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Some experiences of radar observation of cyclonic storms in the southern Bay of Bengal

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ABSTRACT. From a study of eight cyclonic storms observed with the Cyclone Warning Radar, Madras from 1972 to 1977 an assessment of the information obtainable by radar on cyclones in the Indian seas is attempted.

Storms in this part of the Bay may be divided broadly into two categories: (i) well developed ones exhibiting a distinct eye and other features generally associated with hurricanes and typhoons and (ii) immature ones which do not have well developed banding. The latter are difficult to track by radar though useful information can be obtained regarding their structure. Cyclones in the former category can usually be tracked from a range of about 300 to 350 km. Fixes in initial stages have to be co-ordinated very closely with satellite and synoptic evidence, and may have a wide margin of error. Usual radar predictors of storm motion such as echo concentration etc are not reliable for any individual storm. Extrapolation of radar track is usually successful except in cases of recurvature.

Radar gives considerable operationally useful information on size and shape of the eye, areal extent of precipitation, location of sectors of intense precipitation and structure of clouds in different sectors. Shrinkage of the eye usually indicates intensification. Persistent changes in degree of organisation over long periods appear to be a sign of change in storm intensity; changes with time in heights and intensities of individual clouds of the eyewall of a given storm appear correlated with storm intensity. Information on areal distribution of echoes can probably be used in realtime while issuing warnings.

1. Introduction

Systematic radar observations of cyclonic storms in the Indian seas for any appreciable part of their lifetime, have been commenced only since the early seventies, when the first few of the cyclone warning radars were installed. Though a few case studies on individual storms (Raghavan and Lakshminarayanan 1974, Raghavan 1976, 1977, Bhattacharya and De 1976, Mukherjee *et al.* 1977, Raghavan and Veeraraghavan 1979) have been made, there is no comprehensive assessment available of the information that can be obtained by radar on the position, movement, intensity and structure of storms in the Indian seas. In this paper such an assessment is attempted on the basis of the observation of 8 storms with the Cyclone Warning, Madras (listed in Table 1).

The questions which are examined here are :

(1) Do these storms exhibit all the features associated with radar observations of tropical storms in the Pacific and Atlantic ?

(2) What is the realistic range upto which a coastal radar can expect to track a storm, and what would be the accuracy of fixes in various stages ?

(3) Can any of the observed features on the radar be used to predict future motion of the storm ?

(4) Can the radar give an assessment of the intensity of the storm ?

(5) Can the radar give any other operationally useful information on the structure, rainfall distribution and areal extent of the storm ?

2. Radar features associated with storms

The radar features generally associated with a hurricane or typhoon have been classified by Rockney (1956), Kodaira (1964) and Senn *et al.* (1965).

Fig. 1. Pre-cyclone squall line associated with storm A, at 0528 IST of 4 December 1972. Range rings in this PPI picture are at intervals of 100 km; Elevation 0°.

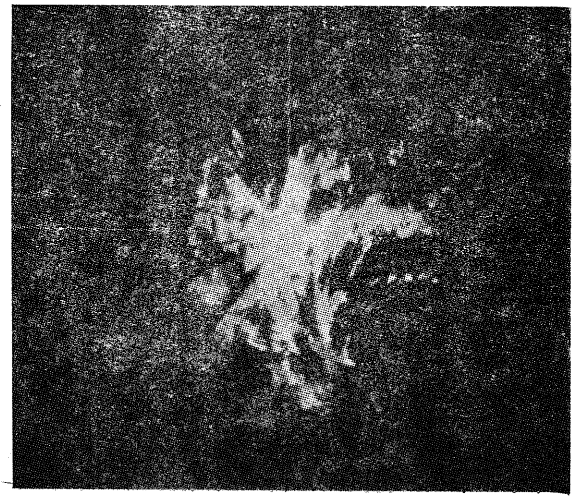

Fig. 2. 1858 IST of 25 November 1975. Spiral bands with storm B indicate storm centre at 11.5°N, 81.6° E agreeing with synoptic centre.

Fig. 3. 0351 IST of 18 October 1976. The spiral arcs seen in association with storm C, indicate a centre of convergence south of 13° N while the synoptically determined centre is at 14° N, 81° E. Range rings are at 100 km intervals.

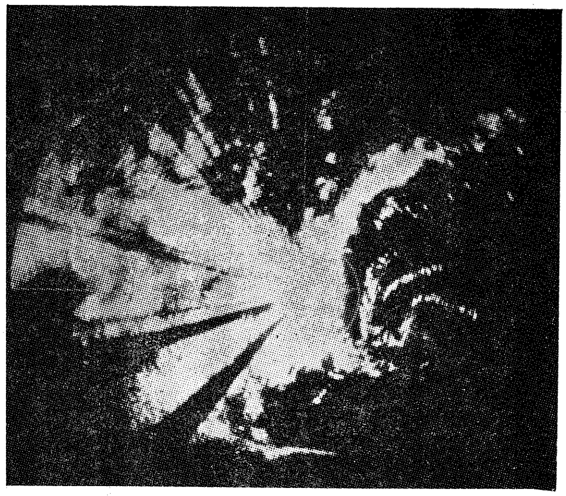

Fig. 4. 0720 IST of 25 November 1976. Range rings at 40 km intervals. In association with storm E a small circulation pattern is seen about 100 km southeast of Madras. The movement of this pattern could be tracked for a few hours. But the echoes were too feeble to be considered as the core of a tropical cyclone.

Precyclone squall lines 300 to 600 km ahead of the storm were observed in the storms at A, B, G, and H of Table 1 (*e.g.*, Fig. 1). Whenever squall lines were observed, the orientation was roughly perpendicular to the direction of motion of the storm at that time but no relation could be established between any parameter of the squall line (such as length, height, intensity, duration) and intensity of the storm. The squall lines when observed can, therefore, be taken as a rough indicator of the direction of storm motion. But since they dissipate long before the storm comes over land their operational utility as motion predictors is limited.

Some distance behind the squall line follows in all cases a region of lines of convective cells of irregular shapes forming *the outer convective activity*. Following these are *inner bands* arranged roughly in the form of concentric logarithmic spirals with areas in between usually occupied by weaker echoes of the *rainshield*. Whenever the eye of the storm cannot be seen by the radar the extrapolation of the spiral bands

TABLE 1

Storm*	Name of storm	Storm*	Name of storm
A	Cuddalore cyclone of 4 to 6 Dec 1972	E	Bay storm of 22 to 29 Nov 1976 (Reclassified as deep depression)
B	Bay storm of 24 Nov to 1 Dec 1975 (did not cross coast)	F	Kavali cyclone of 29 to 31 Oct 1977
C	Bay cyclone of 15 to 21 Oct 1976 (crossed Bangladesh coast near Chittagong)	G	Nagapattinam cyclone of 10 to 12 Nov 1977
D	Kavali cyclone of 15 to 17 Nov 1976	H	Chirala cyclone of 15 to 19 Nov 1977

*Identification letter used in this paper

forms the only means of estimating the centre of the system by radar.

The rainshield echoes often mask the correct orientation of the bands and it is usually necessary to use the iso-echo system of the radar or an attenuator or gain control to cut out weaker echoes and delineate the band orientations. Often the available arcs of these bands are much less than 180° and so the fitting of logarithmic spirals of arbitrary crossing angles can give large errors in estimating the storm centre unless corroborated by independent synoptic or satellite evidence. To establish the reality of a spiral band, it is useful to check in the initial stages that the individual echoes in the band move anticlockwise along the band. Where more than one band is available the crossing angle usually increases with distance from the centre, *e.g.*, the innermost band may fit best with a 10 degrees spiral, the next one with a 15 degrees spiral and so on. While in the majority of storms the crossing angles are 10, 15 or 20 degrees at the latitudes of about 10° to 15° N considered in this paper, in intense storms the inner bands sometimes have still smaller crossing angles, *e.g.*, in the "Chirala" cyclone, the crossing angles of the first three bands was about 5 degrees.

Fig. 2 shows a case of spiral bands from which centre fix was obtained succesfully in storm B. Fig. 3 on the contrary represents the case of storm C, where the apparent centre of convergence of the visible bands is far removed from the synoptic centre. In depressions or marginal storms like C and E of Table 1, either the circulation is poorly developed and the bands do not fit conventional logarithmic spiral curves or there are vortices of circulation, sometimes more than one at a time, which do not coincide with

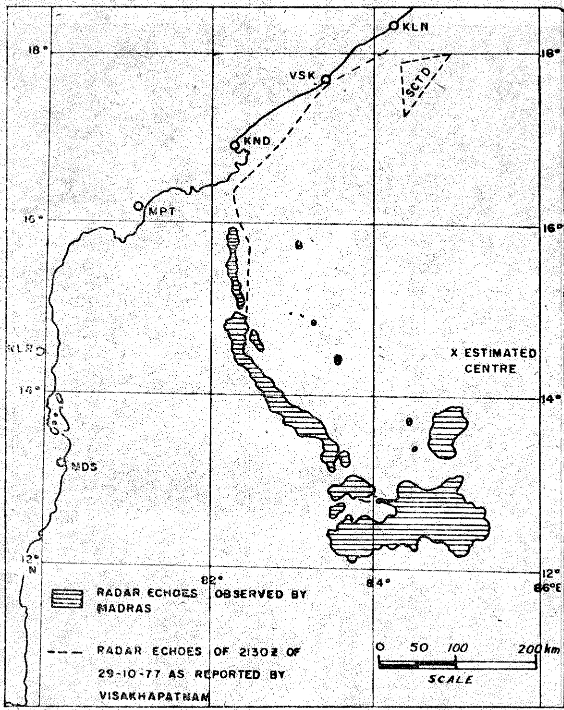

Fig. 5. Kavali cyclone 1977. Composite of radar echoes of Madras and Vishakhapatnam

the synoptic centre of the system as a whole. "False eyes" have been reported in storms of weak or moderate intensity in the Atlantic and south Pacific (Simpson 1954, Barclay 1972). The existence of such vortices should lead to a dissipation of energy preventing intensification of the system.

In the case of storm E, a small and weak vortex within 100 km of Madras could be seen and (Fig. 4) tracked by radar for a few hours on 25 November 1976. However at the first iso-echo level there was no evidence of this circulation and the RHI showed very poor development. One would not except a cyclonic storm within 100 km of a radar, to give such an appearance.

Kulshrestha and Gupta (1964) and Kulshrestha (1970) have observed that some monsoon depressions in north India exhibit banded structure and even have a vortex. This appears to be the case also with post-monsoon depressions and weak storms in the Bay of Bengal but the banding or the vortices are not sufficiently well developed or stable to be tracked unambiguously by radar. Storms such as C and E may be classified — along with depressions — as immature systems difficult or impossible to track by radar. The conclusion that a system with false vortices is not an intense one may itself be a useful information from the radar. Moreover information on rainfall distribution and cloud structure

Fig. 6. 0536 IST of 31 October 1977. Storm F. A partial eyewall is seen in the northwest sector of the storm core. The storm was moving northwestwards.

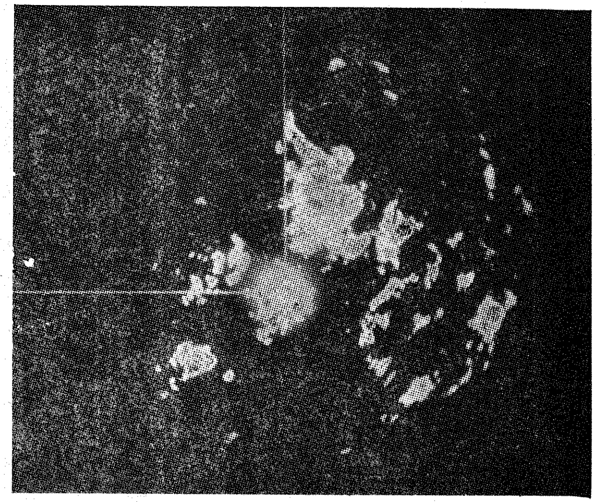

Fig. 7. 0843 IST of 31 October 1977. Storm F. Compare with Fig. 6. In 3 hours the partial eyewall has rotated anticlockwise and is seen in the southwest sector of the core of the system. The storm started moving westwards.

(sections 7 and 8) can of course be obtained by radar observation of such systems.

In relatively well developed systems with good banding, the initial stage when only spiral bands are seen is still a phase when the accuracy of radar fix is poor. Acceptable results are obtained only by co-ordination with satellite and synoptic evidence. The accuracy of fix in such cases can be improved considerably by composing together radar observations from two or more radars if the pictures can be collected at one place in time. Fig. 5 shows an example.

3. Radar observation of the eye

Beyond the spiral band region one would expect to see the wall cloud surrounding the eye of the storm. In the case of immature systems there is often no detectable eye. In storms of moderate intensity such as B and F in Table 1, the eyewall is often partly formed. In the case of storm A (a severe one) only an open eyewall was seen throughout the period of observation. The open eyewall may sometimes be due to the radar not being able to see the far side but is more often real. Simpson and Pelissier (1971) have reported a case of a hurricane which had an open eyewall causing heavy rainfall and wind damage in the sector of the visible eyewall and little or no rain in the open sector. They also observed that when a hurricane is intensifying and its circulation is not in a quasi-steady state, the isotach maximum which normally occurs in the right front quadrant apparently tends to migrate cyclonically at a conserved radius. This can give rise on the radar picture to a break in the eyewall or an apparent rotation of the visible eyewall. Such a rotation in the case of storm F can be seen in Figs. 6 and 7. Fig. 6 shows the eyewall as a crescent on the far side only as seen from the radar and Fig. 7 three hours later shows the nearer side only. This rotation was accompanied by a change of direction of motion.

When the eyewall is visible over an arc of less than 180 degrees it is difficult to locate the geometric centre of the eye. In such cases a reasonably good fix is obtained by treating the eyewall as part of the spiral band system and fitting a small angle spiral. In storm G for example the small incomplete eyewall (Fig. 10 of Raghavan and Veeraraghavan 1979) appeared at one stage as an extension of spiral band. Also see Senn and Hiser 1959). If more than a semi-circumference of the eye is visible the rest of the circumference can be imagined and the geometric centre of the resulting ellipse or circle taken as the centre. Even a small improvement in radar receiver sensitivity helps in some cases to see parts of the eyewall which are not otherwise seen and thereby obtain a more accurate fix. Besides checking the receiver minimum detectable signal frequency it is useful to minimise radar head losses by cutting out, now and then, any component such as PIN modulator which may be having residual attenuation.

When only the spiral bands are seen, the position error could be 30 to 50 km depending on the number of bands, the angle of are, the range, the inherent azimuth positioning errors of the radar, and the beam width effects. When the eye position is fixed by seeing a major portion of the eyewall it is possible to categorise the accuracy as 'good', *i.e.*, error within 10 km. At long ranges a further uncertainty arises due to height of radar beam which is about 4.5 km at 300 km in normal propagation conditions. Hence, if there is a tilt in the eye region there could be displacement of the observed radar eye from the surface centre of the system. The apparent eye shape, diameter and thickness of eyewall are also affected by long range. Due to beamwidth effect a small eye appears smaller still, its shape is distorted and an apparent rotation of its axis is observed (Raghavan and Veeraraghavan 1979).

4. Maximum range of tracking

A typical S band radar with a minimum detectable signal of about —107 dBm and peak power output of + 87 dBm (500 kw) can theoretically detect a rainfall rate of about 1 mm/hr at 300 km on a flat earth. However, since the radar sees the cloud at that range at a height of about 4.5 km, the surface precipitation rate associated with a barely detectable echo will be considerably more than 1 mm/hr or in other words the range at which 1 mm/hr can be detected is less than 300 km. The height of the beam also varies widely with low level refractive index profile. In the October-December season, the radiowave propagation in this part of the Bay is normal or subnormal (Raghavan and Soundararajan 1962). It will be particularly subnormal in cyclone situations because of the lack of humidity gradient in the lower tropospheric levels. Hence the range of detection of echoes on such occasions is generally limited to about 300 km. If the farthest visible spiral band is at about 300 km the farthest centre fix obtainable should usually be about 330 km. This has been the actual experience with storms A, B, D and G of Table 1.

Since the eyewall cloud is expected to be taller and more intense than the other rainbands, it may also be expected that it should be possible to see it at a somewhat longer range than in the case of the other bands. It has been observed that eyes of Pacific typhoons can often been seen by land-based radar from more than 400 km away, though such long range detection is rare in the case of Atlantic hurricanes. Bell (1977) attributes this to the greater vertical extent of moisture in typhoons than in hurricanes. If this reasoning is correct, it should be possible to see the eyewall of a very intense storm at a greater range than in less severe ones. The eyewall of the intense storm H of Table 1 could be seen on 17 November at a range of 400 km. To identify any part of the eyewall as real, one takes some time and so the farthest reliable fix would probably be at less than 400 km even in such a case.

If the weather close to the radar site is favourable for abnormal propagation, it is sometimes possible to detect rainbands associated with a distant cyclone at ranges well in excess of 300 km although the accuracy may be poor. In the case of storm F a long spiral band could be seen in this way at a range of 600 to 700 km and an approximate fix obtained. As the storm came closer the favourable refractive index profile was destroyed.

5. Predictors of storm motion

The average error of 24 hours prediction of point of landfall in the U.S.A. is said to be about 100 nautical miles. Despite the availability of a larger number of coastal radars, geo-stationary satellite pictures and aircraft reconnaissance facilities, large sections of the U.S. coast are kept under storm alert particularly when a storm is moving roughly parallel to the coast (Lawrence 1977). With the relative scarcity of data in the Indian seas, it is of great importance to look for possible ways of improving the prediction of the point of landfall. The most obvious way will be to extrapolate the track observed over a few hours (Annette 1978). The hour to hour positions of storms exhibit some meandering of the track. The apparent meandering by storms D, G and H which exhibited a well formed eye was less than the meandering of A, B and F whose centres were determined from spiral bands or by completing a partial eyewall. There can be two alternative or concurrent explanations for this:

(1) The error in position determination is much less in the case of a storm with complete eye than in the other cases, *i.e.*, the extra meandering in the latter case is due to error in radar fix and not a real phenomenon.

(2) The more intense storms do not meander so much as the less intense ones.

In the case of storms A, D, F, G and H in which radar fixes were obtained with good or fair accuracy, a linear extrapolation was made of a smoothed 6-hour radar track 6, 12, 18 or 24 hours ahead to assess the likely error in forecast of landfall 6, 12, 18 or 24 hours ahead if the forecast had been done only by this method. Table 2 shows the results. The six hour smoothing was done in order to eliminate the effect of short period oscillations. It will be seen that in the case of intense storms (A, D, G and H) the point of landfall could have been forecast to within about 50 km at the time when good fixes became available, an accuracy which cannot be bettered by any other presently available forecast technique. In the case of storm A the fixes were based only on spiral bands upto 24 hours

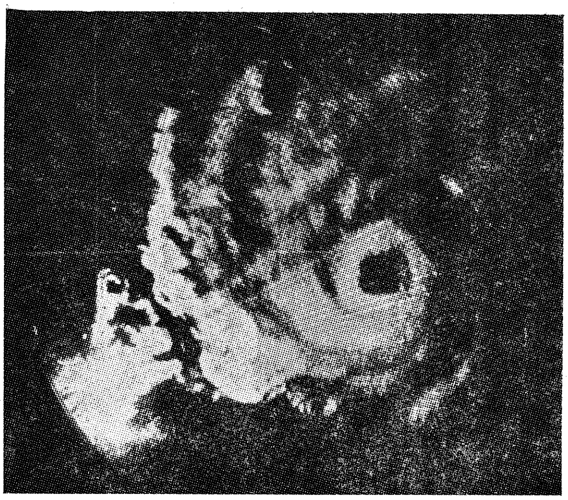

Fig. 8. 0958 IST of 16 November 1976. Storm D. A closed eye is seen and the total radar echo area is about 300 km across. Range rings at 40 km intervals. Off centred PPI picture.

Fig. 9. 1305 IST of 16 November 1976. Storm D. The eye has opened out. Range ring interval 40 km. Compare with Fig. 8.

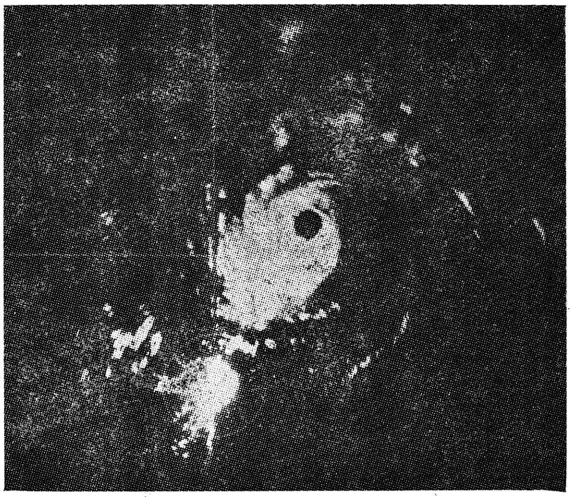

Fig. 10. 1753 IST of 16 November 1976. Storm D. The eye has closed again and shrunk in size suggesting intensification. The total radar echo area has also diminished (this resulted in rain and wind damage being confined to small area). Range ring interval 40 km.

ahead of landfall and hence the 24 hour prediction gives an error of about 95 km. In the case of storm B which not only meandered considerably but recurved this procedure of extrapolation would obviously fail. The case of storm F is discussed later. Hence in *intense* storms, in which there is no synoptic indication of likely major changes of the course, extrapolation of radar track could be considered seriously as a means of prediction. This could result in restricting the warnings of severe weather to fewer districts.

Other radar features considered as predictors of storm motion are: (1) The line perpendicular to the orientation of pre-cyclone squall lines (already discussed in Sec. 2). (2) The direction with reference to storm centre of the area of concentration of rainshield and spiral band echoes (Sadowski 1964, Tatehira and Itakura 1966, Senn 1966 a, b). (3) In the case of unsymmetrical or open eyes the direction in which the eyewall is most prominent (Senn 1966 a, b). In all the storms studied the indicator at (2) is found to be usually misleading. For example in the westward moving storm G, the rainshield echo was to the northeast. The indicator at (3) above is, however, found applicaable to some extent in the case of storm F. Between 00 and 03 GMT of 31 October 1977 the visible

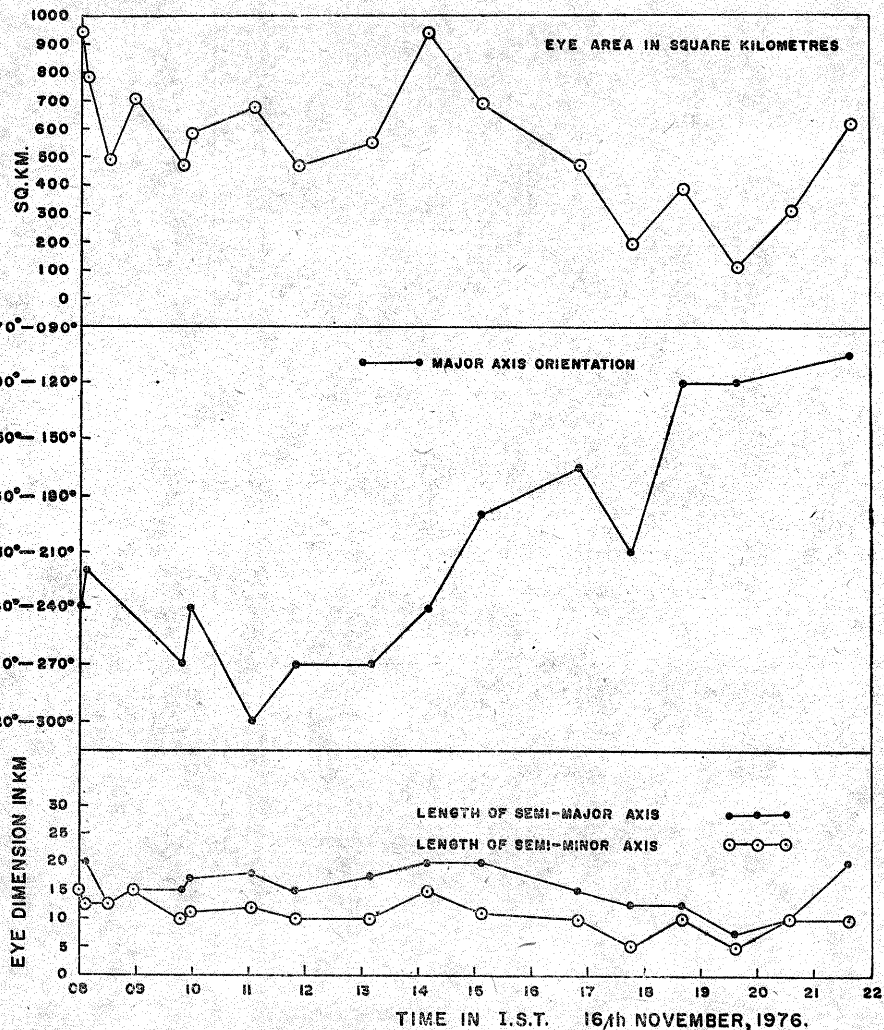

Fig. 11. Kavali cyclone of November 1976. Eye changes.

TABLE 2

Error (in km) in prediction of point of landfall by extrapolating a six-hour smoothed radar track

Storm	Time of prediction (Hours before landfall)			
	6	12	18	24
A	+10	+60	0	—95
D	0	—50	X	X
F	+80	X	X	X
G	+31	—39	X	X
H	—05	+55	+12	+32

X : Data not available.

\+ : Predicted point of landfall is to the right (N or E) of the actual landfall

— : Predicted point is to the left (S or W)

eyewall made a rapid rotation (Figs. 6 and 7) as discussed earlier (Sec. 3). The storm which was till then moving northwestwards simultaneously changed course and moved westwards. An extrapolation of track even 6 hours before landfall could not, therefore, have given a prediction better than 80 km out. In the case of storm A, the visible eyewall was roughly in the western sector and in the direction of motion, but its oscillations from time to time (Fig. 3-a of Raghavan and Lakshminarayanan 1974) do not correlate well with changes in track. Hence the indicator (3) is not a reliable means of track prediction.

6. Assessment of storm intensity

Estimation of storm intensity while it is out at sea is one of the most difficult problems, and often overwarning or under warning results. Baynton (1977) has suggested the use of a pulsed Doppler radar at the head of the Bay of Bengal to obtain the windfield in the storm and

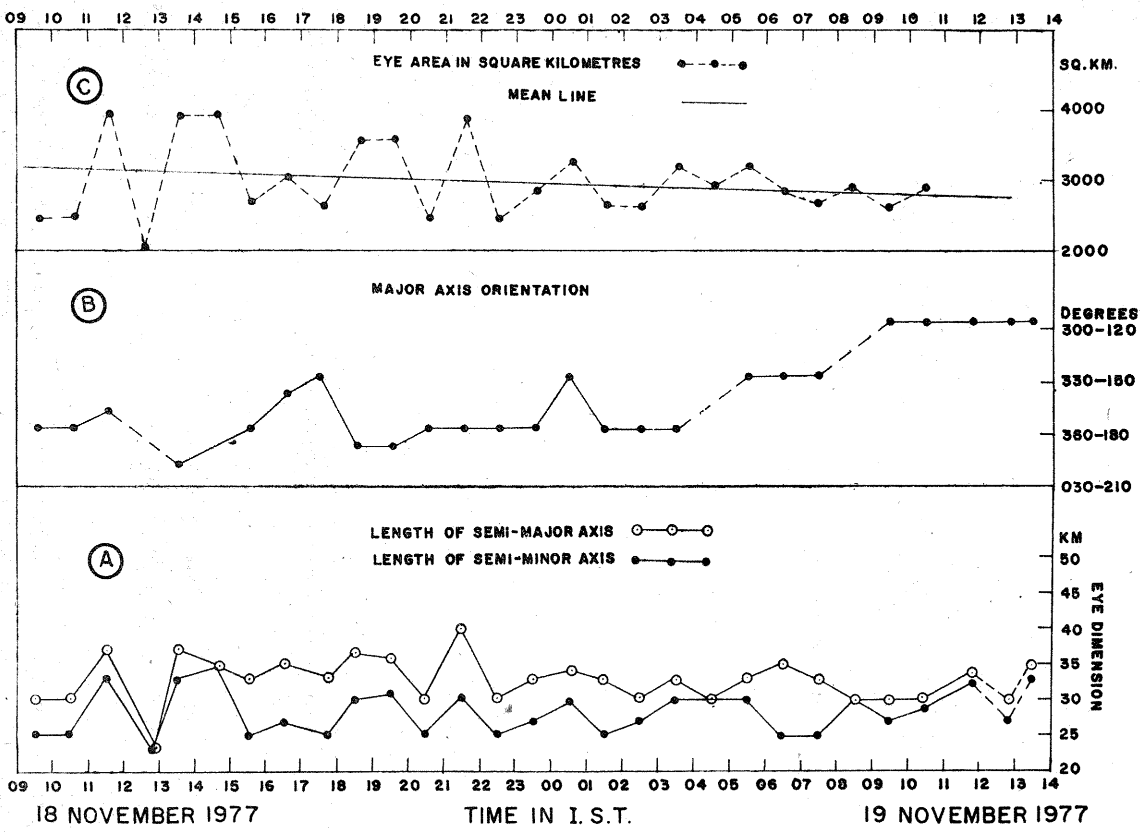

Fig. 12. Chirala cyclone of November 1977. Eye characteristics.

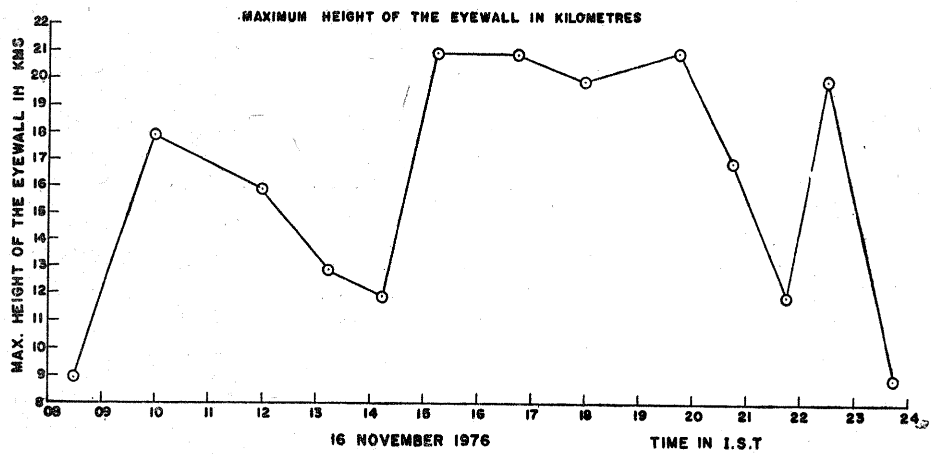

Fig. 13. Kavali cyclone of November 1976

thereby determine the storm intensity. It is, however, worth considering how far the conventional radar itself can be utilised to assess storm intensity.

It is generally recognised that a well-formed closed eye as seen on radar (or satellite pictures) indicates an intense storm. However in many cases the observed eyewall closes and opens repeatedly (*e.g.,* Figs. 8, 9, 10). It appears difficult or atleast operationally impractical to take these as indication of changes in storm intensity. The changes in the *size* of a closed eye (*e.g.,* Figs. 8 and 10), do appear to be related to storm intensity. A recent WMO report (WMO 1977) also indicates that a reduction in eyewall radius as seen in satellite pictures is an indication of intensification. In storms D, G and H the major and minor axes were measured for every hour and the eye area calculated (Figs. 11 & 12 and also Fig. 12 of Raghavan and Veeraraghavan 1979). In the case of storm H (Fig. 12) there

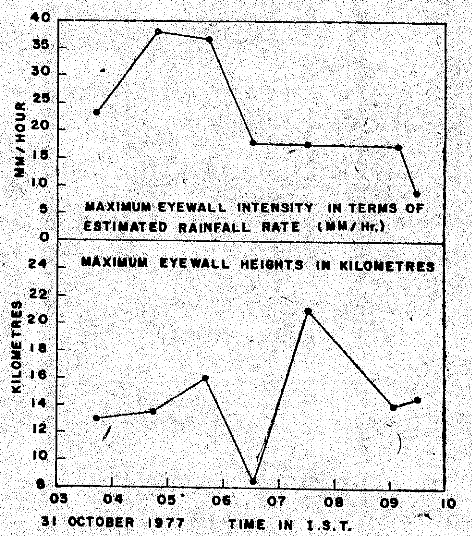

Fig. 14. Kavali cyclone of 31 October 1977

was no appreciable change in eye area but in the other two the eye shrank in size. In the case of storm D, it is known that though the damage was restricted to a small area, it was severe and the winds were estimated to be 120 to 140 kmph. The reduction in the eye size in Fig. 11 suggests that though the areal extent diminished the system became or remained a severe cyclonic storm with a core a huricane winds. As discussed by Raghavan and Veeraraghavan (1979) the reduction in eye size in storm G is remarkable. This storm also became severe with a core of hurricane winds during this period. Hence a consistent reduction of eye size over several hours appears to be a definite sign of intensification. Comparison of eye sizes between one storm and another are however *not* meaningful.

It appears at first sight reasonable to associate the vertical development of the eyewall and its rainfall rate with the intensity of the storm. The radar could observe height of maximum cloud top in the eyewall by RHI presentation whenever any part of the eyewall was within about 200 km range. Assuming normal radio propagation, the observed heights corrected for earth's curvature and finite beamwitdth were plotted against time in the case of storms D, F and H (Figs. 13, 14 and 15). Since the eyewall height in F is far greater than in severe storm H, it is apparent that eyewall heights of one storm and another cannot be compared as indicators of intensity. In the case of storm F, there was probably over-estimation of heights because of abnormal propagation.

Within a given storm the variation in eyewall heights appear to have some relation to intensity changes. In storm D the eyewall height increase (Fig. 13) is roughly simultaneous with decrease of eye size (Fig. 11). In storm H, there is a trend of eyewall heights decreasing (Fig. 16), at the same time as the intensities of rainfall both in the eyewall and elsewhere decreased and the overall size of the radar echo also decreased. Hence within the same storm a consistant change in eyewall height over several hours may probably indicate a corresponding change in storm intensity but the evidence so far available is inadequate to treat this as a reliable method of intensity assessment.

If the radar is properly calibrated, the highest iso-echo level at which the echo is seen can be related to the rainfall rate using a standard radar reflectivity factor *vs* rainfall rate relationship. Despite several corrections applied such computations should be taken only as rough order-of-magnitude values for hour to hour comparison. Figs. 16, 14 and 15 show the variation of maximum eyewall rainfall rate with time in storms D, F and H respectively. A similar curve presented by Raghavan and Veeraraghavan (1979) in Fig. 13 of their paper for storm G shows that the eyewall rainfall rate is positively correlated with storm intensity. In storm H, the rainfall rate is decreasing along with the height decreases already discussed. In storm D, the eyewall rainfall rate increased in the evening when the eye size diminished, and maintained a high value for several hours. In storm F, which was definitely not a severe one, high rainfall rates were present in the eyewall in the early morning hours of 31 October but diminished later. Hence no storm to storm comparison of rainfall rates appears valid but within the same storm the variation of the eyewall rainfall rate may be an indication of variation of storm intensity.

Besides the eyewall parameters, the degree of organisation of the banded structure should reasonably be correlated with the storm intensity. It has not been possible to assign any numerical measure for the degree of organisation but as already mentioned, immature storms such as C and E do not show consistent and stable organised banding. In less intense storms the eyewall is not fully developed. The number of bands was large and their spacing very close in the case of the intense cyclone H and the crossing angles of some of the bands were very small. Hence qualitatively it can be stated that the degree of organisation observed by radar can be regarded as a measure of storm intensity. It appears desirable to formulate a procedure — on the analogy of the Dvorak (1972) system for satellite pictures — to assign a numerical categorisation based on the bands observed, the eyewall development and so on.

In the case of storm H, Fig. 15 suggests that there may be a diurnal variation superimposed on the other changes in the eyewall rainfall rate and eyewall height, with maxima at about 1100 and 2300 IST and minima about six hours after each maximum. Mukherjee *et al.* (1977) have

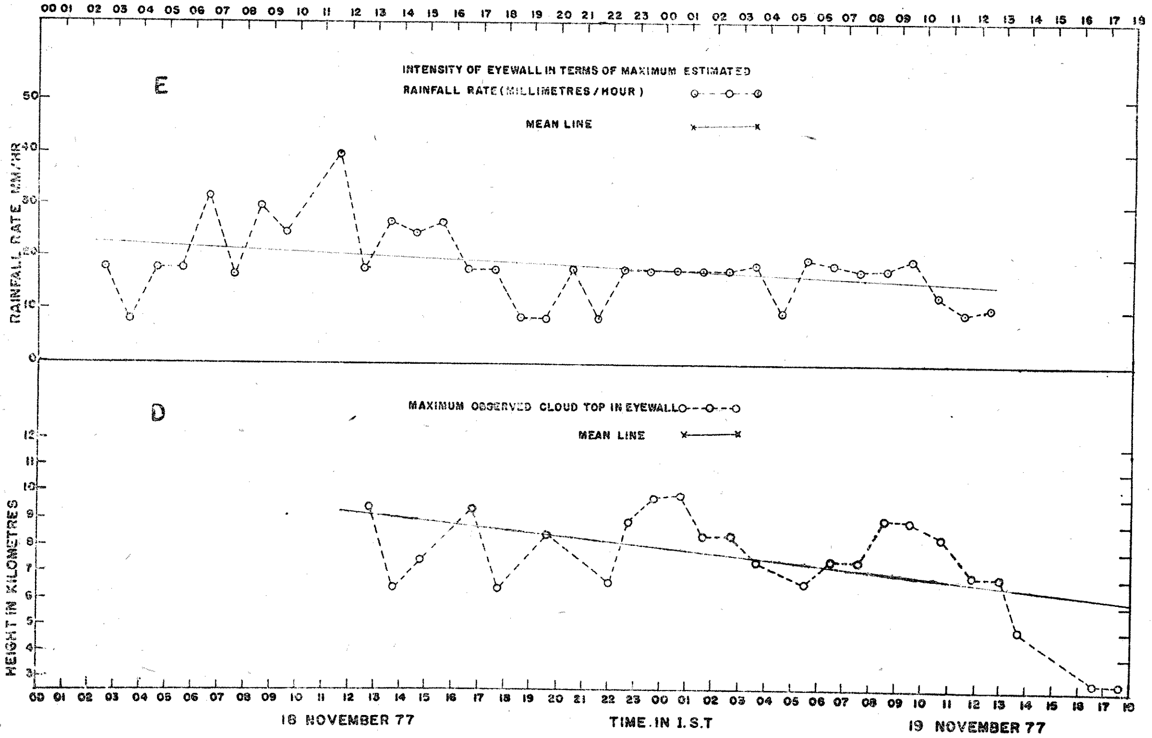

Fig. 15. Chirala cyclone of November 1977. Eye characteristics.

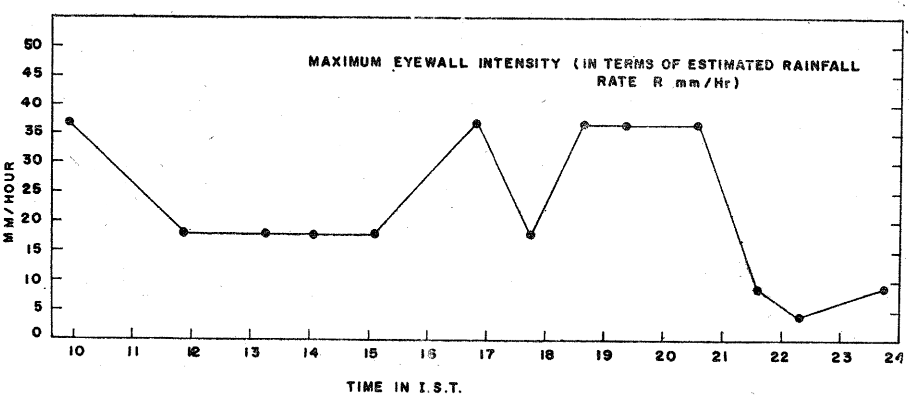

Fig. 16. Kavali cyclone of 16 November 1976

observed that there is a diurnal variation of activity associated with Arabian Sea cyclones, the maximum occurring at night. To eliminate such effects while considering variation of storm intensity, changes in various parameters should be observed for several hours before coming to any conclusion.

7. Other operationally useful information obtainable by radar

The actual distribution of radar echoes in the storm field should give an indication of the areas which will be particularly affected by heavy rainfall and other severe weather. For example, a comparison of Figs. 8, 9 and 10 would show that the areal extent of storm D gradually diminished although the storm was coming closer to the radar. At the time of landfall the damage was confined to an area of about 50 km across. In such cases it should be possible to restrict the warnings to fewer districts than it would otherwise be done, and get greater credibility for the warnings. Care has of course to be taken to allow for the effects of any radar limitations. Information on areal extent is at present indicated roughly in operational messages by the code figure for distance between the end of the outermost observed spiral band and the eye. Also as Raghavan and Veeraraghavan (1979) have

Fig. 17. 2235 IST of 16 November 1976. Storm D. "Streamers" seen to the rear of the storm.

shown the eye of storm G was very small with few bands immediately to the north of the centre. The eyewall was most prominent on the southern side. Hence the maximum damage occurred in a narrow strip close to the point of landfall and relatively less precipitation occurred immediately to the north. This storm also showed a large rainshield echo in the *right rear sector* of the storm (*i.e.*, northeast of the centre)—an unusual feature. This echo remained stable for several hours and moved over areas about 150 km north of the storm track a few hours after the landfall of the eye and caused heavy rain in those areas. The presence of such an echo could be used for flood warnings to the particular area a few hours ahead.

Rockney (1956) has observed that very narrow trailing bands or streamers' of great intensity often occur in the rear of the storms. They apparently form part of the spiral band system but are separated from the centre by 100 km or more of clear area. When they come over land, they often cause very heavy rain and floods over narrow strips of territory. Such 'streamers' were observed in storms D, F and H well to the southeast of the centre but dissipated over the sea. An example is given in Fig. 17. Their non-observance in the other cases may be due to radar range limitations. The presence of such features over the sea if observed for an adequately long period, can be made use of while issuing warnings for rain or flood. It may be possible to do this even in the case of immature storms which cannot be located accurately.

8. Cloud structure

As pointed out by Raghavan (1977), the rainshield area consists of echoes of relatively low heights and exhibiting bright band while the pre-cyclone squall lines, the inner spiral bands and the eyewall itself are distinctly convective and extending to considerable heights. These do not usually exhibit a bright band. The observed vertical structure in the eyewall and inner bands suggests the presence of supercooled water. Thus a detailed study of RHI pictures gives useful information on cloud structure.

9. Conclusions

Study of a number of cyclonic storms observed by radar in the south and central Bay of Bengal shows that storms in this part of the Bay may be either (1) immature ones with poorly developed banding not capable of being tracked properly by radar or (2) well developed ones exhibiting an open or closed eye as well as other features generally associated with a hurricane or typhoon. The latter can be tracked by radar initially from the observed spiral bands and co-ordinating with satellite and synoptic evidence. When a fully formed eye is visible, tracking becomes more accurate. The usual maximum range of tracking is about 300 to 350 km except that in some cases either due to abnormal propagation conditions or unusual storm intensity, longer ranges are possible. When fixes are available for at least six hours with fair or good accuracy, the extrapolated radar track gives a fairly good prediction of point of landfall, provided there are no synoptic indications of major change of course. Other methods of prediction of storm motion from radar features do not seem satisfactory. Besides tracking a storm, radar usually gives information on eye shape and size, eyewall intensity and height, areal extent of the storm, degree of organisation, cloud structure and areal distribution of rainfall. Some of these parameters can probably be carefully interpreted to assess storm intensity and others used operationally in warnings for severe weather and floods.

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