*Mausam*, (1980), **31**, 1, 65-74

551.515.13 (545.5)

# On the formation, structure and decay of a monsoon cyclonic storm near Delhi — A case study

RANJIT SINGH and A. K. BANERJEE

*Meteorological Office, Pune*

(*Received 1 August 1977*)

ABSTRACT. The structure of a monsoon cyclonic storm formed near Delhi on 18 August 1976 has been studied with available data and the factors which led to its rapid intensification and decay have been discussed. There seems to be some structural difference, particularly in upper levels, in storms when they lie over sea than when they lie deep inland. The surface features of the storm as assessed from the autographic records of Delhi have also been presented in this paper.

## 1. Introduction

Structure of a cyclonic storm which lay in the Bay of Bengal has been studied by Rai Sircar (1956) and recently by Tripathi and Saxena (1975). In both these studies, it was found that storms of Bay of Bengal are warm-cored systems extending deep into the upper most layers of the troposphere. On examination of 80 years' statistics of depressions and cyclonic storms that formed between June and September during 1891 to 1970 in the Bay of Bengal, Arabian Sea and over adjoining land areas, Rao (1976) observed that only one cyclonic storm formed over land in each of the month of June, July and September during the above period and none in August. Thus, the scope for studying the structure of land cyclonic storms over the Indian region in the southwest monsoon season (June-September) is very limited. Recently, a monsoon depression from Bay of Bengal on approaching near Delhi intensified into a cyclonic storm on 18 August 1976. In the present paper, some characteristic features connected with the formation, structure and decay of this cyclonic storm have been presented and discussed.

## 2. History of the storm

A low lying over north Bay on 11 August 1976 concentrated into a depression by 12th and crossed north Orissa-West Bengal coast on 13th morning and intensified into a deep depression over Orissa and adjoining Bihar plateau and Gangetic West Bengal. Moving in a northwesterly direction, it weakened into a depression over northeast Madhya Pradesh on 14th. It reached northeast Rajasthan and adjoining northwest Madhya Pradesh and southwest Uttar Pradesh on 16th, when it once again intensified into a deep depression. Thereafter, moving slowly and recurving northwards, it lay as a cyclonic storm over Haryana with its centre near Delhi by 18th morning (Fig. 1b). It then rapidly weakened and moved northward on 19th and lay over Western Himalayas by 20th. The track of the system is shown in Fig. 1 (a).

## 3. Thermal structure of the core

The temperature field associated with the system at different stages of its development and decay reveals the following : (*a*) On 16th when the system intensified from depression into a deep depression, its core region had more or less the same temperatures as those of the surrounding, supporting the view that the core region of Bay of Bengal depressions and even deep depressions over land are neither warm nor cold (Keshavamurthy 1972). (*b*) On 00 GMT of 17th, the system extended up to 300 mb but still its core region at 850 and 700 mb had more or less the same temperatures as its surrounding but it had definitely a warm core aloft at 500 and 300 mb (Fig. 2a) and by 12 GMT of the same day, warming in the core region extended downward to 700 mb (Fig. 2a). (*c*) On 18th at 03 GMT the system further intensified and lay as a cyclonic storm (with central pressure 988.4 mb) very close to New Delhi. The Delhi radar also located spiralling bands converging towards centre lying 50 km northwest of Delhi at 0945 GMT. The satellite NOAA-4 picture of 0410 on 18th, as extracted from the U.S.A. imagery of August 1976 (Fig. 1c), shows the system as a well developed cyclonic storm with cloud bands spiralling into

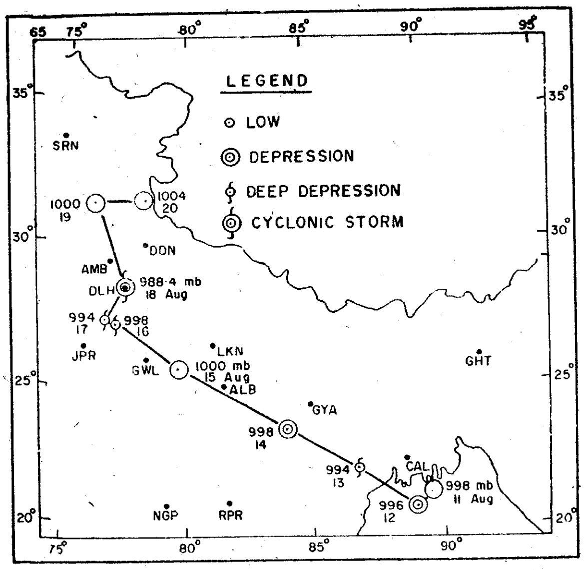


Fig. 1(a). Track of the storm between 12 and 20 Aug 1976 (Position at 03 GMT)

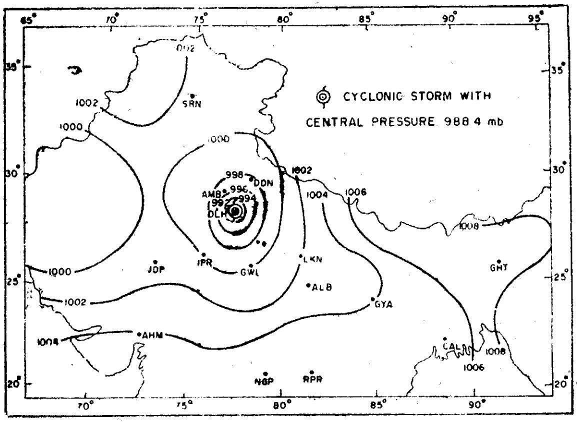


Fig. 1(b). Sea level pressure chart at 03 GMT on 18 Aug 1976

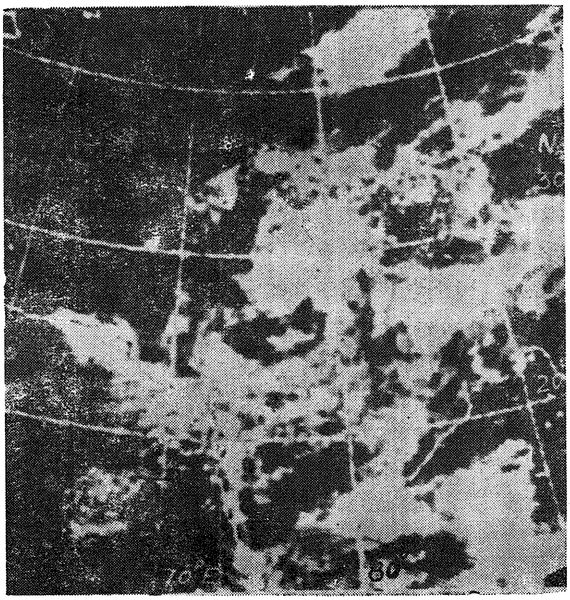


Fig. 1(c). Satellite NOAA-4 picture of 0410 GMT on 18 Aug 1976

it from SW through Gujarat and west Madhya Pradesh and with centre over Delhi. The system extended upto 200 mb level. The core of the cyclonic storm was warm at 500, 700 and 850-mb levels. It had, however, a cold core at 200-mb level and at 300 mb the core was neither cold nor warm (Fig. 2b). (*d*) At 12 GMT of 18th the storm lay north of Delhi and had a cold core right from 850 mb to 200 mb (Fig. 2c). The associated cyclonic circulation again extended upto 200 mb.

### 4. Surface features of the storm

The Figs. 3(a, b, c,) show the anemogram, the barogram and the hyetograms of New Delhi covering the period from 0830 IST of 17 August to 1800 IST of 18 August. The anemogram and barogram show that the storm's centre on its S-N track was closest to Delhi at about 0800 IST when the winds dropped and the rainfall also stopped suggesting that Delhi perhaps lay in the fringe region of the storm's eye (or eye under formation).

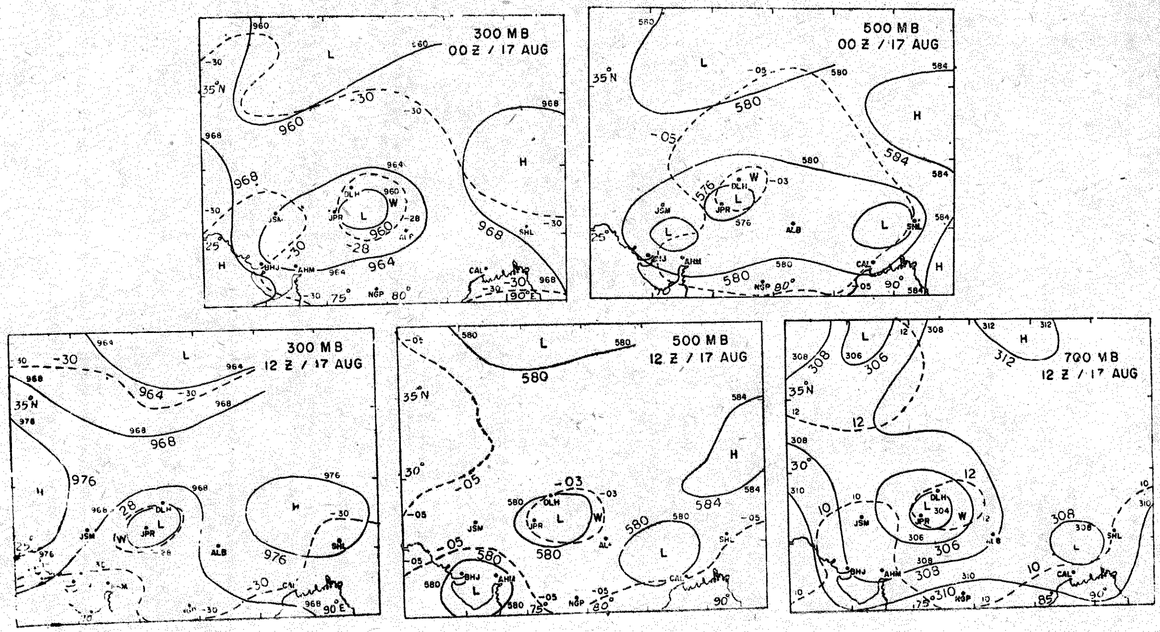


Fig. 2 (a). Constant pressure charts of 17 August

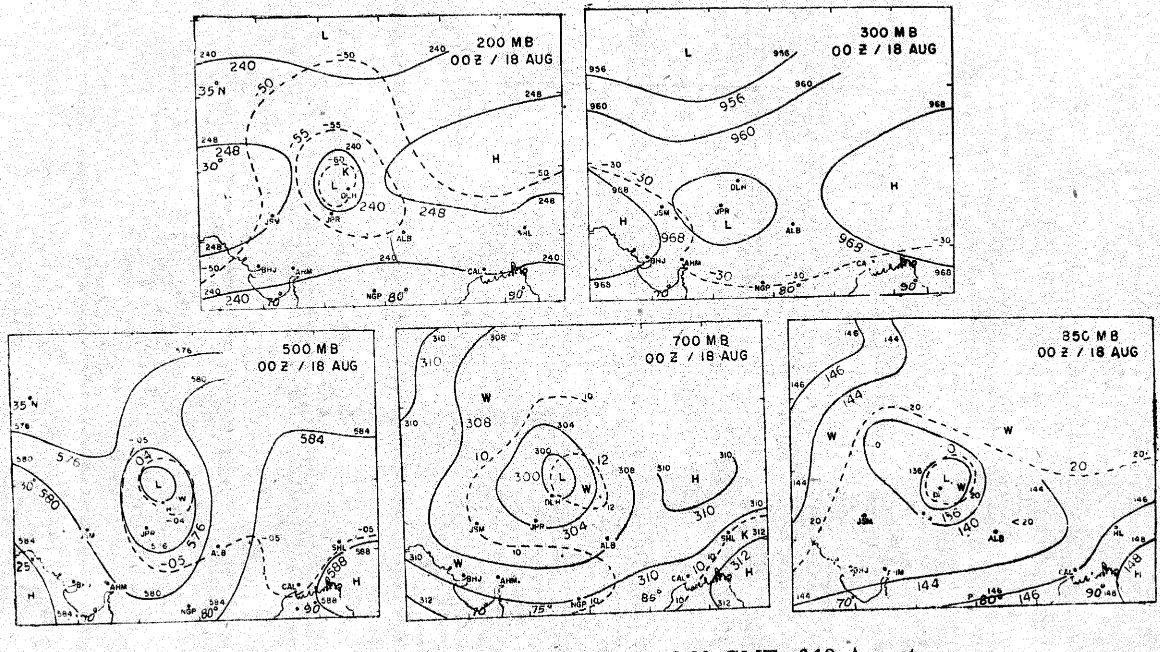


Fig. 2(b). Constant pressure charts of 00 GMT of 18 August

15 cm of rainfall occurred between 1330 IST of 17 August and 0830 IST of 18th when the station was to the north of storm's centre and this shows that the maximum rainfall occurred ahead of the storm in the direction of its movement. This is apparently due to strong vertical motions ahead of the northward moving system.

Only 6.5 mm of rainfall occurred between 0830 and 1415 IST of 18 August and thereafter rain practically stopped. The 0830 IST rainfall chart of 19 August also shows that Delhi and the surrounding stations recorded much less rainfall than on 18th. Maximum precipitation, therefore, occurred during the period when the system intensified into cyclonic storm at 0800 IST of 18 August and the peak intensification period was from 1330 IST of 17 August to 0800 IST of 18 August. The release of latent heat during the process had helped the system to develop a warm core and this is evident from the upper air charts of 0000 and 1200 GMT of

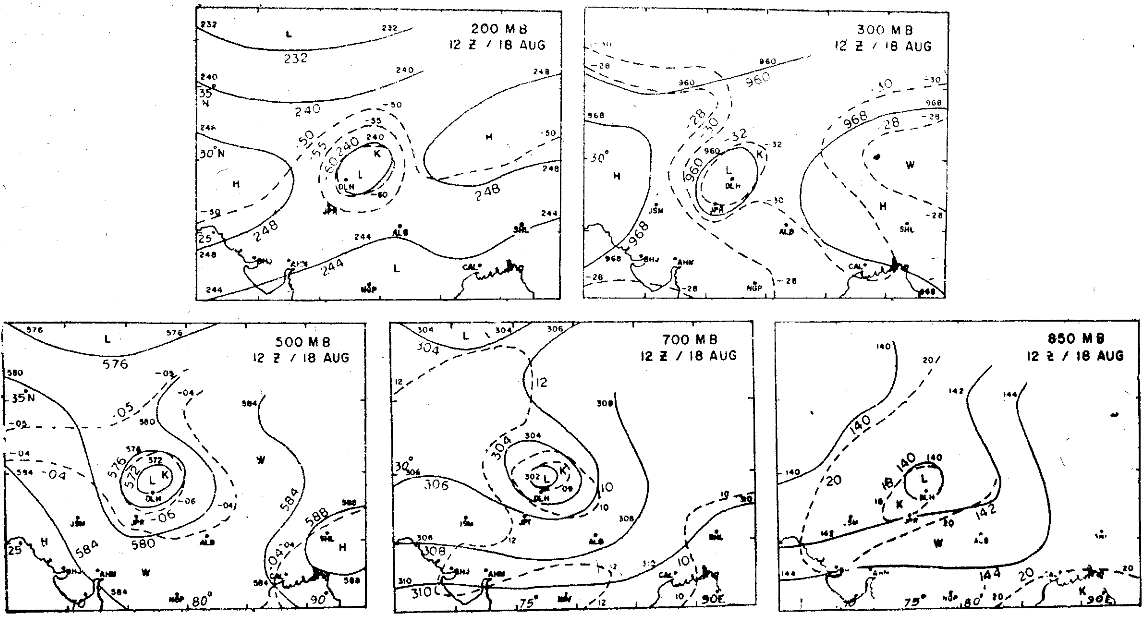


Fig. 2(c). Constant pressure charts of 12 GMT of 18 August

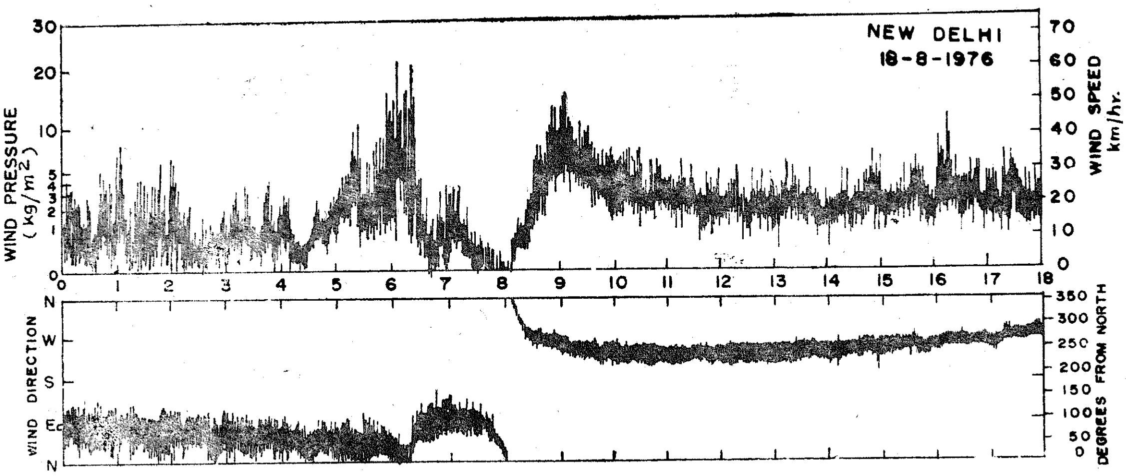


FIG 3a

Fig. 3(a). New Delhi, anemogram of 18 August 1976

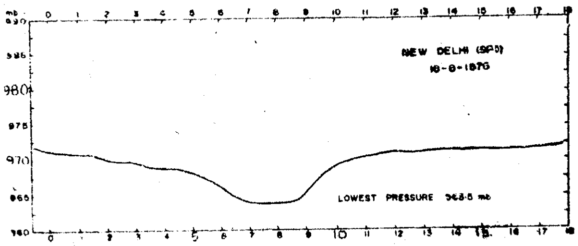


Fig. 3(b). New Delhi (SFD) barogram of 18 August 1976

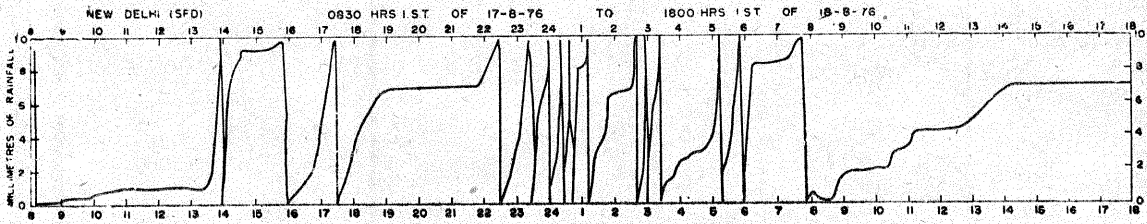


Fig. 3(c). New Delhi (SFD) hyetogram, 0830 IST of 17 August 1976 to 1800 IST of 18 August 1976

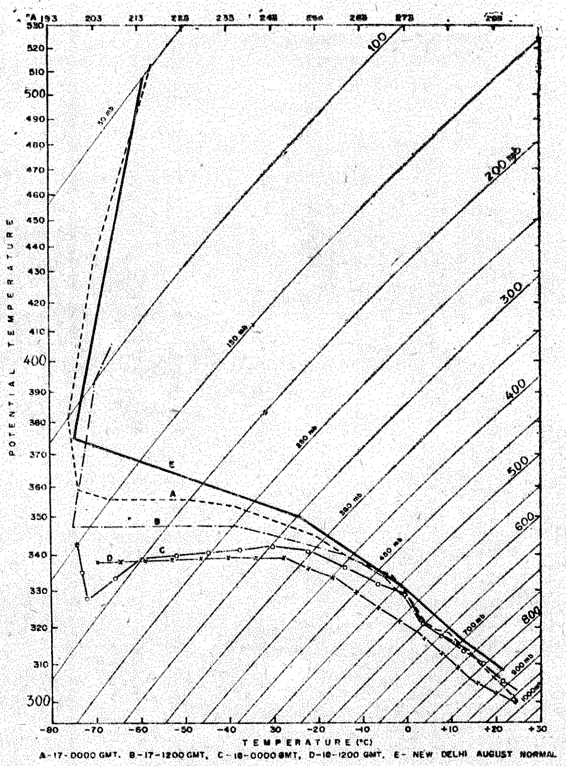


Fig. 4(a). Upper air soundings of New Delhi of 17 & 18 August 1976 showing dry bulb temperature curve

17 and 0000 GMT of 18 August (discussed in previous section and also from various derived charts).

### 5. Maximum sustained wind in the storm

The lowest pressure recorded at New Delhi at 0800 IST on 18 August was 963.7 mb which when reduced to m.s.l. gives a value of 988.4 mb. Delhi recorded a 24-hr pressure fall of 9.8 mb on this day and pressure departure was -11.8 mb. Atkinson and Holiday (1977) gave the following linear and non-linear relationships for the calculation of maximum winds from the central pressure of cyclonic storm formed in the monsoon trough near Asian mainland.

Linear relationship, $V_m=1180.3-1.143\ P_c$

Non-linear relationship, $V_m=6.7\ (1010-P_c)^{0.644}$

where $P_c$ is the minimum sea level pressure (mb) and $V_m$ the maximum sustained (1 min.) wind speed (kt). Utilising the data of Delhi as given in the previous paragraph, we obtain the value of $V_m$ from the two equations as 50.6 kt and 48.9 kt. Delhi experienced the peak gust of 62 km/hr or 41.3 kt which is fairly close to the calculated values from both equations.

### 6. Upper air soundings

To study the structure of the cyclonic storm, the upper air data of 17, 18 and 19 August 1976 for Delhi for 00 and 12 GMT were used to construct thermodynamic diagrams and various

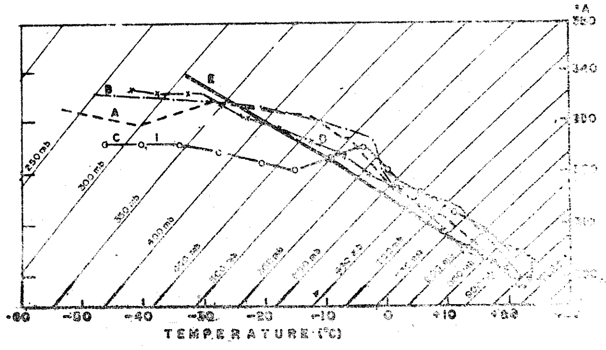
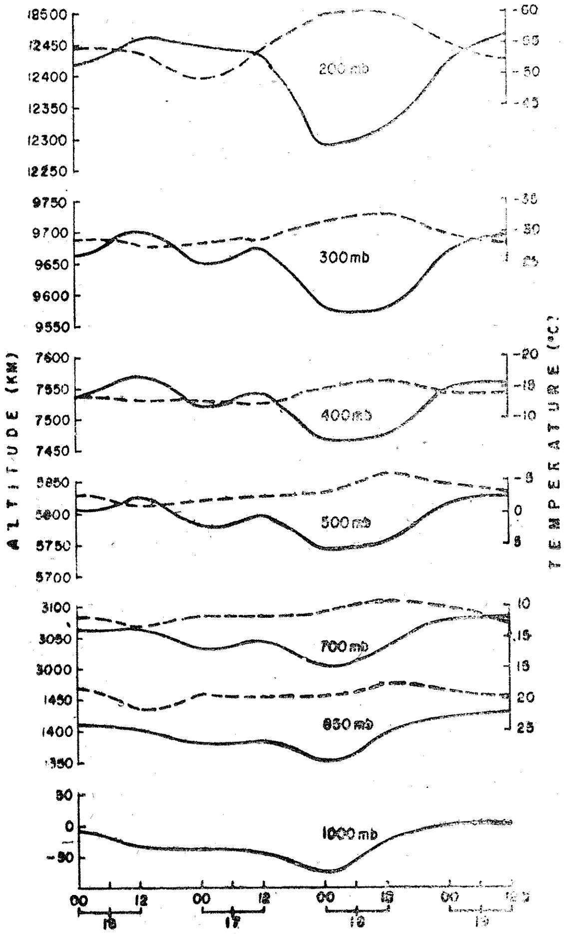


Fig. 4(b). Upper air soundings of New Delhi of 17 & 18 Aug 1976 showing dew point curve (legends for A to E are same as in Fig. 4a)



— Height (gpm), – – —Temperature (°C)

Fig. 5. Vertical time section of Delhi (00 GMT of 16 Aug to 12 GMT of 19 Aug) for heights and temperatures

time sections of Delhi and these are discussed below :

Fig. 4(a) shows the temperature soundings of Delhi at 0000 and 1200 GMT of 17 and 18 August together with the normal sounding of Delhi for August based on long-term data (1951-1970). It is interesting to note that the air over Delhi at all levels on these two days was cooler than the normal atmosphere. This is in contrast to the pronounced warming observed above 500 mb in the case of severe cyclonic storm of 29 September 1971 near Calcutta by Tripathi and Saxena (1975).

### 7. Time section of geopotential heights and temperatures

The heights and temperatures of different

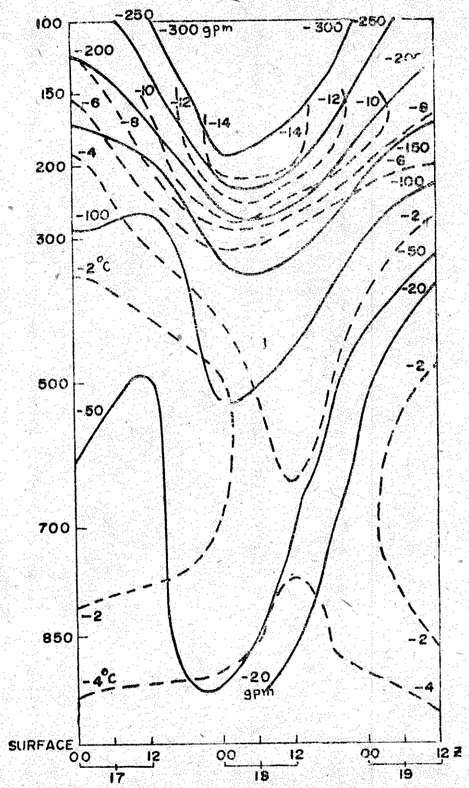


Fig. 6. Vertical time section of Delhi (00 GMT of 17 Aug to 12 GMT of 19 Aug) for ht. & temp. anomalies

standard pressure surfaces over Delhi for the period 16 August to 19 August are shown in Fig. 5. A diurnal oscillation in the geopotential height with relatively small amplitude at 0000 GMT than at 1200 GMT at 700 mb level and aloft and with higher amplitude at 0000 GMT than at 1200 GMT below 700 mb level are noticed on all the days.

Neglecting the small order of diurnal oscillation, a gradual fall of height from 16th to 17th followed by a sudden and sharp fall on 18th at all the constant pressure surfaces is noticed. Then there is a sudden and sharp rise at 0000 GMT of 19th. The fall of geopotential heights is of the order of 75 gpm from 1000 mb upto 400 mb. It increases with altitude and becomes 125 gpm at 300 mb and 200 gpm at 200 mb level.

The track of the storm being approximately from south to north near Delhi, the time section represents a north-south section. The sharp fall in geopotential height on 18th during the passage of storm can be explained by the fact that the centre of cyclonic storm happened to lie very near to Delhi on this day. But the increased fall at 300 mb and 200 mb levels even extending into stratosphere is unlike the findings of Rai Sircar (1956) and Tripathi and Saxena (1975) who observed that the fall of geopotential heights decreased gradually with altitude and finally with a reversal at 200 mb and above when the heights actually increased. As explained by them, this was due to an overlying anticyclone at 200 mb level which resulted in depletion of rising air from below by divergence.

## 8. Time section of height and temperature anomalies

Fig. 6 presents a vertical time section of Delhi from 0000 GMT of 17 to 1200 GMT of 19 August 1976 with 12 hours spacing of the observations. The deviation of day to day geopotential heights and temperatures from the long-term mean for the month August (based on data from 1951-1970) are plotted on the corresponding standard pressure levels. The isopleths of height anomalies are drawn at an interval of 50 gpm in full lines. The isopleths of temperature anomalies are drawn at an interval of 2°C in broken lines. The negative anomalies in heights and temperature exist on almost all the days.

It is observed that the height anomalies decreased uniformly with height extending upto 100 mb and even beyond and they were found to be the least on 18th at all levels.

The temperature anomalies also showed a uniform decrease with height upto 150 mb. They had generally the lowest values at 200 mb level. The troposphere over Delhi experienced the maximum cooling on the 18th when the system had intensified into a cyclonic storm and was lying closest to Delhi.

## 9. Vertical time section of potential equivalent temperature

The potential equivalent temperature serves as a measure of the heat stock of a parcel of air.

Fig. 7 shows time section of Delhi for $\theta_e$ from 0000 GMT of 17th to 1200 GMT of 19th.

The potential equivalent temperature values are the highest at all levels at 1200 GMT of 17th when the system was passing through maximum intensification stage and Delhi lay on its northern periphery. The values gradually fell at all levels at 0000 GMT of 18th when the system intensified into a cyclonic storm and lay centred near Delhi. They became lowest on almost all levels at 1200 GMT of 18th when Delhi lay on the southern periphery of the storm and rose again at 0000 GMT of 19th when the system had moved away sufficiently northwards and weakened into a low.

## 10. Development equation

With a view to locating the factors which lead to development and decay of the storm, different terms in Petterssen's development equation have been examined and discussed. The development

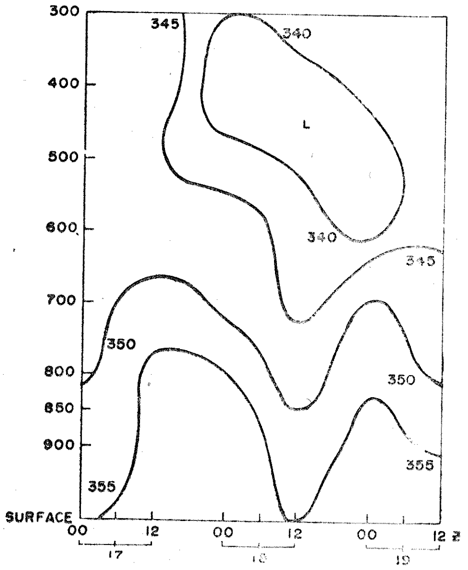


Fig. 7. Vertical time section in equivalent potential temperature ($\theta_e$) (°K) (00 GMT of 17 August to 12 GMT of 19 August)

equation (with usual notation of the symbols) is:

$$\frac{\partial Q_0}{\partial t}=A_Q-\frac{R}{f}\nabla^2\left[\frac{g}{R}\mathbf{V}.\nabla(\delta z)+\log\left(\frac{p_0}{p}\right)\left\{\omega(\Gamma_a-\Gamma)+\frac{1}{c_p}\frac{dw}{dt}\right\}\right]$$

*The non-adiabatic influence*:

$$-\frac{R}{f}\nabla^2\left\{\log\frac{p_0}{p}\cdot\frac{1}{c_p}\frac{dw}{dt}\right\}$$

During August temperature gradient near Delhi at surface is directed from north to south. When cold and moisture laiden airmass in the field of the deep-depression moved northward, the heat transfer from the surface was positive (*Climatological Atlas of India,* India Met. Dep. 1971). The Laplacian of the heat transfer is negative and therefore the non-adiabatic influence contributed positively to cyclone development.

*The adiabatic influence*:

$$-\frac{R}{f}\nabla^2\log\left(\frac{p_0}{p}\right)\omega(\Gamma_a-\Gamma)$$

In tropical system the unstable cloud regions cover a major portion of the tropical systems as in the present case and therefore it is logical to replace $\Gamma_a$ by $\Gamma_s$ where $\Gamma_s$ is the wet adiabatic rate of cooling. For the ascending motion $\omega<0$. From thermodynamic diagrams it was observed that generally $\Gamma_s-\Gamma<0$ and hence Laplacian value is negative. The net effect of this term is, therefore, positive. The buoyancy term, therefore, contributed positively to the development of the system.

*The vorticity advection*:

$$A_Q=-\mathbf{V}.\nabla Q=-V\frac{\partial Q}{\partial s}$$

$$=-V^2\left[\frac{\partial K_s}{\partial s}+K_s\,K_n\right]$$

where $K_s$ is the curvature of the streamlines and $K_n$ is the orthogonal curvature.

The depression came under the influence of a deep eastward moving upper air trough in the westerlies from 16 August onward and lay ahead of it till the evening of 18th. In the present case $K_n$ was very small. $K_s$ was negative down wind and, therefore, made positive contribution to the vorticity advection ahead of the trough which provided the necessary divergence to help maintain the pressure fall inside the storm and hence its intensification.

*The thickness advection*:

$$-\frac{g}{f}\nabla^2\ [\mathbf{V}.\nabla(\delta z)]$$

The 500 mb to 850 mb thickness charts did not indicate any thickness advection near and around Delhi on 17th and 18th. Hence the contribution due to this term was insignificant.

Therefore, the positive contribution of vorticity advection (upper divergence), instability term and adiabatic heating of surface were mainly responsible for the intensification of the system into cyclonic storm on the morning of 18th.

### 11. Decay of the storm

One of the important features of this system was its development into a cyclonic storm over land near latitudes of Delhi. The other important feature was its rapid weakening into a low within the very next 24 hours of its attaining the maximum intensity.

There was no evidence of cold air entrainment from the surroundings by advection except at 500 mb level at 0000 GMT of 18th. The trough in the upper tropospheric westerlies was lying in an area north of 35° N which was equally warm or even warmer (Fig. 2b).

From an examination of the rainfall pattern around the system, it is evident that a large amount of precipitation occurred between 17th and 18th when the system passed through the process of maximum intensification under the influence of upper air divergence and allied factors. Once the system organised itself into a cyclonic storm near Delhi on 18th, vigorous updraft activity would have been unleased. In such intense systems, Asting (1976) found the updrafts to be strongest between 500 and 300 mb. In the absence of fresh supply of moisture from Arabian Sea and Bay currents in the latitudes of Delhi, the following factors could be envisaged as responsible for cooling and consequent decay of the vortex.

It was possible that the water content in the layer between 300 and 500 mb was condensed out first (*See* Section 3). The air rising from this relatively dry layer could then cause cooling at 200 mb due to adiabatic expansion as witnessed at 0000 GMT of 18th where the core of the storm at 200 mb was cold (*See* ascent curves C and D in Fig. 4a). The process would subsequently descend to 300 mb level.

After a certain interval, a stage might be attained when most of the water content in the system would precipitate out, but fine water droplets (formed due to condensation) would remain in suspended form together with strong vertical currents. At this stage it is possible that process of evaporation would overtake the process of precipitation and evaporation due downdrafts might cause cooling at mid-tropospheric levels.

The evaporation process between 0000 and 1200 GMT of 18th was very strong as can be seen from an examination of Fig. 4 (e) where we find that dew point curve of 1200 GMT of 18th rises over that of 0000 GMT of the day from 500 mb and over those of 12 and 00 GMT of 17th, above 350 mb. This might be the cause of relative dryness of intermediate and lower levels. Moistening of the levels aloft may be due to evaporation (Reed *et al.* 1977).

The air after cooling would sink from higher to lower levels and in the process become dry. This could further enhance evaporation and consequent cooling at lower levels. The low energy air was thus observed descending to lower levels at 1200 GMT of 18th.

The massive cooling and generation of low energy air at all levels in the vortex was responsible for the rapid filling up of cyclonic storm and its weakening into a low within the next 24 hours.

### 12. Conclusions

(*i*) The cyclonic storm which formed near Delhi on the morning of 18 August 1976 was a cold-core system at 12 GMT as compared to its surrounding from 850 to 200 mb levels. The core of the system was neither cold nor warm during the earlier stages when it was a depression or deep depression on 15th and 16th. Its core became warm during its peak intensification period between 0000 GMT of 17th and 0000 GMT of 18th.

(*ii*) The temperature and height anomalies were negative at upper levels and were lowest at 200 mb level. This was unlike the Calcutta cyclonic storm of 29 September 1971 studied by Tripathi and Saxena (1975) where the anomalies were observed to be negative at lower levels but were positive at 500 mb and above for temperature and at 250 mb and above for heights.

(*iii*) The system developed into a cyclonic storm at 0830 IST on 18 August mainly because it came under the influence of upper air divergence ahead of the approaching trough in the westerlies from the 16 August onward. The life cycle of the monsoon depression, *i.e.*, its deepening, decay and movement from this stage onward was largely determined by the interaction of the pre-existing depression with the trough in the westerlies. The adiabatic heating from ground and instability of tropical airmasses were the two other contributing factors for the intensification of the system.

(*iv*) The warming in the core region was first observed at 300 and 500 mb levels at 00 GMT of 17th. It gradually descended to 700 and 850 mb levels by 00 GMT of 18th. This is also the period when the maximum rainfall occurred. This agrees with the fact that most of the precipitation is generated in the lower troposphere layers (700 mb and below).

Similarly the cooling of the core region of the storm was first observed at 00 GMT of 18th at 200 mb and then descended to lower levels by

1200 GMT of the same day. The influence of condensation (release of latent heat) and evaporation is observed first in upper tropospheric levels which subsequently descended to lower levels and this suggests that strong vertical motions during the formation of a cyclonic storm are, perhaps, first generated in the upper tropospheric layers (above 500 mb) and subsequently descend to lower levels (700 mb and below).

(*v*) The vortex decayed very rapidly on 18th after 1200 GMT as it developed a cold core on account of low energy air on almost all levels starting from upper tropospheric layers first and descending to lower layers subsequently.

Tentative results based on study of an isolated land cyclonic storm formed in the latitudes of Delhi have been presented and discussed in this paper. A few more such cases need to be studied for arriving at firm conclusions.

*Acknowledgement*

The authors are grateful to Dr. R. P. Sarker, Deputy Director General of Observatories (Climatology & Geophysics) and Shri A. R. Ramakrishnan, Meteorologist for giving valuable suggestions.

## References

Astling, Elfort G., 1976, *Mon. Weath. Rev.*, **104,** 12, pp. 1466-1473.

Atkinson, Gary D. and Holiday, Charles R., 1977, *Mon. Weath. Rev.*, **105**, 4, pp. 421-427.

India met. Dep., 1971, *Climatological Atlas of India*, p. 12.

Keshavamurthy, R.N., 1972, *Indian J. Met. Geophys.*, **23**, 2, pp. 161-164.

Karnegay, Francies C. and Vincent, G. Dayton, 1976, *Mon. Weath. Rev.*, **104**, 7, pp. 849-859.

Norquist, Donard G., Recker Earnest, E. and Reed, Richard J., 1977, *Mon. Weath. Rev.*, **105**, 3, pp. 334-342.

Petterssen, S., 1956, *Weather Analysis and Forecasting*, **1**, p. 324.

Rai Sircar, N.C., 1956, *Indian J. Met. Geophys.*, **7**, 1, pp. 37-42.

Rao, Y.P., 1976, Southwest Monsoon, Met. Monogr. Synop. Met. No. 1/1976, p. 106.

Reed, Richard J., Norquist, Donard G. and Recker, Earnest E., 1977, *Mon. Weath. Rev.*, **105**, 3, pp. 317-333.

Tripathi, S.N. and Saxena, V.P., 1975, *Indian J. Met. Hydrol. Geophys.*, **26**, 4, 479-486.