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Radar Study of the Bay of Bengal cyclone of 19 November 1977

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ABSTRACT. The severe cyclone which hit the Andhra Pradesh cost on 19 November 1977 was observed by the Cyclone Warning Radar at Madras for about 72 hours.

The large range of detectability, the larger radar echo area, tight banding, double eyewall and the high rate of rainfall in the eyewall region all indicate that the storm had an unusually severe intensity on the 17 and 18 of November. There was, however, a general decrease in the total echo area, total areal rainfall, maximum eyewall rainfall rate and maximum cloud top heights in the eyewall from the 18th to the 19th. It is inferred that the storm might have weakened to some extent while still at sea. The eye maintained a nearly constant diameter of 60 km until the storm came close to coast when the eyewall broke up. The storm probably reorganised later with a smaller eye but this could not be observed by radar.

The storm motion during the period of radar observation was northwestwards. Precyclone squall line orientation and extrapolation of radar track were found to be good predictors of storm motion but other radar features were not.

1. Introduction

The cyclonic storm which hit the Andhra Pradesh coast on 19 November 1977 was one of the severest cyclones ever to occur in the Bay of Begnal. Fortunately the storm was under continuous radar surveillance for three days yielding besides positions, very interesting information on its structure and behaviour, which is presented in this paper.

The storm developed at Lat. 7.5°N and Long. 90°E on the morning of 15 November and moved steadily westards (Fig. 1) until the 16th evening. Thereafter it recurved to a northwesterly track probably because of a 'Fujiwhara' interaction with a storm in the Arabian Sea. On the morning of the 17th it was reported to be at about 10°N and 84°E based on observations from the ship *Jagatswamini* which passed through the storm. The ship experienced winds of 60 to 90 kt and rapid fall in pressure. The storm was apparently a severe one with a core of hurricane winds and a central pressure of 940 mb.

2. Radar observation of the storm

The cyclone warning radar at Madras detected the first echoes associated with the system in the form of a few scattered echoes at 300 to 350 km eastsoutheast of Madras, at 10 GMT of 16th, which was about the time when the storm took a northwestward track. Later in the evening these developed into a series of pre-cyclone squall lines (example in Fig. 2) oriented roughly NE to SW, consistent with the northwestward movement of the system from that time. A number of rainbands associated with the system could be seen from the morning of the 17th and a very rough location of the centre could be made at about 11°N and 84°E. By 11 GMT of 17th, radar could (see Fig. 3) a part of the eyewall at 400 km, though this could not have been identified as the eyewall at that time. By 15 GMT of 17th, the far side of the eyewall could be seen and thereafter position could be determined by radar with fair accuracy. By 04 GMT of 18th, a large double walled eye was seen (Fig. 4) with dense banding to the west of it. The corresponding satellite picture (Fig. 5) of 18th morning (NOAA-5 orbit No. 5897) indicates a Central Dense Overcast (CDO) of about 6 degrees across and a total cloud cover 14 degrees across. The double wall disappeared by 18th afternoon and subsequently there was gradual weakening of the intensities of individual echoes, including the eyewall cloud as well as their heights. There was also a reduction of the total echo area. The eyewall also was now and then opening and again closing up. Figs. 6, 7 and 8 show the PPI pictures on the

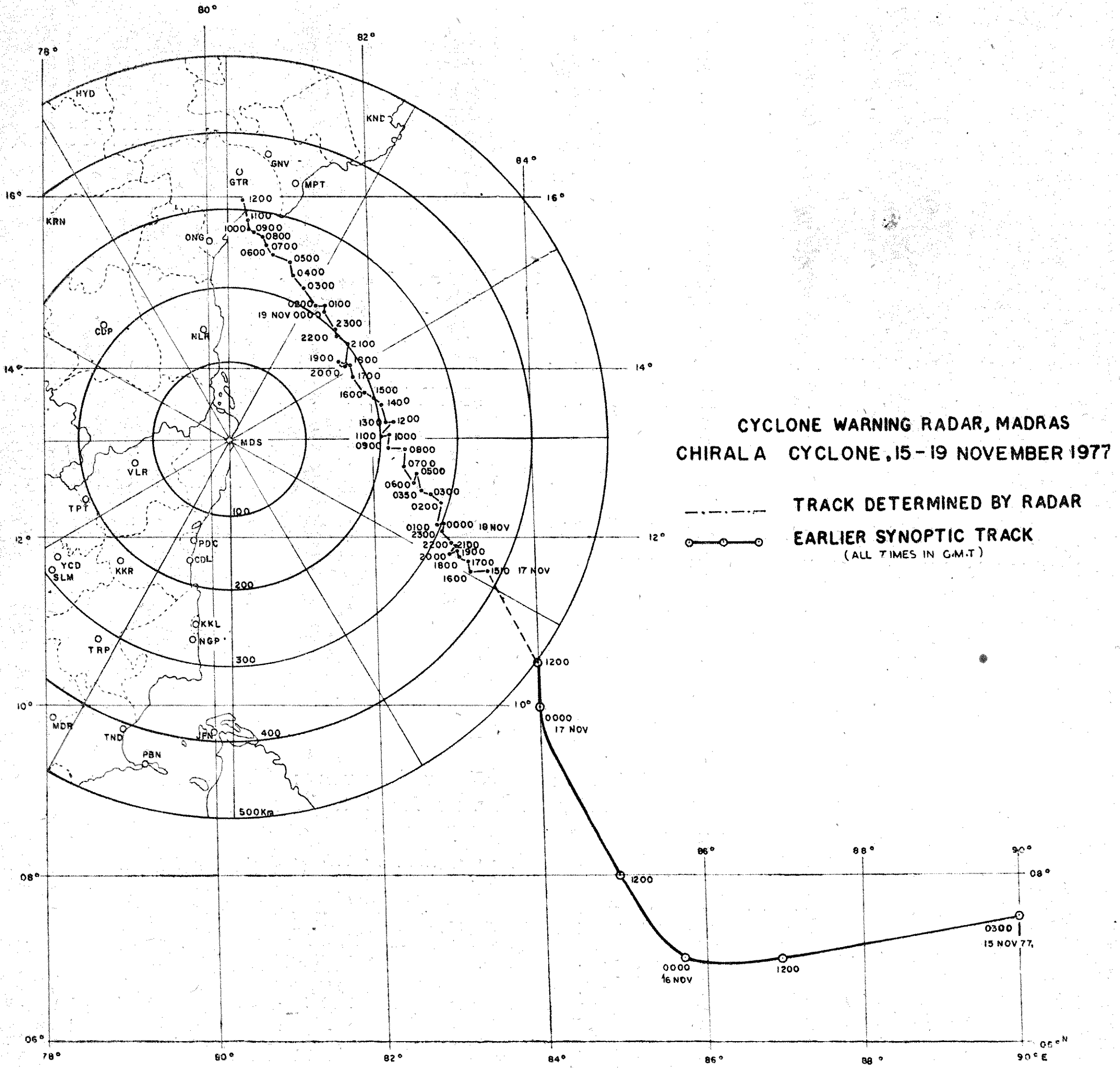

Fig. 1.

18th night and on the 19th. The eyewall started breaking up when the storm was close to coast on the 19th afternoon and thereafter radar could not track the storm.

During the period between 17th evening and 19th afternoon the radar was able to give hourly positions of the storm centre with fair to good accuracy. Table 1 gives a summary of the fixes, their accuracy and method of determination in various stages of the storm. Besides this, hourly radar photographs generally consisting of PPI pictures at various 'Iso-echo levels" and RHI pictures of echoes (including the eyewall) within 200 km of the radar are available. These constitute the data to be discussed.

3. Range upto which the eye can be observed

Radiowave propagation conditions in the October-November season in this part of the Bay of Bengal tend to be normal (Raghavan and Soundararajan 1962). During cyclone situations or vigorous monsoon conditions propagation usually becomes subnormal due to the setting up of a moist adiabatic lapse rate and virtually 100 per cent relative humidity at all lower tropospheric levels (*vide* Fig. 10.3 of Srinivasan and Ramamurthy 1973). This reduces the effective range of the radar and leads to an underestimation of heights of cloud tops. Hence the radar is generally able to detect precipitation upto about

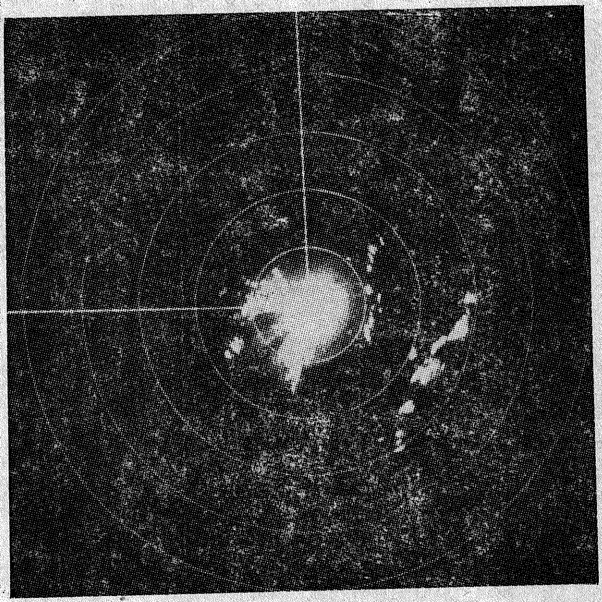

Fig. 2. Precyclone squall lines associated with the Cyclone at 2040 IST of 16 Nov. 1977 All radar PPI pictures presened in this paper are taken at a range setting of 500 km. The interval between range markers is 100 km. Antenna elevation is zero degrees

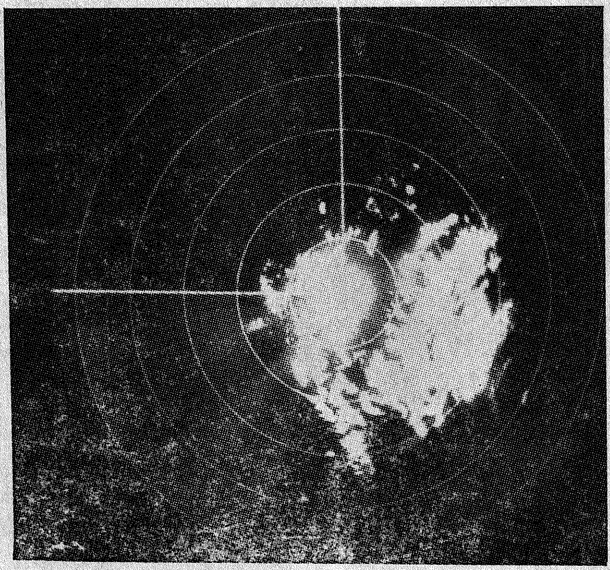

Fig. 3. Part of the eyewall seen at 400 km range for the first time at 1626 IST 17 of Nov 1977

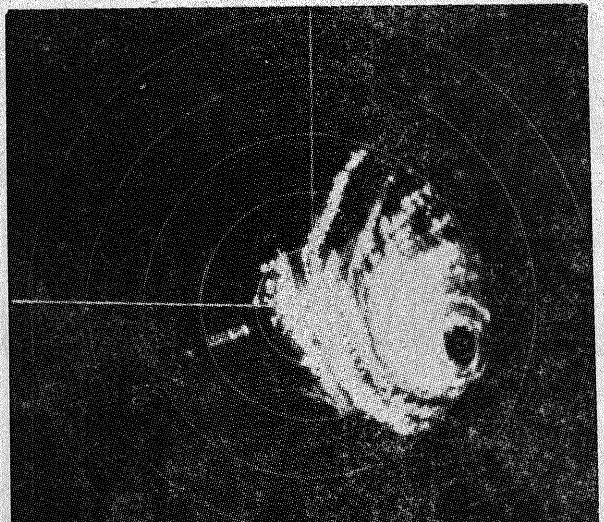

Fig. 4. Double eyewall and dense banding at 0925 IST of 18 Nov 1977

300 km, only extremely well developed clouds being seen at longer ranges.

It is known that eyes of Pacific typhoons are often seen by land radar at ranges in excess of 400 km but similar performance is rare in the Atlantic (Bell 1977). Bell and Tsui (1973) made a study of vertical extent of moisture in typhoons from upper air soundings, taken within 100 nautical miles of the centre. Comparing their results with the corresponding ones for Atlantic hurricanes obtained by Sheets (1969), Bell (1977) concludes that the vertical extent of moisture is greater in Pacific typhoons and that this may explain the difference in radar detectability.

Upper air data over the Bay of Bengal in storm situations are not available, but Bay storms are on the average less severe than Pacific typhoons. In view of the propagation conditions

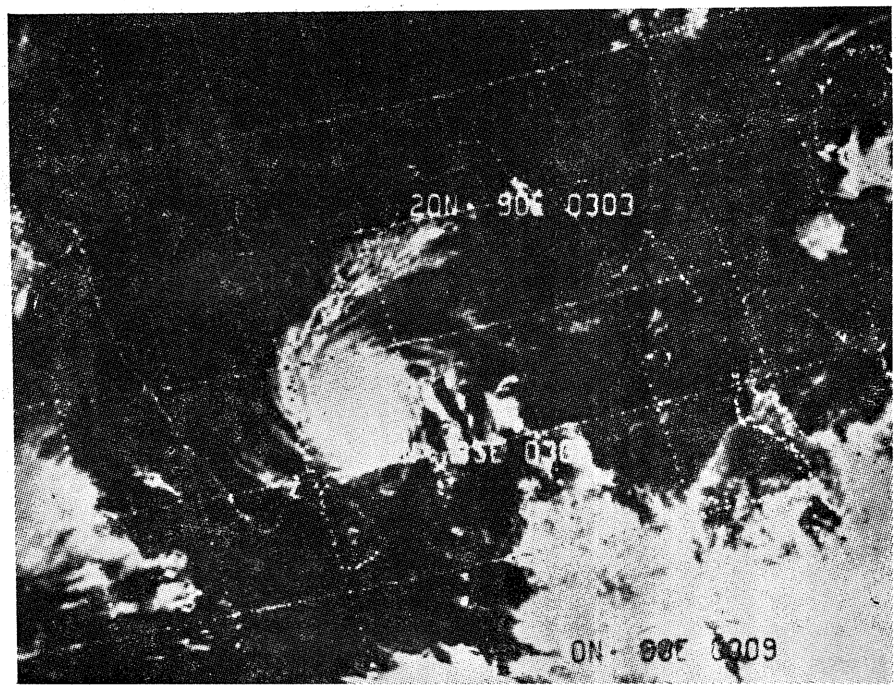

Fig. 5. NOAA-5 visible picture of 18 November morning showing the eye clearly. Compare picture at Fig. 4

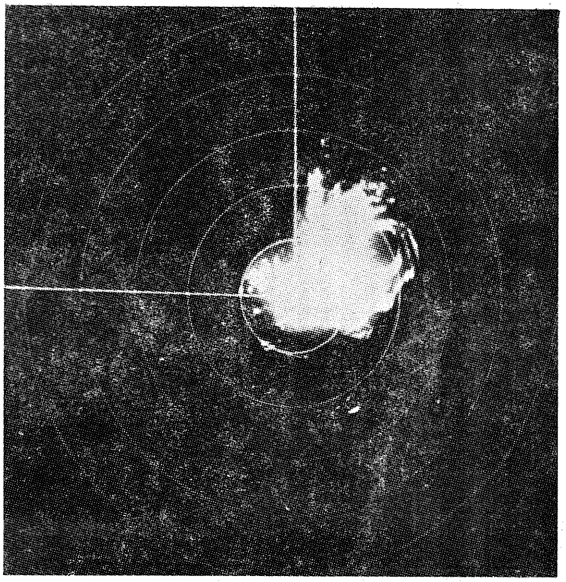

Fig. 6. Eye opened out on 18th night at 2337 IST of 18 November1977

mentioned above and of previous experience of radar detection (Raghavan *et al.* 1980) it appears that the eye of an average storm can be seen upto about 300 km in this season [This statement should be distinguished from the possibility of determining the centre of a storm beyond 300 km, using spiral bands seen by radar within a range of 300 km]. The radar observa-

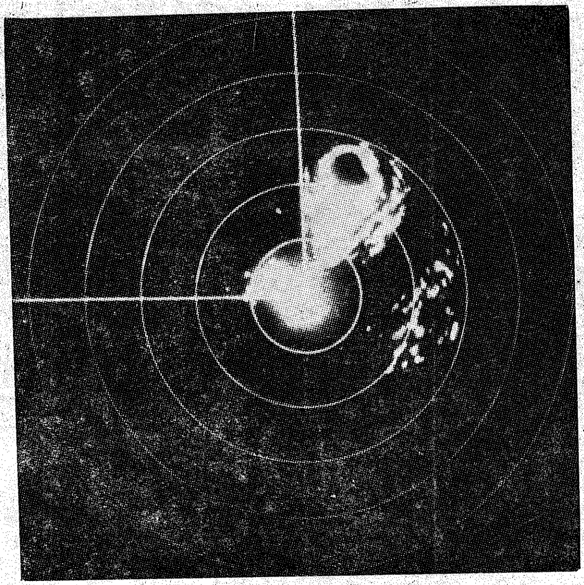

Fig. 7. Closed eye at 1039 IST of 19 November 1977. Note the 'Streamers' to the rear of the strom

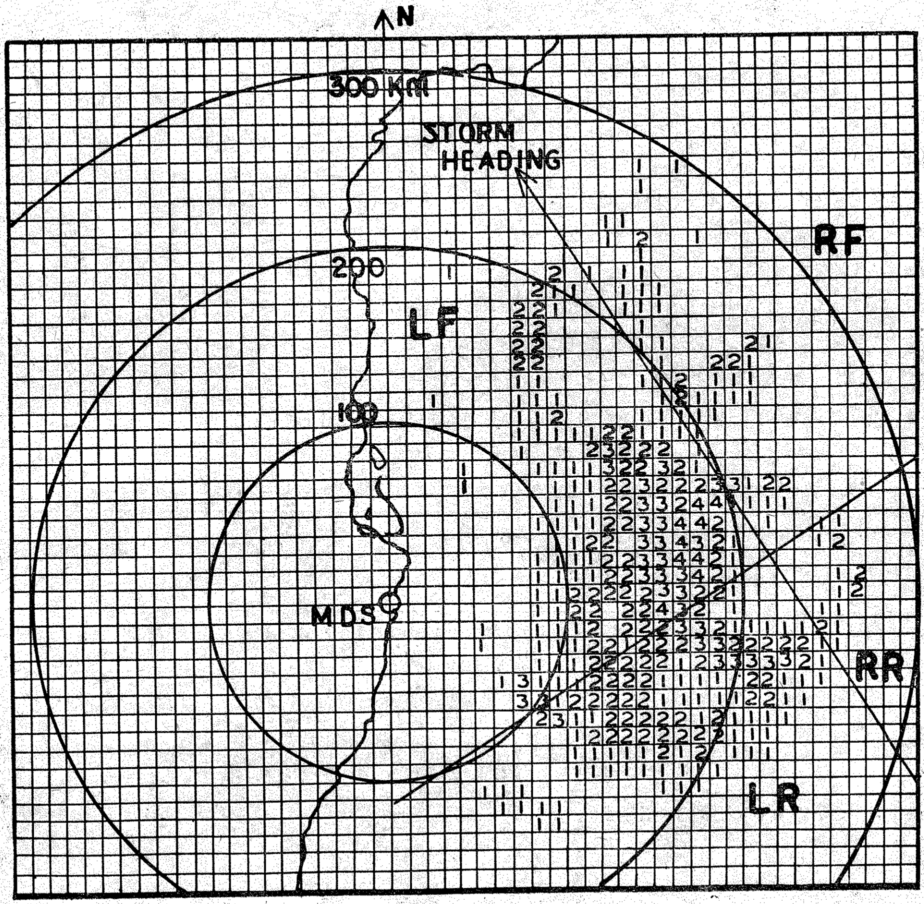

Fig. 8. Example of digitisation of echo intensity

tion of the eye on the 17 November 1977 at a range of 400 km, while there was no evidence of abnormal propagation, is therefore one indication of the severity of the system.

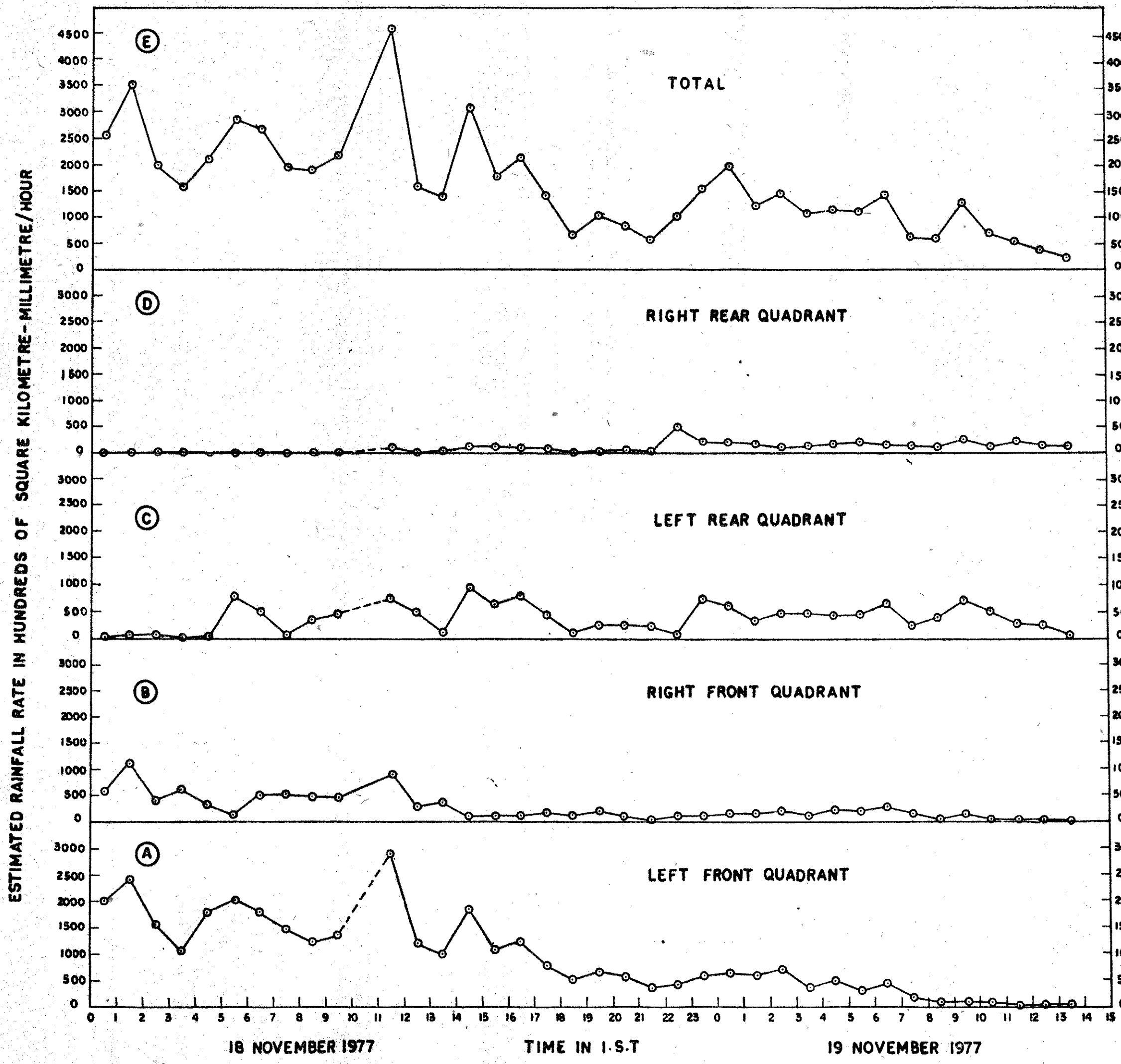

Fig. 9. Estimated areal rainfall

TABLE 1

Summary of radar fixes of cyclone 17 to 19 November 1977

Date (Nov 77)	Time (GMT)	Azimuth (°)	Range from Madras (km)	Lat. (°N)	Long. (°E)	Probable accuracy of fix	Remarks
17	0400 to 1430	—	—	11 to 11.5	83 to 84	Within about half a degree	Centre estimated roughly from spiral bands. Part of the eyewall was visible from 1120 GMT
17	1510	117	375	11.6	83.3	Within 30 km from 1510 to 2100 GMT	Appreciable part of eyewall seen
17	2200	115	320	11.9	82.9	Within 10 km from 2200 GMT of 17th to 0700 GMT of 19th	Major part of eyewall seen
18	0350	105	260	12.5	82.6	—	Double eyewall formed and lasted till 0700 hrs.
	0800	093	230	12.9	82.2		Single eyewall from 0800 GMT of 18th to 0600 GMT of 19th
	1900	056	175	14.0	81.6		
19	0600	014	250	15.3	80.8		
	0700	011	260	15.4	80.7		Eyewall started breaking up.
	0800 to 1200	Fixes within 30 km estimated from Spiral overlay					

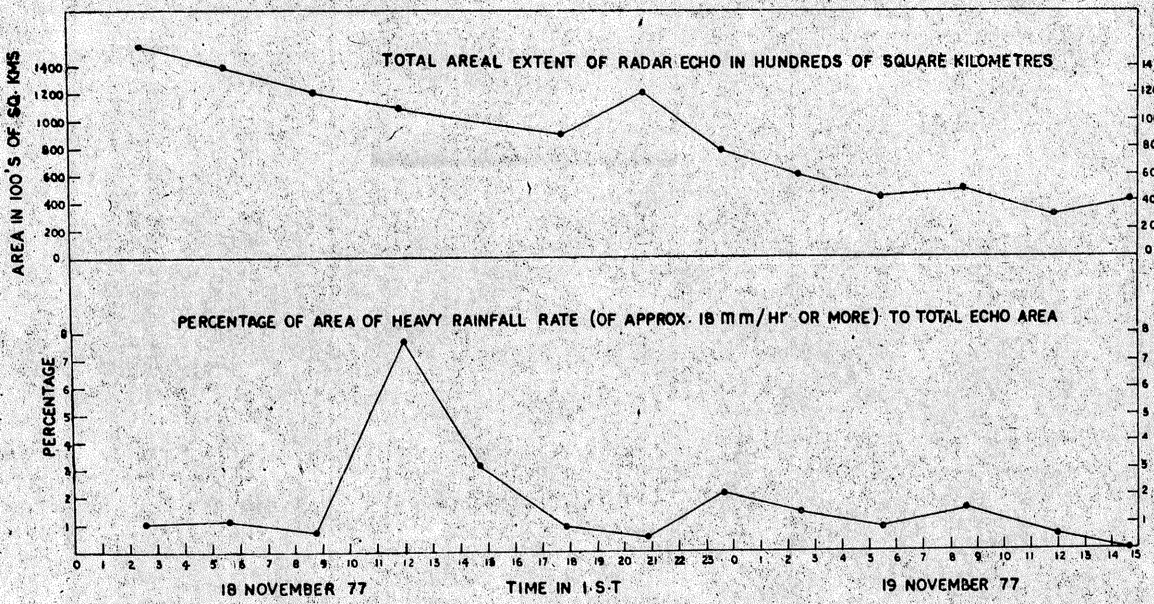

Fig. 10. Total echo area and area of heavy rainfall

4. Other indicators of storm intensity

The "double walled eye" is a feature associated with deep typhoons or hurricanes and attention to this has been drawn by Fortner (1958), Hoose and Colon (1970) and Black *et al.* (1972) among others. While Bell (1977) argues that the term 'double eye' is misleading as the outer 'wall' is only a circular rain band, he concedes that the phenomenon is characteristic of deep typhoons. The double walled eye (Fig. 4) in the present case being the only known instance in the Bay of Bengal is another indication of the severity of the system. As discussed in subsequent paragraphs the period when the double wall was observed coincided with the time of maximum radar echo area, maximum rainfall rate in the eyewall and maximum areal rainfall rate in the storm.

A comparison of Fig. 4 with the satellite picture (Fig. 5) shows that on 18th morning the total radar echo was about 4.5 degrees across in the north-south direction and 3.5 degrees in the east-west direction. The Central Dense Overcast (CDO) in the satellite picture was nearly 6 degrees across. Thus the radar echo is nearly as large as the CDO which is itself larger than average. The total satellite cloud cover is about 14 degrees across and is about 10 times the area of the radar echo. This agrees with the finding of Blackmer (1961), Fujita and Ushijima (1961) and Kulshrestha and Gupta (1964) that in a tropical disturbance the radar echo is one order of magnitude smaller that the satellite cloud cover. According to Dvorak (1972) a large CDO size is a sign of high intensity but there is no indication in the literature relating the size of CDO and total satellite cloud cover. In any case the large CDO size and large radar echo area indicate that the storm was unusually severe on the 18th morning. It will also be seen from Fig. 4 that besides the double wall the storm had a tight banding the innermost bands fitting best with a 5 degree crossing angle spiral overlay. However, the disappearance of the double-wall, the reduction in total echo area and the loosening of the banding later on the 18th and on the 19th morning seem to suggest a gradual weakening of the storm. To study quantitatively whether this is so, the time variation of a number of parameters observed by radar has been examined. Considering the large eye observed to be roughly an ellipse, the semi major axis (a) and the semi-minor axis (b) on the 18th and 19th are plotted against time. The area (πab) of the eye considered as an ellipse was also plot-

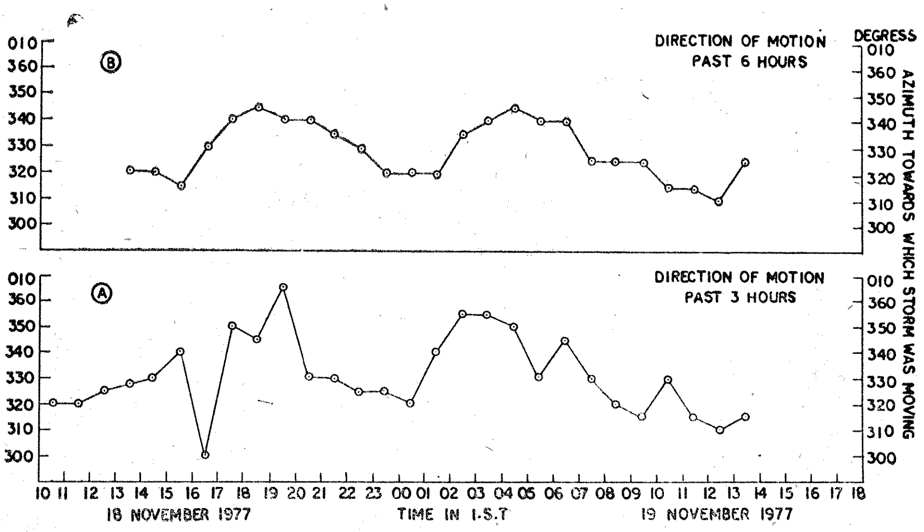

Fig 11. Direction of storm motion

ted and the least square best fit line of the plotted points also drawn vide Fig. 12 of Raghavan *et al.* (1980). It is seen that the eye was nearly circular and had a diameter of about 60 km with no significant change in size. Hence from the size of the eye no conclusion can be drawn about the time variation of intensity of the storm.

Fig. 15 of the paper referred to gives the variation of the maximum cloud top height in the eyewall. The values were taken from the RHI display whenever the eyewall was within about 200 km range and corrected for finite beamwidth and normal propagation (The display is electronically corrected for earth curvature). The least square best fit line is also drawn. It is seen that the cloud tops are rather low (maximum about 10 km) throughout. This may be partly due to subnormal propagation, but assuming no large variation in radio propagation conditions between 18th and 19th, there is a *decreasing* trend in the eyewall cloud heights even while the storm was *approaching* the radar. On this trend is superposed a diurnal variation with maxima at about 11 a.m. and 11 p.m. Pevious experience of Bay storms (Raghavan *et al.* 1980) shows that it would be difficult to conclude on the basis of cloud top heights alone that the storm was decreasing in intensity with time.

The same figure gives the time variation of maximum estimated rainfall rate in the eyewall. The method of estimation needs a little explanation. Assuming a standard relationship between radar reffectivity factor (Z mm^6/m^3) and rainfall rate (*R* mm/hr), echoes appearing at each iso-echo level display on the radar correspond to a particular threshold rainfall rate or more as given in Table 2, if the range is within 200 km, as the radar incorporates corrections for range square and atmospheric attenuation. For ranges from 200 to 300 km the threshold values can be corrected approximately as in Table 2 for the attenuation effects. By this means a rough order-of-magnitude value of maximum eyewall rainfall rate is obtained. The source of error in such estimates are discussed later (section 5).

It is seen from Fig. 15 of Raghavan *et al.* (1980) that the eyewall rainfall rate was a maximum at about 06 GMT of 18th (when the eyewall cloud top heights, total echo area and total areal rainfall were also a maximum). It decreased thereafter although the storm was coming *closer* to the radar. There were subsidiary maxima in the night of the 18th and on the morning of the 19th roughly coinciding with the diurnal variation of cloud height. Experience with other storms in this area (Raghavan *et al.* 1980) suggests that a positive correlation might exist between eyewall rainfall rate and the intensity of the system. Hence the reduction in the rainfall rate might suggest a reduction in storm intensity from 18th to 19th.

5. Rainfall distribution in the storm and its significance

To make a rough estimate of the rainfall distribution in the entire radar echo, the radarscope was divided into a grid of 10 km × 10 km squares. Using the hourly sets of photographs at various iso-echo levels a digitised map of echo intensities was prepared for each hour (example in Fig. 8).

TABLE 2

Threshold rainfall rate R (mm/hr.)

Iso-echo level	Range (km)					
	200	210	230	250	270	290
0	1.0	1.1	1.3	1.5	1.8	2.1
1	2.1	2.2	2.7	3.1	3.7	4.2
2	4.2	4.6	5	6	7	9
3	9	9	11	13	15	18
4	18	19	23	27	32	37
5	37	40	47	55	65	75
6	75	82	97	114	133	154
7	154	168	200	234	273	316

Assigning the appropriate threshold values given Table 2 for all the digits the areal rainfall per hour in hundreds of sq. km mm was computed for the entire radar echo upto a range of 300 km from the radar. Rainfall below iso-echo level 1 was omitted in this process. The total areal rainfall rate thus computed is presented in Fig. 9(E). The areal rainfall rate in the four quadrants of the storm-Left Front, Right Front. Left Rear, and Right Rear are also plotted in curves A, B, C and D of the same figure. The quadrants are designated with reference to the storm heading which has been taken as the mean direction of motion for the next three hours after the hour considered. In Fig. 10 is presented an estimate of the total echo area (including the rainfall below level No. 1) in hundreds of square kilometres. The same figure also gives the percentage of this area which is covered by rainfall rate exceeding about 18 mm/hr (level No. 4).

As discussed in section 4 the total echo area on 18th morning was large and comparable to the satellite CDO. Fig. 10 indicates that this area decreased from 140,000 Sq. km on 18th morning to about 30,000 sq. km at noon of the 19th. The percentage of this area which had heavy rainfall was a maximum of about 7 per cent on 18th and decreased to less than 1 per cent 24 hours later. Hence this figure indicates a significant reduction in the area of precipitation under the influence of the storm from 18th to 19th.

Fig. 9 (E) shows that the total areal rainfall rate had a maximum value of 4,00,000 sq. km mm/hr at 06 GMT of the 18th. This value is an under estimate, the following being the main sources of error :

(*i*) The estimate assumes that the radar is seeing the precipitation close to the ground but the radar beam height increases rapidly with range.

(*ii*) The precipitation below level No. 1 and all precipitation beyond 300 km has been ignored.

(*iii*) The 'threshold' rainfall rates of Table 2 have been assumed for conversion of echo intensities to rainfall rates. The actual precipitation rate for each level could be anywhere from this 'threshold' to the threshold of the next higher level.

If we increase the estimate by 50 per cent for each of these three principal sources of error, the rainfall rate will be about 3 times the value indicated in the figure, i.e., about 12×10^5 sq. km mm/hr or 1.2×10^9 tonnes per hour at 06 GMT of 18th. Watanabe (1963) has estimated that a 'moderate typhoon' (central pressure 940 to 970 mb) gives a rainfall of 1×10^9 tonnes per hour. The energy liberated as latent heat by such a rainfall has been computed by Watanabe (1963) following the method of Longley (1949). A rainfall of 1.2×10^9 tonnes per hour corresponds to about 3×10^{25} ergs/hour or $8.4.\times10^{14}$ Watts. That this rate of energy release was not maintained is clear from the steady decrease of the areal rainfall rate in Fig. 9(E). This decrease cannot be attributed to range limitations of the radar because upto the forenoon of the 19th, the storm was no farther away from Madras than at noon on the 18th.

The maintenance of mature tropical cyclones is dependent on the energy provided by the latent heat release. Adler and Rodgers (1977) estimated the Latent Heat Release (LHR) in the Pacific Typhoon NORA from Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) data. According to them the LHR (calculated over a circular area of 4° latitude radius) increases during the development and intensification of the storm from a magnitude of 2.7×10^{14} W (in the disturbance stage) to 8.8×10^{14}W (typhoon stage). It is also shown by them that the more intense the cyclone and the greater the LHR the greater the percentage contribution of the larger rainfall rates to the LHR. Griffith et al. (1978) who have computed rainfall in some Atlantic storms from satellite imagery found that while total rainfall is not related to storm intensity the rain estimation near the storm core might yield a relationship between rainfall and storm intensity. Hence the decrease in total areal rainfall and the percentage area of heavy rainfall with time coupled with loosening of the banding and other organisational features mentioned in the case of the present cyclone suggests some decrease in intensity of the system. But a categorical conclusion is difficult to arrive at because of the limitations of the radar data already referred to.

While considering the quadrantwise distribution of rainfall in Fig. 9 A, B, C, D, it is necessary to allow for bias due to relative distances of the various quadrants from the radar. The apparent preponderance of rainfall in the LF and LR sectors throughout the period must be due to their proximity to the radar. But on the 18th the LF and LR quadrants are nearly equidistant from the radar site. Hence the relatively larger areal rainfall in the LF sector must be real. On the 19th the LR quadrant is nearer to the radar : yet the apparent precipitation in the LF quadrant is about the same as that in the LR quadrant, *i.e.,* actual precipitation in the LF quadrant was probably heavier than in the LR quadrant. These findings confirm the usual presumption that the rainfall is higher in the forward sector than in the rear.

In the above discussion some evidence has been presented to suggest a gradual weakening of the system while at sea. It is however known that winds have been severe when the storm went over land and the tidal damage has also been severe. How is this consistent with the above arguments? Radar cannot throw any light on this as the eyewall seen on radar broke up rapidly just before landfall. However Rama Sastry and Rao (1978) have found from the estimated wind distribution over land areas that the storm must have reorganised with an eye of smaller diameter at about the time of landfall. The smaller eye would imply reintensification of the system and thereby explain the strong winds and damage over the coastal areas. Therefore the inference arrived at from the radar data is *not* inconsistent with the evidence of damage.

6. Storm motion

During the period of about 33 hours from the night of the 17th to the forenoon of the 19th the radar fixes of the storm were quite accurate (Table 1). The track (Fig. 1) during this period was northwestwards with a slight meandering. Fig. 11 gives the apparent variation of the direction of motion with time. In graph A the direction of motion is taken as the mean motion of the previous 3 hours. The oscillation of this quantity is over a width of 70° . Graph B gives the direction averaged over the previous 6 hours. As is to be expected Graph B shows a smaller amplitude of oscillation than Graph A. Averaging over a longer period should smooth out the meandering effects. Twenty four hours before landfall, *i.e.,* by 12 GMT of 18th, a reliable radar track of the previous 14 hours was available. A linear extrapolation of this mean track would have given a 24 hours prediction of point of landfall within about 50 km provided the possibility of recurvature could have been ruled out. As shown by Raghavan *et al.* (1978) extrapolation of radar track in storms with well formed eyes gives good prediction of point of landfall if recurvature does not occur.

Besides extrapolation of track other radar features which have been considered as possible predictors of motion by Senn (1966 a, b) and others are:

(*i*) Orientation of precyclone squall lines : A number of precyclone squall lines were seen on radar on the night of the 16th (example in Fig. 2) and their orientation was generally northeast to southwest. The direction of storm motion is usually perpendicular to the orientation of the squall lines. This appears to be a good predictor in this case also but is of limited utility as the squall lines dissipated on the 17th long before the storm came over land.

(*ii*) The direction with reference to storm centre of the area of concentration of rainshield echoes : This has been found a very unreliable predictor in the case of Bay storms (Raghavan 1977; Raghavan *et al.* 1980). In the case of this storm the echo concentration was to the west of the centre on the 18th and to the southwest on the 19th and neither of these directions was the direction of motion.

(*iii*) In the case of an open eye the direction with reference to the storm centre in which the eyewall is most prominent is considered likely to be the direction of motion : In the present case there is no such asymmetry of the eye which can be taken as a motion predictor. The orientation of the major axis no doubt rotated to some extent. Considering that the eye was nearly circular the 'major axis' orientation perhaps does not have significance. In any case there was no change in direction of motion corresponding to the rotation of the major axis.

Thus the last two indicators mentioned do not help to indicate the motion of the storm.

The speed of the storm was computed every hour taking average motion of the preceding 6 hours. The speed varies from 4 to 9 knots the fastest speed being on the morning of the 19th when the storm was close to coast. Increase in speed as the storm approached the coast probably could be used as a predictor indicating that the storm would not recurve or skirt the coast.

7. Other interesting features of the storm

Fig. 7 shows a narrow band of intense cellular echoes or 'streamers' in the rear of the storm but well away from the centre. Rockney (1956) was the first to describe such streamers. They have been noticed in other Bay storms also (Raghavan *et al.* 1980) and perhaps need to be watched as a source of flooding if they came over land. In this case they dissipated at sea.

RHI photographs in the direction of the eyewall on the morning of the 19 November. The eyewall and echoes near it were seen as convective towers while the nearer echoes of the rainshield are seen close to the station exhibited a bright band at melting level. The eyewall and cloud close to it do not exhibit a bright band. This is in conformity with the general finding (Kodaira 1964; Raghavan 1977) that the rainshield area consists mainly of stratiform precipitation while the eyewall and areas close to it are convective.

8. Conclusions

A radar study of the intense cyclone during the period 16 to 19 November 1977 shows that :

(*i*) The storm was an unusually severe one on the 17th and 18th as seen from the large radar echo, tight banding, double eyewall, high rate of rainfall in the eyewall and the large range of detectability.

(*ii*) There was a general decrease in the total echo area, total areal rainfall, maximum eyewall rainfall rate and maximum cloud top height in the eyewall from 18th to 19th. The eye maintained a nearly constant diameter of 60 km until the storm came close to the coast when the eyewall broke up. It is inferred that the storm might have decreased to some extent in intensity while at sea. The storm probably reorganised with a smaller eye just at or before the time of landfall but this could not be observed by radar owing to the long range.

(*iii*) When the storm was well out at sea there were precyclone squall lines whose orientation was a good predictor of storm motion. Extrapolation of radar track was also a good predictor, while the echo distribution and eyewall configuration were not.

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