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Vertical structure of a Bay of Bengal cyclonic storm — A case study

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ABSTRACT. On the 29 September 1971, a cyclonic storm of severe intensity passed very close to Calcutta. Calcutta reported a record pressure deficiency of 26 mb at 1200 GMT of 29th, when the storm was close to Calcutta. Upper air soundings of Calcutta were available upto fairly high levels for all hours of observations during the life of the storm except for the evening of the 29th when the sounding terminated at 362 mb. The vertical structure of the storm is characterised by a warm core with temperature anomalies exceeding 8°C centred around the 250 mb level. There is evidence of a cold area at 125 mb and 100 mb levels where the negative anomalies of temperature were lower than 8°C.

1. Introduction

Structure of cyclonic storms and depressions in the Indian Seas has not been investigated in detail for want of aircraft reconnaissance facilities. Most of the existing knowledge on the structure of hurricanes is derived from data collected by U.S. research aircraft in the Atlantic and the Pacific (Koteswaram 1967; Sheets 1967 a, 1967 b, 1968 and Gray 1970, 1973). The only aircraft reconnaissance probes into cyclonic storms in the Indian Seas are the research flights flown by aircraft of the U.S. Weather Bureau Research Flight Facility during the International Indian Ocean Expedition in May 1963 (Colon *et al.* 1970).

Very few storms have passed over or near coastal radiosonde/rawin stations, and on the few occasions when they did, data have been either completely missing or too meagre for any meaningful analysis. A study of the vertical structure of some disturbances in the Bay of Bengal was made by Rai Sircar (1956) but the closest distance of the storm studied by him from a radiosonde station (Calcutta) was about 50 miles.

The present study is of the severe cyclonic storm which was centred closest to Calcutta between 1830 and 1900 IST of 29 September 1971. Radiosonde data of 1200 GMT of 29 September were available upto an altitude of 362 mb. Soundings before and after the passage of the storm near Calcutta were available to altitudes above the 100 mb level enabling a fairly detailed analysis of the vertical structure of the storm to be made.

2. Synoptic situation and brief description of the storm

A well marked low pressure area which lay over the central Bay of Bengal on the morning of the 27 September 1971, moved northwards and concentrated into a depression with its centre near 19°N, 88·5°E by the evening of the same day. Moving northwards, it intensified into a cyclonic storm on the evening of the 28 September and into a severe cyclonic storm on the morning of the 29th. At 0300 GMT of the 29th it was centred near 21·5°N, 88·5°E, *i.e.*, about 130 km from Calcutta. Crossing the Sunderbans coast in the afternoon of the 29th, the severe storm lay close to Calcutta at 1200 GMT. By the morning of the 30th, it weakened into a cyclonic storm and was centred at 0300 GMT of the 30th about 75 km east of Asansol. It continued to move northwestward and on the evening of the 1 October it lay as a low pressure area over east Bihar. The storm caused many houses in the coastal districts of West Bengal to collapse and took a toll of about 60 lives.

Figs. 1 and 2 show the sea-level isobars at 0300 and 1200 GMT respectively, of the 29 September 1971. Fig. 3 gives the track of the storm. The intensity of the system will be obvious from the pressure gradients. Little or no upper wind observations were availabe from near the storm area but at 1200 GMT of 29th the upper winds at Bogra (about 300 km northnortheast of Calcutta) at 0·9 and 1·5 km were 55 and 80 kt respectively.

Extracts from the Current Weather Register of Dum Dum (Calcutta) from 1200 to 1400 GMT of 29 September 1971 are given in Table 1.

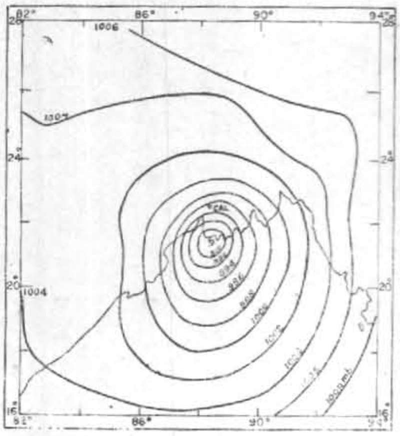

Fig. 1. Sea level chart of storm area 03 GMT of 29 Sep 1971

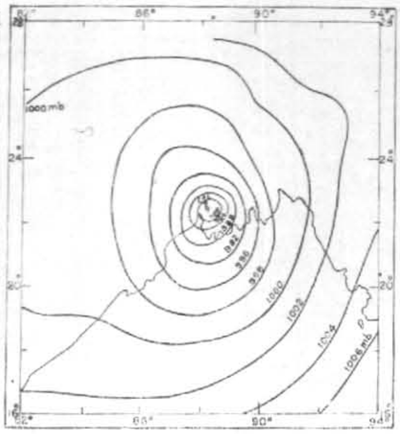

Fig. 2. Sea level chart of storm area 12 GMT of 29 Sep 1971

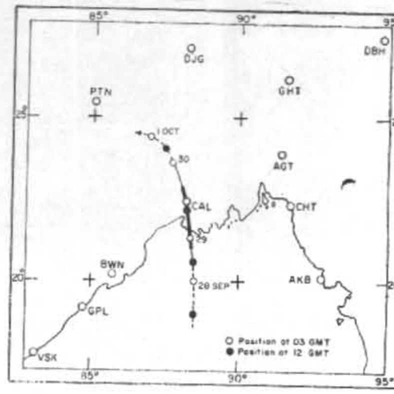

Fig. 3. Track of the storm

TABLE 1

Half-hourly observations recorded at Dum Dum Airport, Calcutta between 1200 and 1400 GMT of 29 September 1971

Time (GMT)	Pressure		Total amount of cloud	Wind		Visibility	Significant Present weather	Temperature		Individual cloud layers (Amt./ht.)		
	QFE	QNH		Direction	Mean/max speed (kt)	(m)		Dry Bulb (°C)	Dew Point (°C)			
1200	978·5	979·0	8	090	25/40	1500	61RA	27	27	7St/05	1Cb/20	8As/58
1230	979·0	979·5	8	090	30/45	1500	61RA	—	—	Do.	Do.	Do.
1300	978·5	979·0	8	110	30/45	4500	21RERA	27	27	Do.	Do.	Do.
1330	978·5	979·0	8	120	35/50	4500	61RA	—	—	Do.	Do.	Do.
SPECI 1400	979·5	980·0	8	140	30/45	5000	21RERA	26	26	Do.	8As/58	

The above observations read with the barogram and anemogram (Figs. 4 and 5) of Calcutta (Alipore) show that the storm centre was closest to Calcutta between 1300 and 1330 GMT.

The lowest pressure recorded at Calcutta (Alipore) was 978·5 mb at 1200 GMT on 29th. This gives a pressure defect of 26 mb — a record for Calcutta. To calculate the maximum wind speed, the relationship, $V_{max}=14\sqrt{1013-P_0}$ (Holliday, 1969) is used. In this relationship, V_{max} is the maximum wind speed in knots and P_0 is the central pressure in millibars. Taking the central pressure 978·5 mb, we get, $V_{max}=82$ kt.

As Calcutta experienced gales reaching 100-120 kmph on the evening of the 29th, winds of the order of the computed V_{max} occurring at the 'gradient' level would not be unlikely. If the relationship is assumed to be valid for storms in the Indian area, the above is an indirect evidence of the storm centre having passed very near Calcutta.

3. Data used

For the study, the upper air data of 28, 29 and 30 September 1971 of Calcutta as available from the records of the Upper Air Section of the Office of the Deputy Director General of Observatories (Climatology & Geophysics), Poona have been used. Data plotted in Fig. 6 were checked from these records. A few observations were picked up from the working charts of Weather Central, Poona.

Data for Calcutta upto 100 mb were available for both the routine hours of observations on all days except for 1200 GMT of the 29th, when the highest level reached was 362 mb. For levels

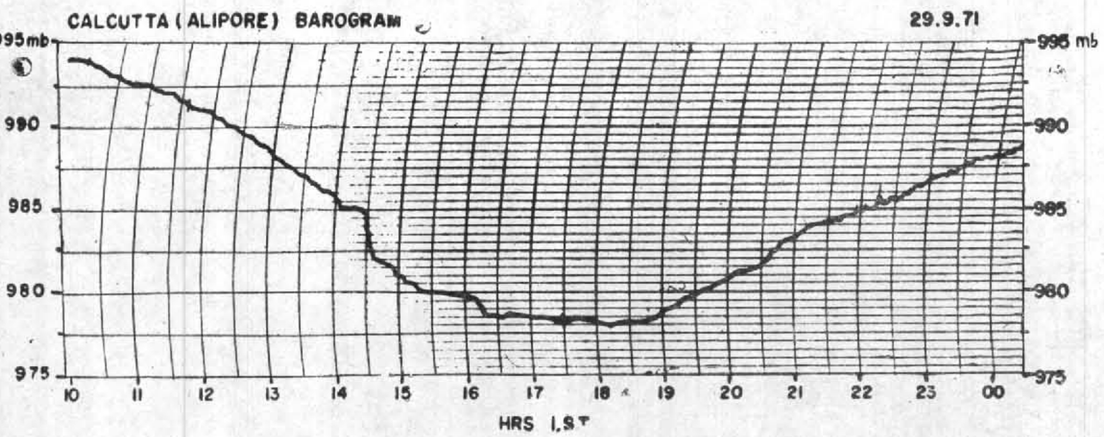

Fig. 4

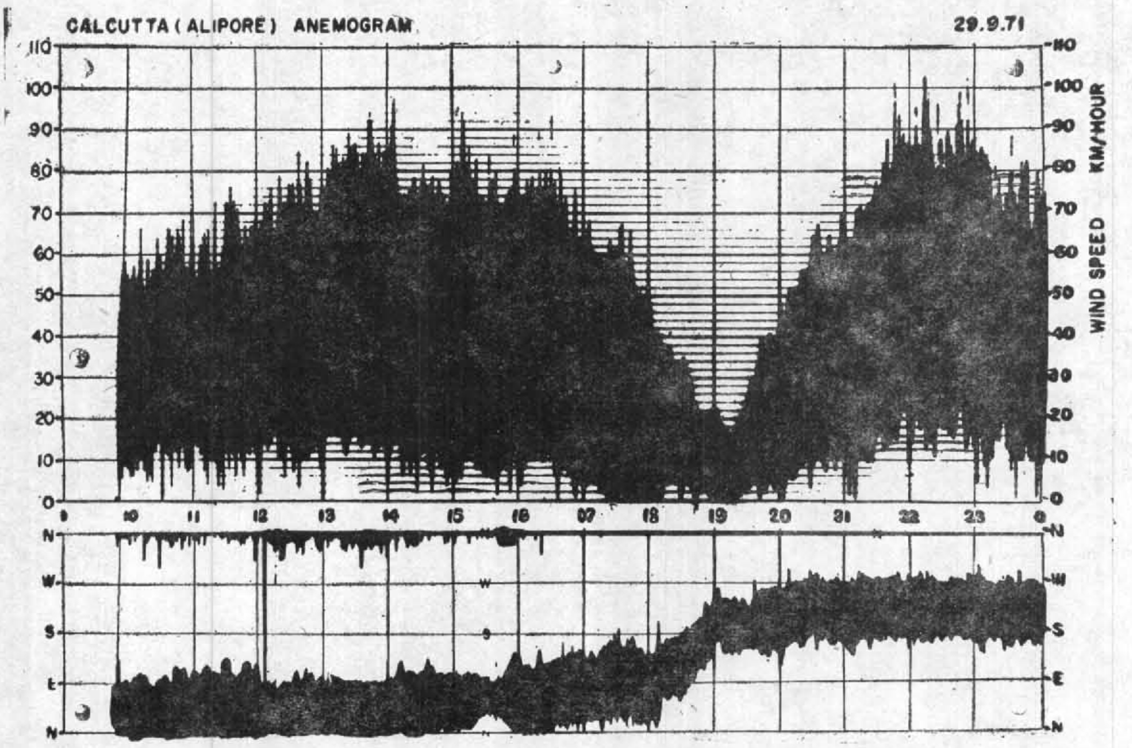

Fig. 5

above 100 mb for which normals are available data was rather scanty. Accordingly, the study was restricted upto the 100 mb level only. Temperatures and heights of pressure levels for 1200 hr GMT of the 29th between 362 mb and 100 mb were extrapolated as described in the next section. Although the extrapolated values cannot be too rigorously justified, for there are no ultimate means for their verification, the qualitative and comparative conclusions based on the values are not unjustified.

Upper wind data during the period 28 to 30 September were extremely poor. It has, therefore, not been possible to analyse the structure of the wind field.

4. Structure of the storm

Fig. 6 shows the temperature soundings from 1200 GMT of 28th to 0000 GMT of 30th, *i.e.*, for the period during which the system was a storm and the normal upper air temperatures of Calcutta for September (00 and 12 GMT combined normals, 1951-1970). The most significant feature of the soundings is the pronounced warming above 500 mb at 0000 GMT on 29th. The warming during 1200 GMT of 28th and 0000 GMT of

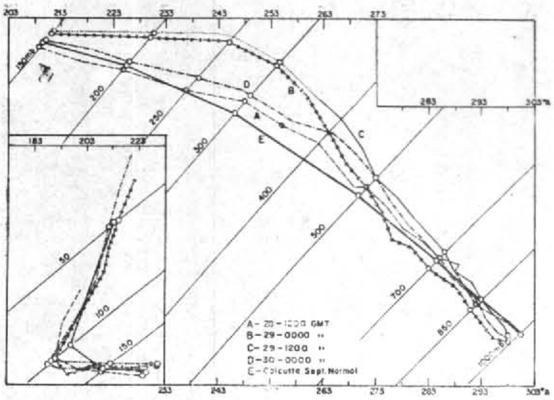

Fig. 6. Upper air soundings of Calcutta on 29 September 1971 at 1200 GMT (sounding extrapolated above 362 mb)

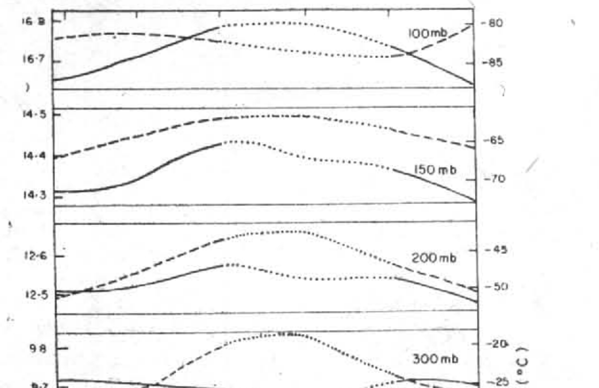

Fig. 7. Variation of heights and temperatures at pressure levels during the passage of the storm at Calcutta

of 29th between 350 and 200 mb was from 5°C to 8°C, the maximum being at the 250 mb level. With the exception of a region near the 100 mb level, the relative warming extended into the stratosphere, temperatures at 80 and 70 mb levels being 8° to 9°C higher at 0000 GMT of 29th than that on the previous evening. At 1200 GMT of 28th the storm was about 220 km ($\sim 2\frac{1}{2}°$) and at 0000 GMT of 29th about 150 km ($\sim 1\frac{1}{2}°$) from Calcutta.

The cyclonic storm rapidly intensified into a severe cyclonic storm between 1200 GMT of 28th and 0000 GMT of 29th. Data near the centre of the storm was only available for 1200 GMT of 29th at Calcutta. During the period 1200 GMT of 28th and 0000 GMT of 29th, however, there was rapid and pronounced warming of the upper troposphere and the lower stratosphere at Calcutta. If similar warming had occurred in the central area of the storm too, during the period, the rapid intensification would be conclusively explained by this warming.

The 1200 GMT sounding of 29th was extrapolated from 362 mb to 100 mb as follows :

The vertical time-section over Calcutta during the passage of the storm (Fig. 8) was prepared and the temperature anomalies at each level worked out from the upper air normals. Smooth isopleths of temperature anomalies were drawn for the available anomaly values and the isopleths extended through the missing levels, keeping in view the gradients and trends. From these interpolated anomalies, temperatures were estimated at each of the standard levels from 300 mb to 100 mb. The extrapolated temperatures were used to determine the heights of the standard pressure levels ignoring the virtual temperature correction, as any assumption regarding relative humidities would have been unrealistic. Isopleths of height anomalies so obtained were checked with the height anomalies derived from extrapolations as in the case of temperature extrapolations described above.

The extrapolation was cross-checked by using the method given by Gentry (1963) for estimating the drop in pressure at the surface due to warming of the different layers of an air column, if the height of some upper pressure level can be assumed to remain constant during the passage of the storm. The extrapolated heights of different standard pressure levels between 362 mb and 100 mb can be seen in Fig. 7. It would be seen that extrapolated heights for 1200 GMT of pressure levels upto 150 mb are lower than the 0000 GMT values on 29th and follow the trend observed for levels below 362 mb. The extrapolated height of the 100 mb level, however, works out to be the same as at 0000 GMT (Actually it would have been somewhat higher if virtual temperature corrections were not ignored). Taking this level as the 'no-change in height' level and integrating for each successive layer of 100 mb thickness from the surface to 100 mb level using the expression,

$$\frac{\partial p_o}{\partial t} \approx -\frac{1}{p_o}\sum_{n=1}^{n=8}\frac{1}{\overline{T}_n}\frac{\partial \overline{T}_n}{\partial t}\ln\frac{p_{n+1}}{p_n}$$

where p_0 is the pressure at the surface, p_n is the pressure : $n \times 10^2$ mb and $\overline{T}_n$ is the mean virtual temperature in the layer from p_n to p_{n+1} and the upper boundary is 100 mb. Gentry (1963), the computed pressure change at Calcutta between 0000 GMT and 1200 GMT of 29th works out to be 13·9 mb against the observed pressure change of 14·5 mb (allowing for the diurnal variation of pressure). In integrating for layers above 400 mb the extrapolated values of temperature were used. Such close agreement in the computed and observed pressure change is, of course, coincidental. If virtual temperatures were used above the 400 mb the computed pressure change would have been greater. Nevertheless, it is a good check on the extrapolation.

There was slight cooling (1°-2°C) upto 500 mb between 1200 GMT of 28th and 0000 GMT of 29th. Most of this cooling was apparently due to rain. The warming between 0000 and 1200 GMT of 29th from surface upwards was obviously due to the proximity of the warm core of the storm as the centre passed very close to Calcutta and due to the latent heat released from extensive rainfall. It is of interest to note that the warming at 1200 GMT of 29th was not limited to a rise in temperatures only. The equivalent potential temperatures rose appreciably at 1200 GMT on 29th both due to a rise in temperature and due to an increase in the humidity mixing ratios (Fig. 10). This will be further discussed later. The temperatures fell after 1200 GMT of 29th but continued to remain high upto 0000 GMT of 30th when the storm had passed Calcutta.

It will be noticed that practically the whole of the middle and upper troposphere was considerably warmer than the normal on all the days including the morning of 30th.

5. Variation of height and temperature at different pressure levels

5.1. *Variation of heights*

The variation of heights of pressure surfaces during successive twelve hours from 0000 GMT of 28th to 1200 GMT of 30th is shown in Fig. 7.

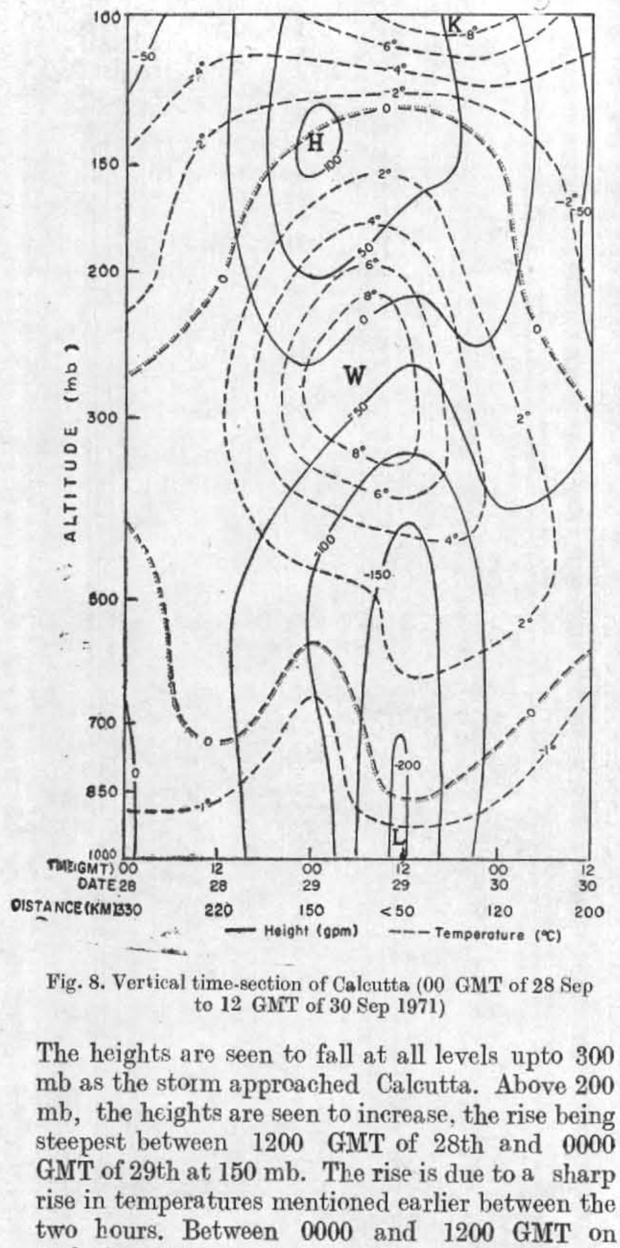

Fig. 8. Vertical time-section of Calcutta (00 GMT of 28 Sep to 12 GMT of 30 Sep 1971)

The heights are seen to fall at all levels upto 300 mb as the storm approached Calcutta. Above 200 mb, the heights are seen to increase, the rise being steepest between 1200 GMT of 28th and 0000 GMT of 29th at 150 mb. The rise is due to a sharp rise in temperatures mentioned earlier between the two hours. Between 0000 and 1200 GMT on 29th the heights (extrapolated above 400 mb) fell upto 125 mb (not shown). The height (extrapolated) of the 100 mb level as mentioned earlier remained unchanged.

The maximum fall of height during the passage of the storm at 1200 GMT of 29th was in the lower levels, being 150 gpm at 1000 mb gradually decreasing to 60 gpm at 362 mb, the last level for which observations were available. The extrapolated heights from 300 mb to 150 mb showed a reduced fall of around 40 gpm and little or no change at 100 mb.

After the passage of the storm, the observed heights rose steeply upto 362 mb above which

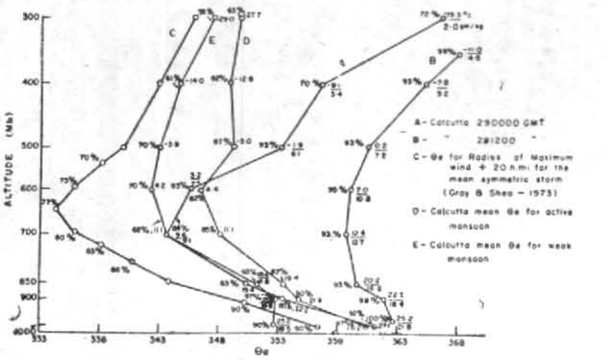

Fig. 9· Equivalent potential temperature profiles (θe) (°K)

the extrapolated values showed a less steep rise upto 200 mb and a fall above.

5·2. *Variation of temperatures at pressure levels*

Temperatures increased at all levels upto 100 mb between 0000 GMT and 1200 GMT of 28th and fell by 5°C and 2°C at 80 mb and 70 mb respectively in the stratosphere. Between 1200 GMT of 28th and 0000 GMT of 29th as mentioned earlier, there was considerable warming of the upper troposphere, and the lower stratosphere except for a slight cooling at 125 mb and 100 mb levels.

During the passage of the storm near Calcutta at 1200 GMT on the 29th, the temperatures rose from the previous observations by 1·5°C to 3°C from the surface to 362 mb. Above this level the extrapolated values indicated a slight warming upto 150 mb and a slight cooling at 100 mb. After the passage of the storm temperatures generally fell throughout the largest estimated fall being around 250 mb. Incidentally it is around this region that the temperatures had registered the highest rise at the approach of the storm between 1200 GMT of 28th and 0000 GMT of 29th.

6. Vertical time-section

Fig. 8 gives the vertical time-section of Calcutta from 0000 GMT of the 28th to 1200 GMT of 30 September 1971. The system was a storm between 1200 GMT of 28th and 0000 GMT of 30th only. At the two extremes it was a depression. The spacing of the observations being twelve hours, fine details of the structure are not revealed. The storm centre was closest to Calcutta between about 1830 and 1900 IST of 29th and the actual time of the 1200 GMT ascent of 29th was 1850 IST. Thus, the 1200 GMT sounding on 29th represents the vertical structure of the storm within less than 50 km of the centre. The track of the storm being approximately south to north, the time section repesents a north-south section. The method adopted for extrapolating heights and temperatures at 1200 GMT on 29th above 362 mb, has been explained earlier.

The height anomalies show the lowest anomaly of 200 gpm extending to 700 mb. Negative anomalies above the storm extend to about 250 mb with the positive height anomalies above. The highest anomaly lies at 150 mb at 0000 GMT of 29th, *i.e.*, ahead of the storm. There is a close similarity between these and the anomalies associated with the passage of hurricane *Cleo* near Miami, Fla on 26 August 1964 (Koteswaram 1967 a). After the passage of the storm, *i.e.*, in its rear, positive anomaly maxima as seen head of the storm is not found. The asymmetry in the height anomalies is evident. This is obviouly due to weakening of the system and cooling of the atmosphere between 1200 GMT of 29th and 0000 GMT of 30th.

Temperature anomalies show above normal values upto about 150 mb in the storm and below normal values above. The highest anomalies of over 8°C are seen in the core centred around the 250 mb level extending from about 300 mb level to a little below 200 mb level. The lowest negative anomalies of temperature of—8°C and perhaps less were observed at 100 mb. No attempt was made to extrapolate 1200 GMT temperatures of 29th to the tropopause level. The temperatures at the tropopause level at 1200 GMT on 28th, 0000 GMT on 29th, 0000 GMT on 30th were however about 188°K with little variation at the three hours. Even assuming that the temperature did not fall much below this value at the tropopause level during the passage of the storm centre near Calcutta, the departures from normal would be about 10°C. Thus, the lowest negative anomalies of temp. of—8°C to—10°C perhaps existed over and near the core between 100 and the tropopause.

7. Equivalent potential temperature

Fig. 9 shows the equivalent potential temperapure (θ_e) at different levels at 0000 GMT (A) and 1200 GMT (B) on 29 September 1971 (upto 362 mb only). The noticeable increase in the equivalent potential temperature between the two hours is due both to an increase in the temperature and in the humidity mixing ratios. Values of these elements as well as of the relative humidities at different pressure levels are given along the curves.

In both the curves the equivalent potential temperature decreases upto 700 mb but the decrease in curve B (1200 GMT of 29th) is very little, showing a considerable decrease in convective instability in the evening when the storm centre was close to Calcutta.

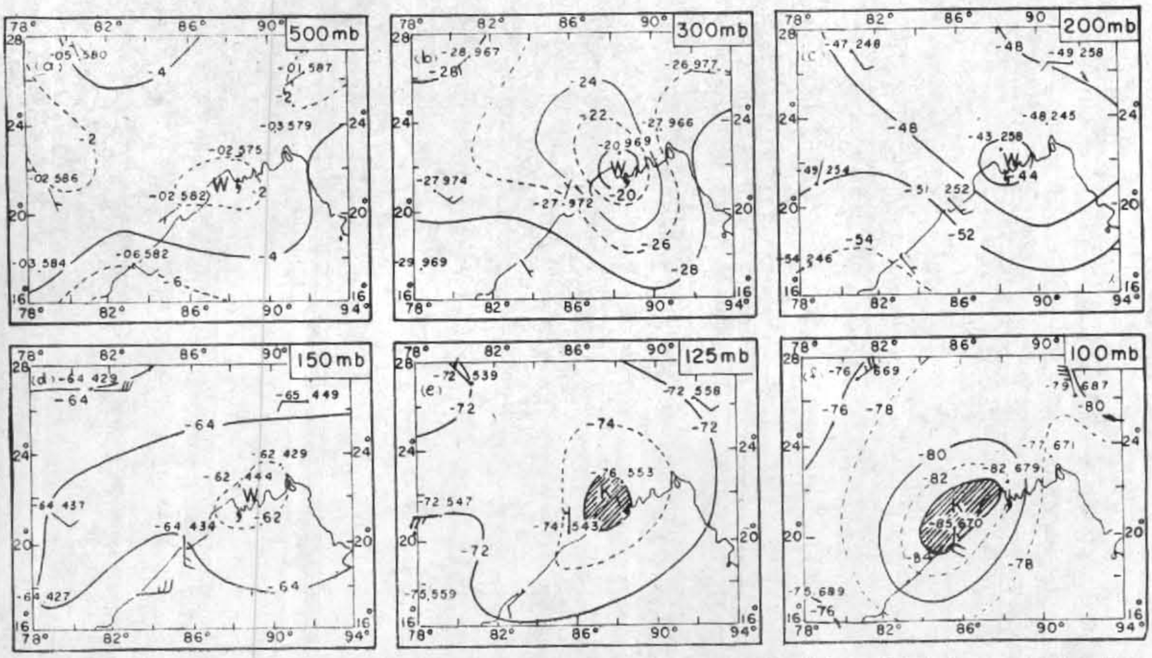

Fig. 10. Geopotentials of isobaric surfaces, temperatures, wind shears (between two levels immediately above and below the isobaric surfaces) and isotherms at 00 GMT of 29 September 1971

Curve A closely corresponds in shape to the equivalent potential temperature profile (C) of a mean symmetric storm at a distance away from the radius of maximum wind given by Gray and Shea (1973). Incidentally, the profile is similar to the profile of the mean equivalent potential temperatures for Calcutta in the monsoon season (Curves D and E for active and weak monsoon conditions respectively—Srinivasan and Sadasivan 1975). Only the values of θ_e and relative humidities at different levels differ. Curve B however differs considerably from the profiles of θ_e nearer the eye given for a number of storms by Gray and Shea (1973). In curve B the characteristic slope of θ_e between 900 and 700 mb is absent. On the contrary, it is suggestive of an almost moist adiabatic ascent upto 500 mb. As a matter of fact, the vertical temperature distribution at 1200 GMT on 29th upto about 500 mb closely corresponds to that which would result from moist adiabatic ascent of surface air having $\theta_e = 362°K$ — the value at 1200 GMT on 29th. High relative humidites (>90 per cent) throughout, show no evidence of subsidence.

8. Evidence of upper cold region

The vertical time-section shows the lowest negative anomalies of temperature of less than −8°C at 100 mb. Figs. 10 (a) to 10 (f) show the temperature in the vicinity of the storm at 0000 GMT of 29th — the only hour at which Calcutta, Bhubaneswar and Dacca upper air observations were available. Isotherms at the different levels have been drawn with the help of wind shears between two levels, one immediately above and the other immediately below the pressure level obtained from original flight sheets.

The figures clearly show the warm region above the storm from 500 mb to 150 mb. At the 125 mb and 100 mb levels the temperature distribution is reversed and there is a cold region above the storm (Koteswaram 1967 b). As mentioned earlier, the study was not extended above 100 mb.

9. Summary and Conclusions

The rapid intensification of the system has been commented upon earlier. A considerable part of the pressure deficiency is due to the temperature changes which occur above the 500 mb level (Gentry 1963). If the warming in the central area of the storm was similar to the one at Calcutta between 1200 GMT of 28th and 0000 GMT of 29th, the warming apparently played a considerable part in the intensification of the storm during the period. Data from the core of the storm during the period being absent, no unequivocal statement to that effect can, however, be made. Vertical wind shears (850-200 mb) which inhibit development of cyclonic storms during the monsoon could not be assessed due to complete lack of upper wind data from the field of the storm.

The downward slope of pressure surfaces upto 300 mb (Fig. 7) is reversed at 200 mb and above, particularly between 1200 GMT of 28th and 0000

GMT of 29th. This would suggest an upper tropospheric ridge to the north of the centre. A similar ridge was not evident on the southern side of the storm, obviously due to the weakening of the system. The absence of data above 362 mb on the 29th evening and spacing of observations did not permit a precise estimate of the horizontal extent of the ridge.

The system was demonstrably a warm-cored one with the highest anomaly exceeding 8°C (with respect to Calcutta normal temperatures) centred around the 250 mb level near the core. The lowest negative anomalies of temperature of—8°C and less occurred in the core around the 100 mb level.

There is evidence of a cold area above the storm at the 125 mb and 100 mb levels (Figs. 10 a to 10 f) on the 29th morning. Evening observations of the 29th when the storm was over Calcutta, had they been available, would have more precisely defined this cold area.

The APT pictures of the storm were not well defined but there was no evidence of an eye at any stage. The equivalent potential temperature profile of the 29th evening compared to the profiles given by Gray and Shea (1973) confirms this.

The passage of the storm almost over Calcutta provided a rare opportunity to study is vertical structure. Absence of wind data and termination of the Calcutta sounding at 362 mb when the storm was closest to the station, limited the scope of the study. The broad features of the vertical structure of the storm are, however, quite well brought out in the study.

Acknowledgement

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