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Structure of an immature cyclonic storm in the Bay of Bengal as revealed by radar

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ABSTRACT. Poorly developed or immature cyclonic storms are common in the Bay of Bengal particularly when their residence time over the sea is short. These often do not exhibit on the radar or satellite pictures, all the features normally associated with tropical storms. Spiral rainbands are not stable, a complete eyewall is not formed; false eye' circulations develop and probably inhibit intensification. The rainshield area consists of shallow echoes with bright bands while the spiral band and eyewall areas have tall convective clouds probably consisting of supercooled water. Observed features on radar do not give any indication of future motion.

The intensity of such immature systems is difficult to assess from observed winds owing perhaps to asymmetry of structure. They are also difficult to locate and track with the available meagre synoptic data, coastal radar pictures and twice-a-day satellite pictures. A specific case of radar observation of a storm of this type is examined to see how best such storms can be located, tracked and classified.

1. Introduction

The structure of cyclonic storms in the Bay of Bengal is not so well known, as that of their counterparts in the Pacific and Atlantic Oceans. This is due to the relative scarcity of synoptic observations over the Bay and the fact that there are very few cases of radar observations and practically no aircraft reconnaissance. Some of the storms do not appear to develop beyond the immature stage as defined by Riehl (1954). Such storms often do not clearly exhibit on the radar or satellite pictures all the features normally associated with text book patterns of well developed storms. Also while the observed pattern on satellite pictures of mature storms persist recognisably from one day to the next (Fett and Brand 1975) the cloud pattern associated with the weaker storms are unstable and difficult to distinguish in successive satellite or even radar pictures. The location and tracking of these storms with the available synoptic data, coastal radar pictures and twice-a-day 'APT' pictures is therefore rendered difficult. It is the purpose of the present paper to examine the structure of one such immature storm as revealed by radar to draw some conclusions as to how best such storms may be located and tracked.

2. Typical structure of a storm

The typical structure of Atlantic hurricanes and Pacific typhoons as seen by radar, has been described by Rockney (1956) and by Kodaira (1964). The radar echoes may be classified into the following types from the periphery to the centre.

(1) *Pre-hurricane squall lines* — These are lines of thunderstorms a few hundred kilometres ahead of the centre. The lines are straight or wavy and are usually but not always oriented perpendicular to the direction of storm motion.

(2) *Outer convective activity* — These are rather disorganised rows of cells following the pre-hurricane squall lines.

(3) *Rainshield area* — An area of widespread light precipitation containing some hard core cells, found mainly in the front quadrants of the storm. Spiral band patterns can usually be distinguished within this region, (Senn *et al.* 1965).

(4) *Inner spiral bands* — These are bands of echoes well organised along logarithmic spirals converging to the centre of the storm. Hence these provide a good means of location of the system even if the eye is not seen.

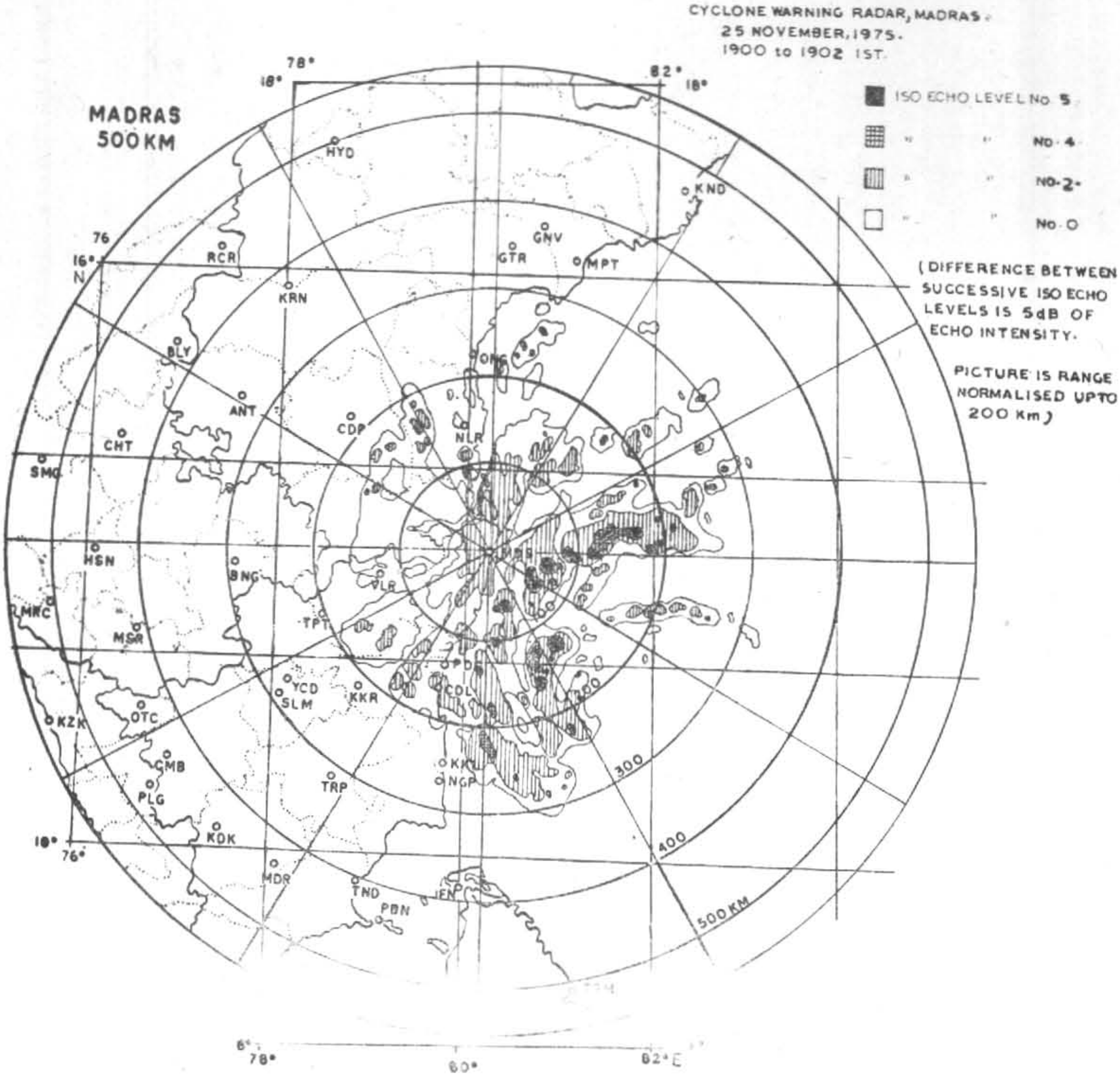

Fig. 1

(5) *Eyewall* — The intense circular or elliptic wall cloud partly or wholly surrounding the clear area of the eye of the storm. The eyewall usually consists of the end of one or more well defined spiral bands. It has a well defined inner edge but poorly defined outer edge.

All the features enumerated above as typical are not necessarily present even in well developed storms. Often there is a preponderance of rainbands in the forward sectors with little or no rain in the rear (Rockney 1956, Sadowski 1964, Tatehira and Itakura 1966, Kadowaki *et al.* 1968). The wall cloud itself may be only partly formed and may be changing in configuration (Simpson and Pelissier 1971). Both these phenomena have been used by some workers as indicators of future motion of the system (*i.e.*, the storm is expected to move in the direction of concentration of the echoes — Sadowski 1964, Tatehira and Itakura 1966, Senn 1966 a, b). The rainshield area contains diffuse echoes and orientation of individual bands can in some cases be distinguished on the radarscope only by gain reduction or isoecho display (Senn *et al.* 1965). False eyes or rival centres of circulation appear similar to the real eye on the radar. Pressure minima have been independently observed in association with such circulations (Simpson 1954, 1956, Simpson and Starrett 1955, Barclay 1972). A "circular exhaust cloud" to one side of the centre of a weak storm has also been observed from manned spacecraft (Gentry *et al.* 1970). Deformation of spiral bands is known to occur over land. The observed 'eye' may also be displaced with reference to the pressure centre of the storm (Kodaira 1964).

3. Limitations of radar

A land-based radar station is not always well placed to observe all the features enumerated above. For example a radar located to the rear of a storm may see very few echoes. The effective radar range is limited by earth curvature and it varies with variations in radio propagation conditions. Parts of the eyewall or spiral bands away from the radar site may not be seen, particularly if their heights are low. Observed height of echoes may be overestimates or underestimates due to under-correction or over-correction by standard refraction correction curves. Intensities of long range echoes may be underestimated due to the radar beam illuminating the upper parts only of distant clouds.

4. Storm of 24-27 November 1975

The immature storm which is specifically considered here originated as a well marked low pressure area with its central region near 11·0° N, 87·5°E on the morning of 23 November 1975 and could be located on the APT picture from the satellite ESSA-8. At 0300 GMT of 24th the system was declared depression centred at about 8·5°N, 84·5°E. By 15 GMT it became a cyclonic storm with centre at 10·5°N and 83° E. The storm moved initially northwestwards and by 25th evening it was declared a severe cyclonic storm with estimated central pressure of 988 mb. Its closest approach was at 21 GMT of the 25th at a point about 150 km southeast of Madras. From 26th afternoon it moved northeastwards. It weakened into a cyclonic storm on 28th and eventually dissipated over the sea. Here it is relevant to note that the judgement of the intensity of the system is mainly based on the winds reported by ships and the upper winds upto one kilometre level at Madras and Karaikal. The storm also caused high surface winds at Madras and heavy rainfall in the coastal districts of Tamil Nadu. It did not however show well defined banding features on the satellite pictures.

5. Radar observation

The sytem was observed by a radar at Madras from the 23rd to the 27th. Specifications of the radar are as given by Raghavan and Lakshminarayanan (1974). The nominal range of the radar is taken as 400 km but effective range varies widely with season due to changes in radio refractive index distribution. According to Raghavan and Soundararajan (1962) microwave propagation in the Madras area in the October-November season is generally normal or subnormal. In cyclone situations, owing to high humidities extending upto the mid troposphere, propagation becomes definitely subnormal and the effective range for detection of most precipitation is reduced to about 300 km.

On the 23rd, lines of convective cells were seen on radar for several hours. From 15 GMT onwards an intense squall line about 600 km long and oriented NE-SW persisted for several hours without much systematic movement. Whether this can be considered to be a pre-cyclone squall line and can be taken as an indicator of likely intensification of the system is an operationally relevant question, the answer to which is not clear.

6. Rainshield and spiral bands

On the 24th irregular lines of convective cells which could be categorised as outer convective activity were seen during the day. There was no organised movement agreeing with upper winds, showing that the cells were constantly forming and dissipating, any observed movement being due to propagation of cells. From 15 GMT onwards a number of curved bands with weaker echoes in between were observed. This was apparently the rainshield area, but by observation and tracing the scope at successive isoecho levels, the orientation of individual precipitation bands within this shield could be discerned. It was characteristic of this storm that while it was often difficult to identify individual spiral bands on the normal picture it was possible to do so on the isoecho levels when the weaker echoes could be eliminated. To illustrate this point a typical picture (at a later hour) of the echoes at various intensity levels is shown in Fig. 1. The degree of organisation of the echoes gradually improved in the next few hours. At 21 GMT of 24th, the relatively disorganised echoes within 100 km of the station showed a bright band (Fig. 10). However as the echoes appeared to be convective it is probable that the bright band is due to ice cyrstals falling from the cirrus above and melting as postulated by Senn *et al.* (1965). This apparently constituted the rainshield area. Beyond this region and up to 300 km range three spiral bands could be distinguished by the isoecho observational procedure discussed above. Although the width of arc was only about 80 degrees it was possible to treat the three bands as spirals with crossing angles of 10 (inner band), 15 (middle band) and 20 (outer band) degrees and obtain a common centre of convergence at 10·9°N and 82·6°E which tallied with the last available synoptic position allowing for movement since then. Although the storm was within 400 km no part of the eyewall was seen perhaps due to

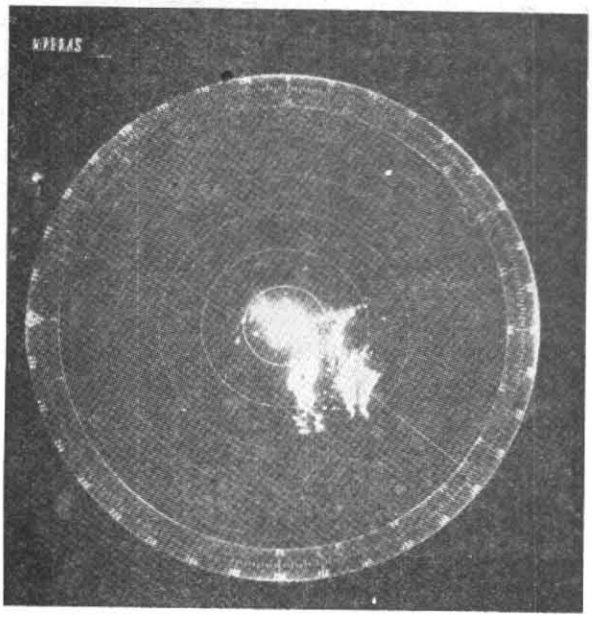

Fig. 2. 4 December 1972 at 2216 IST
Spiral band associated with Cuddalore cyclone 1972, when the storm was 335 km from the radar

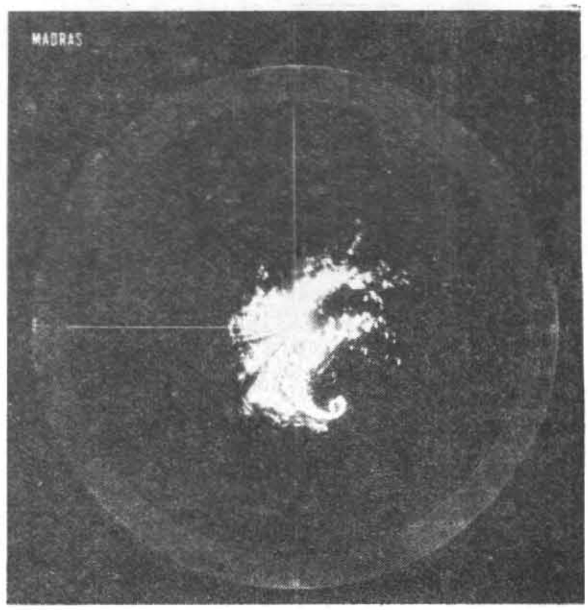

Fig. 3. 26 November 1975 at 0211 IST
Storm at 21 GMT of 25 November 1975. Part of the eyewall is seen. Note the 'globule' at one end of the eye wall

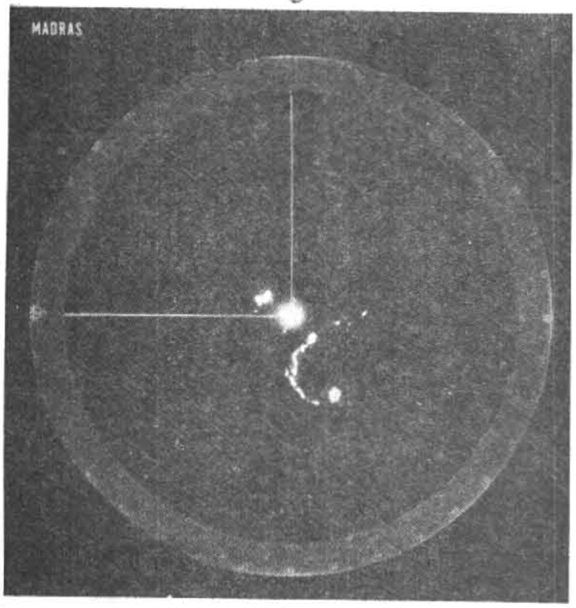

Fig. 4. 26 November 1975 at 0212 IST
At isoecho level No. 4 35 mm/hr or more rainfall intensity

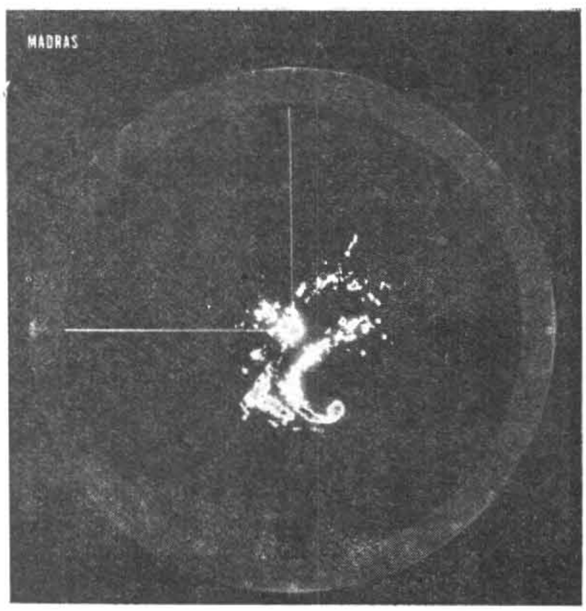

Fig. 5. 26 November 1975 at 0214 IST
Level 2, 8mm/hr or more rainfall intensity

PPI photographs presented are at 500 km range. Interval between successive range markers is 100 km and elevation is zero degree poor development or perhaps due to limitation of the effective range of the radar. The question that arises is whether we are justified in making extrapolation from such spiral arcs and estimating the centre. When we do not see the eye, how do we decide whether the apparent centre of convergence of observed bands is the real centre of the storm? A comparison with the Cuddalore cyclone of 1972 (Raghavan and Lakshminarayanan 1974) tracked by the same radar may be useful. Fig. 2 shows a pattern similar to the present case, when the centre of that storm estimated with spiral overlays was at about 335 km and agreed with the synoptic centre. Subsequently the bands persisted but only 9 hours later when the storm was within 260 km could a part of the eyewall be seen. Hence it appears that with a storm at over 300 km one cannot generally expect to see the eyewall, but by extrapolation of spiral bands, a lead time of the order of 9 hours can be obtained in radar location of the system. While the subjective spiral overlay technique leads to appreciable errors in fix unless the eye itself is visible (Jordan 1963) it is precisely in such a case the overlay technique has to be used most. To avoid gross errors, the reality of the observed banding features may be tested by the following criteria :

(1) An appreciable arc say 90° or more of two or more bands should be visible and remain stable for a few hours.

(2) The existence of circulation should be established by observation of echo motion along the band.

(3) The centre of convergence of the observed band should agree reasonably well with evidence from available synoptic and satellite data.

The last mentioned condition appears vital, for otherwise, an isolated radar fix without coordination with other evidence, could easily mistake any auxiliary vortex or false eye for the real centre of the system.

7. Open eyewall

With these considerations, the assumption that the centre of convergence of the bands at 21 GMT of the 24th represented the real centre of the storm appears justified. However after 00 GMT of 25th, the bands started disorganisation and this was followed by a reorganisation again from 05 GMT onwards. By 09 GMT 2 bands of appreciable angle of arc could again be located. By 1330 GMT (Fig. 1) 3 bands could be distinguished and yielded a centre fix at 11·5 °N, 81·5° E, *i.e.*, 225 km from the radar site. As at previous hours the crossing angle of the innermost band was the smallest

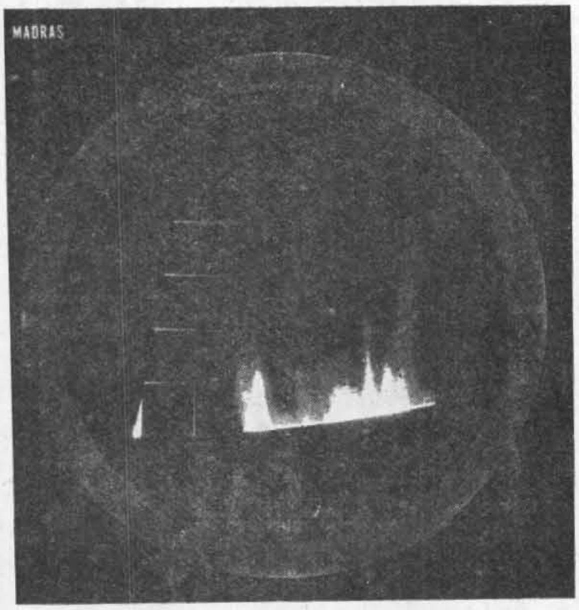

Fig. 6. 26 November 1975 at 0226 IST

Range nomalised Grey scale RHI picture at azimuth 176 deg. Height markers at interval of 5 km, range marker at 40 km interval. Total range presented is 200 km. (RHIs are corrected for earth's curvature, but further correction for beam width and refraction is to be applied)

and the outermost the largest. At this time a crescent shaped echo was seen within the innermost band. The height of the echo was small and its intensity corresponded to a rainfall rate of only 8 mm per hour. Although by this time the storm was synoptically considered to be a severe storm the pattern again got rather disorganised but regrouped by about 1730 GMT with 3 spiral bands; a tall tower near one end of the innermost band was seen on the RHI suggesting it may be part of the eyewall. By 20 GMT the innermost band of about 100 degrees of arc was very intense – rainfall rate greater than 70 mm/hr — and had a tall tower at its southeastern end. This was probably an open eyewall. A large open eye with major and minor axes of 120 and 90 km respectively could be postulated. The reason for not seeing the rest of the eyewall, could not be any deficiency in radar performance, as the radar was detecting echoes beyond that range even in the direction of maximum precipitation. The probable explanation is that the system was unsymmetrical and the rest of the eyewall was not formed.

8. False eye

By 21 GMT the band presumed to be the eyewall was still better defined, covering 210 degrees of

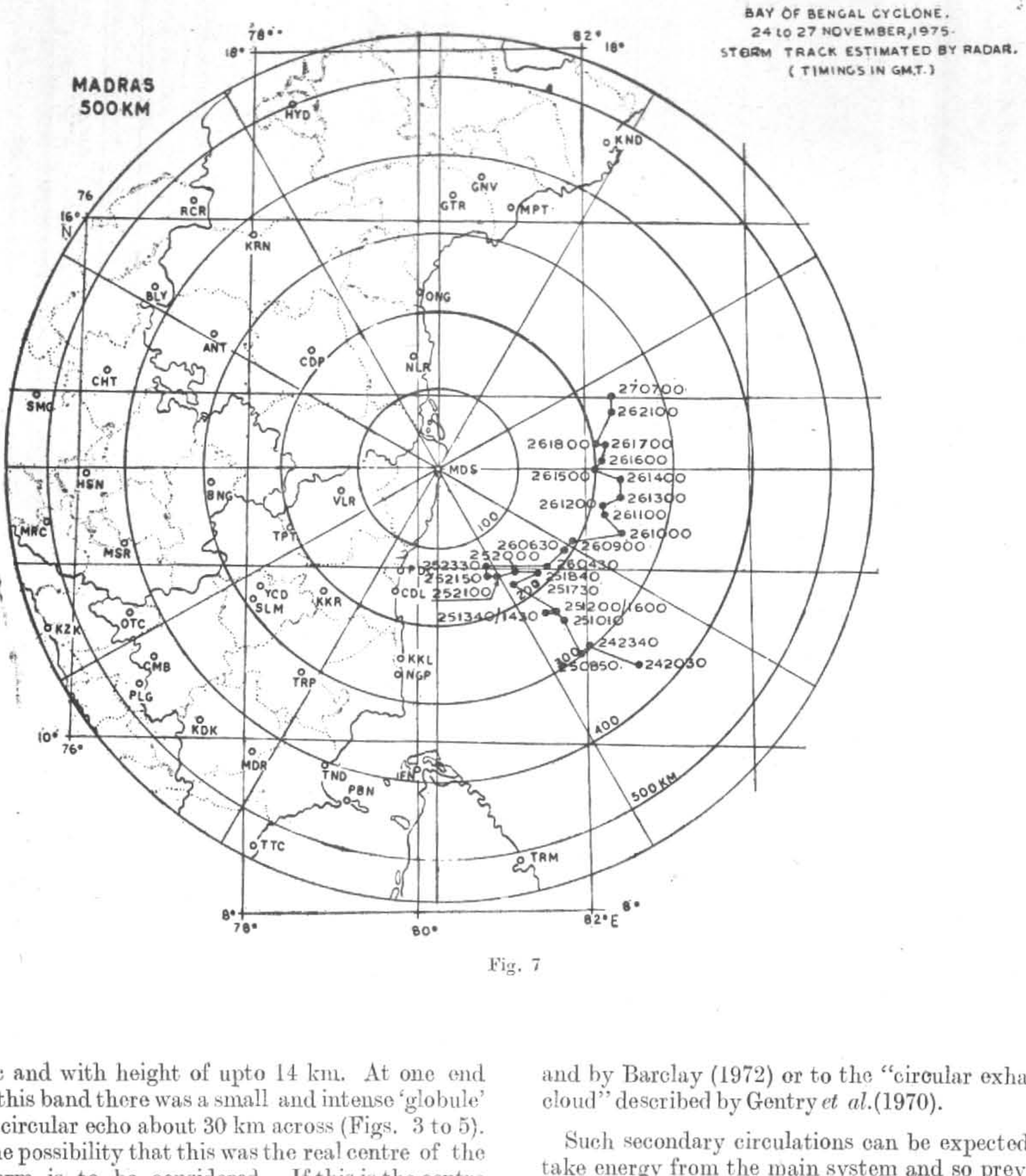

Fig. 7

arc and with height of upto 14 km. At one end of this band there was a small and intense 'globule' or circular echo about 30 km across (Figs. 3 to 5). The possibility that this was the real centre of the storm is to be considered. If this is the centre of the system it does not coincide with the centre of convergence of the main band treated as eyewall nor does it provide continuity with previous fixes. This 'globule' was also short lived as comapred to the band. The gradual fall of surface pressure at Pondicherry, the nearest coastal station upto 2230 GMT with a rise thereafter (allowing of course for diurnal variation) would suggest a movement towards that station rather than a southward shift which would result if this 'globule' is taken as eye. Hence it appears likely that this small circulation is a subsidiary circulation similar to the 'false eye' reported by Simpson (1954, 1956) and by Barclay (1972) or to the "circular exhaust cloud" described by Gentry *et al.*(1970).

Such secondary circulations can be expected to take energy from the main system and so prevent its intensification and would therefore be a characteristic of a weak or weakening storm. This observation also underlines the importance of distinguishing between such 'parasitic' circulations and the main system.

9. Dissipation of bands and eastward movement

In the next few hours there was again a gradual disorganisation of the bands and regrouping. By 0430 GMT of 26th the centre of convergence had shifted about 50 km eastwards and no clear eyewall could be seen. Surface pressure values at Pondicherry and Cuddalore had started rising, though

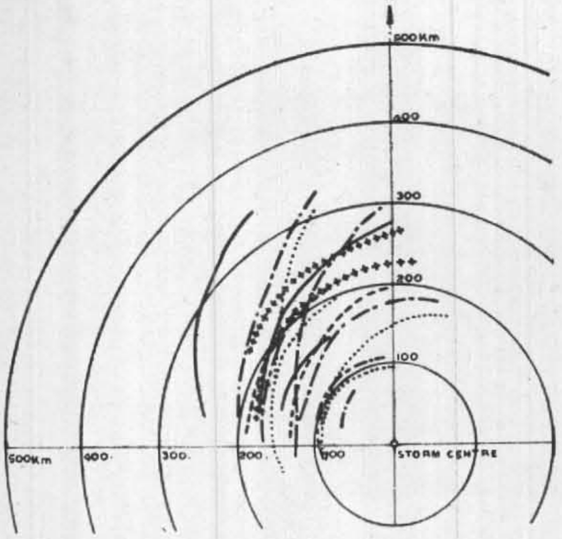

Fig. 8. 25 November 1975

—— indicate 0200 IST, ++ signs 0511 IST, - - - 1415 IST, ... 1544 IST and —.—. indicate 1630 IST observations

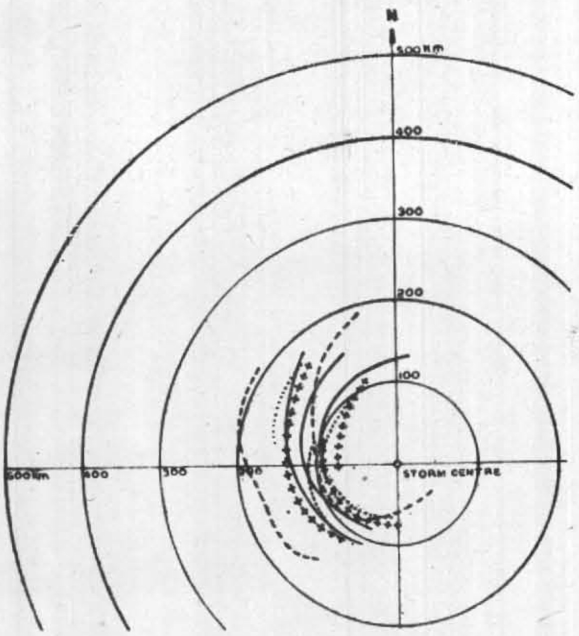

Fig. 9. 26 November 1975

—— indicate 2025 IST, ++ sign 2125 IST, - - - 2230 IST and .... indicate 2330 IST observations

Madras reached its minimum pressure only at 09 GMT. After 10 GMT of 26th a gradual northward movement was observed but due to disorganisation of bands, the confidence in fixes became poorer. By that night echoes nearer the station started indicating horizontal stratification and bright band, while over the spiral band there were convective echoes (Figs. 11 and 12). Beyond the band there were no echoes. On 27th the radar echoes further decreased in areal extent and in degree of organisation. As seen from satellite picture (ESSA-8) of 27th morning the storm had moved to about 14° N and 82·5°E. The radarscope became almost clear by 15 GMT of 27th.

10. Storm track and prediction of movement

The track of the storm as estimated by radar is given in Fig. 7. The usual tendency of storms to meander about a mean direction of travel is apparent. Since the radar fixes are based on extrapolation of spiral bands, part of the scatter of points could be due to 'fix' errors. The radar fixes are, however, broadly in agreement with the synoptic positions. The APT pictures did not at any stage show a clear eye or even distinct banding features. Hence a more precise comparison is not possible.

As mentioned earlier, the mean movement from 26th afternoon was northward. Could this have been predicted? Extrapolation of a meandering radar track especially when the eye is not clearly seen on the radar is evidently unreliable. Surface pressures at coastal stations of Tamil Nadu had started rising, but upper winds at that stage were not favouring a northerly or northeasterly course. Hence there was no clear indication to decide that the earlier predicted northwesterly movement towards the coast would not continue.

Predictions of future movement from radar pictures, are not made merely by extrapolation of past movement but from the two indicators mentioned earlier as employed by various workers elsewhere, *viz.*, (1) crowding of echoes in the forward sector and (2) in the case of an open eye, the strongest part of the eyewall being in the direction of motion. To test the first of these indicators the orientations of the spiral bands at various times were redrawn with radar-estimated storm centre as origin (Figs. 8 and 9). It must be emphasised that only data for those hours at which the centre could be estimated with reasonable confidence have been used. In Fig. 8 corresponding to the 25th when the storm was moving northwest, the bands are crowding in the northwestern sector. In Fig. 9 corresponding to 26th evening, when the storm was at the latitude of Madras and moving north, the bands are crowding to the west or southwest of the centre. This distribution evidently is unrelated to storm motion. If the band in Fig. 4 is presumed to be the eywall, the second indicator is also not realised. Thus these two predictors

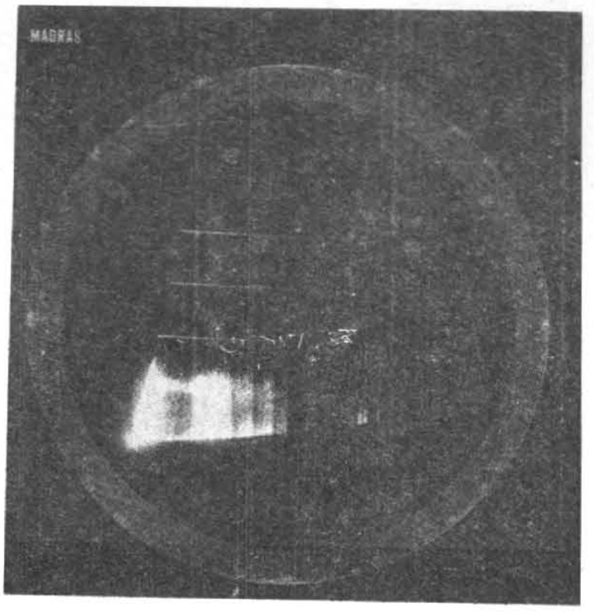

Fig. 10. 25 November 1975 at 0304 IST

RHI picture Azimuth 090 deg. showing bright band over rain shield area (attenuation applied 10 dB)

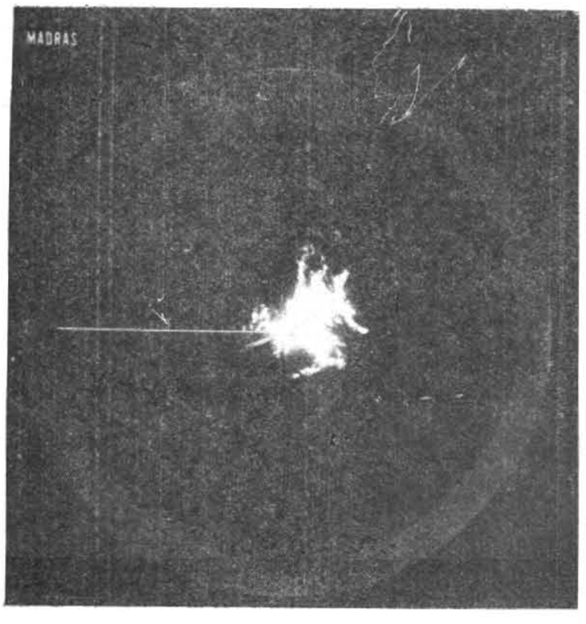

Fig. 11. PPI photograph on 27 November 1975 at 0213 IST

(*See* legends below figures on page 226 also)

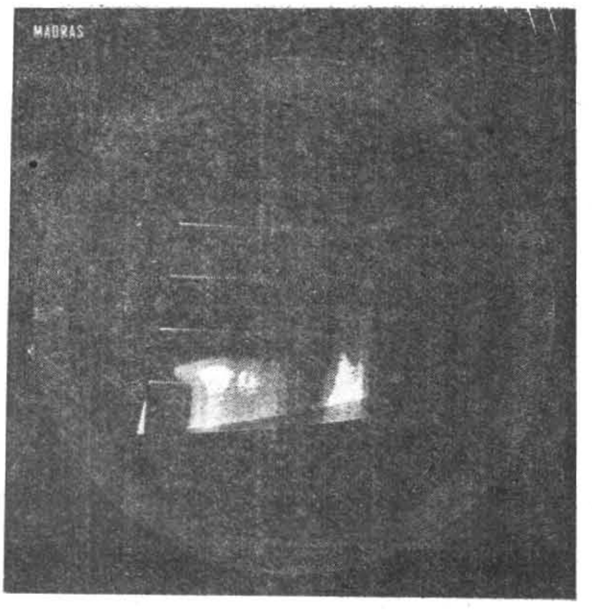

Fig. 12. 27 November 1975 at 0218 IST

Range normalised Grey scale RHI picture Azimuth 065 deg. corresponding to PPI at Fig. 11.

though perhaps successful in some systems elsewhere are not indicative of storm motion in this case. Figs. 8 and 9 also indicate that there was no systematic translation or rotation of the bands as a whole. No definite relationship between the orientation of these bands and the storms motion or intensity could be established. Thus unlike well developed storms where recognisable patterns persist for 24 hours or more (Fett and Brand 1975) the patterns in an immature storm do not seem stable.

11. Vertical structure

A feature referred to earlier is that the rainshield echoes though generally convective were of relatively low height and exhibiting a bright band at the freezing level of 5 km (Fig. 10) on the RHI. The echoes constituting the innermost spiral band and the eyewall were, however, having distinct tall towers, without bright band. Fig. 12 which is a range normalised grey scale picture shows simultaneously the rainshield each with bright band at freeezing level at the nearer ranges and the higher convective tower over the spiral band area farther away (*See* Fig. 11 for the corresponding PPI). The intensity contours in the rainshield area tend to be horizontal while in the spiral band the contours are vertical. Fig. 6 shows a similar vertical contour configuration of the eyewall. The presence of bright band with weak echoes above, is indicative of melting ice particles at the zero degree isotherm level with solid particles above them. The vertical contours with high intensity extending above the freezing level, would indicate the presence above the zero degree level of super-cooled water of relatively high reflectivity with no distinct melting layer. This is an interesting difference in cloud structure. If this is a common feature of most storms, it will have practical implications for storm modification efforts.

12. Conclusions

The Bay of Bengal storm of the last week of November 1975 was declared a severe cyclonic storm on the basis of surface and low level winds which are the normal criteria used for classification of storms. The storm caused heavy rainfall and strong winds along the coast. However, the radar and satellite pictures did not indicate a well developed system. The rain bands were not stable and the configurations were changing frequently. The storm did not have a fully developed eyewall at any time. None of the observed radar features could serve as predictors of motion. The storm also had a false eye at one stage which could have acted against intensification. The system was, however, basically similar in structure to tropical storms elsewhere. Hence it appears that the storm was probably throughout in the immature stage (Riehl 1954).

Such storms appear to be common in the Bay of Bengal. The few observed winds are perhaps not representative in such cases owing to asymmetry of wind field. Hence the classification of such systems purely on the basis of the meagre wind data may sometimes be in error. The systems are also difficult to locate and track from the satellite and radar pictures. By careful coordination of synoptic, satellite and radar data a fair measure of success can be achieved in classifying, locating and tracking such weak systems and issuing realistic warnings.

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