaswamy (1958, 1962 and 1968) showed that a mid-latitude trough in the westerlies occasionally intrudes southwards into India during breaks, wiping out the Tibetan high at 500 hPa. An extensive survey of long period (1888–1967) synoptic daily weather charts was made by Ramamurthy (1969) for the peak monsoon months (July and August). He showed that the rainfall pattern changed strikingly by a shift in the heavy rainfall activity at the foot of the Himalayas in breaks. The westerly flow dominated over north India in the lower troposphere, and the mid-latitude westerly troughs moved across the Himalayas, shifting the sub-tropical ridge southward in the middle and upper troposphere. Compositing the evolving flow patterns during active and break monsoon spells, Alexander et al. (1978) showed that an anomalous ridge (trough) in the lower and middle troposphere extends from the Indian peninsula (15°–20°N) towards the south Bay of Bengal during break (strong) monsoons.

In recent years, several investigations have been carried out to understand the evolution-mechanism of active-break monsoon cycles. An important aspect on the active-break spells has come from the Krishnamurti et al. (1985) study of divergent circulation on the 30–50 day time scale. Monsoon breaks occurred when the ridge lines of the eastward propagating 30–50 day global scale intraseasonal mode and the westward propagating 10–20 day monsoon mode arrived simultaneously over central India. Murakami et al. (1986) suggested that the interaction between the annual cycle and the 30–50 day mode results in the monsoon cycle, in which the active-break cycle is a part. Performing the empirical orthogonal function analysis of the entire FGGE-year velocity potential field, Chen et al. (1988) isolated the annual cycle and the 30–50 day mode of divergent circulation at 200 hPa. They showed that the northeastward propagation of the planetary scale 30–50 day mode over the Indian monsoon region induces local transient Hadley circulation. Through this type of circulation, the planetary scale 30–50 day mode couples with and steers northward the low level 30–50 day monsoon troughs and ridges that originated around the equator. The northward migration of these low

level transient troughs and ridges causes, respectively, the deepening and filling of the monsoon trough over central India, resulting in active-break monsoon. In addition to the 30–50 day mode, the Indian summer monsoon rainfall is significantly contributed to and modulated by the 10–20 day intraseasonal monsoon mode (Chen and Chen, 1993).

The characteristic distribution of monsoon rainfall in space and time over central and north India during active and break phases implies changes in the diabatic heating rates within the monsoon trough and adjoining regions. The importance of diabatic heating in inducing monsoonal flow in the lower and upper troposphere has been demonstrated by Murakami et al. (1970) from their numerical experiments on Indian monsoons. Therefore, it is important that we examine the diabatic heating fluctuations within the monsoon trough and in the adjacent areas to understand the developmental episodes of rains over India during the summer season. This paper presents the computations of the diabatic heating over the Indian monsoon region in terms of apparent heat source (Q_1) and of apparent moisture sink (Q_2) for the summer monsoon 1979. The active/break phases are determined on the basis of rainfall distribution over the central parts of India. The mean tropospheric circulation features, as well as the temperature and moisture structure (in terms of-precipitable water), for the active and weak/break phases are also studied. The spatial and temporal fluctuations of Q_1 and Q_2 Over the monsoon trough area and their linkage with the active-break cycle of monsoon are discussed.

Section 2 deals with the data utilized and the computational procedures. Section 3 illustrates the mean tropospheric circulation patterns, and temperature and moisture structure for different phases of monsoon. Section 4 presents the results and discussion on the temporal, spatial and vertical distribution of the apparent heat source and of the apparent moisture sink over the trough area during the season as well as on the development of weak/break phases of monsoon. Summary and conclusions are given in Section 5.

2. Data and methodology

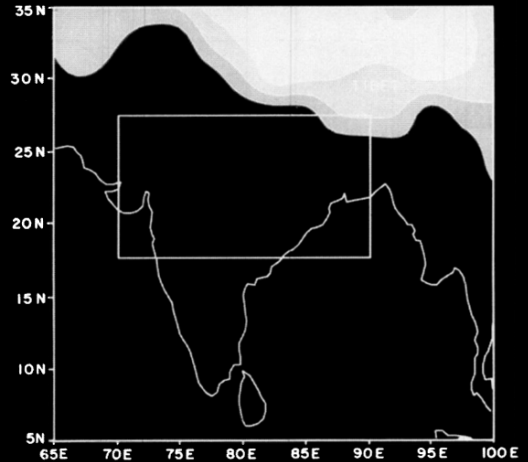Daily FGGE Level III b data $(u, v, T$ and Rh) of the European Centre for Medium Range

Fig. 1. ECMWF FGGE-Level III b data domain at $2.5° \times 2.5°$ grid interval used in the study. The rectangular box covers the domain of monsoon trough bounded by $17.5°–27.5°N$ and $70°–90°E$. The shaded area represents the topography of 1500 m and above.

Weather Forecasts (ECMWF) for 1200 UTC at all the mandatory levels (1000–100 hPa) for the period 1 May through 30 September 1979 are utilized for all computations. The ECMWF data were regridded to $2.5°$ (long) $\times 2.5°$(lat) resolution from the original grid interval of $1.875°$ archived at the National Center for Atmospheric Research with the bilinear interpolation (Vincent, 1982). The data domain $(5°–35°N$ and $65°–100°E)$ and the monsoon trough area bounded by $17.5°–27.5°N$ and $70°–90°E$ are shown in Fig. 1. The daily rainfall data over the Indian stations, averaged for each $2.5° \times 2.5°$ grid square, are utilized to obtain the daily rainfall distribution over the monsoon trough area.

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

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

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

$$(A) \quad (B) \quad (C) \qquad (2)$$

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 where $p_0 = 1000$ hPa. The terms indicated as (A), (B), and (C) of eqs. (1) and (2) are local change, horizontal and vertical advections of heat and moisture, respectively.

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

$$\frac{\partial u}{a \cos \omega \partial \lambda} + \frac{\partial v}{a \partial \omega} + \frac{\partial \omega}{\partial p} = 0, \tag{3}$$

where u and v are the eastward and northward components of horizontal wind v, a the radius of earth, ω 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

$$\omega_s = -g\rho_s \left(\frac{u_s}{a \cos \omega} \frac{\partial h}{\partial \lambda} + \frac{v_s}{a} \frac{\partial h}{\partial \omega} \right), \tag{4}$$

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. The smooth topographic contours of 1500, 3000 and 4500 meters are shown in Fig. 1. For the upper boundary, the vertical p-velocity satisfies $\omega = \omega_T$ at $p = 125$ hpa, where:

$$\omega_T = \left(\frac{\dfrac{\partial \theta}{\partial t} + v \cdot \nabla \theta - \dfrac{(p_0/p)^{R/C_p}}{C_p} Q_R}{-\dfrac{\partial \theta}{\partial p}} \right), \tag{5}$$

as suggested by Nitta (1977) and used by Luo and Yanai (1983). Eq. (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 Dopplick (1972). The p-velocity is obtained by integrating eq. (3) downwards with the boundary conditions (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 Ps and 100 hPa for Q_1, and between Ps and 300 hPa for Q_2 by

$$\langle Q_1 \rangle = \frac{1}{g} \int_{300}^{ps} Q_1 \, dp \text{ and } \langle Q_2 \rangle = \frac{1}{g} \int_{300}^{ps} Q_2 \, dp,$$

and are measured in Watts per meter square (Wm^{-2}). Because the terrain gradients are very large in both the x and y directions along the northernmost boundary of monsoon trough area the $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ at the northern boundary are smoothed by extrapolation. The apparent heating rate (Q_1/C_p) and the apparent drying rate (Q_2/C_p) measured in K day^{-1} are computed at all grid points for all the levels and averaged 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 of and detrainment of water vapour (Yanai et al., 1973). The precipitable water (w) in an air column from Ps to 300 hPa level is computed with

$$w = \frac{1}{g} \int_{300}^{ps} s \, dp,$$

where s is specific humidity.

3. Mean tropospheric features during different phases of monsoon 1979

3.1. Phases of monsoon

The 1979 summer monsoon over India set in over the southern part of India on 11 June, advanced rapidly northward across the south peninsula up to 20°N by 20 June, and covered (except the extreme northwest) the central part of the country by 30 June. The period prior to 11 June and the period 11 to 20 June are identified as preonset and onset phases of monsoon, respectively.

During the period from 21 June until the end of the season (30 September) the monsoon fluctuated from ample rain over central parts and the west coast of India to substantial decrease of rainfall over the entire sub-continent except the foot-hills of Himalayas. While the former episode is usually known as the strong or active monsoon, the latter is known as the weak or break monsoon. The transition from active to break and break to active phases are not abrupt. The strong monsoon activity of the active phase gradually weakens to reach the break monsoon condition, which in turn passes through a revival process to re-activate the monsoon. The active and weak/break phases of monsoon 1979 are identified on the basis of rainfall over central India, which is represented with the rainfall averaged over all $2.5° × 2.5°$ blocks within the rectangular box of Fig. 1, except for the blocks close to the foothills of Himalayas between $25°–27.5°N$ and $80°–90°E$. Shown in Fig. 2 is a histogram of daily rainfall averaged over the trough area. The solid curve across the histogram represents the long term (1901–1980) daily normal rainfall. In this figure, there are several epochs of greatly above or below normal rainfall which last consistently for periods of $≥8$ days. This figure also reveals episodes of rainfall fluctuating around the mean on a much smaller time scale of 5 to 7 days, with near normal average rainfall for the period. In this study, we have identified the epochs with large and consistently (for more than 8 days) above (below) normal rainfall as active (weak/break) monsoon phases, and those with smaller scale fluctuation as normal or revival phases of monsoon from mid-season break to second active phase.
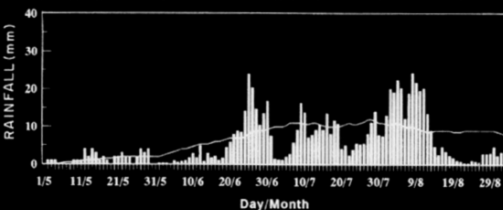
As determined from the criteria defined above,

Fig. 2. Histogram of areal mean daily precipitation (mm day^{-1}) over the trough area except for the blocks close to the foothills of Himalayas between $25°–27.5°N$ and $80°–90°E$. The solid curve across the histogram represents long term (1901–1980) daily normal rainfall.

the period of active, weak/break and normal phases, duration, percentage departure of rainfall from normal, and synoptic scale disturbances which formed or moved across the monsoon trough area during different phases are shown in Table 1. The period 1–8 July with far below normal rainfall (-62%) over central India has been termed weak phase instead of break phase. Traditionally, a break in monsoon occurs after the monsoon is fully established over the entire country. In this case, monsoon activity weakened over central India while it was still advancing to the extreme northwest of India.

The rainfall series (Fig. 2) exhibits two spells of far above normal rainfall over central India (active phases), once during 21–30 June and the other during 1–13 August. The two active spells are separated by a time interval of about 40–45 days, in between which the monsoon activity fluctuated from weak to normal and then to the mid-season break phase before reviving to the second active phase. Normally, July and August are the peak rainy months of the season, and the month of September is characterized by the withdrawal phase of monsoon. In 1979, after the prolonged break commencing on 14 August, monsoon did not revive till end of August and overlapped with the withdrawal phase. We consider the period 14–31 August only to represent the break phase.

The horizontal distribution of rainfall rate per day over the entire country for the different phases of monsoon 1979 identified above are displayed in Fig. 3. Broad rainfall distribution appears over central parts and the west coast of India during active and normal phases (21–30 June, 9–19 July and 1–13 August), whereas a substantial decrease in rainfall ($≤5$ mm day^{-1}) occurred over the entire subcontinent, except the foothills of Himalayas, during weak/break phases (1–8 July, 20–27 July and 14–31 August). The contrast of rainfall distribution between the active and break phases is found to be consistent with the circulation features presented in the next section.

3.2. Mean circulation pattern

The mean flow pattern at lower (850 hPa), middle (500 hPa) and upper (200 hPa) tropospheric levels for different phases of monsoon were examined here. Remarkable changes in the flow patterns for active and weak/break phases are seen at all levels. Chen and Chen (1993), using

Table 1. *Period of different phases of the 1979 Indian monsoon with duration, departure of average during different phases: rainfall from normal for the period, and synoptic weather systems with life duration (in brackets) prevailing during different phases*

Episodes	Period	No of days	% Dep. of average rainfall	Phases of monsoon	Synoptic weather systems
1	21–30 Jun	10	70	Active	Dep: (23–26) MTC: (22–27)
2	1–8 Jul	8	−62	Weak	Dep: (7–9)
3	9–19 Jul	11	4	Normal	Low: (15–18)
4	20–27 Jul	8	−56	Break	
5	28–31 Jul	4	−10	Revival	Low: (27–31)
6	1–13 Aug	13	82	Active	MTC: (1–6) Dep: (6–10)
7	14 Aug–23 Sep	41	−55	Break	

Dep: Depression; low: low pressure area; MTC: mid-tropospheric cyclone.

the same data for the period 17 June to 19 July, have shown in detail the daily streamline synoptic analysis at 850 hPa level along with the locations of the 30–50 day northward moving troughs and ridges identified by Krishnamurti and Subramanyam (1982). These maps show mid-latitude westerlies over north Indian latitudes during the break phase. These changes in monsoon circulation at 850 hPa have indicated that the 30–50 day trough is replaced by the 30–50 day ridge, causing typical changes in rainfall distribution from active to break phases. However, the changes in the 500 hPa flow pattern are found to be the most pronounced in bringing out the characteristic features of the active-break situations. Hence, we shall focus our discussion on the active-break phases at this level.

The 500 hPa mean flow patterns for different phases defined in Table 1, (except for the revival phase of 28–31 July) are shown in Fig. 4. The pronounced east-west oriented monsoon trough is seen between latitudes 20° and 22.5°N during active phases of monsoon (21–30 June and 1–13 August). The sub-tropical ridge lies along the latitudes 27.5°–32.5°N across the Indian longitudes. For the normal phase of 9–19 July, the strong northwesterly/northerly flow over western India, associated with the subtropical anticyclone, unusually penetrated southward to 15°N. This shifted the western end of the trough axis southward with weak westerlies to the south of it in turn. The mean circulation features and the distribution of rainfall rate per day for the period 9–14 July and 15–19 July are shown separately in

Fig. 5. While the mean circulation feature and the rainfall distribution for the period 9–14 July resembled an active monsoon situation, the same broke down during the later period of 15–19 July. The normal episode 9–19 July thus had a short spell of active monsoon (9 to 14 July) and spatially varied mixed monsoon activity for the remaining 5 days (15–19 July), leading to the mid-season break monsoon over the entire country during 20–27 July.

The mean wind during the weak/break phases is anticyclonic over central India between 20°–25°N, and the east-west trough of the active phase is replaced by the subtropical ridge across the anticyclonic centre with strong westerlies to its north. A trough is seen over the equatorial east Arabian. Arabian sea and the adjoining land area near 10°N with weak westerlies (<2.5 mps) to the south of it. Such features of break situations are shown also by Alexander et al. (1978). Using filtered wind data at 850 hPa for the 1979 summer, Krishnamurti and Subramanyam (1982) illustrated strengthening or weakening of the Indian monsoon by successive northward passage of the trough or ridge line, respectively, along the Indian longitudes. The weak break phases of monsoon coincided with the passage of the ridge line across latitudes 20°–25°N during its northward propagation.

3.3. Mean temperature and moisture structure

The mean temperature structure for the active-weak/break phases is examined from the analysis
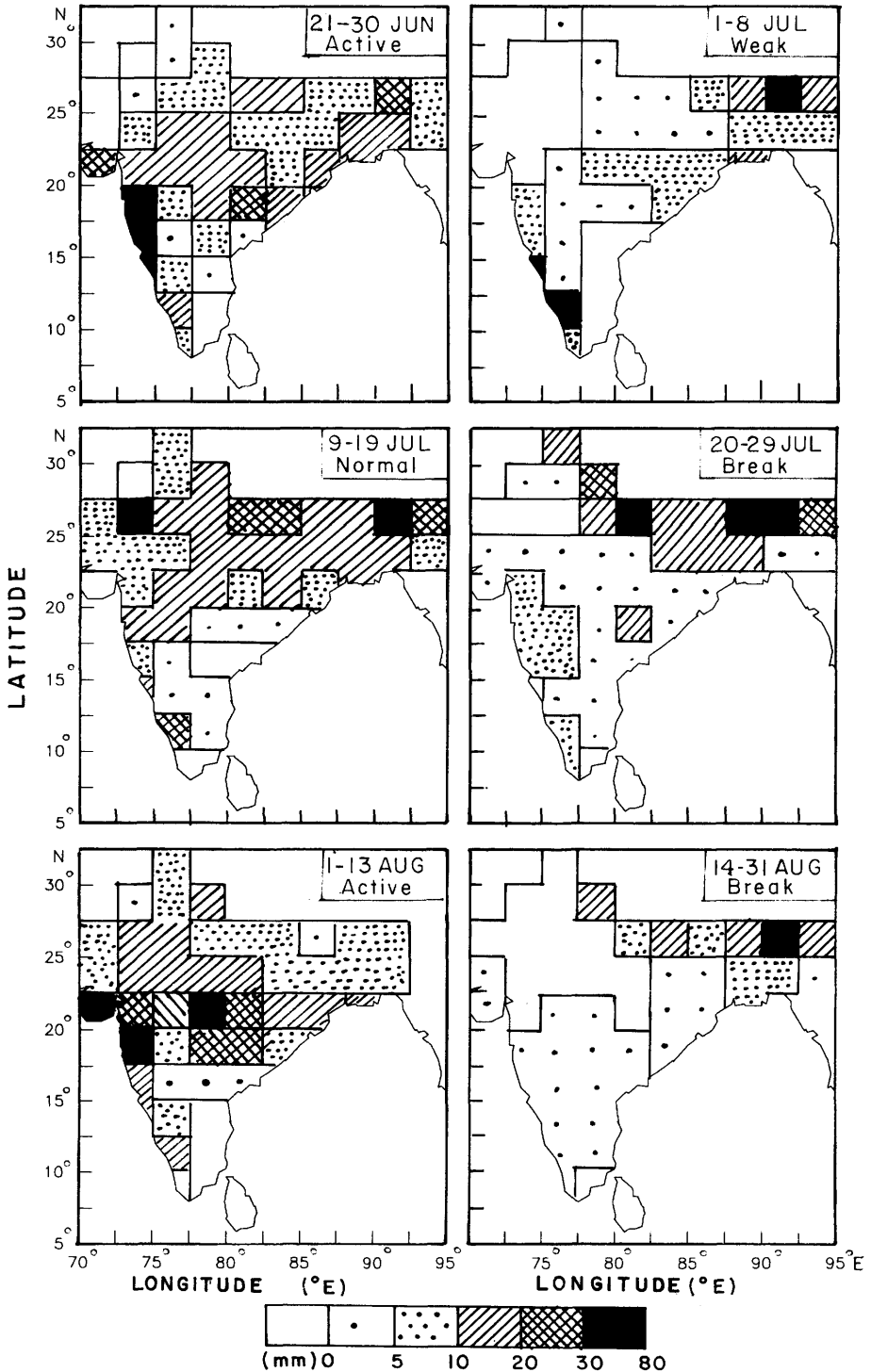
Fig. 3. Analysis of horizontal distribution of rainfall rates per day during different phases of monsoon.
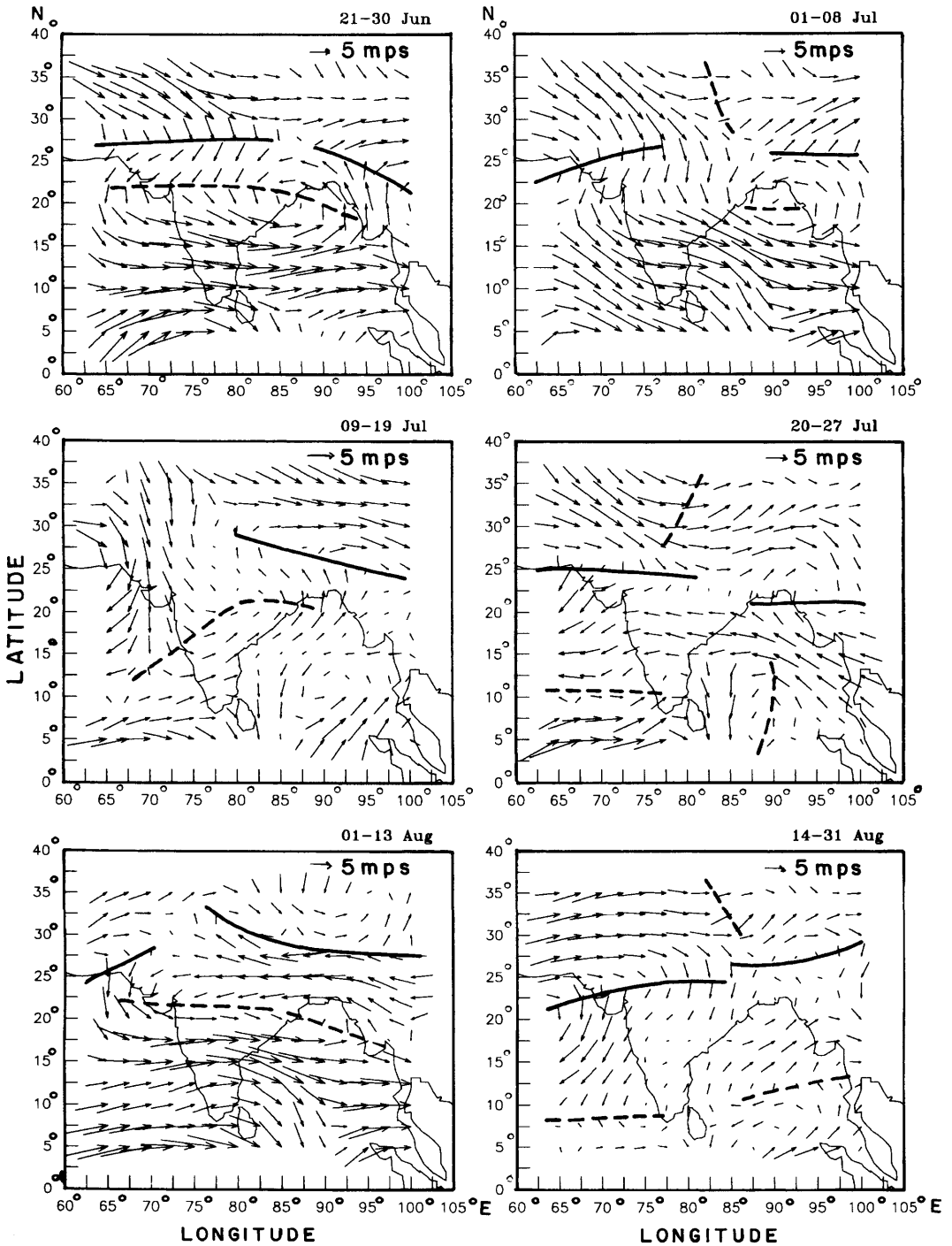
Fig. 4. ECMWF-FGGE Level IIIb mean winds at 500 hPa level for different phases of monsoon. The axis of the troughs and ridges are shown by dashed and solid lines respectively. (Unit vector arrow represents 5 mps).
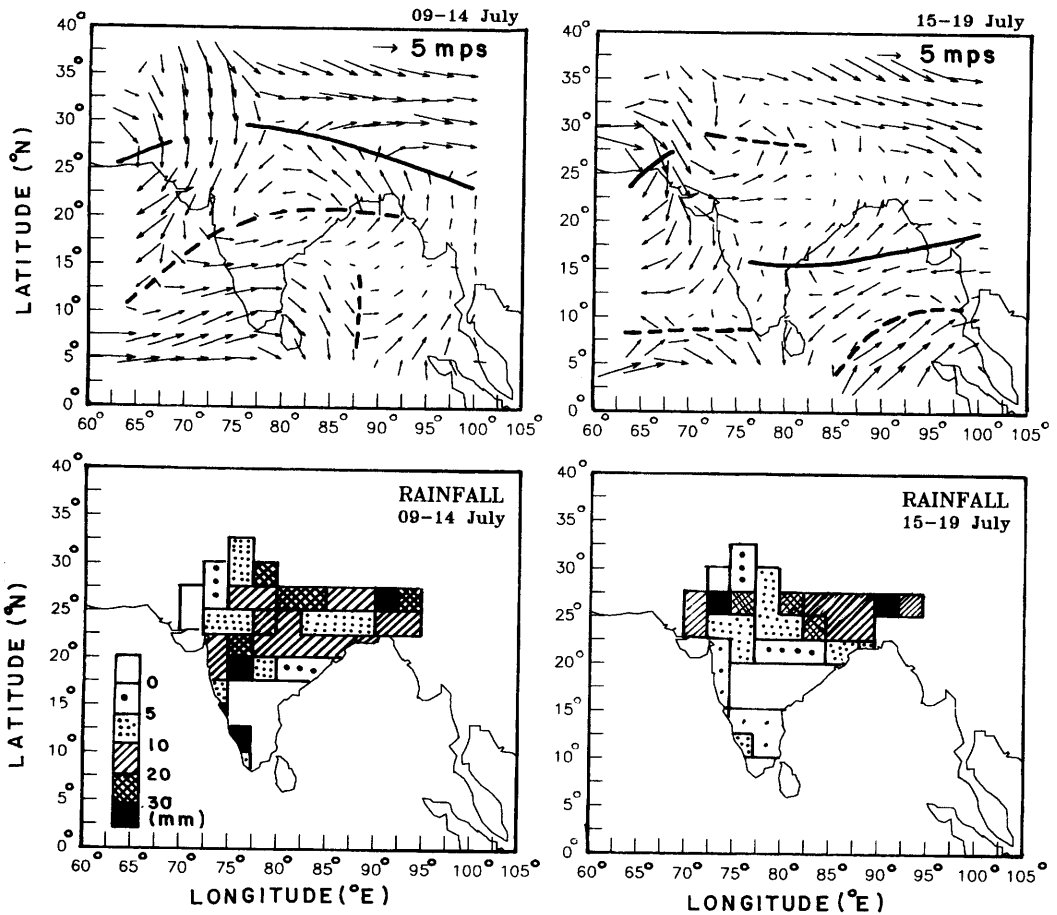
Fig. 5. Same as Fig. 4 but for the periods (a) 9–14 July and (b) 15–19 July 1979, (top panel) and spatial distribution of rainfall rates (similar to Fig. 3) for the same periods (lower panel).

of FGGE-IIIB temperature data. The meridional profiles of temperature at 500 hPa level for active and weak/break phases along longitudes 72.5°E and 87.5°E (representing the western and eastern parts of the trough) are shown in Figs. 6a, b. Striking differences are noted in the temperature profile between the two phases and between the two parts of the trough area. In comparison to the break phases, warmer air prevailed over the trough area between 17.5°N and 27.5°N during the active phases. In general, temperature increased from south to north, but the western part showed a steep fall of temperature north of 27.5°N while the temperature over the eastern part continued to increase up to 32.5°N. It is shown in Fig. 6a that the fall in temperature to

the north of 27.5°N over the western part was greater during weak/break phases than during active phases. The gradient of fall of temperature for the weak/break phases was about 1.4 K/(2.5° latitude) and that for the active phases was 0.7 K/(2.5° latitude). The temperature over the eastern part increased with a stronger gradient [1.25 K/(2.5° latitude)] to the north of 27.5° to 32.5°N during the weak/break phases than during the active phases [0.8 K/(2.5° latitude)]. Pant (1983) has shown from the analysis of 500 hPa temperature at a station in Sinkiang (on the western part of Tibetan Plateau) that break monsoon in 1979 occurred simultaneously with the sudden cooling of the Plateau, and that the revival of monsoon activity took place with the rise in
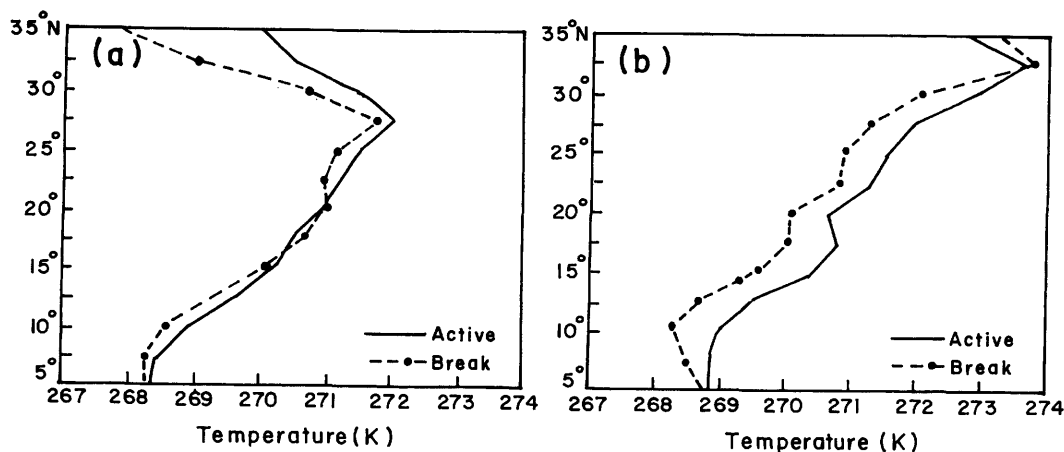
Fig. 6. Meridional temperature profile at 500 hPa level for active (solid line) and weak/break (dashed line) situations over (a) western (along 72.5°E) and (b) eastern (along 87.5°E) parts of the monsoon trough area.

temperature to near normal values. According to him, this temperature decrease was caused by the intrusion of cold air in association with the deep trough in the mid-latitude westerlies to the north of India. This trough can be seen in the mean winds of the weak/break phases (Fig. 4). A rise in temperature to the north of 27.5°N over the eastern part of the trough during break phases can be attributed to the latent heat released by organized cumulus convection over the region, which results from the shift of the heavy precipitation zone northwards towards the foothills. The rainfall data for summer showed that northeast India near the foothills (north of 27.S°N) had heavy precipitation with maximum 80 mm day^{-1} during weak/break phases (except for the prolonged break phase of 14–31 August when the maximum reached only to 37 mm day^{-1}). The rest of India experienced insignificant rainfall varying from 0–5 mm day^{-1} (see Fig. 3).

The moisture structures for the active/break phases are examined from the analysis of precipitable water over the Indian monsoon region (Fig. not shown). Greater precipitable water was observed over the entire trough area during the active phases compared to that in the weak/break phases. The average precipitable water amount over the trough area was 62 kg m^{-2} for the active phases and 50 kg m^{-2} for the weak/break phases. The weak/break phases are marked by the intrusion of drier air into the trough area from the northwestern part.

4. Results and discussions

4.1. Temporal and spatial variations of heat source and moisture sink

The computations of the apparent heat source (Q_1) and apparent moisture sink (Q_2) over the data domain showed very interesting spatial and temporal variations within the season. Hence, the daily values of (Q_1) and (Q_2) at various grid points and at different tropospheric levels were analyzed to study the changes in their distributions in relation to the active/break cycle of monsoon 1979. The results of these analyses are discussed in the following sub-sections.

4.1.1. Vertical time section of heating rate and drying rate. Displayed in Fig. 7 is the vertical time section of the 3-day running mean of the area average heating rate [Q_1/C_p] and drying rate [Q_2/C_p] above the trough area between Ps and 100 hPa level for Q_1/C_p and between Ps and 300 hPa level for Q_2/C_p for the period from 1 June to 29 August. The maximum heating rate existed in the middle troposphere between 500 and 400 hPa, while the maximum drying rate appeared between 600 and 500 hPa. Prior to the onset of monsoon (11 June), the heating rate above the trough area was negative or unusually small (<2 K day^{-1}), with a large drying rate (4–8 K day^{-1}) near the surface layer up to the 850 hPa level. During the two active monsoon phases of
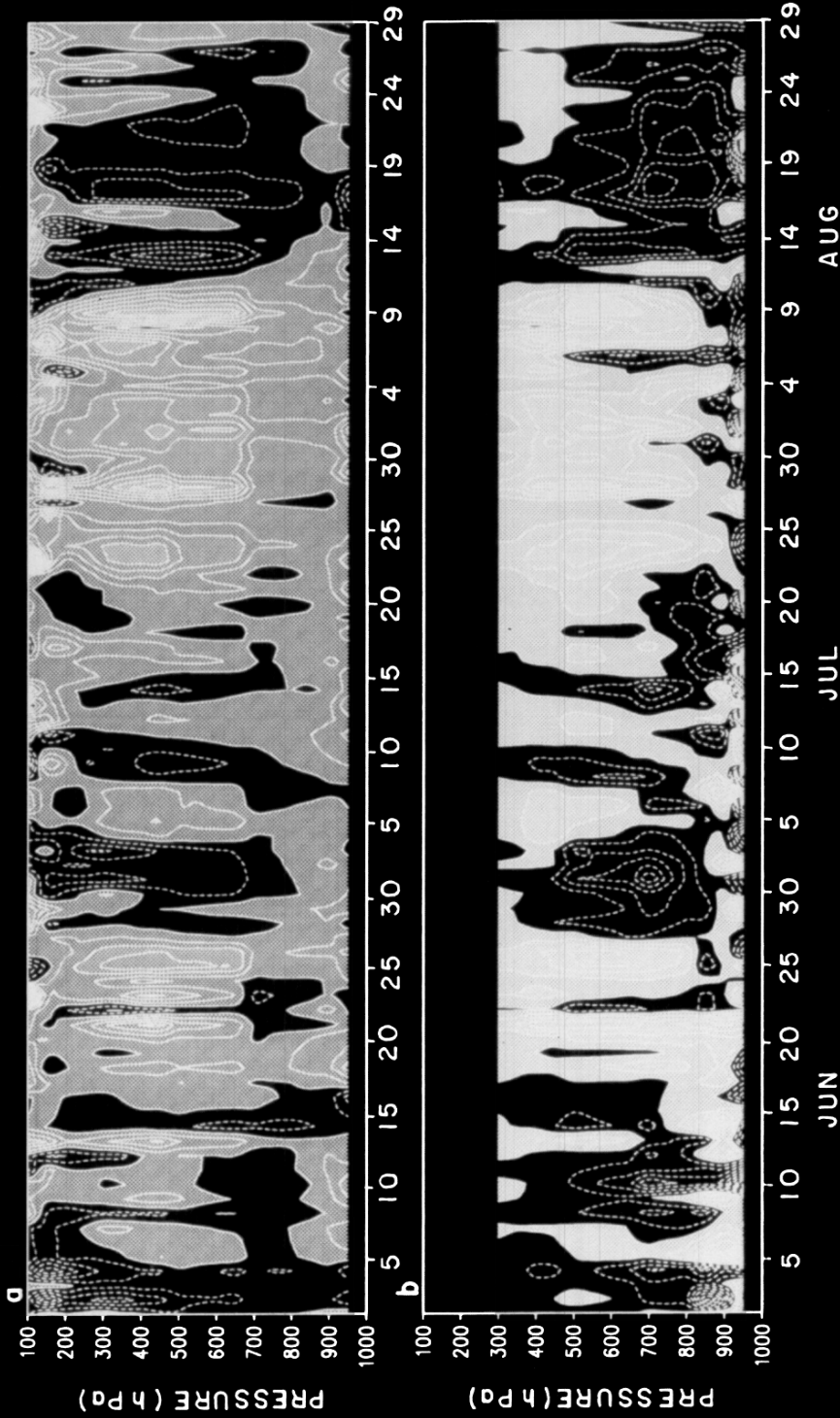
Fig. 7. Vertical time section of areal mean (a) heating rate Q_1/C_p and (b) drying rate Q_2/C_p ($K°\ day^{-1}$). Isolines are at $2\ K\ day^{-1}$ intervals. Positive areas are shaded and the dashed lines represents negative values.

21–30 June and 1–13 August, the maximum heatings of 8.8 K day^{-1} and 11.5 K day^{-1} were located at between 500 and 400 hPa levels on 21 June and 9 August (Fig. 7a) respectively. Accompanying with these maximum heatings were the equally strong drying rates with peak values of 6.6 K and 10.5 K day^{-1}, (Fig. 7b), respectively, between 600–500 hPa. The peaks in the mid-tropospheric heating and drying rate recurred with a time interval of 30–50 days during the season. Thus, strong heating rates with values greater than 4 K day^{-1} prevailed in the layer between 600 and 300 hPa above the trough area during the two active phases (21–30 June and 1–13 August) and the revival phase (28–31 July). Obviously, such intense heating of the middle troposphere resulted from the heavy precipitation associated with the passage of synoptic scale disturbances across the trough area. For the remainder of the season (i.e., weak, normal, mid-season and prolonged break phases), the heating rate fluctuated with a range of ± 2 K day^{-1}, but reached its lowest value of < -4 K day^{-1} on several occasions during the prolonged break phase. Weak heatings of about 2 K day^{-1} reappeared for a short period over the trough area at the end of August.

The vertical distribution of drying rates (Fig. 7b) is relatively consistent in magnitude with that of the heating rate, except that a deep layer of moisture sink ($\geqslant 4$ K day^{-1}) existed between 850 and 350 hPa level during the two active phases. This consistency indicates that there was organization of cumulus convection over the monsoon trough area during the active phases of summer monsoon 1979.

4.1.2. Horizontal distribution of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$. The time averages of vertically integrated heat source $\langle Q_1 \rangle$ and moisture sink $\langle Q_2 \rangle$ are denoted by $\langle \bar{Q}_1 \rangle$ and $\langle \bar{Q}_2 \rangle$ respectively. Shown in Figs. 8 and 9 are the horizontal distributions of these quantities for the following periods: (a) active (21–30 June), (b) weak (1–8 July), (c) second active (1–13 August) and (d) prolonged break (14–31 August) phases. The $\langle \bar{Q}_1 \rangle$ and $\langle \bar{Q}_2 \rangle$ distribution for the normal (9–19 July), mid-season break (20–27 July) and the revival phases are not shown. Prior to the onset of monsoon (1 May–10 June), cooling dominated the monsoon trough area with a weak heat source and moisture sink centers appearing over peninsula, south of 20°N.

The monsoon became active over central India on 21–30 June, when the values of $\langle \bar{Q}_1 \rangle$ and $\langle \bar{Q}_2 \rangle$ intensified and shifted northward to form an east-west oriented pattern across the trough area with the highest value (>400 W m^{-2}) located over central India. The 200 Wm^{-2} isoline covered the area (75°–82.5°E and 15°–22.5°N) coinciding with the large scale precipitation over the trough area (Fig. 3), associated with the westward passage of a depression during 23–26 June (see Fig. 10d). During 22–27 June the precipitation was enhanced over the western part of the trough area due to *in situ* formation of an MTC. Following this active monsoon phase is the weak monsoon phase (1–8 July). Either a negative (<200 Wm^{-2}) or very weak positive values (< -200 Wm^{-2}) of $\langle \bar{Q}_1 \rangle$ and $\langle \bar{Q}_2 \rangle$ appeared over the northern part of the trough area, while the heat source and moisture sink (~ 200 Wm^{-2}) shifted to the southeastern part of the trough area and the adjoining south peninsula/southwest Bay of Bengal, forming a north-south oriented pattern. As shown in Fig. 9b, when the second active phase of monsoon occurred during 1–13 August, large positive values of $\langle \bar{Q}_1 \rangle$ and $\langle \bar{Q}_2 \rangle$ once again covers the entire trough area as well as the head Bay of Bengal. The heating centers with values larger than 400 Wm^{-2} lay over central and northwest India, and the 200 Wm^{-2} isolines covered the larger part of the trough area. The large heating centers during 1–13 August were caused by the heavy precipitation over central and northwest India because of the formation of two synoptic scale disturbances: an MTC (1–6 August) and a westward moving depression/severe cyclonic storm (6–10 August). For the second break phase, the heating distribution exhibited a pattern similar to that of weak phase 1–8 July.

4.1.3. The x–t diagram of heating and drying rates. Shown in Figs. 10a and b are the x–t diagrams of the 3-day running mean of the heating rate (Q_1/C_p) and drying rate (Q_2/C_p) at 500 hPa along 22.5°N for longitudes 70°–90°E for the period from 1 June to 29 August. Thus, this figure represents the zonal variation of heating and drying along the central part of the trough area. A westward propagation of heating exceeding 5 K day^{-1} is shown in Fig. 10a during 21–26 June, 5–10 July, 16–25 July, 27 July–1 August and 4–11 August, suggesting a separation period of 10
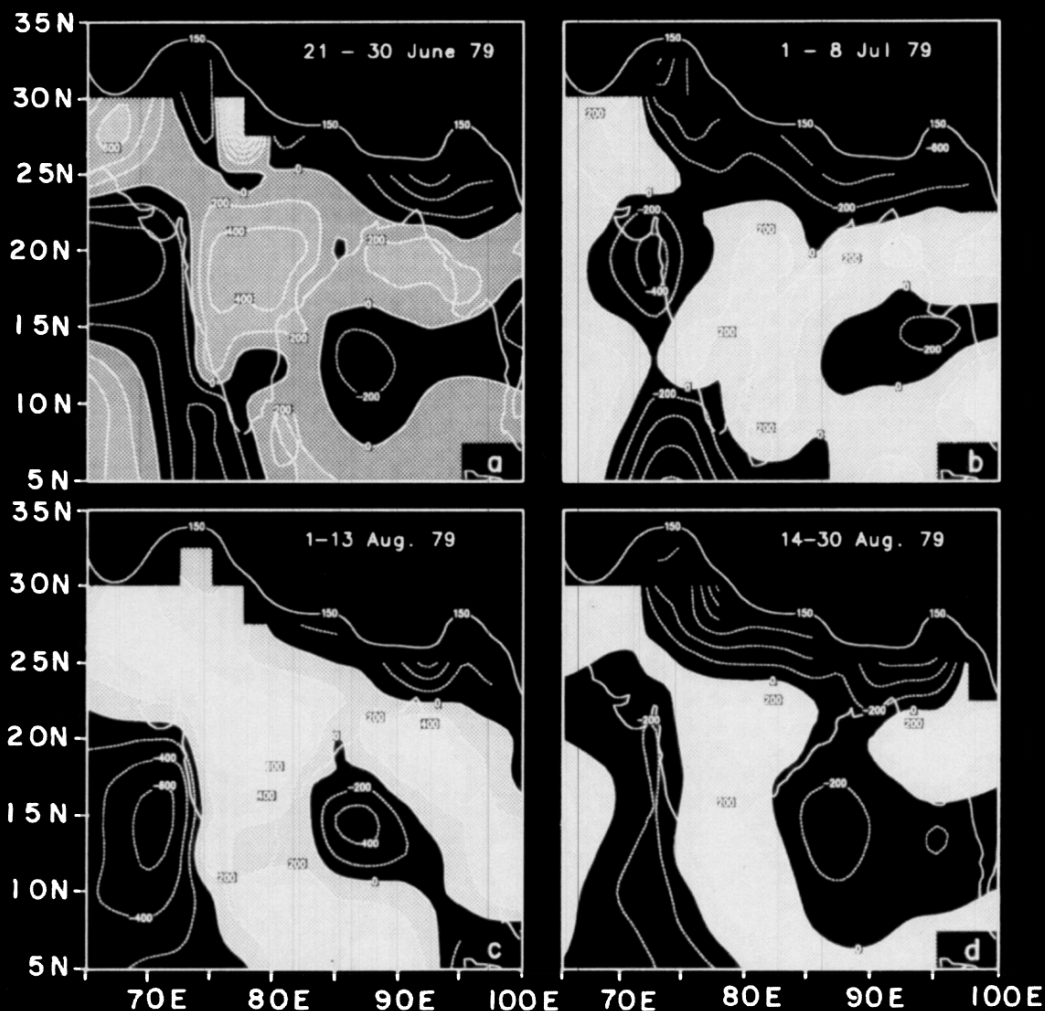
Fig. 8. Distribution of vertically integrated apparent heat sources $\langle Q_1 \rangle$ averaged over different phases of monsoon. The contour interval is 200 Wm^{-2} and positive areas are shaded. The 150 decameter is shown in the figure.

to 15 days. A nonpropagating heating zone also developed within the belt 85°–90°E during 28–30 June, the significance of which is not clear. Fig. 10a revealed that when a strong heating zone (>10 K day^{-1}) propagated to the west of 80°E cooling (<-5 K day^{-1}) developed over the eastern part between 85°–90°E for the second active phase. Subsequently, cooling also appeared over the western part between 70°–80°E after a period of 3–5 days. Such events also occurred during 26 June–3 July, and 12–18 July following the other heating epochs of 23–26 June and 5–10 July. But in these cases change took place rather slowly

over the entire monsoon season, low heating dominated the belt between 80°–85°E. Thus, diabatic heating and cooling propagated alternately across the trough, the process being quicker in the first fortnight of August. Since $\langle Q_1 \rangle$ is associated closely with $\langle Q_2 \rangle$, the propagation of heating zones follows closely the suite of drying zones.

The daily mean rainfall rate for each 2.5° longitudinal belt across the trough area is also shown in Fig. 10c. This figure shows the westward propagation of zones of heavy rainfall (>20 mm day^{-1}) during the three major epochs: 23–28 June, 7–9 July and 6–13 August. In Fig. 10d is shown the
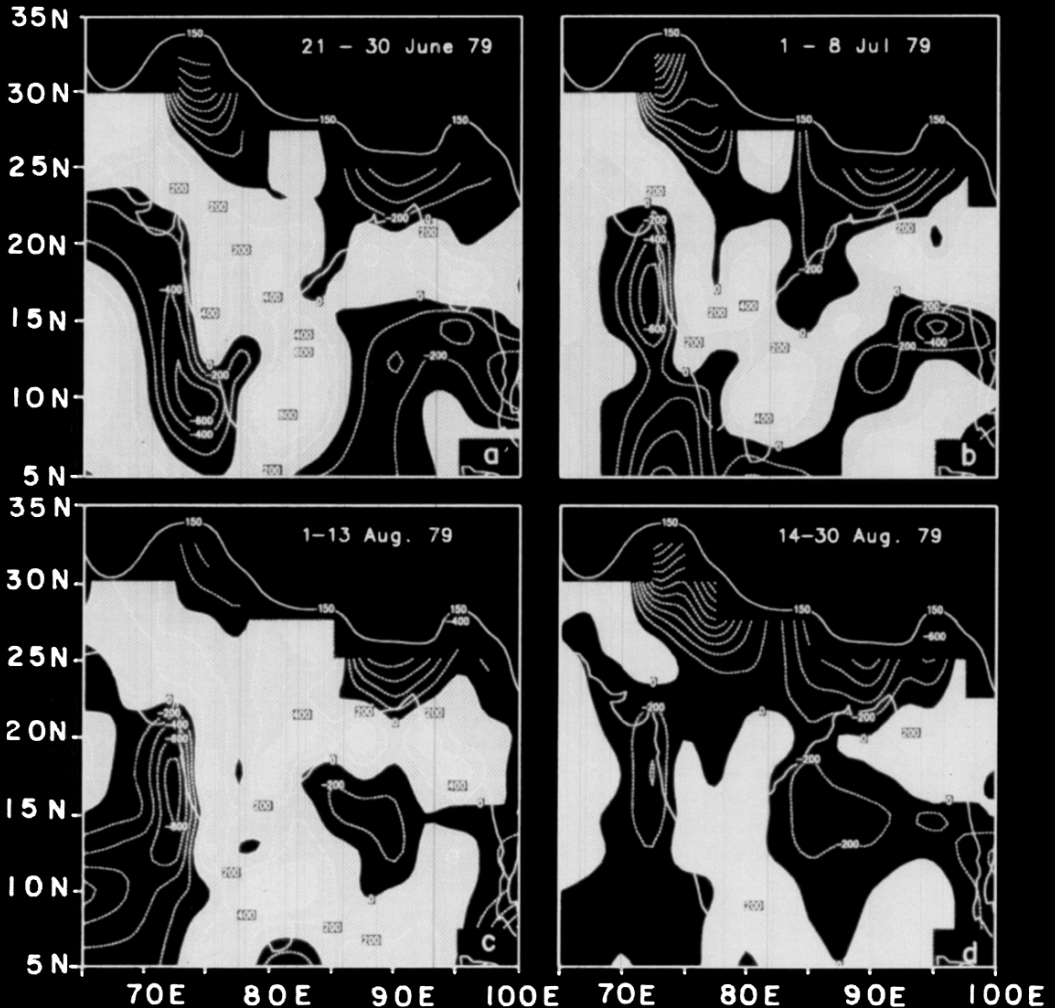
Fig. 9. Same as Fig. 8 but for apparent moisture sink $\langle Q_2 \rangle$.

propagation of the major synoptic scale disturb-ances (monsoon lows, monsoon depressions and severe cyclonic storms) for the corresponding period. As could be speculated, good association is seen between (c) and (d). It is clear that the diabatic heating-and drying rates on 23–26 June, 5-10 July and the overlapping situations on

28 July–1 August and 4–11 August (Figs. 10a and b) are associated with the westward movement of heavy rainfall zones on 23–28 June, 5–9 July and 6–13 August. This suggests that the heating over the trough was mainly due to latent heat release. The heating zone over the belt 85°–90°E during 28–30 June, did not propagate westward because

Fig. 10. The x–t diagram of (a) heating rate Q_1/C_p, (b) drying rate Q_2/C_p at 500 hPa level along 22.5°N, (c) mean rainfall for each 2.5° longitude belt and (d) longitudinal position of the center of synoptic scale systems between 70°–90°E longitude during the period of 1 June–30 August, 1979. The contour intervals are 5° day^{-1} for both $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$, with the shaded part representing positive areas and dashed lines for negative contours. The contour intervals of rainfall are 10 mm day^{-1} and the shaded part represents no rain.
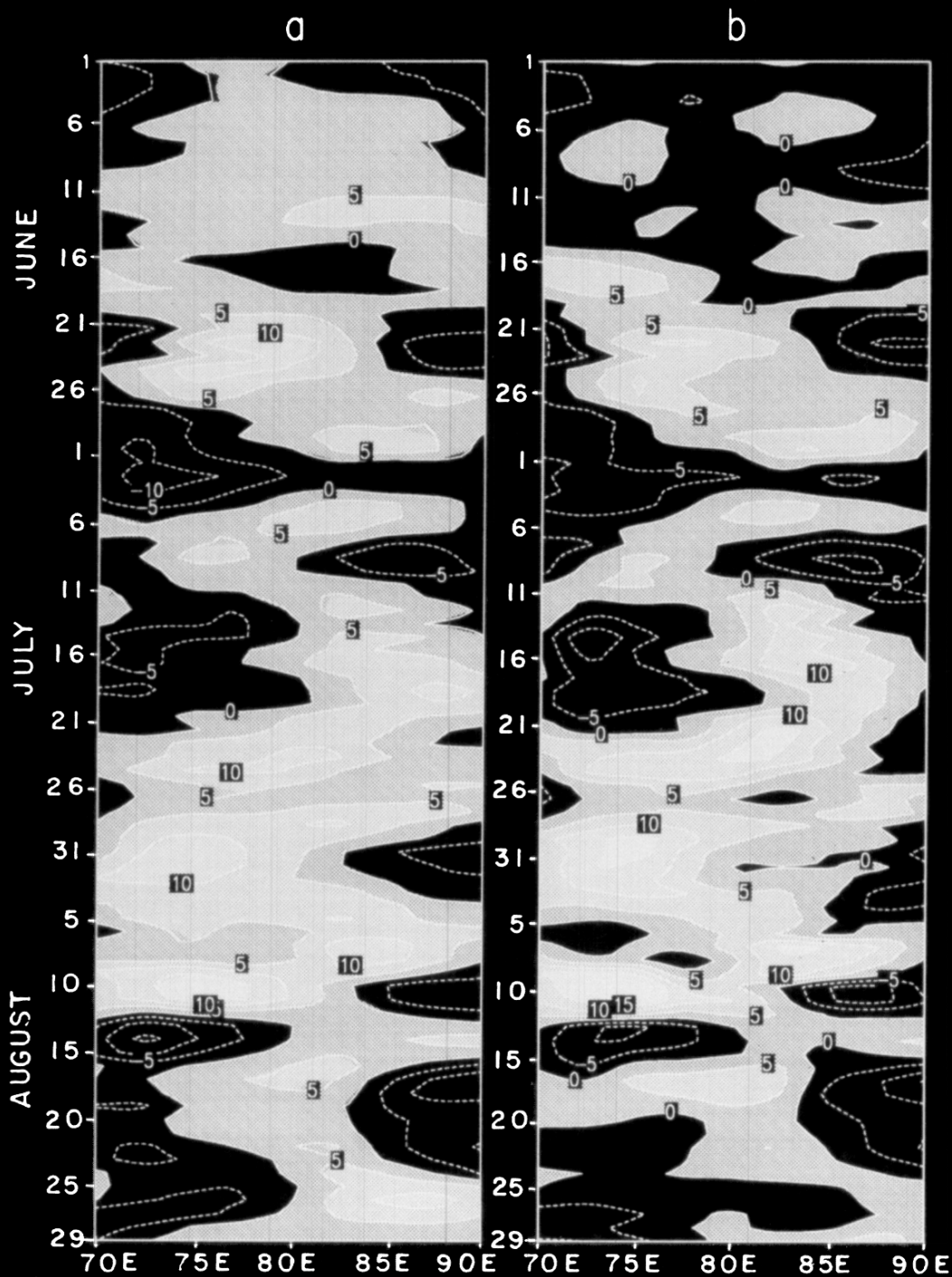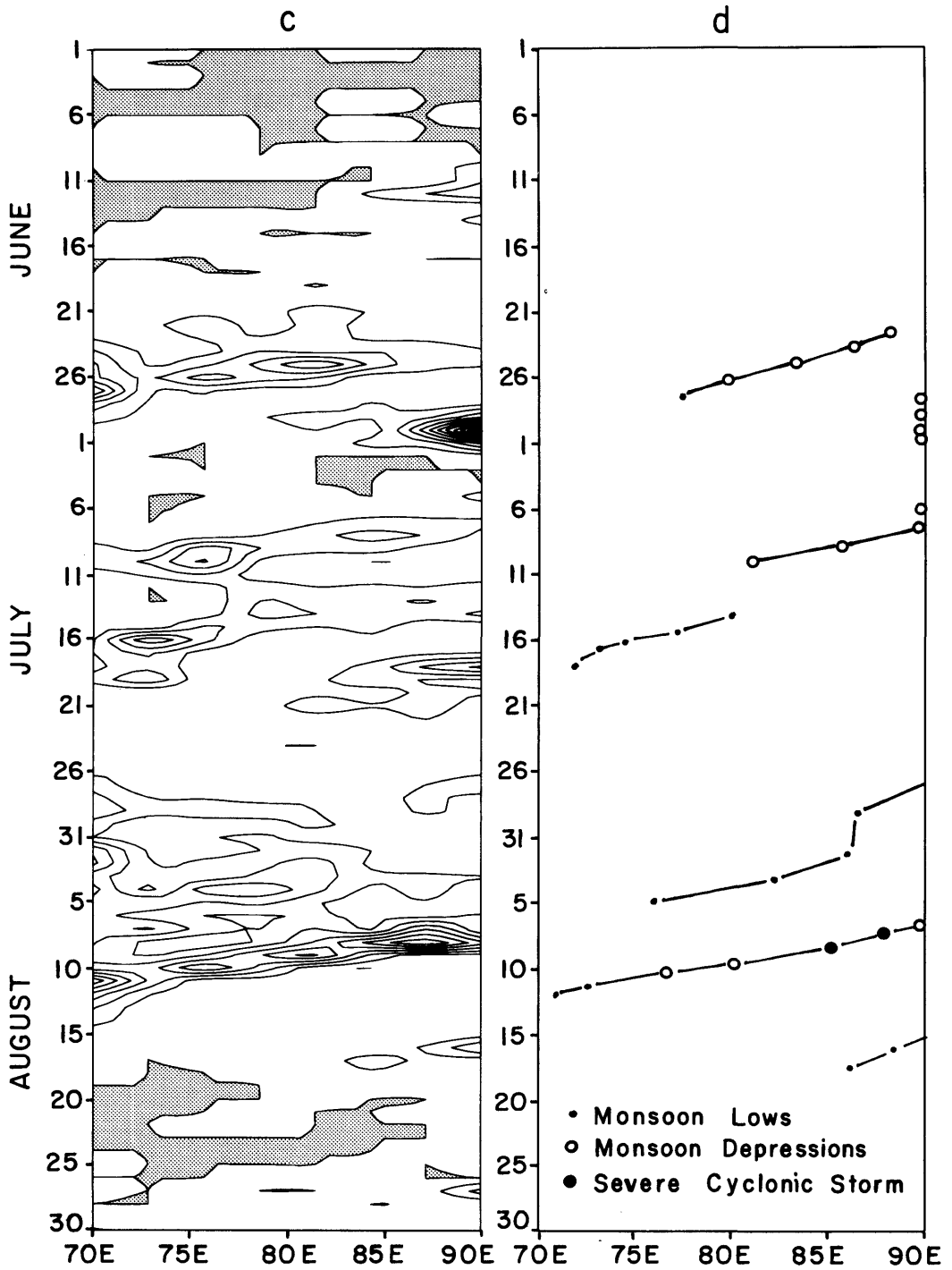
Fig. 10.

Fig. 10. (cont'd).

its source, a monsoon depression which formed over the Bay of Bengal, had moved northwards along 90°E longitude. The heavy rainfall zone was also confined to the east of 85°E (Fig. 10c). As the westward moving synoptic disturbances weakened and dissipated, the heating was replaced by cooling (<-5 K° day^{-1}) over the western part. Fig. 10a shows also that the cooling developed over the western part at the end of the active/normal phases of the monsoon, 28 June, 14 July and 11 August. The cooling (<-5 K day^{-1}) initially associated with the active phases extended from 28 June and 11 August, continued into the weak/ break phases (until 5 July and the end of August, respectively). Thus, we conclude that the replacement of the heat source over the western part by a heat sink heralds either a weakening of the monsoon or the beginning of a long break.

During the normal phase (9–19 July), a low pressure area developed near 80°E over the northern trough area (near 27°N) and moved westward (Fig. 10d). This system caused heavy rainfall over the northwestern part of the trough. The rainfall activity subsequently declined over the trough during the mid-season break (20–27 July).

4.2. Development of weak/break phases

We had seen from Figs. 8 and 9, that strong latent heating and moisture sink dominated the eastern part of the trough area during active phases, while cooling and moisture source the western part. This east-west differential heating supports the finding of Das (1962). He showed that, in July, the mean diabatic heat source develops over northeast India and a relatively cool area of marked subsidence prevails over northwest India. The diabatic heat source is established by the latent heat release from precipitation due to synoptic disturbances embedded in the monsoon trough. With the westward passage of the disturbances, the rainfall zone is shifted to the western part of the trough and is sometimes enhanced due to the in situ formation of an MTC. Such incidences of heavy rainfall over the western part occurred during the post-active or normal phases. Consequently, the diabatic heat source moved to the western part and a cooling developed over the eastern part, possibly due to evaporation from wet soil. Such a contrast in the east-west distribution of diabatic heating can be observed

from the interdiurnal variation of $\langle Q_1 \rangle$ and $\langle Q_2 \rangle$ associated with the westward passage of synoptic scale disturbances. An example of such a daily variation of $\langle Q_1 \rangle$ is shown in Figs. 11a,b for 7 and 10 August. During this period a monsoon depression formed over the head Bay of Bengal on 6 August and developed into a severe cyclonic storm on 7 August as it moved westwards. Having entered the Indian peninsula on 8 August, the storm weakened to a depression the next day and moved rapidly to the west of 80°E. The daily track of the cyclonic system from 6 to 10 August is marked in Fig. 11b. The development and persistence of the heat source in the eastern trough is obviously related to the formation of the storm. However, cooling appeared over the western part on this day. After the system moved to the west of 80°E on 9 August, the east-west contrast of heating and cooling reversed with a strong heating center in the west and cooling over the east, on 10 August (Fig. 11b).

Such a reversal in differential heating suppressed organised convection at the eastern end of the monsoon trough. Propagation of disturbances farther west in the late active/normal monsoon phases resulted in their weakening/dissipation over northwest India and in their favoring a southward penetration of the westerly trough from the north. By then, the monsoon circulation associated with weak/break conditions was established.

It is believed that the movement of the heat source and moisture sink towards northwestern India has made it possible for the mid-latitude westerlies in the lower troposphere to penetrate southward due to low orography. The diabatic cooling already developed over the eastern part: enabled the westerlies to move over northern India pushing the subtropical ridge southward.

5. Summary and conclusions

The spatial and temporal distributions of diabatic heating over the Indian monsoon trough in relation to active-break phases of the 1979 summer monsoon were investigated using the ECMWF FGGE Level III b data. The monsoon progressed through two major epochs of active-break phases. Consequently, the mean tropospheric circulation, particularly at 500 hPa, had undergone large changes. The monsoon trough was replaced by
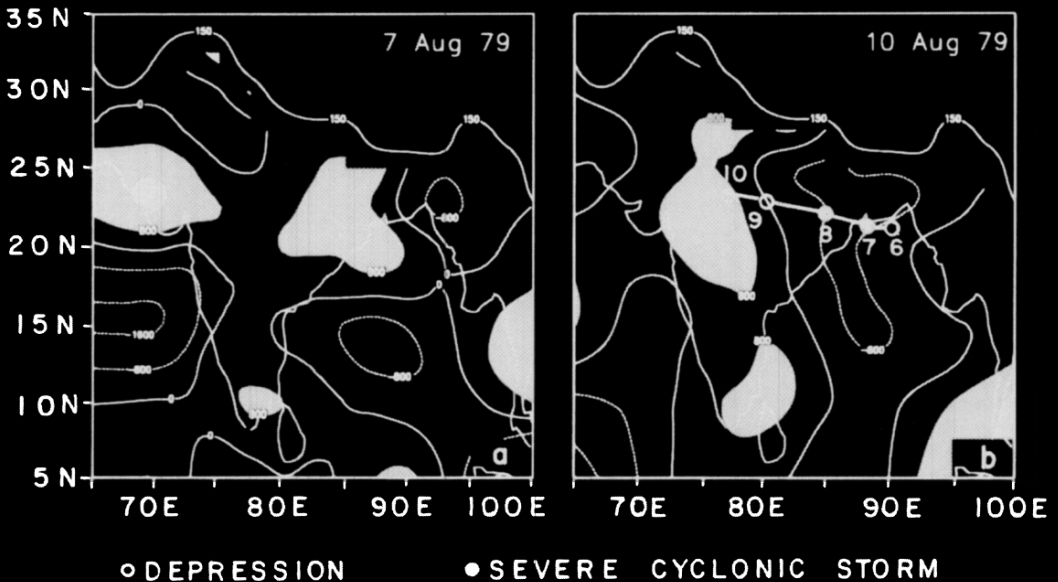
○ DEPRESSION   ● SEVERE CYCLONIC STORM

Fig. 11. The daily distribution of vertically integrated apparent heat source $\langle Q_1 \rangle$ for 2 days — 7 and 10 August shown in (a) and (b), respectively. The contour interval is 800 Wm^{-2} with solid (dashed) line representing positive (negative) values. The daily locations of the depression/severe cyclonic storm are shown in (b).

the subtropical ridge with a mid-latitude trough in northwestern India. The relatively cooled midlatitude trough caused a temperature decrease north of 27.5°N on the western part of the monsoon trough area, initiating a break phase.

The apparent heat source and moisture sink over the monsoon trough area exhibited two major heating periods separated by an interval of about 45 days. The heating rate had its maximum values in the mid-tropospheric layer between 500–400 hPa, while the drying rate possessed its maximum values in the slightly lower layer between 600–500 hPa. The temporal and spatial distributions of heating and moisture sink indicated that the diabatic heating of this area was primarily contributed by the latent heat released from cumulus convection and agreed with the spells of peak rainfall activity over central India.

The rainfall series (Fig. 2) and the vertical time section of heating rate and drying rate revealed that a 30–50 day mode of oscillation of diabatic heating over the trough area resulted from the northward propagating 30–50 day mode. In the intraseasonal scale the 30–50 day northward propagating mode was linked with the major active-break cycle of monsoon 1979.

In the sub-seasonal scale, diabatic heating centers propagated westward. The x–t diagram of both heating and drying rates (Figs. 10a, b) revealed that the 10–15 day mode in the mid-tropospheric (500 hPa) heating and drying rate affected the mid-season fluctuation of monsoon.

As revealed from the x–t diagram, the diabatic heating (cooling) appeared in the eastern (western) part of the trough during the early stage of the active/normal monsoon. This pattern was reversed in the later stage of the active/normal monsoon and cooling developed over the eastern part. This development of diabatic heating over the trough area led to the weak/break monsoon circulation.

Krishnamurti and Ramanathan (1982) have shown through a numerical experiment that the heat source over northeast India is important to the evolution of the monsoon flow over the Arabian sea. This study showed that the shift of the diabatic heat source from the northeast to the northwestern part of India with cooling developing over the northeast India led to break monsoon condition. However, our conclusion concerning the effect of the east-west differential heating on the development of weak/break monsoon circulation is based on the result of only one summer.

In order to test the sensitivity of the heat source over northwest India generated from the excessive precipitation leading to the weak/break monsoon as in the 1979 case, it is necessary to pursue further diagnostic analysis of other summer seasons.

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