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STUDY OF THE STRUCTURE OF A MONSOON DEPRESSION OVER THE BAY OF BENGAL DURING SUMMER MONEX

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ABSTRACT

Based on the data gathered during the Summer MONEX over the Bay of Bengal in July, 1979, a detailed observational study of the structure of a monsoon depression during the period of 3—8, July has been made. It has been revealed that the early disturbance of this depression was a mid-tropospheric cyclone. The subsequent rapid development was due mainly to the barotropic instability process of the basic zonal and meridional airflows.

The cyclonic circulation of the depression extended in vertical upward to 500—400 mb level. Prior to the formation of the depression, the extremely strong westerly and northerly winds at the lower and middle levels, reaching the intensity of the low-level jet (22 m/s and 18.5 m/s, respectively), were observed. Post to the formation of the depression, a strong wind ring at the radius of 300—350 km from the depression center encircled the depression, with the wind maximum being at 850 mb. During this period, the maximum of the positive vorticity was of the magnitude of order of 10^{-4}/s. The warm core at 400—300 mb was very remarkable. Finally, intrusion of the dry air over the depression may be an important factor leading to the weakening of the depression.

I. INTRODUCTION

During the Indian summer monsoon season, monsoon depressions often occur mainly over the Bay of Bengal, and then move westward or northwestward and bring large amount of rainfalls over the Indian subcontinent. Therefore, the frequency of depression genesis in one year is closely related to the drought conditions over India. Many researchers have studied the genesis, development, structures and movement of monsoon depressions. For instance, Krishnamurti et al. [1],[2] analyzed the detailed structure of a developed depression in August, 1968, utilizing the upper-air soundings at the land stations over India, and performed further the numerical experiment of the monsoon depression. Godbole [3] constructed a composite three-dimensional structure of the monsoon depression using five depressions of 1973 and obtained very similar results to those by Krishnamurti et al. It should be pointed out, however, that the previous studies on the structures of depressions have been done mainly based on the data at the land stations where the depressions were normally fully developed or tended to dissipate. Due to the data unavailability over the Bay of Bengal, very few analyses of the formative stage of monsoon depressions have been made. During the Second Phase of the Summer MONEX, Bay of Bengal Experiment, many upper air observations were gathered, especially for a monsoon depression forming during the time period of 3—9 July. Recently, Nitta and Masuda [4] have published their preliminary results of the three-dimensional structure of the depression based on the analysis of the above data source. Unfortunately, the vertical extent of their study is confined in the layer below 500 mb. The present paper is aimed at the analysis of the three-dimensional structure in the whole troposphere (surface—100 mb), utilizing all the data sources available to us in order to understand better the complete picture of the structure and development process of the depression. Therefore, the results obtained by our analysis should be more reasonable.

II. DATA AND THE COMPUTATIONAL METHOD

During the experimental period from 3 July to 9 July 1979, two research aircrafts, the NCAR Electra and NOAA P-3, altogether made 91 aircraft dropwindsonde observations over the Bay of Bengal to measure mainly upper air wind, temperature and relative humidity (or dew point temperature) below the flight level. The data sets of the aircraft dropwindsondes used in our study are the ones reprocessed and checked by NCAR. The data above 500 mb level were taken from Astling et al. [5] who had collected and compiled the wind and temperature data in the layer of 200—300 mb made by the commercial aircrafts. In addition, the satellite wind measurements were also included in the analysis. Combining the above different data sources with the conventional and special upper air soundings at the land stations around the Bay of Bengal, we can have a rather dense data coverage.

After having cross-checked and kept the vertical and horizontal continuity, we subjectively analyzed the u,v,t,t_d,h fields. Twelve data levels in vertical (surface, 950, 900, 850, 800, 700, 600, 500, 400, 300, 200, 100 mb) were taken, with 1° latitude/longitude horizontal grid length. This horizontal resolution is nearly equal to the average distance between two consecutive dropwindsondes and may adequately describe the synoptic-scale, even some meso-scale, features of the structure of the depression. The divergence, vorticity and vertical velocity were computed by using the following equations

$$\zeta=\frac{\partial v}{\partial x}-\frac{\partial u\cos\varphi}{\cos\varphi\partial y}, \tag{1}$$

$$D=\frac{\partial u}{\partial x}+\frac{\partial v\cos\varphi}{\cos\varphi\partial y}, \tag{2}$$

$$D_K'=D_K-\frac{K}{M}(\omega_N-\omega_T)/\Delta p, \tag{3}$$

$$\omega_K'=\omega_K-\frac{K(K+1)}{2M}(\omega_N-\omega_T), \tag{4}$$

where D_K' is obtained from Eq. (2), $M=\sum_1^N K=N(N+1)$, N is the integer level number for the top level, ω_N is the computed, uncorrected vertical velocity at level $K=N$, and ω_T is an assumed, corrected vertical velocity at the top of the column. Here, it is set to zero. Δp is the pressure difference between the lower and upper levels. $dy=a\cos\varphi d\lambda$, $dy=ad\varphi$, φ is the radius of the earth.

III. SYNOPTIC SITUATION AND DEVELOPMENT OF THE DEPRESSION

Fig. 1 shows the flow patterns at 500 mb and 850 mb over the studied area. On 3 July (Fig. 1(a)), a cyclonic circulation was first observed in the middle troposphere (700—400 mb) with its centre located in the eastern part of the Bay of Bengal. Careful analysis of the track of this cyclonic circulation shows that this cyclone had its origin over the South China Sea and seemed to be the remanents of a typhoon. Below 700 mb, the cyclonic circulation was not discernible, only with a monsoon trough observed at the surface. This evidence implies that the early disturbance of the studied depression is a mid-tropospheric cyclone. Later, the cyclone penetrated downward to 850 mb on 5 July. It is noted that there were very strong westerly winds or low-level jet (LLJ) at the lower levels over the extensive area to the south of the depression, with the speed maximum (20—26 m/s) located at 13°—14°N. Therefore,

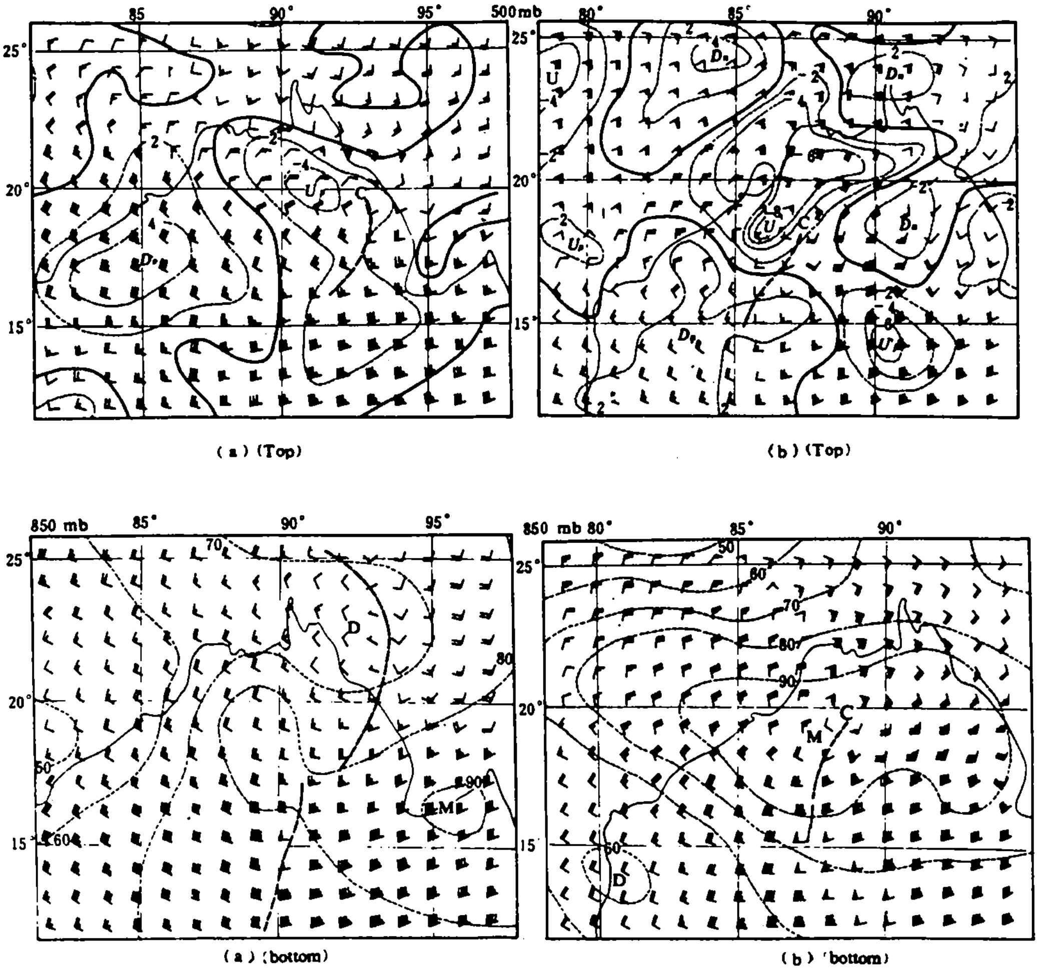


Fig. 1. The 500 mb (top) and 850 mb (bottom) flow patterns over the Bay of Bengal and its neighbouring. (a) on 3 July, (b) on 7 July. Symbols of wind: triangle denotes 20 m/s, a full bar 4 m/s and half a bar 2 m/s. The dashed lines in 500 mb airflow charts represent the vertical velocity ($\omega = \frac{dp}{dt}$). Unit: 10^{-3} mb/s. The dashed lines in 850 mb airflow charts represent the integrated relative humidity from 100 mb to 500 mb. Unit: %.

this may produce the strong positive shear vorticity to the north of LLJ axis.

In order to examine the instability mechanism of zonal airflows for the disturbance growth, we have computed the necessary condition for combined barotropic and baroclinic instability of a zonal flow with horizontal and vertical wind-shear, as defined by

$$\frac{\partial[q]}{\partial y} = \beta - \frac{\partial^2[u]}{\partial y^2} - \frac{\partial}{\partial p}\left(\frac{f_0^2}{\sigma}\frac{\partial[u]}{\partial p}\right), \tag{5}$$

where $\beta = \frac{\partial f}{\partial y} = z\omega\cos\varphi/a, f_0$ is the Colioris parameter at the reference latitude, $\sigma = -[\alpha]\left(\frac{\partial \ln[\theta]}{\partial p}\right)$, $\alpha = \frac{1}{\rho}$ is air density, $\theta = T\left(\frac{1000}{p}\right)^K$ and $K = 0.288$.

The shaded area between 19°—22°N in Fig. 2 shows the region of negative $\frac{\partial[q]}{\partial y}$ which means that the zonal airflow is dynamically unstable for the depression growth in this region. Actually, the latter growth of the depression did occur in this latitude belt. The negative gradient of absolute vorticity is mainly caused by the horizontal shear of the zonal flow. Therefore, the mechanism of barotropic instability may be responsible for the early growth of the depression.

In order to justify further the importance of barotropic instability in the disturbance growth, we computed the area-averaged $[u'v']$ (see Table 1). The kinetic energy exchange due alone to barotropic process is expressed by

$$\frac{\partial[\overline{K_E}]}{\partial t}=\langle K_Z\cdot K_E\rangle=-\overline{[u'v']}\frac{\overline{\partial[u]}}{\partial y}\,, \tag{6}$$

where [ ] denotes the zonal average, (') the departure from the zonal mean, ($-$) the meridional average, and K_Z and K_E represent the total zonal kinetic energy and eddy kinetic energy. As seen from the distribution of the zonal mean wind (Fig. 2), $\frac{\partial[u]}{\partial y}$ is always negative in the latitude band of 14°—23°N. If $[u'v'] > 0$, K_Z is transformed into K_E; if $[u'v'] < 0$, the opposite case is true. Table 1 indicates

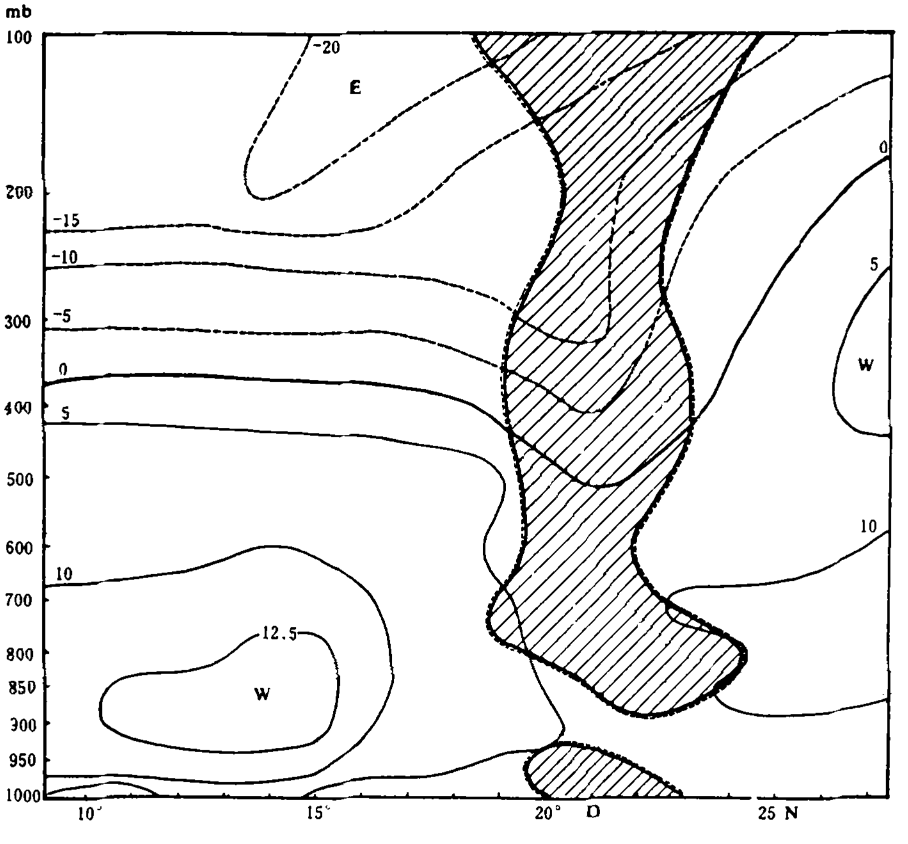


Fig. 2. The cross-section of the zonal mean u-components over the Bay of Bengal. The shaded area means the area of the negative $\frac{\partial[q]}{\partial y}$.

that the kinetic energy was mainly transformed from K_Z into K_E in the layer of 850—200 mb on 3 July. Two days later, the barotropic transformation of kinetic energy remarkably increased (also $-\frac{\partial[u]}{\partial y}$ increased), especially in the layer below 800 mb. This condition is very favorable for the growth of the depression. The early mid-tropospheric cyclone did not penetrate downward to the surface and did not grow rapidly in the layer below 400 mb, until 6 July. Since then, the barotripic transformation from K_Z to K_E greatly reduced. It is possible that the subsequent development and intensification of the depression mainly depend on CISK mechanism. On 7 July, the depression came to its mature stage (Fig. 1(b), with the easterly wind greatly increasing in the northern sector. The depression began to accelerate westward and on 8 July it reached the interior of the peninsula. Although the circulation of the depression significantly weakened, a cyclonic circulation centre was still detectable at 850 mb and 500 mb.

Table 1. The Area-averaged $[u'v']$ over the Bay of Bengal
Unit: m^2/s^2

Level (mb) / Date	Sur.	950	900	850	800	700	600	500	400	300	200	100
July 3	-2.7	-4.1	-3.5	2.3	2.8	9.6	2.6	1.1	1.7	0.1	7.6	-0.1
July 5	1.1	35.2	23.5	25.7	28.4	15.1	10.8	-0.1	-0.0	-0.9	11.4	-6.9
July 6	2.2	5.0	1.4	-0.6	-1.6	-8.0	-4.5	-5.9	1.0	-0.2	-0.7	-0.5

To sum up the above discussions, we come to the conclusion that although the early disturbance of this depression is first observed at the middle levels, when the mid-tropospheric cyclone penetrates downward to a favorable area at the lower level, i. e., the area of strong positive shear vorticity to the north of LLJ axis, the disturbance may rapidly grow into a developed depression due to the barotropic instability of the basic airflow and deriving a large amount of supply of kinetic energy from the basic airflow.

IV. WIND FIELD AND KINEMATIC FIELD

In order to describe the differences in wind fields between the different stages of development, the conditions on 5 July (formative stage) and 7 July (mature stage) have been selected to make comparisons. Fig. 3 is the N-S cross-sections of u-component through the center of the depression, showing that there was very strong westerly winds in the region of 10°—18°N below 850 mb, with u_{max} (18.5m/s) located at 850 mb. As previously described, the distributions of this kind of zonal wind may produce strong positive vorticity to the north of the LLJ axis (see the dashed lines in Fig. 3). The easterly winds at the lower and middle levels were weak, prevailing over the region to the north of 23°N. The westerly LLJ was overlain by the upper easterly jet. As indicated from the zeroline of isotach, the cyclonic vortex was mainly confined in the layer from 850 mb to 400 mb. On 7 July, the wind speed significantly increased. Beside the previous u_{max} at 14°N (the wind speed also increasing up to 20 m/s), another stronger westerly u_{max} (25m/s at 950 mb) near the surface may be observed at 400 km from the depression center. The easterly wind also increased, with the strongest wind speed (about 15 m/s) being at 300 km from the depression center. It is also deduced from component vertical distribution that the axis of the depression center inclines in vertical from north to south.

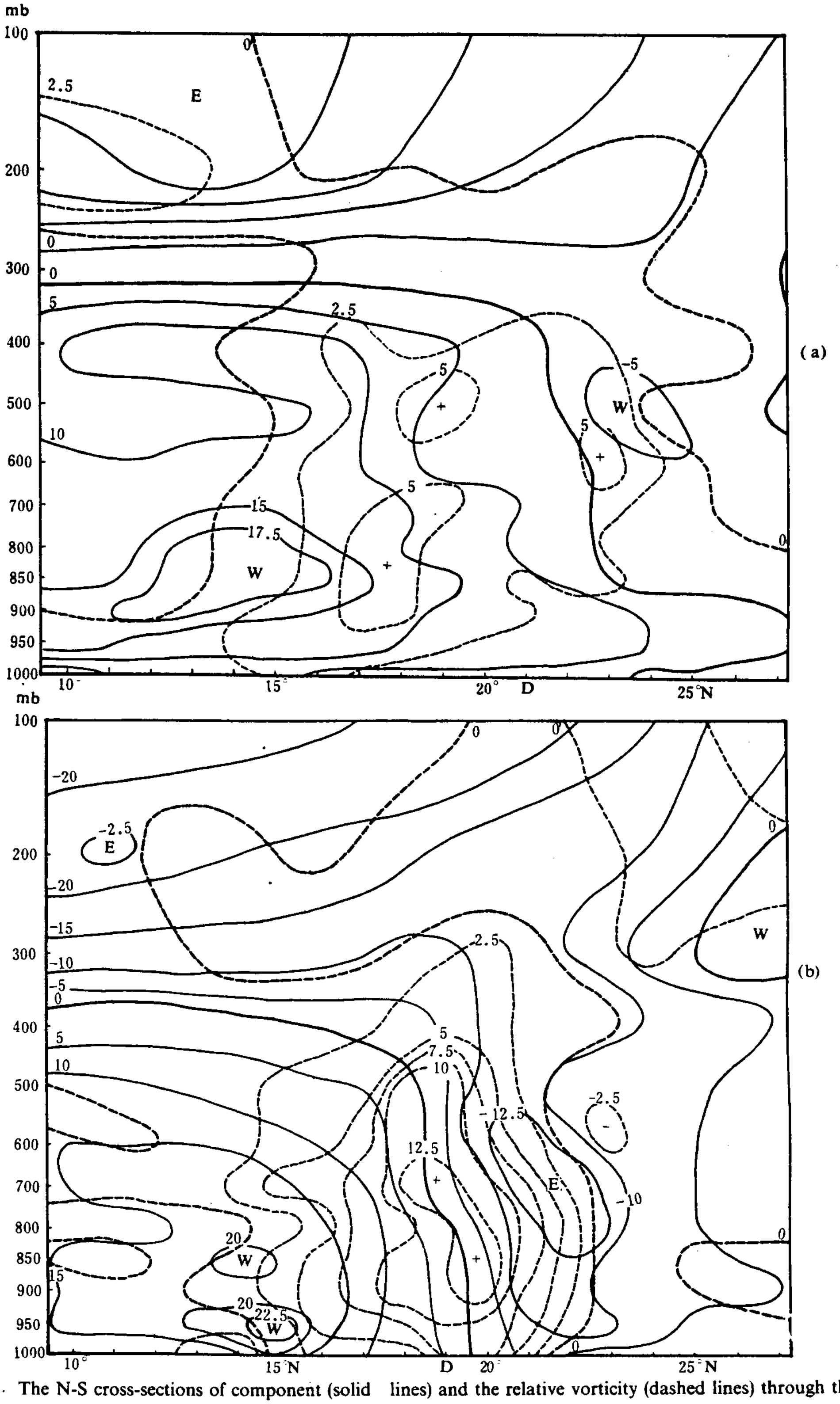
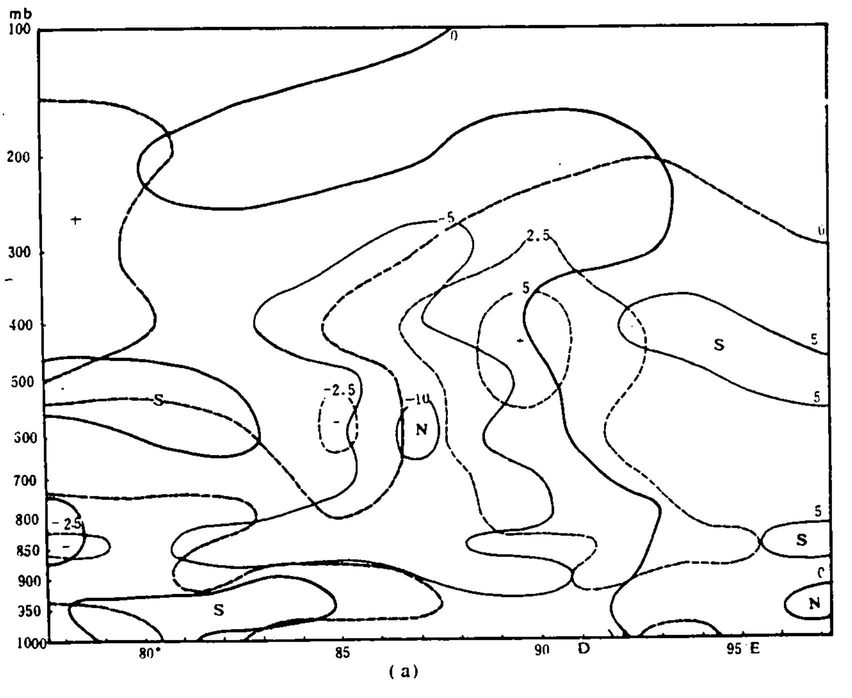


Fig. 3. The N-S cross-sections of component (solid lines) and the relative vorticity (dashed lines) through the depression center. (a) 5 July; (b) 7 July. Unit of the wind: m/s. Unit of the vorticity: 10^{-5}/s.

The cross-sections of component on 5 July indicates that the north wind prevailed in the northern sector of the depression with the maximum being at 86—88°E (see the solid lines in Fig. 4). There was an area of strong positive vorticity to the north of the depression center which favored the development of the depression. Actually, the stronger north winds occurred at 15°N (Fig. 4c), with a maximum of 22 m/s observed at 87°E at 950 mb. Therefore, both of the northerly LLJ and westerly LLJ may play an important role in the development of the depression. The barotropic instability of the zonal and meridional airflows should be both considered. On 7 July, the south wind greatly increased, with its speed generally exceeding the north wind speed. The zero-isolines of isotach showed the westward vertical inclination which was in good agreement with the results obtained by [1] and [3]. The vertical extent of the depression cyclonic circulation at the mature stage reached 400 mb. Fig. 5 is the vertical profiles of the area-averaged zonal wind $[\bar{u}]$ during the different development stages of the depression. During the pre-storm stage (3 July), the westerly wind at the lower level and the easterly wind at the upper level was relatively strong. The vertical wind shear between 200 mb u and 850 mb u was 23.9 m/s which is same as the climatological mean (20—25 m/s).During the formative stage (5 July), the zonal winds at the lower and upper levels got weaker with the vertical wind shear of 19.3 m/s. During the development, mature and weakening stages (6—8 July), the zonal wind significantly decreased, the lower limit of the upper easterly wind descended from 300—400 mb to about 600 mb, and the mean vertical wind shear decreased down to 15 m/s. On 9 July, when the depression had dissipated over the northern India, the zonal wind over the Bay of Bengal increased again and the vertical wind shear restored to the climatological value (21m/s).The fact that the decrease of the vertical wind shear occurs prior to and during the formative stage of the depression is in good agreement with the finding made by Raman [6].



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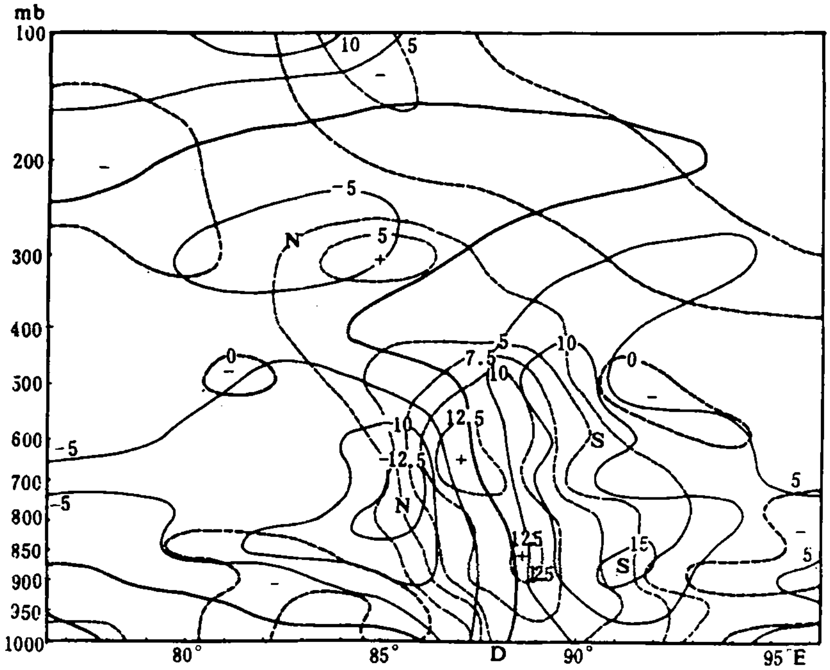

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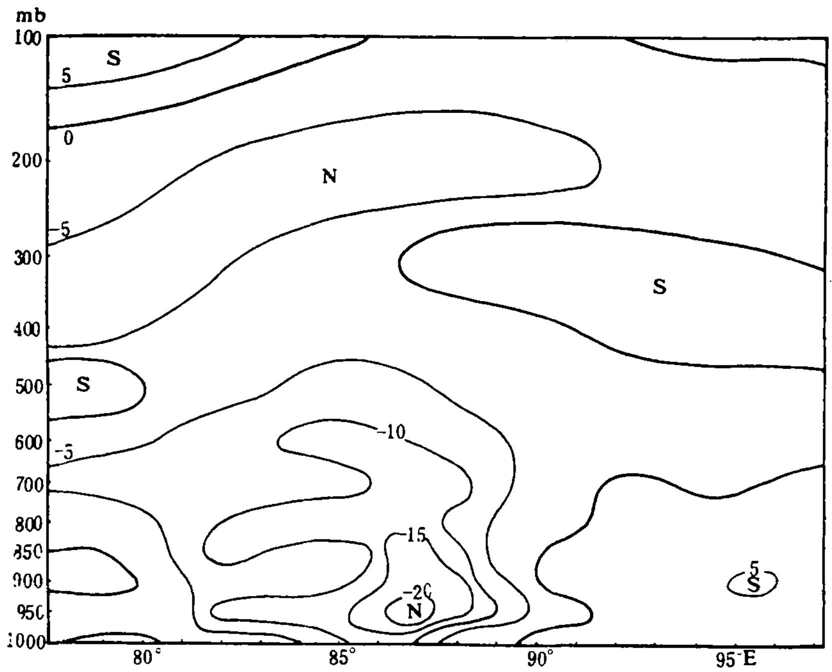


(c)

Fig. 4. The W-E cross-section of v-component (solid lines) and the relative vorticity (dashed lines) through the depression center.

(a) 3 July, along 21°N, (b) 7 July, along 9°N, and (c) 5 July, along 15°N.

Unit is same as Fig. 3.

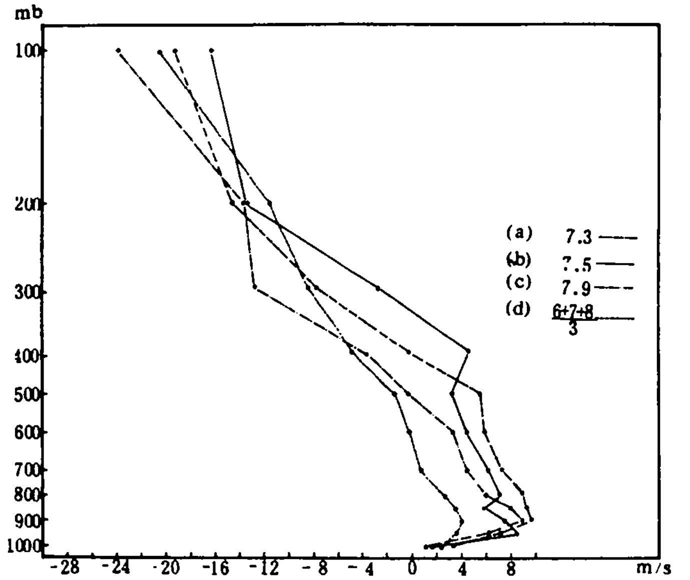
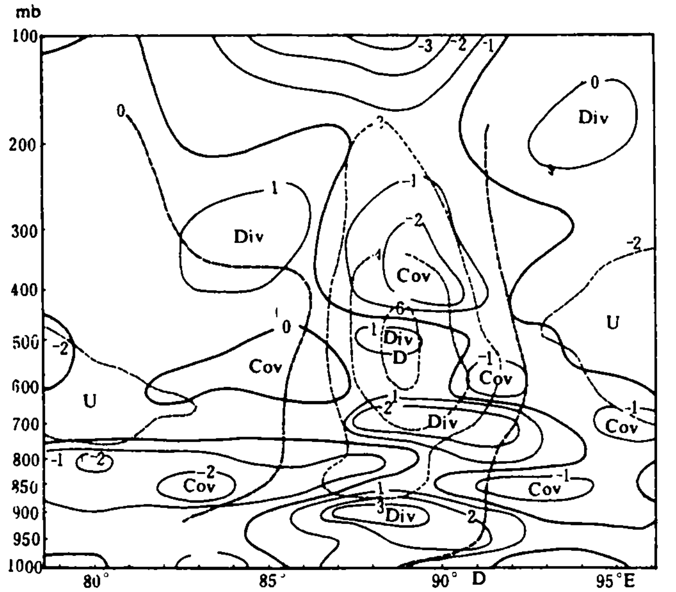


Fig. 5. The vertical profiles of the area-averaged u-component, $[\bar{u}]$, (in the area of 5° latitude radius from depression center) during the different developmental stages.
(a) 3 July, (b) 5 July, (c) 9 July and (d) average of 6—8 July.
Unit: m/s.

The evolution of the vorticity field is very remarkable. On 5 July (Figs. 3 and 4), a maximum of the positive vorticity was found at 400—500 mb, with the westward sloping axis. This vorticity maximum corresponds to the mid-tropospheric cyclone. On 7 July, the vorticity magnitude increased from 6×10^{-5}/s to 14.4×10^{-5}/s reaching the magnitude of the order of 10^{-4}/s. The layer of the positive vorticity extended in vertical up to 300 mb above which the negative vorticity may be noted. The vorticity maxima were found at 600—700 mb and 900—950 mb, respectively.



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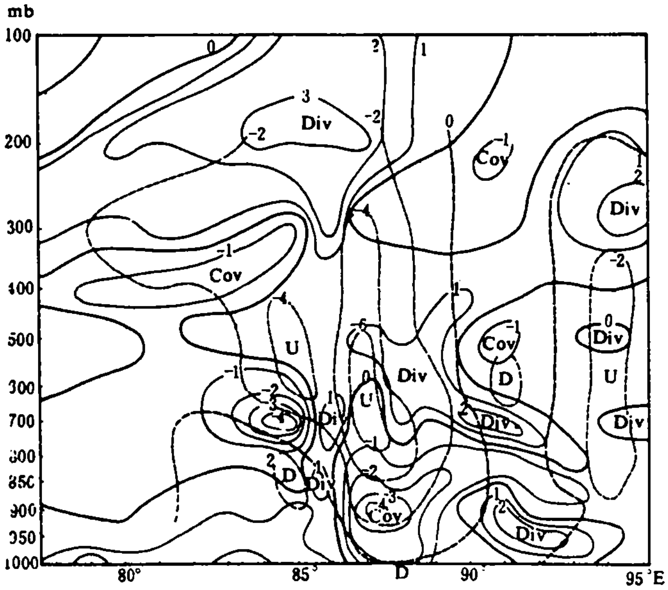


(b)

Fig. 6. The W-E cross-sections of the divergence (solid lines) and the vertical velocity ($\omega = \frac{dp}{dt}$) through the depression center.
(a) 5 July , and (b) 7 July.
Unit of the divergence: 10^{-5}/s,
Unit of the vertical velocity: 10^{-3}mb/s.

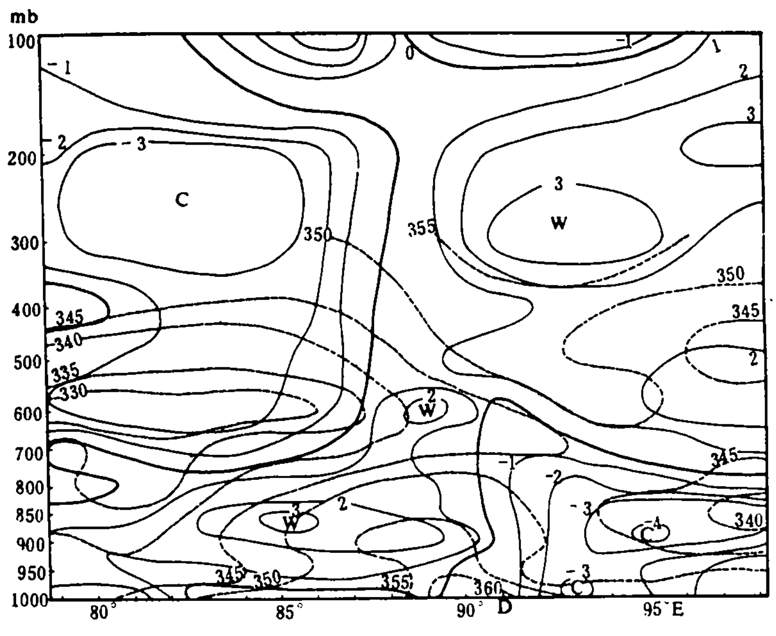
The divergence field on 5 July was mainly characterized by a remarkable convergence region in the middle and upper troposphere, also reflecting the presence of the mid-tropospheric cyclone (Fig. 6).The divergence dominated the lower troposphere. On 7 July, the vertical distribution of the divergence was in sign reverse to that on 5 July, with a strong convergence layer below 700 mb and a deep divergence layer above 700 mb, which is typical for the developing or mature tropical storms in tropics. But, the height of the non-divergence level is slightly lower in the depression case. Because the upper divergence field did not exist during the formative stage of the depression, this condition may not be an important factor affecting the development of the depression. The initiation and growth mechanism should be sought in the dynamical factors at the lower and middle levels.

The vertical cross-sections of the vertical velocity show that the downward motion dominated most of the depression area on 5 July, only with the upward motion being over the eastern section of the depression, which implied that the mid-tropospheric cyclone during the formative stage was mainly characterized by the downward motion. This kind of the downward motion may be favorable for the downward penetration of the cyclone. Once the depression circulation reached the surface, the dominant downward motion in the depression rapidly turned into the upward motion. At the mature stage, the layer of the upward motion was very deep and reached its peak in magnitude. The maximum vertical velocity was generally located in the western sector of the depression which coincided with the cloud and rainfall patterns in the depression (the major cloud area was located in SW sector of the depression). A further analysis of the horizontal patterns of the vertical velocity at 600 mb (Fig. 1) clearly shows how the extensive area of the downward motion in the depression on 5 July was changed into the large area of the upward motion on 6 July (not shown) and 7 July. Also, the maximum upward motion was found to be in the western sector. After the depression landed on 8 July , however, the area of the strong upward motion shifted to the eastern sector.

The above discussion implies that in order to explain the rapid growth from 5 July to 6 and then to 7 July, the key problem is to understand why the extensive area of the downward motion in the depression could change into the large area of the upward motion. This may be related to the downward penetration of the mid-tropospheric cyclone and the subsequent enhancement of Cu-convection.

V. TEMPERATURE AND MOISTURE FIELDS

As the depression developed, the warming in the midlle and upper troposphere in the depression became more significant (see the solid lines in Fig. 7). On 3 July, only slight warming may be observed at the mid - and upper-levels and cooling occurred at the lower level. On 5 July, the warming at the upper level intensified, with the maximum of the temperature departure found at 300 mb; cooling still dominated the lower troposphere. At the mature stage of the depression, the significant warming occurred throughout the troposphere with the maxima at 400 mb and 600 mb . The fact of the two warming centers at the middle and upper levels, respectively, has been also pointed out in other studies on typhoons and hurricanes. Comparing Fig. 8(b) and 8(c), we can find the tendency of downward propagation of warming which may be associated with the enhancement of stable precipitation in the depression at the mature stage. Fig. 7 also shows the θ_{se}-vertical distributions (dashed lines). A tongue of dry and cool air with the lower θ_{se} was seen to advect over the Bay of Bengal on 5 July while a typical θ_{se} vertical cross-section similar to typhoons may be observed on 7 July. Note that the θ_{se} isolines in the central area of the depression bulged upward due to severe activities of Cu-convection there. Fig. 8 shows the variations of the vertical profiles of the area-averaged θ_{se} within the depression. It may be seen that the θ_{se} increase in the middle troposphere was very significant as the depression developed, thus leading to the decrease in the potential instability. This resulted from the neutralization of the stratification due mainly to Cu-convection. When the depression moved



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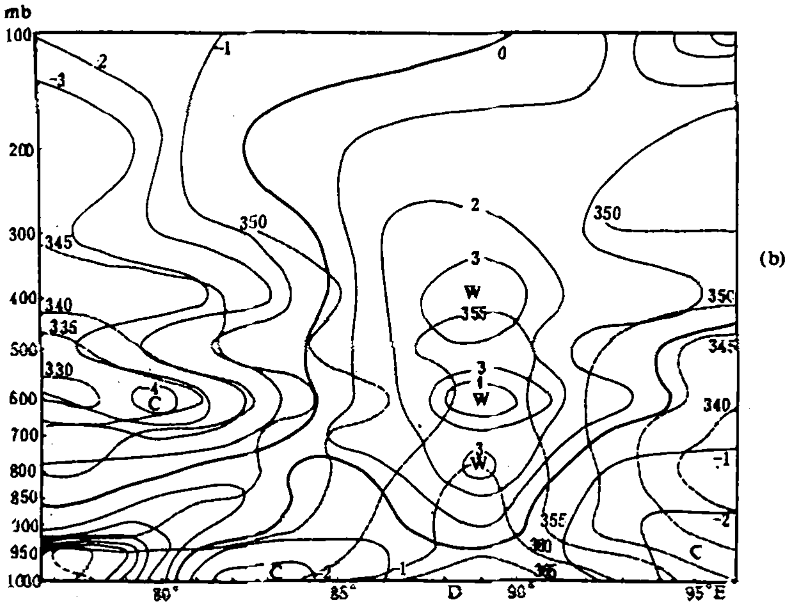

Fig. 7. The W-E cross-sections of the temperature departures from the zonal mean (solid lines) and θ_{se} (dashed lines).
(a) 3 July, (b) 5 July. Unit: °C.

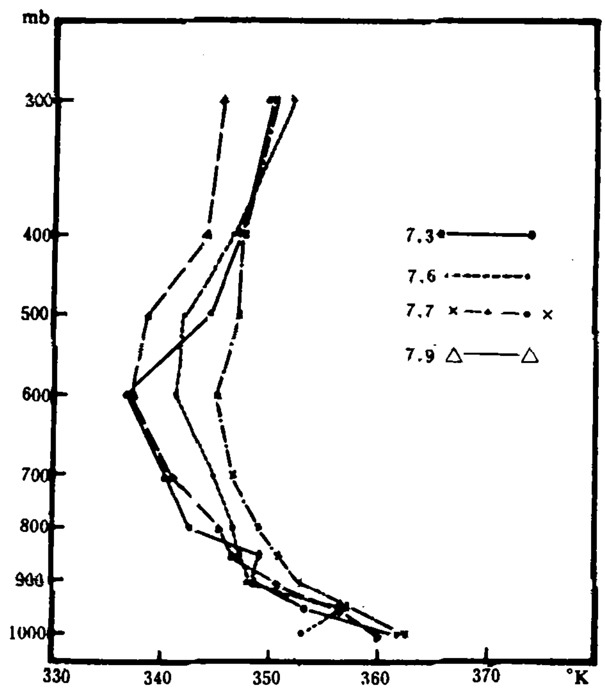

Fig. 8. The variations of the vertical profiles of the area-averaged θ_{se} (the area for averaging is same as in Fig. 5).

out of the Bay of Bengal, the atmospheric stratification came back to the condition similar to that on 3 July.

Finally, we will discuss the evolution of the moisture field in terms of the relative humidity (Fig. not shown). On 3 July, a near-saturation layer was found at 400—500 mb which coincided with the mid-tropospheric cyclone . Therefore, this cyclone itself was warm and moist. A relatively dry layer was found under the cyclone. This fact may be seen from Fig. 1 more clearly, which denotes the pressure-weighted relative humidity from 100 mb to 500 mb $(\overline{RH} = \frac{1}{g}\int_{500}^{1000} RH\, dp)$. A dry region was located to the north of the cyclone center while a moist region was located to the south of the cyclone center. On 5 July , a deep moist layer may be observed within the whole depression area, with the near-saturation layer reaching 400 mb. The increase of the vertical extent of the moist layer was very rapid. The condition on 7 July was broadly similar to that on 5 July. When the depression moved inland on 8 July, the major moist layer shifted to the western sector of the depression due to the intrusion of the dry air at the mid - and upper-levels over the depression. This pattern of the moisture field was in agreement with the major cloud and rainfall patterns in the depression . Intrusion of the dry air may be an important factor leading to the weakening of the depression, which has been pointed out by one of the authors of the present paper in the paper on the structure of a depression over the Arabian Sea in June, 1979[7].

VI. SUMMARY

Based on the data sets gathered during the Summer MONEX over the Bay of Bengal in July 1979, a detailed observational study of the structure of a monsoon depression forming during the period of 3—8 July, has been made. The major results have been brought out as follows:

(1) The early disturbance of the depression under study was a mid-tropospheric cyclone. Then, the cyclone penetrated itself downward to the surface. Owing to the presence of the strong northerly and westerly low-level jets at the lower and middle levels, the disturbance could rapidly develop at the side of the positive vorticity of the low-level jets through the mechanism of the barotropic instability.

(2) The cyclonic circulation of the depression extended upward to 500—400 mb level and the axis of the depression center assumed a southwestward vertical inclination. Above 400 mb, the upper easterlies showed the diffluent flow pattern. Prior to the formation of the depression, the extremely strong northerly and westerly winds at the lower and middle levels, reaching the intensity of the low-level jet (22 m/s and 18.5 m/s, respectively), were observed. Post to the formation of the depression, a strong wind ring at the radius of 300—350 km from the depression center encircled the depression, with the wind maximum being at 850 mb. Besides, there was another wind maximum near the surface.

(3) At the mature stage, the maximum vorticity was of the magnitude of the order of 10^{-4}/s. The deep layer of the positive vorticity extended upward to 300 mb, with the maximum found at 700—600 mb. At the lower and middle levels, the vertical velocity (divergence) field was changed from the dominant downward motion (divergence) in the depression prior to the formation of the depression into the strong upward motion (convergence) post to the depression formation. The regions of the upward motion and convergence were mainly located in the western and southern sectors.

(4) At the mature stage, the warm core at 400—300 mb was very remarkable; there was another warm core at 600 mb; the θ_{se} vertical distributions in the depression were very similar to those observed in the typical typhoons. The evolution of the moisture field during the depression development was very unique, with the relatively dry area in the depression prior to the

formation changed into the deep moist layer post to the formation. Then, the depression rapidly weakened due possibly to the intrusion of the dry air over the depression, thus destroying the warm and moist structure in the central region of the depression.

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