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# Some structural features of a Bay of Bengal tropical cyclone

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**सार** — उपग्रह इनसेट-1 बी और तटीय रेडार द्वारा दीर्घ अवधि तक के समक्षणिक प्रेक्षणों के कारण 9 से 14 नवम्बर 1984 के बंगाल की खाड़ी में उत्पन्न चक्रवात की संरचना का विस्तृत अध्ययन किया जा सका है। तूफान आकार में छोटा था और तूफान की आंख छोटी थी, कुछ समय तक उसमें दोहरी भित्ति वाली अक्षी दिखाई दी। तूफान की आंख की भित्ति में रेडार परावर्तकता का प्रबल असममित वितरण था। क्रोड़ में अधिकतम पवन और वर्षा दर बंटन में अनुरूप असममितों का अनुमान लगाया है। क्रोड़ में दाब प्रवणता 1 एचपीए प्रति कि. मी. से अधिक हो गया था। अधिकतम पवनों की त्रिज्या के ऐसे अनुमान तूफान महोर्मि की प्रागुक्ति करने में संक्रियात्मक रूप में उपयोगी होंगे। अधिकतम परावर्तकता की त्रिज्या में परिवर्तन और तूफान की आंख की भित्ति की मोटाई चक्रवात की प्रबलता के परिवर्तन से नकारात्मक रूप में सम्बन्धित प्रतीत होती है।

वर्षा बंटन अपेक्षानुसार तूफान के उत्तर की तरफ काफी फैला था किन्तु मद्रास-श्रीहरिकोटा पट्टी पर चार दिनों की अवधि तक अधिकतम (बड़ी आकाशीय प्रवणता सहित) भी दिखाई दिया। भूमिपात के बाद यह प्रणाली अनेक घंटों तक चक्रवात के रूप में बनी रही और भूमि पर भी एक द्विभित्तिक आंख को विकसित किया।

ABSTRACT The structure of the Bay of Bengal cyclone of 9 to 14 November 1984 could be studied, in detail, thanks to simultaneous observations over a long period by coastal radars and the satellite INSAT-1B. The storm was small in size and had a small eye. It exhibited a double walled eye for some time. There was a highly asymmetric distribution of radar reflectivity in the eyewall. Corresponding asymmetries are inferred in the maximum wind and rainfall rate distribution in the core. The pressure gradient in the core exceeded 1 hPa/km. It was possible to delineate a radius of maximum radar reflectivity corresponding approximately to the radius of maximum winds. Such an estimation of radius of maximum winds will be operationally useful in storm surge prediction. Changes in the radius of maximum reflectivity and the eyewall thickness seem to be correlated negatively with changes in cyclone intensity.

The rainfall distribution extended well to the northern side of the storm as expected, but also exhibited a maximum (with a steep spatial gradient) in the Madras-Sriharikota belt over a period of four days. After landfall the system persisted as a cyclone for several hours and developed a double-walled eye over land also.

## 1. Introduction

There have been few detailed studies of the structure of tropical cyclones in the Bay of Bengal because of paucity of data over the sea. The Bay of Bengal cyclone of 9 to 14 November 1984 which struck the coast near Sriharikota offered a unique opportunity for such a study as it could be observed for several days by three coastal radars as well as the Indian National Satellite INSAT-1B. Some interesting results from this detailed observation are presented and their practical utility in cyclone forecasting pointed out.

## 2. The cyclone

Table 1 gives the "T numbers" reported by the Meteorological Data Utilisation Centre, New Delhi at various times and the corresponding maximum sustained windspeeds (MSW) according to Mishra (1984).

The track of the storm during the period 11 to 14 November when detailed radar and satellite observations were available is shown in Fig. 1. Except for an initial westnorthwesterly movement the cyclone maintained a northerly motion up to 00 UTC of 13th morning but stalled thereafter. After being nearly stationary for almost 24 hours it moved west, crossed the coast a little north of Sriharikota on 14th at 03 UTC and thereafter moved in a zig-zag fashion in a southerly direction over land, still remaining a cyclone for several hours. Biswas *et al.* (1988) have discussed the interesting track peculiarity and the possible reasons for it. There are divergences in the tracks* estimated by the INSAT and the cyclone detection radars (CDR's) and between the radar fixes themselves. The differences of the order of 0.2 degree are largely due to the different perceptions of the centre of the eye by the various observing platforms. Such differences have been discussed by Raghavan *et al.* (1985) in relation to the structure and intensity of cyclones. The differences in this case was crucial in the sense that the southerly movement over land could not be detected by the INSAT.

Figs. 7 and 9 show the entire extent of the storm in its mature and most intense stage on 13th afternoon as seen by satellite and radar. A small well-formed eye can be seen in both the satellite and radar pictures. The most striking feature besides this is the small horizontal extent of the storm, the total cloud coverage in the satellite picture being about 6 degrees wide and the

*The tracks determined by INSAT and CDR, Madras are shown in Fig. 1. Tracks determined by the other two radars are not presented here.

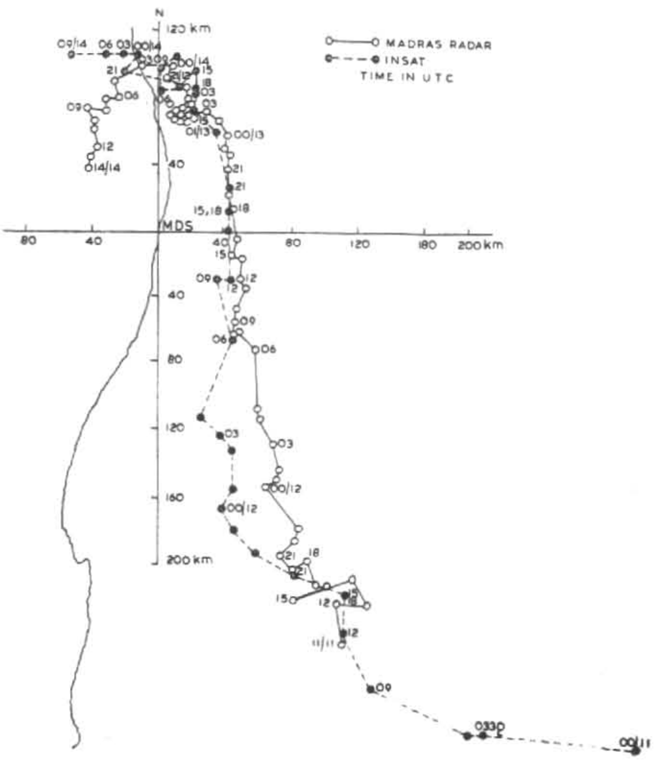


Fig. 1. Track of Sriharikota cyclone, 11 to 14 November 1984

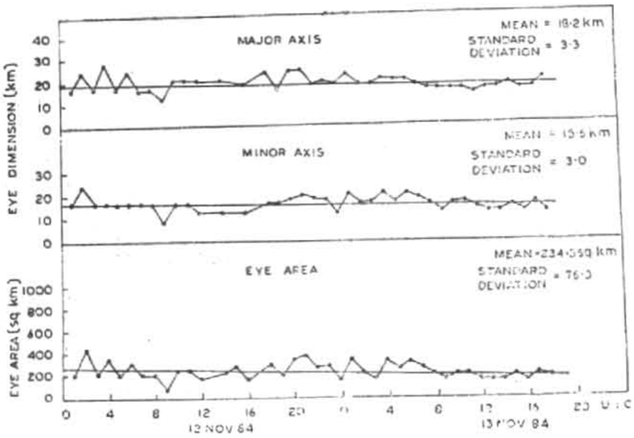


Fig. 2. Sriharikota cyclone. Variation of eye dimensions from 01 UTC of 12 Nov to 18 UTC of 13 Nov 1984

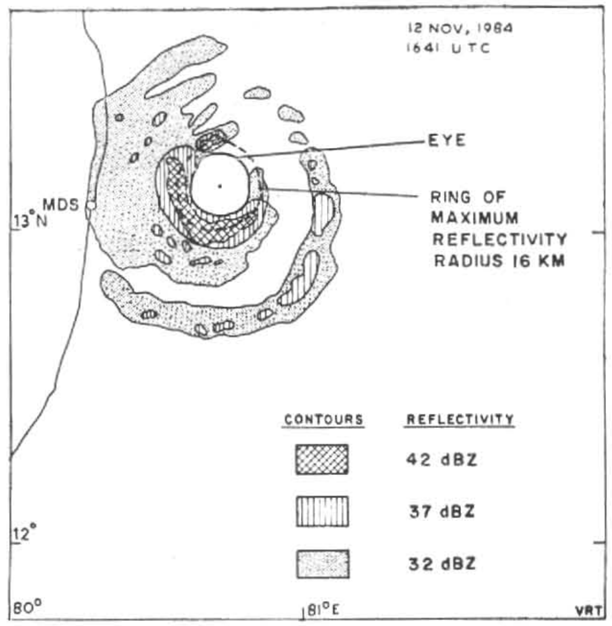


Fig. 3. radar reflectivity distribution in the core of the cyclone at 1641 UTC of 12 Nov 1984

TABLE 1

| Date | Time (UTC) | System classification | T. No. | MSW (m/sec) |
|---|---|---|---|---|
| 9 | 06 | Deep Depression | 1.5 | 13 |
| 10 | 03 | Do. | 2.0 | 15 |
| 10 | 12 | Do. | 2.0 | 15 |
| 11 | 03 | Do. | 2.0 | 15 |
| 11 | 0530 | Cyclonic storm | 2.5 | 18 |
| 11 | 12 | Severe cyclonic storm | 3.0 | 23 |
| 12 | 03 | Severe cyclonic storm with a core of hurricane winds | 5.0 | 46 |
| 12 | 12 | | 5.0 | 46 |
| 13 | 03 | | 5.5 | 52 |
| 13 | 10 | | 6.0 | 59 |
| 13 | 12 | | 6.0 | 59 |
| 14 | 03 | | 4.0 | 33 |

precipitating area shown on radar less than 2 degrees across. The "streamers" seen on the rear in the radar picture represent the limit of the storm on that side and they are within 200 km of the centre.

### 3. Eyewall structure and asymmetry

The eye itself was small (about 20 km in diameter) and the core area, the eyewall region was only 50 km. across. Variation of the eye dimensions (Fig. 2) over a period of two days was small despite apparent changes in intensities as judged by satellite T numbers and changes in radar-observed structure. A decrease in eye size on the morning of the 12th, is however, noticeable in Fig. 2. This was due to the formation of an inner eyewall (Fig. 10) constituting a "double eye" characteristic of deep systems. This coincided with the intensification of the system into a severe storm with a core of hurricane winds. The double eye did not persist for long.

The beautiful symmetric look of the eye in Fig. 9 is deceptive. Typical radar reflectivity distribution in the eyewall can be seen in Figs. 3 and 8. Fig. 3 is composited from radar isoecho PPI pictures exhibiting echoes above thresholds of 42, 37 and 32 dBz respectively and Fig. 8 is a digital radar grey scale picture. It can be seen that the eyewall reflectivity structure is highly asymmetric. The asymmetric nature of the eyewall is a frequently observed characteristic of cyclones in the Bay of Bengal as well as in other basins. The asymmetry of the radar reflectivity distribution should lead us to expect similar asymmetries in the rainfall and wind distribution in the core of the cyclone. Airborne radar studies by Jorgensen (1984) and by Marks and Houze (1984) in Atlantic hurricanes have shown that radar reflectivity maxima are approximately co-located with the wind maxima in the eyewall. In the Chandbali cyclone of 1984, Biswas *et al.* (1988) found a wind maximum in the left sector of the eyewall where the radar also showed the maximum eyewall development. Raghavan and Veeraraghavan (1979) and Raghavan *et al.* (1984) observed similar asymmetries in the radar-observed eyewalls and corresponding asymmetries in the wind damage over land. Intense rainfall preferentially in the left sector of the cor region has been observed by Ramakrishnan (1937), Koteswaram and Gaspar (1956) and Raghavan *et al.* (1984). In the present cyclone the distribution of the maximum wind or rainfall in the core region could not be directly mapped because of the peculiar track and the lack of data on the appropriate scale. Nevertheless, on the basis of the previous work quoted above it can be presumed that the distribution of radar reflectivity in the eyewall gives a fair representation of the distribution of maximum wind and rainfall-rates.

In Fig. 3 a ring indicating the maximum radar reflectivity in the eyewall is drawn. This yields a "Radius of Maximum Reflectivity ($R_m$)" which will represent approximately (within about 5 km) the Radius of Maximum Winds (RMW) of the cyclone. The practical importance of the measurement is that the RMW can be inferred there from to a sufficient degree of accuracy for use in storm surge prediction (Raghavan 1987). The RMW is involved directly in storm surge prediction in two ways—one, in estimating the point of maximum surge (to the right of the point of landfall) and two, in the computation of the surge height itself.

Fig. 4 shows the hour-to-hour variations of the radius of maximum reflectivity. A sharp decrease in $R_m$ can be noticed following the intensification of the cyclone on the 12th. Thus, $R_m$ appears to decrease more sharply with storm intensification than the eye size (Fig. 2) does. Some authors have found statistically a negative correlation between eye size and storm intensity in various basins. Others have found that a decrease with time of eye size of a given storm is associated with intensification (Bell 1975, Schwerdt *et al.* 1979, Ducheng 1985, Meighen 1985, Raghavan and Veeraraghavan 1979, Raghavan *et al.* 1980, Raghavan 1985, 1987). From the present example it appears that the $R_m$ variation is a better indicator of cyclone intensification than the eye size. Although cyclone intensification is a complex process, it should be expected from angular momentum considerations alone that decrease in RMW should be associated with intensification. Some time lag is, however, noticed between the intensification and the reduction in $R_m$.

It is also of interest to know the horizontal thickness (or width) of the eyewall. This will help infer the horizontal swath of maximum wind damage on landfall. Fig. 5 shows the eyewall thickness estimated from radar

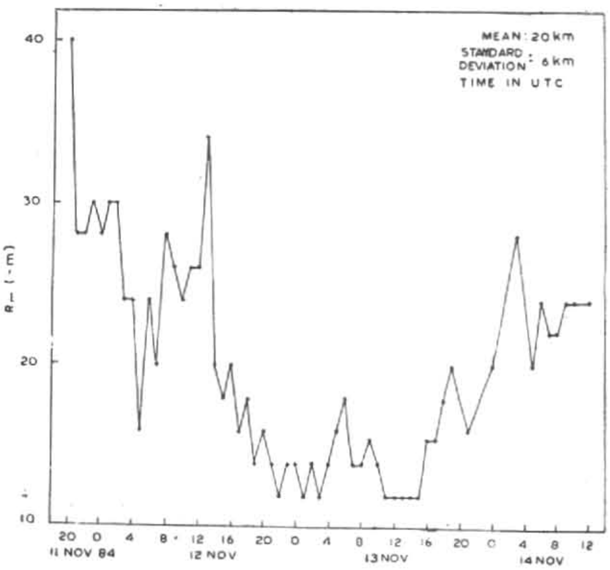


Fig. 4. Variation with time of the radius of maximum radar reflectivity in the eyewall ($R_m$)

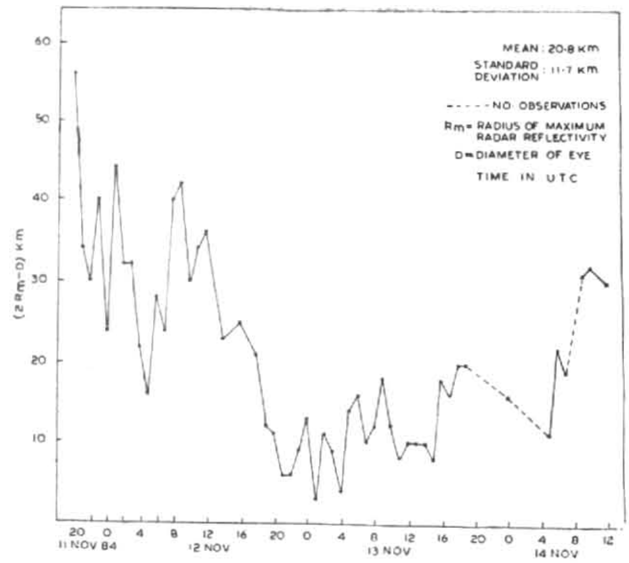


Fig. 5. Variation with time of the thickness of the eyewall ($2R_m$—$D$) km

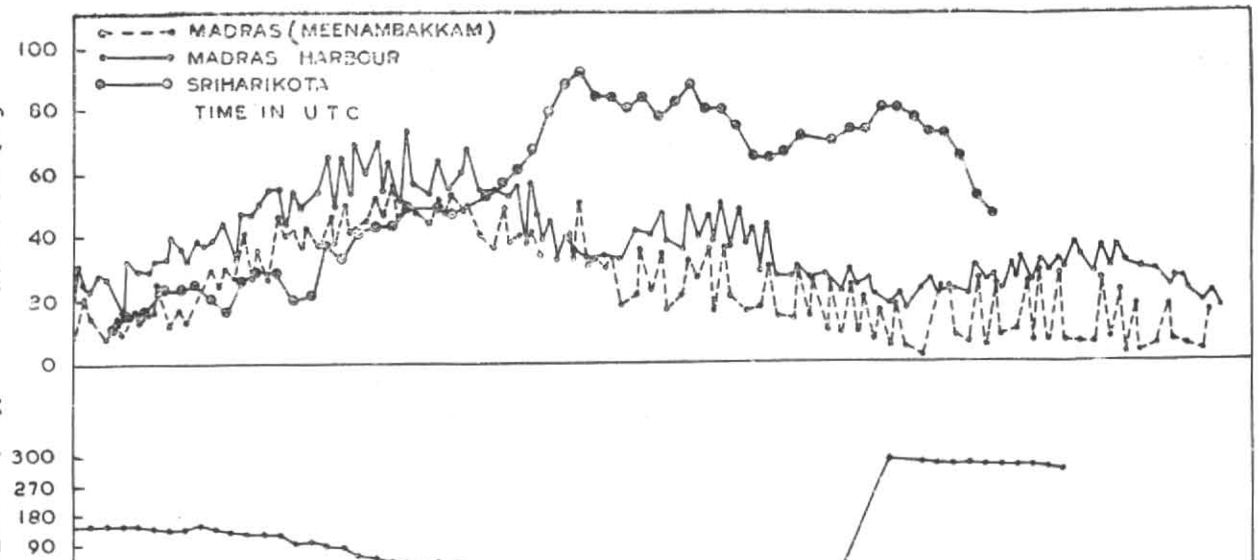


Fig. 6. Peak wind speeds at Madras and Sriharikota in relation to cyclone positions from 12 to 14 November 1984


Fig. 7. INSAT-1B imagery at 10 UTC on 13 November 1984; Visible picture

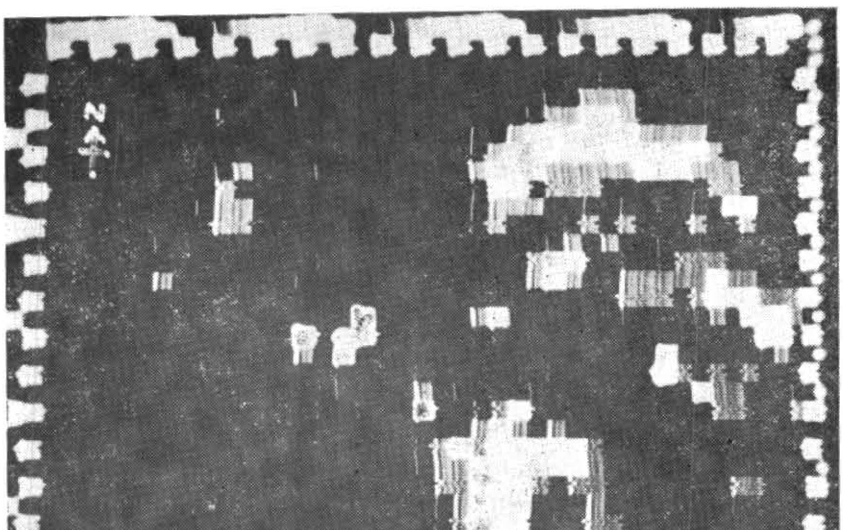


Fig. 8. Digital radar picture at 0500 UTC, 12 November 1984 showing 8 levels of reflectivity. Note the asymmetry in the eyewall

Fig 9. Radar PPI picture at 1207 UTC, 13 November 1984; Range markers are at 40 km interval

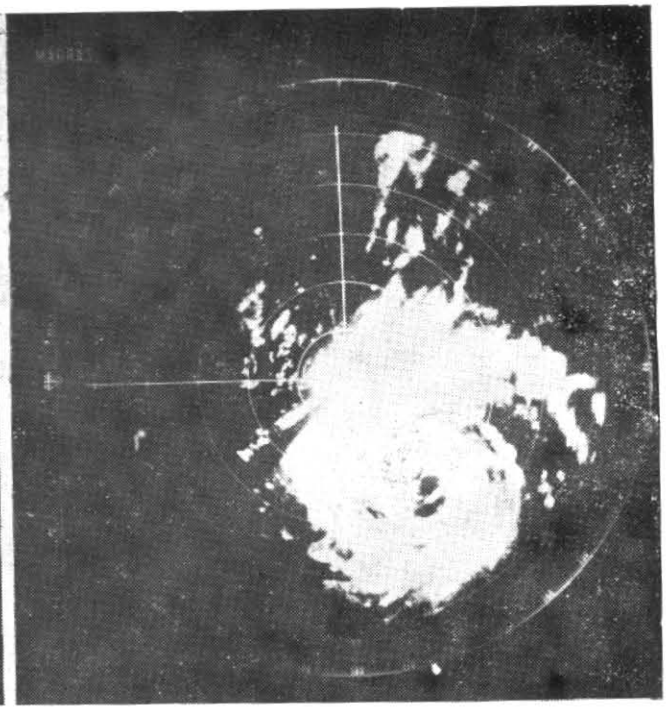

Fig. 10. Radar PPI picture at 0500 UTC 12 November 1984 showing double walled eye

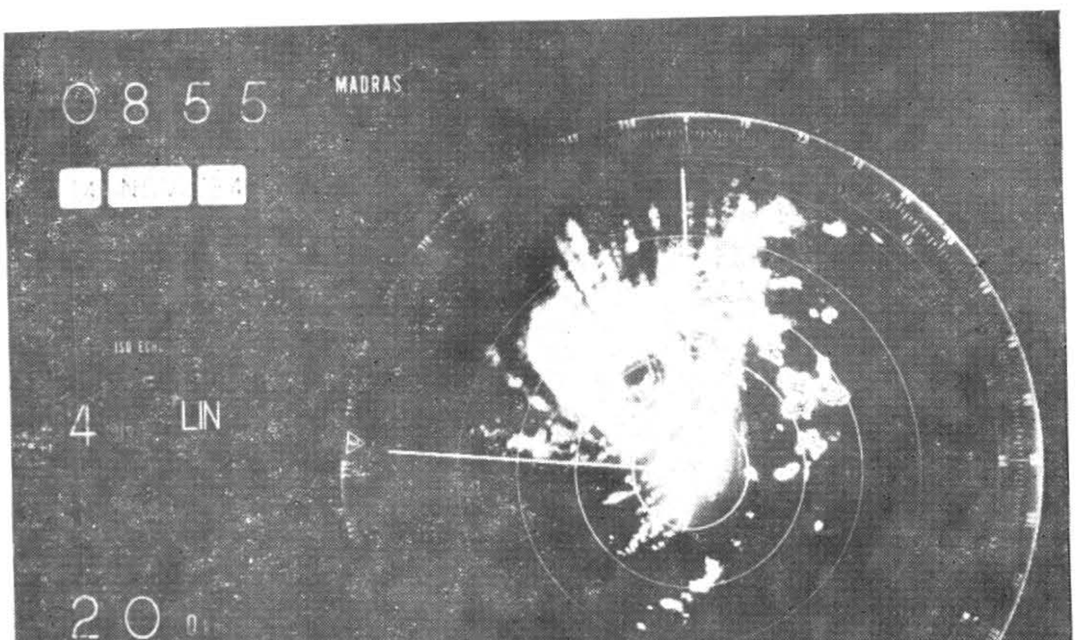


Fig. 11. Radar PPI picture at 0855 UTC of 14 November 1984. Note double walled eye over land. The striated appearance in the northwest sector is due to radar shadows in that direction

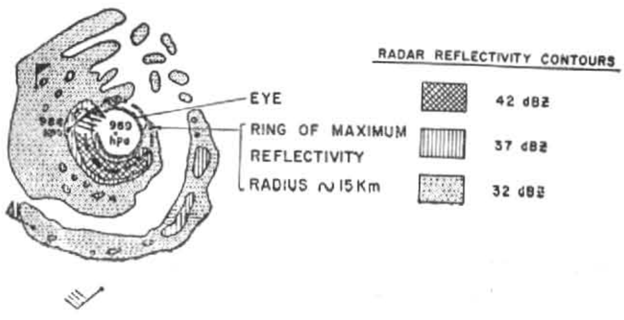


Fig. 12. Model of surface structure of Sriharikota cyclone of November 1984

pictures. One can notice a gradual decrease in this thickness immediately following the intensification on the 12th. There is a small increase immediately preceding landfall. This suggests a negative correlation between eyewall thickness and cyclone intensity. Meighen (1985) has observed a slight negative correlation in Australian cyclones. Ducheng (1985), however finds a positive correlation between intensity and eyewall thickness in typhoons affecting China. This phenomenon needs to be studied in more cyclones.

#### 4. Surface observations

Thus far we have inferred the cyclone intensity only from satellite pictures. Since the storm was very close to Madras on the 12th and lay very close to Sriharikota for about 24 hours on the 13th the wind observations at these stations (Fig. 6) are useful. Madras showed a wind of about 35 m/sec on 12th but it was outside the RMW. Hence, the maximum wind must have been higher than 35m/sec. The maximum sustained wind inferred from satellite pictures on this day was 46 m/sec. Thus, although the storm centre was as close as 45 km from Madras, the city perhaps escaped the full fury of the storm because of its small core size. Sriharikota recorded winds up to 47 m/sec at 0630 UTC of 13th .On the 13th Sriharikota was at the RMW or very close to it as can be inferred from Figs. 1 and 4. Therefore the actual maximum wind was probably] the closer to 47 m/sec than the 59 m/sec inferred from the satellite.

Sriharikota recorded the lowest pressure of 984.2 hPa at 0710 UTC of 13th. Assuming a wind of 47 m/sec the the central pressure is estimated to be 969 hPa using the formula of Mishra and Gupta (1976). Thus, there would have been a pressure gradient of about 1 hPa/km from RMW to centre. If the wind is assumed to be 59 m/sec the central pressure would be 944 hPa and the gradient would be 2.6 hPa/km. Fig. 11 gives a model of the core of the storm at the surface giving the pressure, wind and radar reflectivity distribution.

#### 5. Landfall

On the morning of the 14th the storm crossed coast at about 03 UTC at the northern edge of Sriharikota island. Thus the Sriharikota station was still at the RMW. It recorded a new minimum pressure of 984.1 hPa at 0255 UTC. The wind (Fig. 6) was estimated to be about 40 m/sec though the satellite inferred (T.No.4.0) wind was only 33 m/sec Winds of Sriharikota subsequent to about 11 UTC on 13th are estimates, as the wind tower fell at about that time. The minimum central pressure at this time would, therefore, be 978 or 989 hPa depending on the wind assumed.

After landfall the system continued to be a cyclone exhibiting an eye over land. The eye size (Fig. 2) remained the same but the $R_m$ (Fig. 4) and eyewall thickness (Fig. 5) showed a sharp increase indicative, perhaps of of a reduction of organization of the system. However, at about 09 UTC of 14th, *i.e.*, some 6 hours after landfall an inner ring appeared in the eye (Fig. 11) and persisted for about 4 hours. Formation of an inner ring in the eye of a hurricane at sea would denote an intensification (Willoughby *et al.* 1982) but the significance of this over land is not clear. But it is apparent that the system remained a cyclone for nearly 12 hours as it travelled southwards over land. A ground survey after the cyclone by a touring officer has confirmed this.

#### 6. Rainfall distribution

Spatial distribution of twentyfour-hour rainfall up to 0830 IST of 12, 13, 14 and 15 November is shown in Figs. 13 to 16. On each figure the corresponding segment of the radar determined track of the cyclone centre is indicated. It is not possible to delineate the spatial distribution of rainfall in the core as the core was entirely over the sea up to the 13th. On the 14th the storm existed as a cyclone for less than half the period of the isohyetal map. However, the total rainfall associated with the system exhibits the expected large extension on the poleward side. There is also a large spatial gradient of rainfall very close to the coast on all the days in the Madras-Sriharikota belt irrespective of the actual position of the cyclone.

#### 7. Conclusions

The cyclone was of small horizontal extent and had a small core region with asymmetries in the radar reflectivity distribution in the eyewall indicative of corresponding asymmetries in wind and rainfall rate distribution. The pressure gradient in the core probably exceeded 1 hPa/km. It was possible to delineate clearly a radius of maximum reflectivity which could be used to infer the radius of maximum winds for storm surge prediction and other purposes. Changes in radius of of maximum reflectivity and the eyewall thickness seem to be negatively correlated with changes in cyclone intensity. The system persisted as a cyclone for several hours after landfall and developed a double walled eye over land.

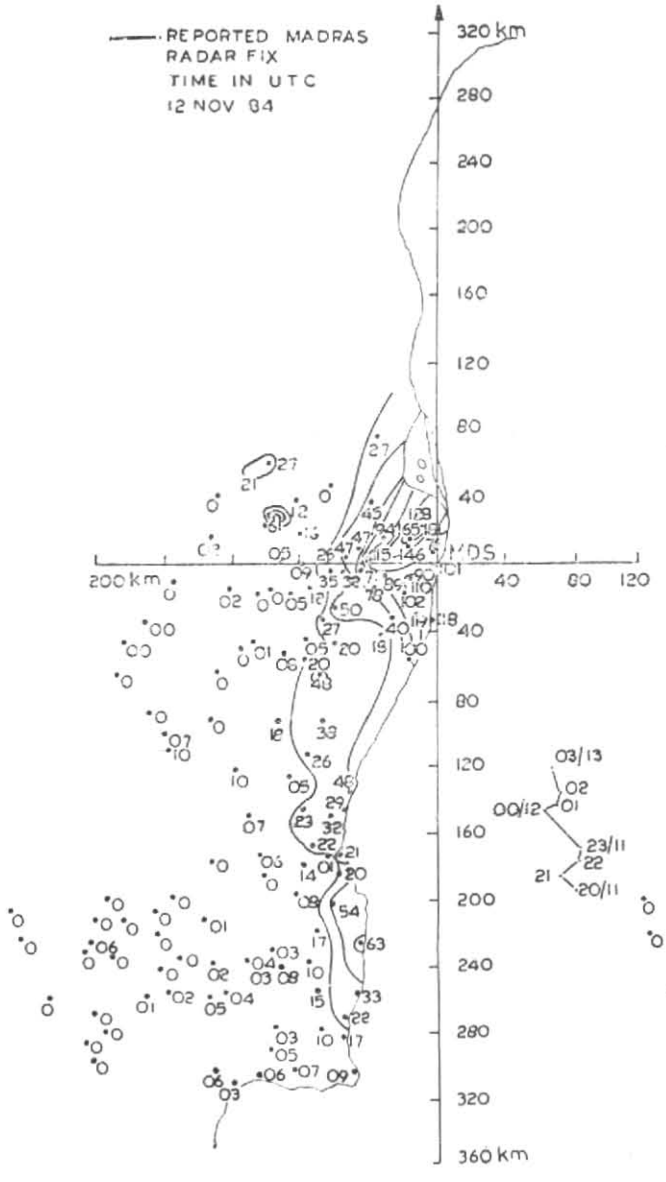


Fig. 13

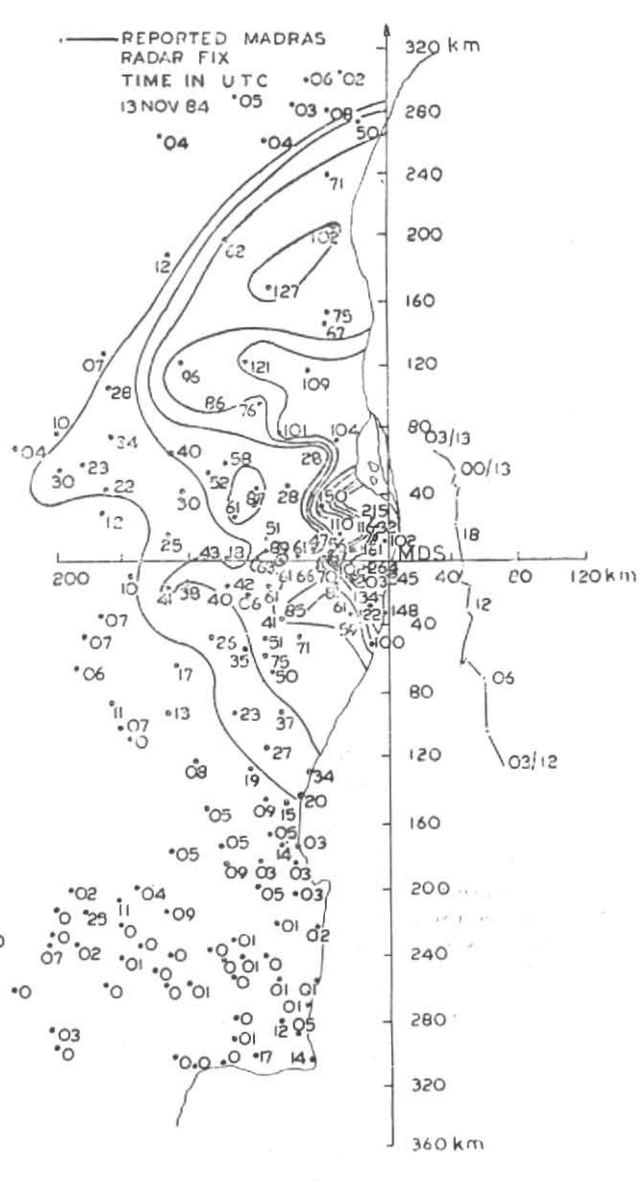


Fig. 14

Figs. 13 & 14. Spatial distribution of rainfall associated with the Sriharikota cyclone for the 24 hours ending 0830 IST of 12 November 1984 (Fig. 13) and 13 November 1984 (Fig. 14). Radar determined track of storm for this period is also indicated

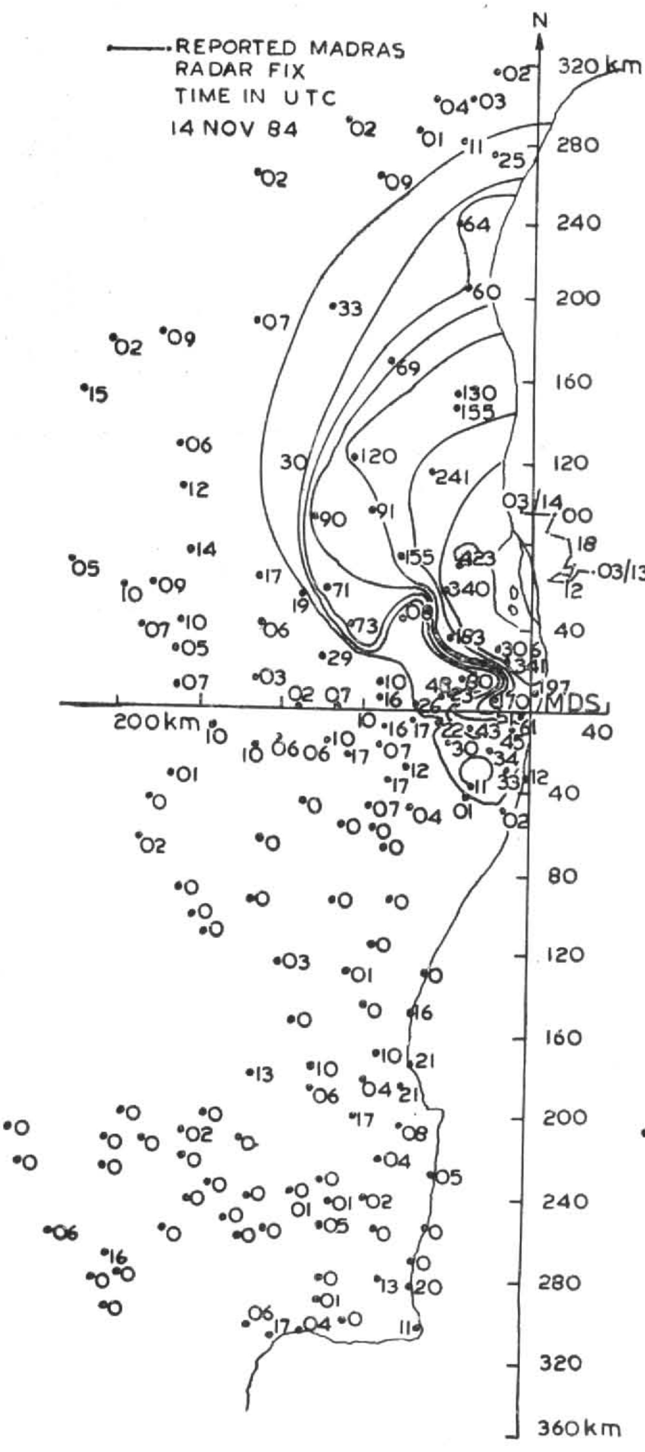


Fig. 15. Same as Fig. 13 except for 14 November 1984

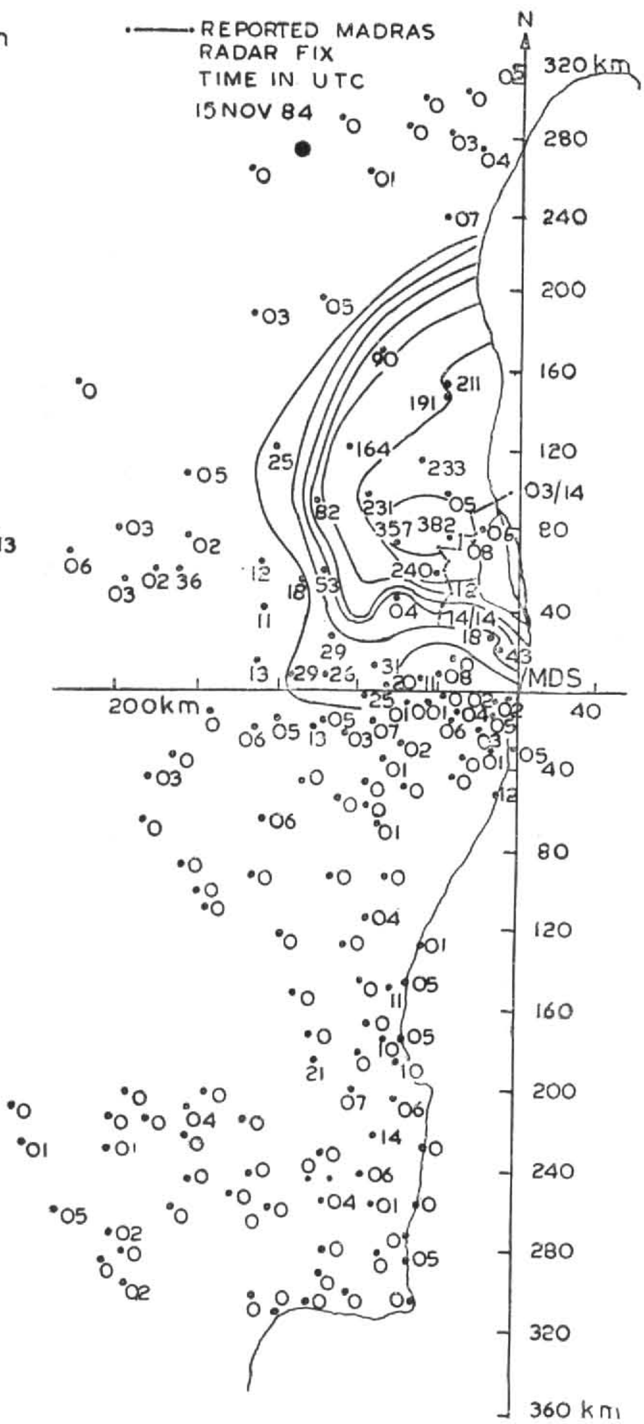


Fig. 16. Same as Fig. 13 except for 15 November 1984

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**References**

Bell, G.J., 1975, In "Typhoon Modification", Proc. WMO Tech. Conf., WMO No. 408, pp. 19-29.

Biswas, N.C., Sen, A.K. and Hansda, A.K., 1988, *Mausam*, **39**, 1, pp. 107-116.

Ducheng, Z., 1985, Report of the seminar on the application of radar data to tropical cyclone forecasting, Bangkok, Nov-Dec 1983, Report No. TCP-19, WMO/TD-No. 26.

Jorgensen, D.P., 1984, *J. atmos. Sci.*, **41**, 8, pp. 1268-1285.

Koteswaram, P. and Gaspar, S., 1956, *Indian J. Met. Geophys.*, **7**, 4, pp. 339-352.

Marks, F.D. (Jr.) and Houze, R.A. (Jr.), 1984, *Bull. Amer. met. Soc.*, **65**, 6, pp. 569-582.

Meighen, P.J., 1985, Report of the seminar on the application of radar data to tropical cyclone forecasting, Bangkok, Nov-Dec 1983, Report No. TCP-19, WMO/TD No. 26.

Mishra, D.K., 1984, *Vayu Mandal*, **14**, 1 & 2, pp. 62-66.

Mishra, D.K. and Gupta, G.R., 1976, *Indian J. Met. Hydrol. Geophys.*, **27**, 3, pp. 2852-90.

Raghavan, S., 1985, Report of the seminar on the application of radar data to tropical cyclone forecasting, Bangkok, Nov-Dec 1983, Report No. TCP-19 WMO/TD-No. 26.

Raghavan, S., 1987, "Derivation of Input Parameters for storm surge prediction from radar observations". Lecture at WMO. Second Regional Workshop on Cyclone Storm Surge, Calcutta, December 1987.

Raghavan, S., Rengarajan, S. and Varadarajan, V.M., 1980, *Mausam*, **31**, 1, pp. 81-92.

Raghavan, S., Rengarajan, S., Natarajan, V. and Ramaswami, V., 1985, *Mausam*, **36**, 1, pp. 111-112.

Raghavan, S., Saxena, R.C., Subba Reddy, E.V., Rengarajan, S., Ramaswami, V., Premkumar, S.W. and Ramakrishnan, B., 1984, *Vayu Mandal*, **14**, 1 & 2, pp. 39-45.

Raghavan, S. and Veeraraghavan, K., 1979, *Mausam*, **30**, 1, pp. 21-30.

Ramakrishnan, K.P., 1937, India Met. Dep. Sci. Notes, VII. No. 74, pp. 65-73.

Schwerdt, R.F., Ho., F.P. and Watkins, R.R., 1979, NOAA Tech. Rep., NWS 23, NTIS, U.S.A.

Willoughby, H.E., Clos, J.A. and Shoreibah, M.G., 1982, *J. atmos. Sci.*, **39**, 2, pp. 395-411.