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Radar observations of tropical cyclones over the Indian Seas

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सार — भारतीय समुद्रों में उठने वाले उष्णकटिबंधीय चक्रवातों के संबंध में रेडार प्रेक्षण पर यहाँ एक समीक्षा प्रस्तुत की गई है। सक्रिय चक्रवातों का पता लगाने तथा चक्रवातों के संबध में पूर्वानुमान के लिए रेडार के उपयोग के साथ-साथ चक्रवातों की सरंचना, पवन, वर्षा वितरण और चक्रवात की चाल के संबंध में रेडार प्रेक्षणों से उपलब्ध सूचना पर चर्चा की गई है। भारत में प्रचालनात्मक डॉप्लर रेडारों के सम्भावित आगमन के संदर्भ में प्रचालन और अनुसंधान के लिए रेडार के उपयोग के संबंध में भविष्य की संभावनाओं की रूपरेखा प्रस्तुत की गई है। अन्य प्रेक्षणों और रेडार के एक साथ अध्ययन द्वारा जिन क्षेत्रों के चक्रवातों के संबध में हम बेहतर जानकारी प्राप्त कर सकते हैं, कुछ ऐसे महत्वपूर्ण क्षेत्रों की सूची यहाँ दी गई है।

ABSTRACT. A review is presented of the radar observation of tropical cyclones in the Indian seas. The use of radar in operational cyclone tracking and forecasting as well as the knowledge gained from radar observations of the structure, wind and rainfall distribution and motion of cyclones are discussed. In the context of the expected introduction of operational Doppler radars in India, the future prospects in the use of radar for operations and research are outlined. Some important areas where our understanding of cyclones can be improved by studies with radar in conjunction with other observations are listed.

Key words — Radar, Doppler, Cyclone structure, Eye, Eyewall, Motion, Wind, Rainfall distribution.

1. Tropical cyclone as observed by radar

1.1. *Suitability of radar for tropical cyclone observation*

The tropical cyclone (hereafter referred to as 'cyclone' or TC for short) is a meteorological phenomenon particularly suited for observation and study by microwave weather radar, because of the spatial and temporal scale of the cyclone as well as the organized pattern of precipitation in it which the radar can detect.

1.2. *Radar capabilities*

Conventional pulsed weather radar as used operationally in most countries functions at a radio wavelength of 10, 5 or 3 cm. At these wavelengths the radiation from the radar is scattered back by precipitation particles. Thereby the position and structure of precipitating weather systems are detected. The power returned by a particle to the radar is proportional to the sixth power of the particle diameter. The sum of the sixth powers of the drop diameters in unit volume is known as the radar reflectivity factor (loosely called "reflectivity" although this is strictly not correct). The reflectivity factor represented by the symbol z is expressed in $mm^6\ mm^{-3}$ or more commonly in dBZ *i.e.* decibels above a value of 1 $mm^6\ mm^{-3}$.

1.3. *Tropical Cyclone (TC) parameters observable by radar*

The structure of the TC and of individual precipitation elements (e.g. cloud tops, presence of a stratified melting layer) can be deduced. By continuous of frequent observation the movement of the precipitating weather system or individual precipitation cells can be tracked. Pulsed Doppler radar which has

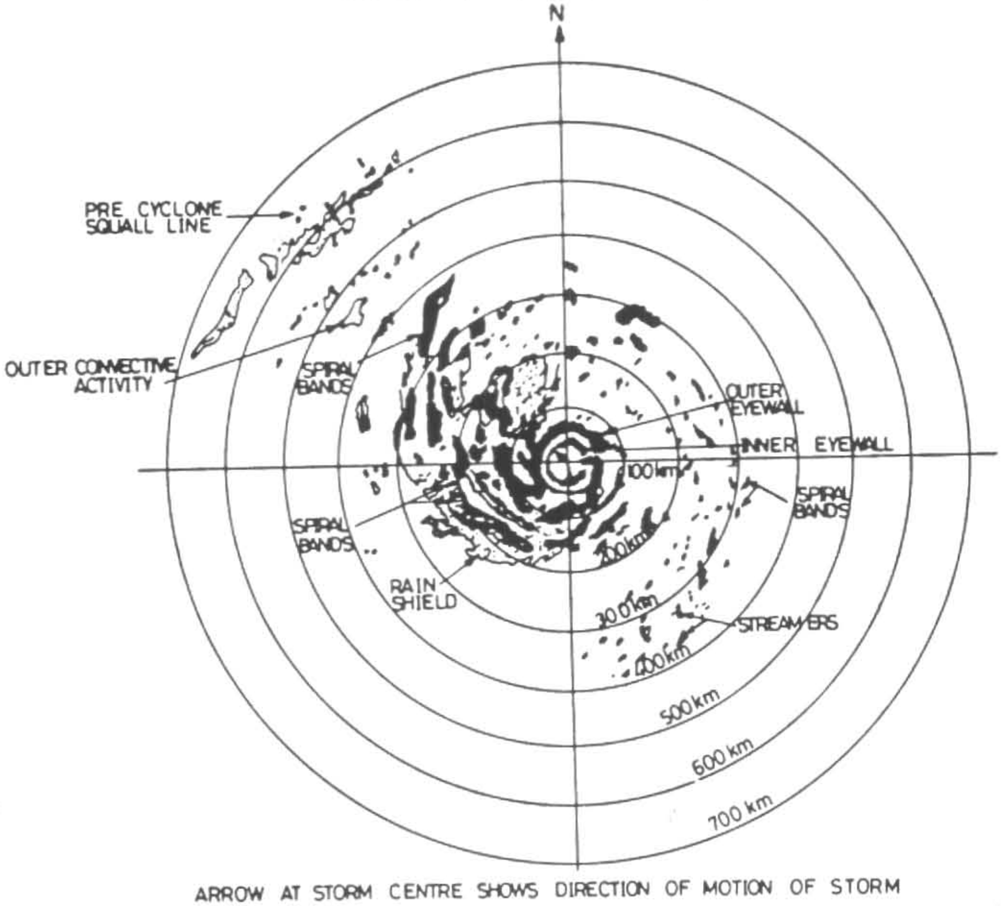

Fig. 1. Horizontal structure of a tropical cyclone as seen by radar (after Raghavan 1985). This is a composite of radar echoes from several cyclones in the Bay of Bengal

been in research use for over two decades and is coming into operational use in recent years can in addition measure the component of velocity of the particles towards or away from the radar and thereby portray the wind field in the weather system. The width of the velocity spectrum can be used to infer turbulence and wind shear.

1.4. *Limitations of radar observations*

Certain limitations of radar observations have to be recognised at the outset. The range upto which a groundbased radar can observe is limited mainly by the earth's curvature. The detectability of a precipitating cloud will depend on its range and its height. The maximum range will also vary with radiowave propagation conditions which in turn depend on the temperature and humidity distribution in the lower troposphere. Though shorter wavelengths produce higher echo intensity, radio waves of wavelength less than 10 cm are attenuated by intervening precipitation in the propagation path. This reduces effective range and also vitiates quantitative measurements. In addition Doppler radars have maximum limits of range and velocity which depend on the specifications of the radar. These limitations imply that a large number of radars are required to cover the country or the entire coastal area. Airborne radars can go close to the weather system under study but have other limitations of size, weight and cost. They cannot be used over land for reasons of safety. There have been very few cases of airborne radar observation of TC's in the North Indian Ocean basin.

1.5. *Radar observations in India*

Radar observations started in India in the early 50's with radars operating at a wavelength of 3 cm mainly to detect local thunderstorms. In the early seventies a set of 10 cm radars were set up along the Indian coasts mainly to detect and track cyclones. The wavelength of 10 cm enables long distance tracking (nominally up to about 400 km) free from attenuation by intervening rainfall. Doppler radars are expected to be introduced shortly at these locations. The neighbouring countries around the Bay of Bengal also have a few weather radars capable of tracking cyclones.

2. Cyclone structure as observed by radar

2.1. *Model of TC structure*

The first published radar observation of a cyclone was made from aircraft by Maynard (1945) of the U.S. Navy. Though Henry Piddington (1848) in India realised as early as the last century that it was coiled up like a serpent and christened the phenomenon as a "cyclone", it was only from the radar that the spiral structure of the rain bands could be observed for the first time. Based on observations in several TCs in the Atlantic and the Pacific from airborne and ground radar, a simple structural model was given by Rockney (1956) and later by Kodaira (1964). In the Indian region the first published radar detection of a cyclone was by De and Sen (1959) using a 3 cm radar at Calcutta. Fig. 1 gives the typical horizontal structure of a well-developed TC obtained by Raghavan (1985) by compositing radar echoes from a number of cyclones in the Bay of Bengal. Following these authors the radar echoes from a TC may be classified as below:

(*i*) Pre-cyclone squall lines,

(*ii*) Outer convective activity,

(*iii*) Spiral rain bands and rain shield,

(*iv*) Eyewall (sometimes a double wall),

(*v*) Streamers.

2.2. *Airborne radar observations*

Willoughby (1988) who used observations with air-borne radars including Doppler, has given the typical reflectivity (hence precipitation) distribution. It is possible to derive from this the air motions even in the absence of direct Doppler measurements. Willoughby (1988) has also illustrated the "secondary" (*i.e.*, radius-height plane) circulation.

2.3. *Radar-observed products*

The observed echo structure apart from being of intrinsic scientific interest enables the position of the centre of the cyclone to be determined. This leads to the tracking of TC motion, prediction of further motion and estimation of the intensity of the TC. It is also possible to assess the spatial distribution of rainfall and Latent Heat Release (LHR). The detailed observation of the structure of the TC can also be used to infer the Radius of Maximum Winds (RMW) and the areas of maximum wind damage in the core of the TC. Doppler radar may enable determination of the maximum wind.

2.4. *Development of features*

The features listed refer to a typical well-developed TC and may not be present in all TCs. As the TC develops from an initial disturbance some of these features are seen to develop gradually and undergo changes from time to time. Even so, because of the large size of the TC, a single stationary radar is unlikely to see all the features at one time. A composite of pictures from several radars with overlapping coverage or a time composite of observations with the same radar will give a more complete description of the entire TC. Land-based radars will still not be able to see parts of the TC which are far away from them because of range, height and signal strength limitations. Much of the recent knowledge of TC core structure has come from airborne radar observations.

2.5. *Pre-cyclone squall lines*

Pre-cyclone squall lines (Fig. 1) are lines of convective cells appearing about 300 to 500 km ahead of the TC centre and usually well separated from the spiral rain bands of the TC. They may be straight lines or of zig-zag shape but do not follow the spiral pattern of the rain bands. Each line may be up to a few hundred km in length and there may be several lines roughly parallel to each other. The set of squall lines may undergo changes due to decay and regeneration of component cells as in other mesoscale systems but do not appear to form large mesoscale anvils as most other squall lines do.

They move with the rest of the TC at the same speed. Hence usually they arrive over land before the core of the TC and cause heavy convective precipitation over narrow strips. In the Bay of Bengal, Raghavan *et al.* (1980) found that in all cases in which they were observed their orientations were roughly perpendicular to the direction of TC motion at that time. They proposed that the orientation be used as a predictor of TC Motion.

2.6. *Outer convective activity*

Outer convective activity (Fig.1) or outer bands are names assigned by some authors to echoes largely convective but poorly organized which are observed in some TC's behind the pre-cyclone squall lines but ahead of the organized spiral bands.

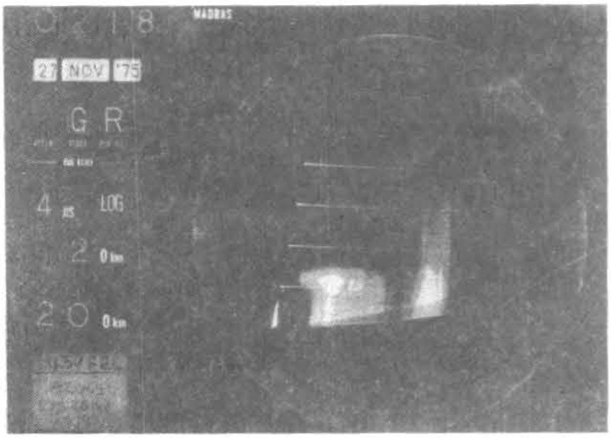

Fig. 2. RHI (Range-Height Indicator) Gray scale presentation of echoes from convective and stratiform precipitation in a tropical cyclone. The echo at right is from convective precipitation and exhibits vertically oriented reflectivity contours. Echo at left is stratiform exhibiting horizontally oriented contours with a maximum at freezing level (melting band). Height markers at 5 km intervals and range markers at 40 km intervals. [Reproduced from Raghavan (1977); courtesy IMD].

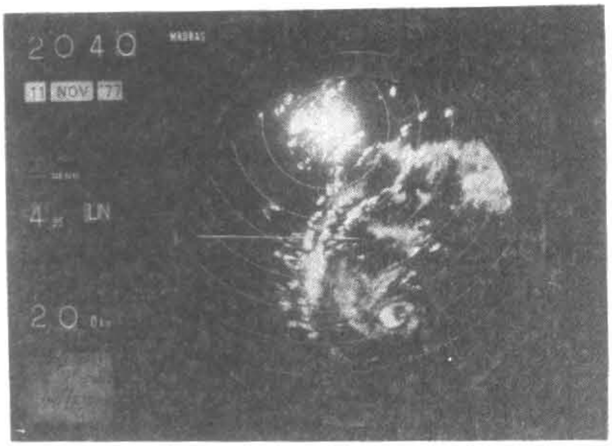

Fig. 3. Eye forming as an extension of the innermost spiral band. 2040 hrs. IST, 11 November 1977. (from Raghavan and Veeraraghavan 1979; courtesy IMD). Off-centre PPI (Plan Position Indicator) picture range marker interval 40 km.

2.7. *Spiral bands*

The spiral bands are precipitation elements arranged along spiral arcs which appear to converge to the centre of the TC. These occur in the region between the outer bands mentioned above and the centre of the TC. These arcs correspond approximately to logarithmic spirals (Raghavan 1985).

The crossing angles of the spirals tend to be small in intense cyclones and relatively large in weaker ones. The bands may often change their organization and tend to break up or distort in shape when they come close to land. Each band is typically 5 to 50 km wide and may be up to several hundred km in length. Some TC's have a large number of bands packed densely; in others there are few bands with large spaces in between. The spiral shape of the bands enables them to be extrapolated to find their centre of convergence and thus the centre of the TC approximately when the eye of the TC is not seen by radar.

A weak TC may exhibit several curved arcs each converging to a different centre there being apparently several rival vortices. (This may be the reason for the TC not intensifying). Mukherjee *et al.* (1977) have described the formation of secondary vortices in an Arabian sea Cyclone. According to them these may exhibit high winds, marked shift in wind direction, pressure fall and copious rainfall. In depressions, rain bands have been observed, but are not sufficiently organised to determine a centre. Hence radar cannot track weak TC's or depressions although it can give other useful information such as rainfall distribution.

In cases where a radar sees only a part of a spiral band, a composite may be made from echo patterns from two or more radars to construct a long enough spiral band to obtain a centre position which is beyond the nominal range of any one radar.

2.8. *Rain shield*

Interspersed with the spiral bands are relatively weak echoes without specific organization which have been termed the rain shield by some authors. The precipitation in these areas is stratiform while that in the spiral bands may be convective or stratiform. In Fig. 2 the echo on the left is from the stratiform rainshield and exhibits horizontally oriented reflectivity contours while the echo on the right which is from a spiral band is convective and has vertically oriented contours.

2.9. *The eye*

When the TC intensifies, the intermost spiral band tends to reduce its crossing angle and become a circle. At the end of the band an eyewall forms approximately

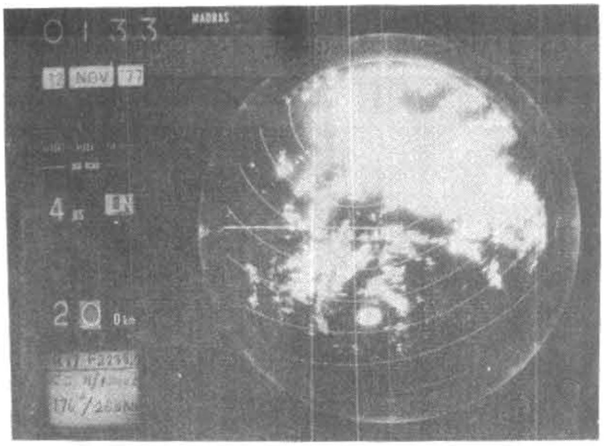

Fig. 4. Same TC as in Fig. 3 but at 0133 IST, 12 November. Eye has separated into a ring. (Compare with previous figure). (from Raghavan and Veeraraghavan 1979; courtesy IMD).

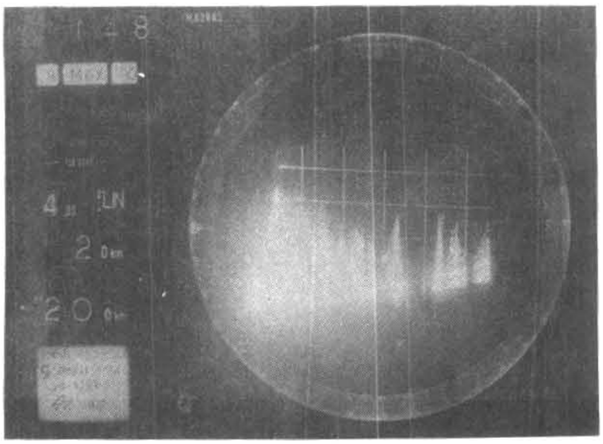

Fig. 5. RHI, 8 May 1990, Madras Radar, showing double eyewall of a TC. Note that the eyewall tapers outwards with height; (courtesy IMD). Height markers at 5 km intervals and range markers at 40 km intervals. Corresponding PPI may be seen in Fig. 15.

in the form of an arc of a circle. Gradually this may separate from the band into a distinct ring or part of a ring with an echofree (or nearly echofree) area inside, namely the eye (Raghavan 1990, 1993). Figs. 3 and 4 with an interval of about five hours between them show this process. This normally occurs at about the time when a TC becomes severe. Holland (1987) has discussed the mechanisms by which such a transformation could occur.

Individual TC's differ widely in structure; there can be cases of intense TC's without forming an eye (Weatherford and gray 1988). On the other hand a "false eye" can develop at the end of a spiral band

Fig. 6. TC at 0958 IST 16 November 1976. Note the polygonal eye. (from Raghavan *et al.* 1980; courtesy IMD). Range setting 200 km.

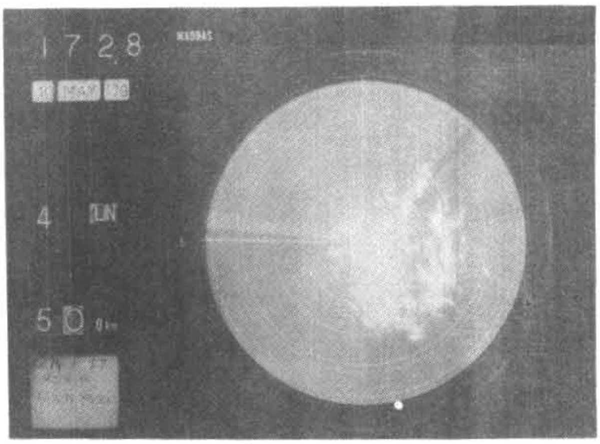

Fig. 7. Eye of TC seen as a comma at 425 km range. 1728/9 IST 10 May 1979. (courtesy IMD). PPI picture; range marker interval 100 km. The large range of detectability is due to anomalous propagation.

in a weak TC without being at the centre of the system and may contain a separate pressure minimum on the high pressure side of the spiral band. (Simpson 1956, Barclay 1972 and Raghavan 1977). This also represents a rival vortex which may inhibit intensification of the TC.

2.10. *The eyewall*

The eye as seen on radar consists of a small, wholly or nearly echo-free area surrounded wholly or partly by a ring of convective precipitation known as the eyewall. The eyewall often slopes outwards with height (Fig. 5), *i.e.*, eye diameter usually increases with height (Willoughby 1988, Raghavan 1993). Precipitation particles fall out of the slopping eyewall

Fig. 8. Cyclone eye over land in West Bengal; Calcutta Radar, 15 August 1974, 1117 UTC. (courtesy IMD).

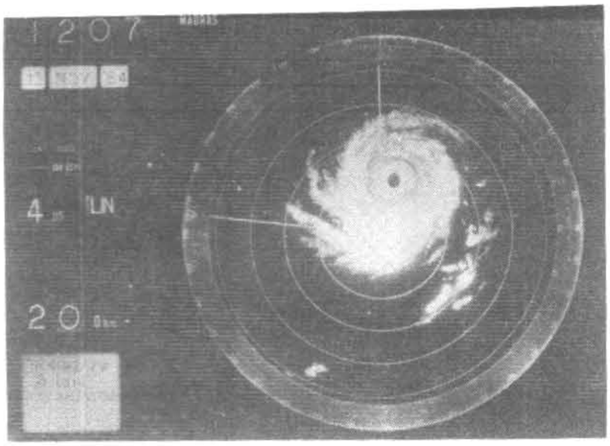

Fig. 9. TC at 1207 UTC. 13 November 1984 eye looking perfectly symmetrical in the raw video display. (from Raghavan *et. al.* 1989; courtesy IMD).

into a precipitation shaft and from a region of high radar reflectivity. Precipitation-driven downdrafts are also present in this region.

2.11. *Characteristics of the eye*

In some TC's only a partial eyewall is seen. If only the nearer side is seen it is possible that the farther side is not seen merely because its reflectivity or height is too low. It is however also possible that the wall is only partly formed. In some cases only the farther side of the eyewall may be seen (Raghavan *et al.* 1980). Fig. 6 shows a fully formed polygonal eyewall, but this opened out later and closed again with a smaller diameter (not shown). The convective nature of the eyewall is clear from the RHI (Range-height Indicator) picture. In Fig. 7 the eyewall is visible as a comma at a range of 425 km. This was possible because of animalous radio wave propagation but it is not possible to say whether the eyewall is completely formed. On the next day when the TC had come closer it was possible to see the complete eyewall but a day later when the TC was still closer, only a partial eyewall could be seen, probably because of subnormal propagation conditions setting in when the TC comes over land the eyewall tends to break up. Fig. 8 shows an exceptional case in which a well formed eye persisted after considerable land travel.

The eyewall is often an unsymmetrical structure around the eye. In Fig. 9 the eyewall appears as a perfect ring, but the reflectivity distribution is highly unsymmetrical. (Iso-echo pictures are those in which echoes above a selected threshold of reflectivity are alone exhibited. The echoes appearing at the higher thresholds obviously are more imtenses). While the eye of an intense TC tends to be a circle, ellipses, polygons or irregular shapes are quite common (Fig. 6). These shapes may vary with time and also rotate around the centre. Raghavan *et al.* (1985) demonstrated the varying and irregular geometry of the eye of a weak TC in the Bay of Bengal. The shape may also appear distorted due to radar observational limitations. For instance, in Figs. 3 and 4 the elliptical shape of the eye with major axis pointing towards the radar has been shown by Raghavan and Veeraraghavan (1979) to be due to radar pulse width and finite beamwidth effects.

2.12. *Double-walled eye*

In intense cyclones a second eyewall sometimes forms around the existing one. The outer wall may be merely a spiral band wrapping itself around the inner eyewall. An example of this in a Bay of Bengal cyclone may be seen at Fig. 5 (RHI) and 15 (PPI, Plan Position Indicator). The space between the two walls known as a moat is largely echofree; (sometimes there is a connecting band between the walls). The two eyewalls need not be concentric. This is known as an asymmetric double eye. There are other cases, however where two concentric rings known as symmetric double eye appear, though none has been reported in the Indian seas. Continuous air-borne radar observation has shown that a cyclical formation and dissipation of the symmetric double eye structure occurs in intense TC's of the Atlantic and Pacific Basins. Corresponding variations in the intensity of the TC

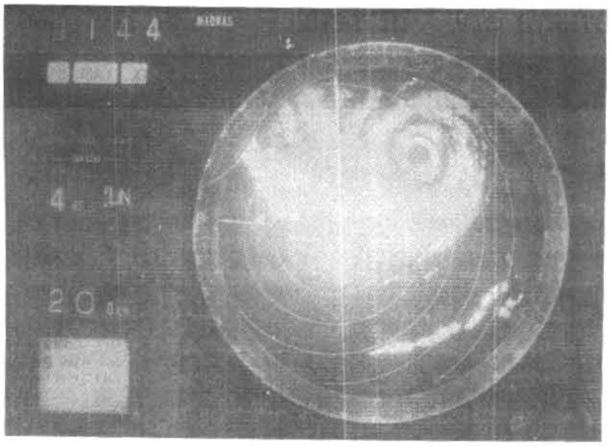

Fig. 10. Double walled eye of intense TC. PPI 8 May 1990, Madras Radar (courtesy IMD). Corresponding RHI may be seen in Fig. 6.

have been observed. Asymmetric double eyes do not undergo such cycles; the reason for this difference is not understood. A double wall of either type generally occurs in deep TC's (say 940 hPa or lower central pressure) but not in all of them. Wind maxima at both eyewalls corresponding to the two radii of maximum radar reflectivity have been observed by aircraft. Colon *et al.* (1970) found from aircraft reconnaissance of an Arabian sea TC an eye of diameter 12 nautical miles with an eyewall width of about 8 nautical miles. The central pressure was 947 hPa. The maximum wind at the 900 hPa level was 96 knots at 12 nautical miles radius. The wind decreased to 65 knots at 18 miles radius but peaked again to 95 knots at 32 miles radius. This was apparently a case of a double-walled eye with wind maxima at both the walls. Raghavan *et al.* (1989) have documented a double wall over land in a Bay of Bengal cyclone.

2.13. *TC centre determination from observation of the eye*

The observation of the eye by radar enables determination of the centre of the TC with considerable accuracy. Where a complete circular eyewall is observed the geometric centre of the ring is easily identified and taken as the centre of the TC although the point of MSLP (minimum sea level pressure) or the "wind centre" may not necessarily coincide with it. When the eyewall is partial or of irregular shape with unsymmetrical distribution of radar reflectivity the determination becomes a little ambiguous. The partial eyewall may be completed subjectively by the analyst to obtain a circle or ellipse and the centre of that figure taken as the centre of the TC. To reduce subjectivity the reflectivity-weighted centroid of the eyewall rather than the geometric centre may be taken as the centre. Meighen (1985) showed in Australian cyclones that fixes obtained by this method give a smoother track. The physical basis for this may be that the wind centre tends to be located closer to the arc of maximum reflectivity in the eyewall.

In a semi-automated system used in the USA with airborne radar the operator subjectively determines a centre point. From this point the software estimates the location of the inner edge of the eyewall along radials at different azimuths, the inner edge being defined as the closest point at which the reflectivity is 4 dBZ higher than at the centre. The centre of the

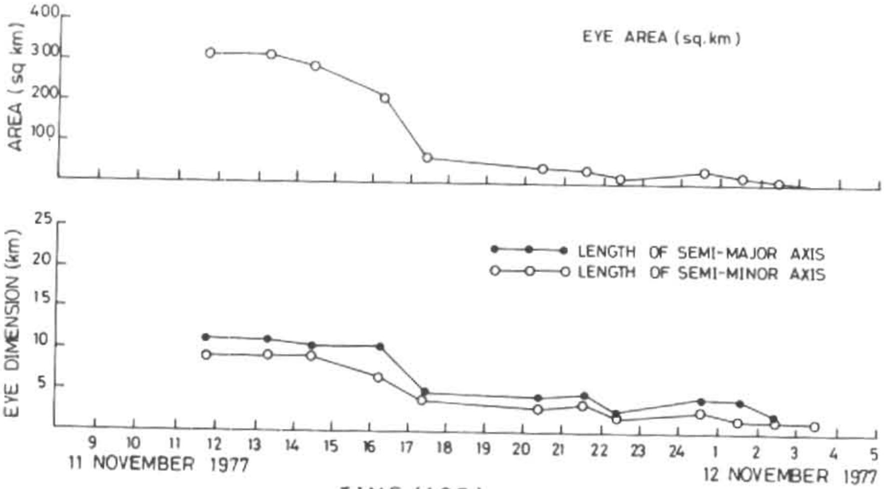

Fig 11. Time variation of eye dimensions of Nagappattinam cyclone 1977. (After Raghavan and Veeraraghavan 1979; courtesy IMD).

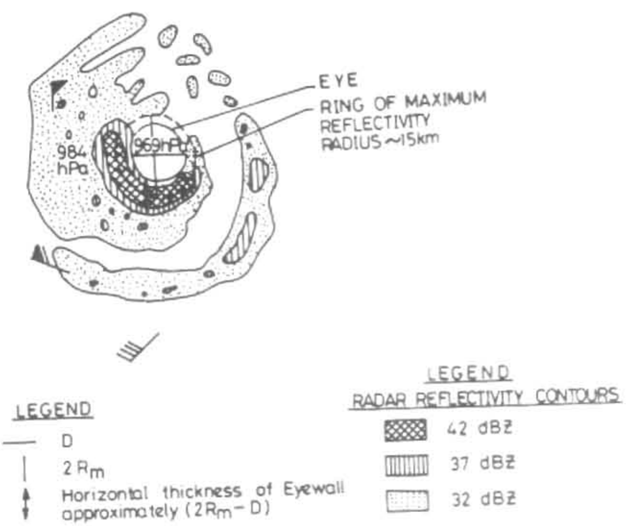

Fig. 12. Model of surface structure of cyclone of November 1984. (After Raghavan *et al.* 1989; courtesy IMD).

circle that fits the locations of the inner edge points is taken as the objective estimate of the centre of the eye.

2.14. *Streamers*

Beyond the eyewall the pattern of spiral bands and rainshield repeats although not symmetrically. Behind the central mass of echo there are usually more echo-free areas but further away, the rear ends of the spiral bands often extend as nearly straight convective lines associated with heavy precipitation. Rockney (1956) called them streamers. These move with the TC and are often responsible for narrow strips of heavy rainfall in the rear sector of the TC. Examples of streamers may be seen at Figs. 9 & 10.

2.15. *Variation of eye configuration and size*

The inner edge of the eyewall may have a variety of shapes but in most cases it can be treated as an ellipse with semi-major and semi-minor axes a and b which can be measured from the radar picture. The axial dimensions observed by radar range from a few km to over 50 km. Fig. 11 shows the variation of the eye dimensions of a TC with time.

2.16. *Radius of maximum reflectivity*

Another possible measure of the size of the eye is the radial distance from TC centre to the point of maximum radar reflectivity in the eyewall. Raghavan *et al.* (1989) have defined this as the Radius of Maximum Reflectivity (RMR) or R_m in Fig. 12, where the eyewall is unsymmetrical a line can be drawn through points of maximum reflectivity and an average value of R_m obtained.

The importance of this parameter is that the RMR coincides roughly with the Radius of Maximum Winds (RMW) of the TC determined independently of the radar. Since reflectivity is a measure of rain rate this means that maximum rain rate also coincides with the RMW. Jorgensen (1984) found in several hurricanes that the zone of maximum eyewall radar reflectivity was several km radially outward from the RMW at low levels while at higher levels the locations of both coincided. Marks and Houze (1987) who had the benefit of winds from Doppler radar found in a hurricane that the tangential wind maximum was 4 km radially outward from the reflectivity maximum and both sloped radially outward with height. In the airborne radar study of Colon *et al.* (1970) referred to earlier, the RMW coincided approximately with the middle of the radar-observed eyewall. By comparing radar observations with post-cyclone wind damage surveys Raghavan and Veeraraghavan (1879) and Raghavan *et al.* (1984) found that the tracks of the maximum wind damage and eyewall reflectivity maximum were approximately co-located. Hence RMW can be taken as approximately equal to the RMR. However, since the height at which radar measures the RMR varies with range it is difficult to establish whether, in general, the RMR is outside the RMW or vice versa.

The measurement of RMR is used operationally in the India Meteorological Department (IMD) to estimate the RMW for use in storm surge prediction.

2.17. *Echo heights and reflectivities*

Fig. 13 shows the radar-determined echo heights in the core and periphery of a Bay of Bengal TC. Although some errors due to the observations being at different radar ranges may be involved, it is generally seen that the heights in the core or eyewall region are lower than in peripheral areas. This is common in many TC's although the eyewall is predominantly convective and very tall convective clouds do occur in the eyewalls of some TC's. By contrast, tops of severe thunderstorms in northeast India often extend beyond 20 km. Thus the echo top heights in TC eyewalls are often lower than in local severe storms. Heights obtained by stereoscopy or from IR imagery from satellites are relatively higher perhaps because of a blanket of cirrus which shows up on the satellite but at the same time the convection does not penetrate the tropopause.

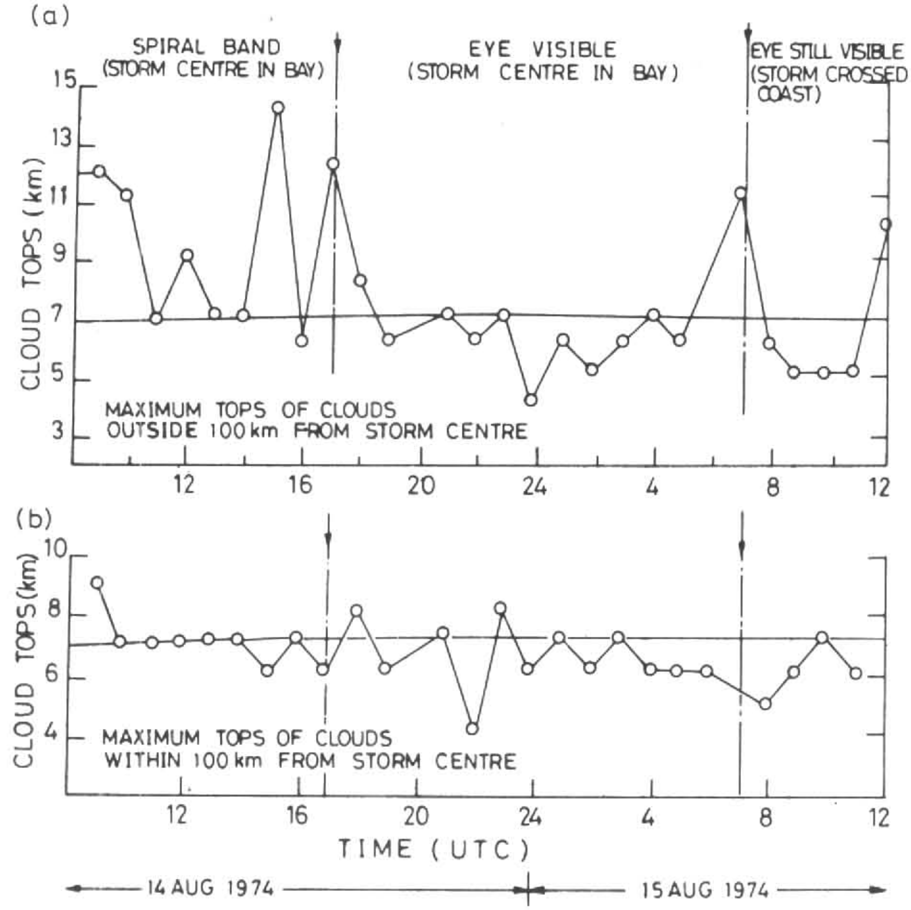

Fig. 13. Maximum echo tops in Bay of Bengal TC of 14 to 15 August 1974. (a) beyond 100 km from TC centre; (b) within 100 km from TC centre. (courtesy IMD).

The reflectivity in the eyewall region has a maximum value of about 40-45 dBZ (Fig. 12) at low levels (850-700 hPa) and decreases rapidly beyond the freezing level. Similar results have been reported in other basins whereas much higher dBZ values are found in mid-latitude thunderstorms. It was found that the eyewall is dominated by updrafts but their velocities are generally weaker than in local severe storms. Observations of vertical velocities are not available in TC's of the Indian seas but judging from the heights and reflectivities, convection appears to be generally weaker in TC's than in local severe storms.

2.18. *Asymmetry in reflectivity distribution in the eyewall*

The reflectivity distribution around the eyewall is generally asymmetric and there are corresponding asymmetries in the wind distribution. At latitudes higher than about 20 degrees the eyewall echo concentration and reflectivity as well as wind are highest in the right and front, but several cases have been documented in the Atlantic with highest reflectivity to the left of the track (Marks and Houze 1987). The reflectivity maximum coincides, as already noted, with maximum wind and rain rate. The concentration of these quantities in the left sector is considered unusual by some scientists but in most southern Bay of Bengal cyclones (south to about 20 degrees N) maxima of these quantities were found in the left sector (Biswas *et al.* 1988, Raghavan 1990, Raghavan and Veeraraghavan 1979, Sivaramakrishnan and Sridharan 1989). This has been verified by post-cyclone damage survey and rainfall analysis which indicated maximum wind damage and highest intensities of rainfall in the swath traversed by the left sector of the eyewall, in these cases (Raghavan and Veeraraghavan, 1979; Raghavan *et al.*, 1984). In the Atlantic basin Simpson and Pelissier (1971) documented the case of Hurricane Celia (1970) which exhibited the isotach maximum in the left sector of the eyewall. They attributed it to a cyclonic rotation around the vortex centre which occurs in a non-steady state cyclone. The sector of maximum wind and reflectivity appears to be generally to the left in slow moving TC's and to the right in fast moving ones as predicted by the model of Shapiro (1983). Since the speed of motion of the TC usually increases with latitude, the apparent dependence of the position of the reflectivity and isotach maxima on latitude is explained.

Direct observation by Doppler radar in the Pacific has also shown asymmetries in the Doppler velocity in the eyewall region.

2.19. *Mesoscale structure*

Airborne radar observations in the Atlantic basin (Jorgensen 1984) showed that the (spiral) rain bands do not exhibit well defined wind maxima or highly organised vertical motion. The strongest updraft cores (upto 16 ms^{-1}) and most (over 60%) of the vertical mass transport was in the eyewall. The most significant finding was that outside the eyewall stratiform precipitation predominated with embedded convective cores, the structure being similar to the mesoscale structure found in tropical cloud clusters and squall lines.

Stratiform rain was found to contribute over 60% of inner core rainfall.

Raghavan (1990) has pointed out that in Bay of Bengal TC's the eyewall and spiral bands are essentially convective and no large meso-scale anvils have been observed in contrast to the findings of Raghavan *et al.* (1983) that in non-cyclone tropical convection mesoscale anvils are common. But since Bay of Bengal results are only from land-based non-Doppler radar they cannot be regarded as conclusive. In particular it is possible that mature TC's differ in this respect from weaker systems. This is an area to be investigated.

2.20. *Effect of landfall*

The structure of a TC undergoes modifications on landfall due to increased surface friction over land and the reduced water surface available for evaporation of moisture. The added surface friction reduces the wind speed and increases the cross-isobaric flow towards the low pressure centre. The eyewall usually collapses (an exception may be noted in Fig. 8), the banded structure is distorted and the rainfall and wind distribution also should be expected to change. The increased inflow may however cause increase in mass convergence and upward motion. As a result it is possible that in some cases stronger rotational winds

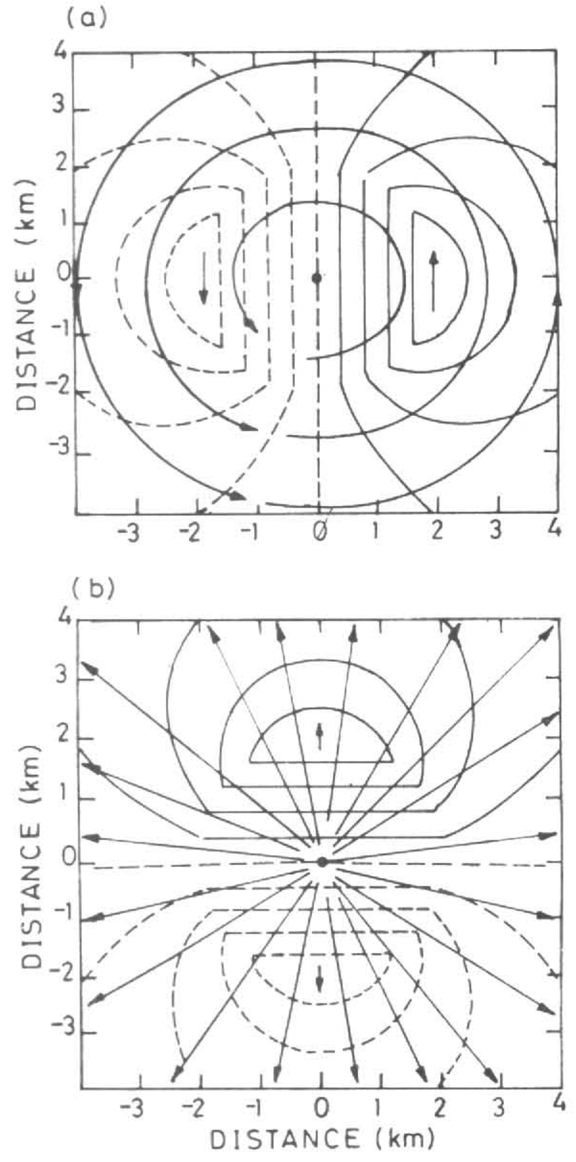

Fig. 14. Doppler velocity pattern corresponding to (A) an axisymmetric vortex and (B) axisymmetric divergent flow. (from Burgess and Lemon 1990; courtesy AMS). Radar is assumed to be south of the picture.

can develop. The eyewall over land in Fig. 8 and the observation of a double wall over land mentioned in para 2.12 may perhaps be explained in this manner. In the TC depicted in Fig. 13 higher echo tops in the core region than outside it are seen after landfall while the reverse was the case over sea.

Mesocyclones and tornadoes may develop either in the eyewall region or the rainbands on landfall of the cyclone, showing localised high reflectivity (and wind in the case of Doppler radar) maxima on radar. The cause is probably frictional drag leading to strong

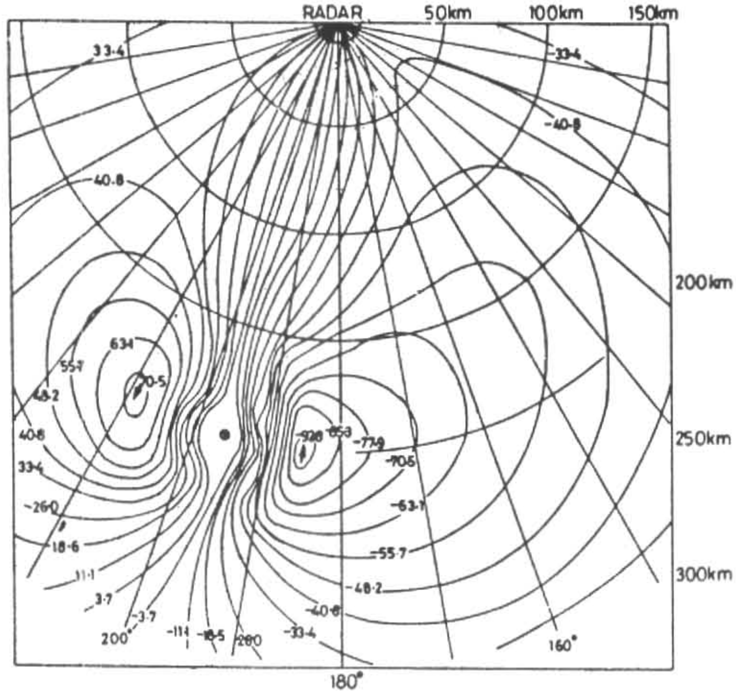

Fig. 15. Radial (with respect to radar) Velocity distribution in a Bay of Bengal Cyclone located at range 200 km and azimuth 196° from a Doppler radar. Speeds in knots. Positive away from the radar. (Simulation by Baynton 1978; courtesy AMS).

vertical shear. These have been extensively documented in the Atlantic basin. In India no tornado cases in tropical cyclones have been documented although damage patterns suggest that they were perhaps present. No radar observations are available.

2.21. *Doppler radar observations*

As Doppler radars are expected to be inducted in the operational network in India shortly, we shall briefly consider the prospects for operations and research using these radars.

As indicated earlier, the Doppler radar can determine the component of velocity of hydrometeors towards or away from the radar, in addition to all the information that a conventional radar gives. This radial component is known as Doppler velocity. If three or more radars are located fairly close to one another the three dimensional wind field in any precipitating system can be derived. In the operational context it is feasible to have only a single radar. Using what is known as a Velocity-Azimuth Display (VAD) technique it is possible with certain assumptions to derive a vertical profile of the wind in a limited area around the radar. Using the equation of continuity it is possible to derive the vertical motion (the fall velocity of hydrometeors is derived from the radar reflectivity and separated from the air motion). The variance of the Doppler velocity can be used as a measure of turbulence. Modern Doppler radars are highly automated and have algorithms to derive various additional products in real time.

What is of importance in the tropical cyclone context is the capability to detect signatures of certain meteorological phenomena from the "isodop" pattern, *i.e.*, the spatial pattern of Doppler velocities. The isodop patterns corresponding to (A) an axisymmetric vortex and (B) axisymmetric divergent flow are given in Fig. 14. Ideally a TC should exhibit a couplet of oppositely direct Doppler velocity maxima as in the figure. These maxima are located on the eyewall of the cyclone. A simulation of the Doppler velocity pattern of the Bay of Bengal cyclone of November 1970 on a hypothetical Doppler radar located at Khepupara (21.9° N, 89.1°E) in Bangladesh made by Baynton (1978) is reproduced in Fig. 15. If this ideal picture is seen, the maximum wind velocity in the cyclone, *i.e.*, its intensity is determined in addition to the position of the cyclone centre. At short ranges the kinematic properties of the vortex can be computed.

However, in practice the eyewall may be partial or unsymmetrical; hydrometeors may not be present at all the relevant points. The couplet may therefore not be seen in all cases. At short ranges the pattern may be distorted. Further, depending on the radar specifications, echoes having velocities greater than a

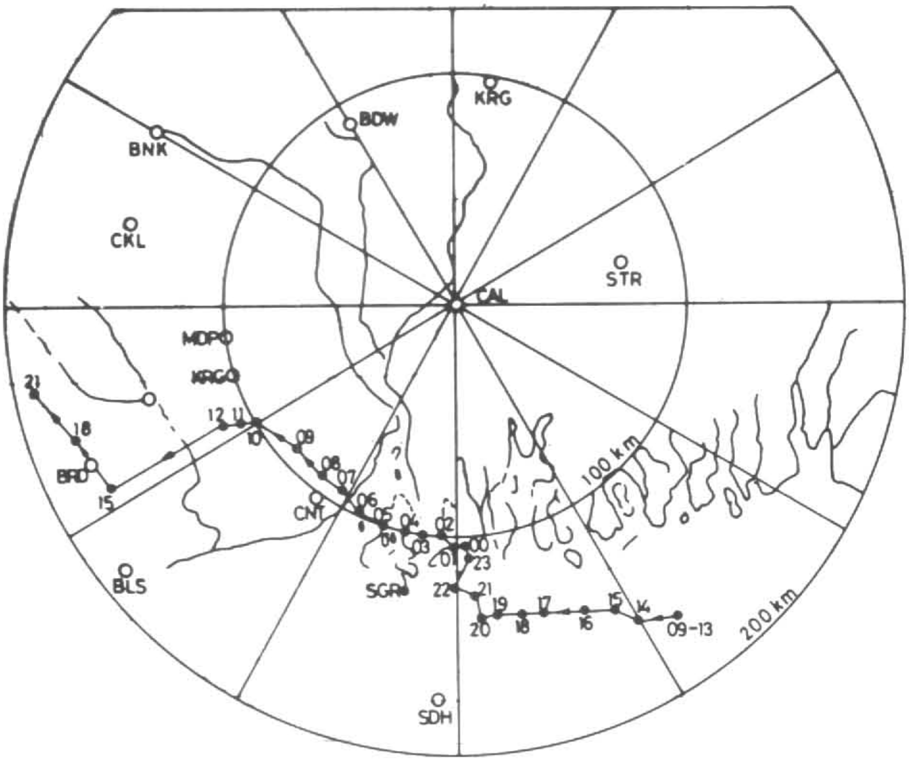

Fig. 16. Track of TC 14 to 15 August 1974 determined by Calcutta radar (courtesy IMD). The Eye was seen from 17 UTC of 14th to 18 UTC of 15th. From 07 UTC of 15th the eye was over land (Fig. 8). Note the track oscillations.

Fig. 17. Track of Bay of Bengal cyclone 15 to 19 November 1977. (After Raghavan 1987; courtesy IMD).

certain limit or range beyond a certain limit may get "folded over" and superposed on other echoes exhibiting lower velocity or range. These ambiguities are sought to be resolved by computer algorithms, not always successfully. There is in fact very little operational experience anywhere in the world with tracking of tropical cyclones using ground-based Doppler radars. Airborne Doppler has been more successful as the aircraft can go close to the storm.

3. Cyclone motion

3.1. *Plotting of a radar track*

Radar has been widely used to track the motion of TC's and with varying degrees of success to predict the future motion over short periods. The centre positions determined by radar either by observing the eye or by extrapolating the spiral bands or from the Doppler pattern can be plotted at regular intervals of time and the track of the TC determined. Examples of such tracks can be seen at Figs. 16 to 18. The accuracy of such tracks will depend on the accuracy of each fix. The latter depends on the echo configuration seen by the radar which in turn will depend on the intensity of the

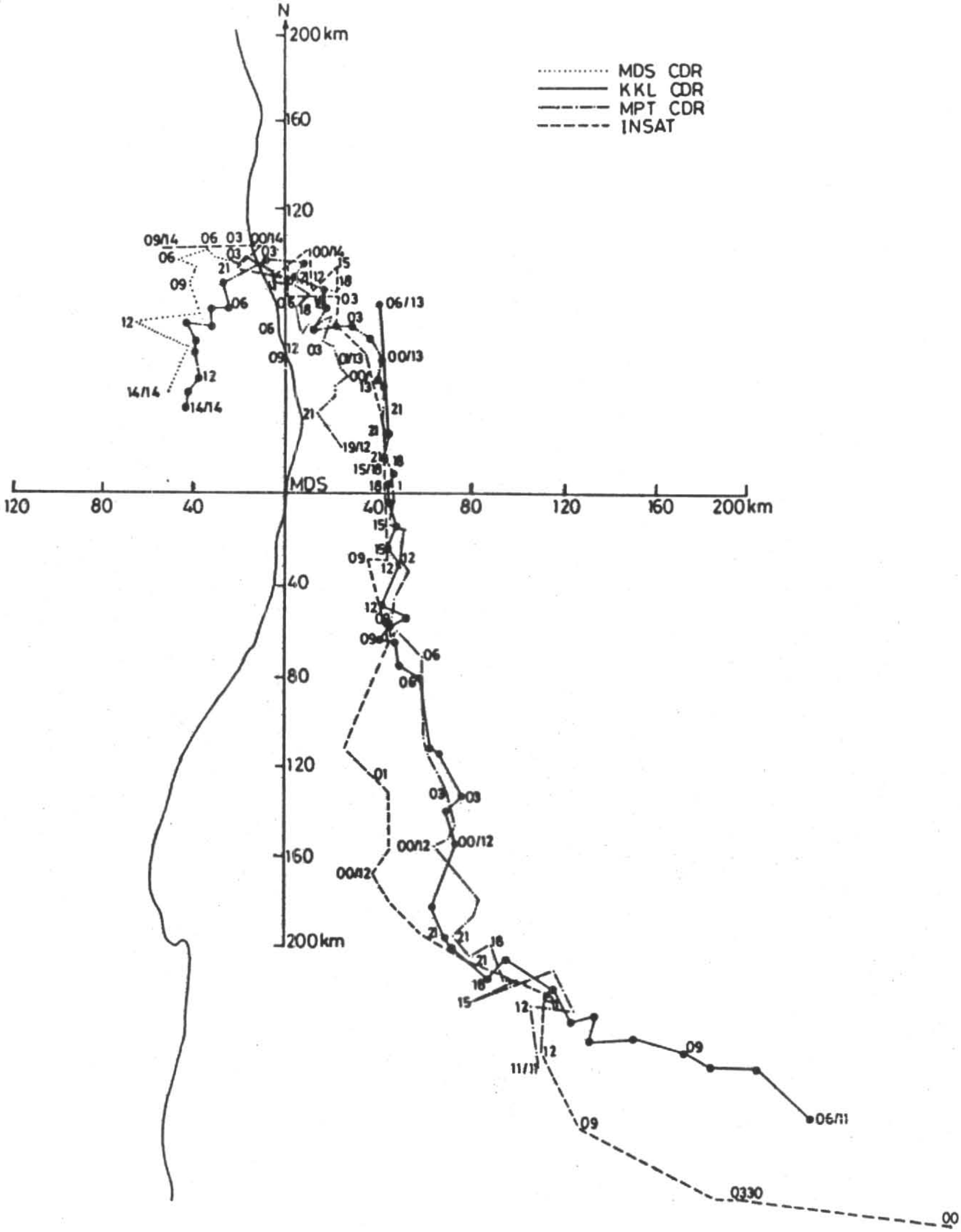

Fig. 18. Track of Bay of Bengal cyclone 11 to 14 November 1984 from three Cyclone Detection Radars (CDR's) at Karaikal (KKL), Madras (MDS) and Machilipatnam (MPT) and satellite (INSAT) (courtesy IMD). Time is indicated in two digits followed by date in two digits whenever date changes.

cyclone, its range from the radar and the characteristics of the radar. In manually operated radars there may be some personal errors of the observer. Several studies have been made by comparing fixes of the same TC from different land-based (manual) radars and satellite (Raghavan *et al.* 1985, Naidu *et al.* 1992, Rajesh Rao *et al.* 1992) and differences of the order of 20 km are found in the cases when a well-formed eye is observed. Fig. 18 shows tracks of the same TC determined from three radars and a geostationary satellite.

To take account of errors it is useful to draw circles around each point showing the probable error in the fix. If an envelop is drawn tangentially to the circles a realistic trend of the motion is obtained. It is to be expected that these circles of confusion will be larger in the case of weak TC's where the eye may not be well-formed or stable or the positions may have been obtained from spiral band extrapolation.

3.2. *Track oscillations*

While some of the apparent oscillations in the track can be attributed to radar observational errors there is often a real oscillation or meandering about a mean path. Fig. 16 is an example. The centre of the eye is believed to rotate cyclonically around the pressure centre of the TC resulting in a trochoidal motion of the eye centre (Barclay 1972, Muramatsu 1986). Theoretical considerations leading to the expectation of trochoidal motion may be seen in Yeh (1950) and Kuo (1969). [A recent study by Holland and Lander (1993) attributes track oscillations to interactions of the cyclone with mesoscale systems within the cyclone circulation]. Some authors have also linked the trochoidal motion with changes in the shape of the eye. Muramatsu (1986) shows that the system centre follows a smoother track than the trochoidal one from radar eye centres. Oscillations in the track can also arise if the TC motion is stalled or it makes a loop especially when changes in upper wind regime cause recurvature. An example of stalling and looping can be seen in Fig. 18.

3.3. *Smoothening and extrapolation of the track*

The fine structure of motion detected by the radar helps to pinpoint the exact path over the coastal terrain and can be used for short period forecasts. However a meteorologist interested in evaluating the overall motion of the system and forecast the motion over a longer period, may prefer to smoothen out some of the short period oscillations. This is particularly important when TC positions are included in warning messages sent to the public.

When a smoothened track or an envelop of the track is available for several hours the average speed of motion can be determined. The track can then be extrapolated to predict motion for several more hours and predict the point and time of landfall (Raghavan *et al.* 1980, Meighen 1985). An example of linear extrapolation is shown in Fig. 17. The linear extrapolation is often remarkably successful over short periods but evidently it can be applied only if there are no meteorological indications of radical changes in direction or speed of motion of the TC. Instead of linear extrapolation, fitting of a polynomial to available radar fixes has been tried. Better results can be obtained if the radar observations are combined with other data. Interactive displays can be used to combine imagery of a network of radars and of a satellite to obtain the best past track and extrapolation can be attempted from such a track.

3.4. *Predictors of TC motion*

Some radar-observed features have been tried as short period predictors of TC motion. The orientation of pre-cyclone squall lines has already been mentioned. Senn (1966) found an echo concentration mainly in the forward right quadrant and therefore a good indicator of TC motion. But others do not find it reliable (Meighen 1985, Raghavan *et al.* 1980). In the case of unsymmetrical eyewalls the direction (with respect to the TC centre) in which the eyewall reflectivity is highest was seen in some cases to be the preferred direction of motion (Senn 1966). Raghavan *et al.* (1980) presented a case where the eyewall was formed in the northwest sector of the TC core and the storm was moving northwestwards. Three hours later the eyewall rotated to the southwest sector. The direction of motion also rotated anticlockwise correspondingly. But this again does not happen in all TC's and hence is not a reliable predictor. Prediction of track (by whatever means) gives a knowledge of not only the point of landfall but the angle of approach of the TC with reference to the orientation of the coastline. Both these help the prediction of storm surge (see Section 7).

4. Winds in cyclones

4.1. *SPA winds in cyclones*

Wind vectors derived from the observed movement of radar echoes from Small Precipitation Areas are known as SPA winds. With non-Doppler radars this can be done by plotting the positions of individual echoes manually at frequent intervals and determining their motion. This can be done in real time by preparing movie loops or by digital techniques. Since these facilities have not been available in operational radars in India such derivations have not been made. The wind which the echo motion represents will evidently depend on the echo height. Since the radar sees echoes at different ranges at different heights the range will also be a factor. If the wind field is not uniform in the horizontal, the wind obtained from radar in one sector may not be representative of other sectors.

4.2. *Doppler winds*

Within the Doppler range a velocity field is available subject to the problems of range and velocity ambiguities mentioned in Section 2. Airborne Doppler radar observation made it possible for the first time to get winds in tropical cyclones at other than flight level. The most important velocity observation is the couplet of maximum Doppler velocities at the eyewall. If this can be observed it gives a direct indication of the intensity of the TC which is operationally very important. However, the limitations mentioned in Section 2 are to be borne in mind. Observation of the maximum wind can of course be made only within the Doppler range which is less than the maximum radar range for reflectivity measurements. In the case of an incomplete eyewall it is possible that the maximum wind is underestimated.

4.3. *Winds from profilers*

Wind profilers and MST (Mesosphere Stratosphere Troposphere) radars have been used to profile the winds in parts of tropical cyclones in other basins. The profiler suffers the disadvantage that it can see only overhead and therefore the limited part of the TC which comes over the radar station. But in this area the vertical motion and turbulence can be studied and, of course, vertical time sections will be available. At the moment the MST radar near Tirupati in Andhra Pradesh is the only equipment of this type in India.

4.4. *Derivation of surface wind over land*

Wind measured or estimated by radar is not the surface wind but the wind at an altitude depending on range. The wind occurring over the sea may also change at landfall. Attempts have been made to relate lower tropospheric winds measured by radiosonde or wind profilers to the surface wind over land in tropical cyclones. Using such relationships it may be possible to derive from the radar measurements, the surface wind at landfall.

5. Radar indicators of TC intensity

5.1. *Radar-observed features and intensity of TC*

Several attempts have been made to correlate radar observed features with cyclone intensity and intensity change. While a similar correlation in the case of satellite imagery (Dvorak 1984) has been successful, the results in the case of radar have been ambiguous. The features considered from non-Doppler radar are eye diameter, radius of maximum reflectivity, eye shape and configuration, double eye, thickness (*i.e.* horizontal width) of eyewall, heights of echotops in the eyewall, number, thickness, length and crossing angle of spiral bands, echo area and reflectivity, and Latent Heat Release (LHR). Relationships were established by Meighen (1985) in Australian TC's between TC intensity and number of spiral bands (positive correlation), crossing angles (negative), thickness of spiral bands (negative), eyewall thickness (poor negative correlation) and eye diameter (negative, individual TC's only). According to Raghavan (1985) besides eye diameter, the shape of the eye (approximating to a complete circle), formation of double eyewall, small crossing angles of spiral bands are all good qualitative indicators of intensity. A negative relationship in the case of eyewall thickness was found in one TC by Raghavan *et al.* (1989). As mentioned earlier, echotop heights in the eyewall may often be lower than those in severe thunderstorms and therefore high correlation of heights with TC intensity is not to be expected. Raghavan and Varadarajan (1981) computed the distribution of LHR in a Bay cyclone from radar-estimated rainfall and found that the LHR within the core radius (taken as twice the eye radius) was well-correlated with intensity but the rainfall and LHR in the whole TC had no such relationship with the intensity. A similar conclusion was drawn by Griffith *et al.* (1978) from satellite imagery. Also,

TABLE 1

Size, rainfall extent and radar echo dimension of some Bay of Bengal cyclones (After Raghavan 1991)

S. No.	Cyclone date of landfall	Size D1 (km)	Echo dimension D2(km)	Extent of rainfall 2 cm or more per day			Ratio X1/D2	Ratio D1/D2
				Total extent (X1 km)	Left of track (X2 km)	Right of track (X3 km)		
1.	19 Nov 1977	800	500	470	120	350	0.9	1.6
2.	12 May 1979	700	400	510	210	300	1.3	1.7
3.	14 Nov 1984	250	200	240	100	140	1.2	1.3
4.	8 Nov 1989	200	150	150	50	100	1.0	1.3
5.	9 May 1990	600	400	630	150	480	1.5	1.5
Mean ratios							1.2	1.5

the relative contribution of higher rain rates to the total storm rainfall increases as the TC intensifies. There is probably also a time lag between maximum LHR and maximum intensity.

However the correlations of some of the parameters with intensity is of opposite sign to those found by Meighen (1985) and Raghavan (1985).

5.2. *Relation between eye size and TC central pressure*

Bell (1975) found statistically that smaller eyes were associated with deeper typhoons in the Pacific. Shea and Gray (1973) found similar inverse relationship between RMW and TC intensity represented by Minimum Sea Level Pressure (MSLP) but there was a wide scatter of points.

However, in a given TC changes with time of eye size, RMR or RMW should from theoretical considerations correspond to changes in TC intensity. This has been found to be so in many cases (Raghavan, 1990). A very good correlation between eye radius and central pressure in an Atlantic hurricane was shown by Marks (1985).

According to Raghavan *et al.* (1989) RMR changes are better than eye size changes as indicator of intensity changes. Thus decreases in eye size or RMR with time is taken to imply intensification; conversely if the radar indicates an increase in these parameters it should signify weakening of the TC. While this may be true, there are two pitfalls in such an inference. There can be a lag of several hours between TC structure changes and wind changes (Dvorak 1984). Secondly, deterioration in seeing conditions of the radar due to range attenuation or sub-normal propagation can lead to an apparent widening of the eye. There can also be diurnal variation in the echo configuration (Mukherjee *et al.* 1977), which should not be interpreted as changes in cyclone intensity.

5.3. *Double walled eye*

The double walled eye and its variations as an indication of TC intensity has been discussed in para 2.12.

5.4. *Doppler parameters and Intensity*

The above correlations are in respect of land-based non-Doppler radars and are therefore subject to the various limitations of such radars. In the case of Doppler radar the intensity (*i.e.* the maximum wind in the eyewall) is directly determined if the maximum velocity couplet in the eyewall is observed.

6. Rainfall distribution in cyclones

6.1. *Pattern of rainfall in a TC*

Since there are identifiable features where high rates of precipitation are concentrated, a distinct spatial pattern of precipitation exists and usually persists for several hours. Since the track of the TC is predicted, the entire spatial pattern can be extrapolated over several hours and the future position of each feature can also be predicted, the main source of error being in the track forecast. Extrapolation of the oceanic precipitation pattern is convenient as the radar sees better over the sea than over land (but the precipitation pattern may change on landfall - see para 2.20). This forms a basis for short period forecasting of rainfall (and floods) likely to occur over land areas. Depending on the particular feature which is expected to come over a specific coastal area, localised warnings of heavy rain can be given for specific times.

6.2. *Estimation of precipitation*

Precipitation rates are estimated by radar by assuming a statistical relationship between the reflectivity factor and rain rate. The magnitude of the estimate is subject to several sources of error but the spatial distribution is well-portrayed up to a range of about 200 km in level terrain. Unfortunately in India real time digital processing of radar data has not been available on a regular basis. But in the absence of quantitative estimates the identifiable features can still be extrapolated in space and time and useful qualitative forecasts and warnings can be produced.

Precipitation distribution can also be computed from satellite imagery but this does not give the spatial and temporal resolution that is possible with radar.

Computation of Latent Heat Release from radar-estimated precipitation rate has already been referred to in Section 5.

6.3. *Echo size*

The mass of precipitation echo seen by radar can be considered to be a measure of the size of the system. Several early studies noted that dimension of the radar echo was about one tenth of the satellite cloud imagery seen in association with the TC. (The satellite may see high cloud over a large area with no corresponding precipitation seen by the radar). The ratio will evidently depend on the brightness temperature and reflectivity factor thresholds set for the satellite imagery and the radar echo respectively. The ratio of the estimated size (D1) of the TC to the echo dimension (D2) for a few TC's which crossed the Andhra Pradesh coast is shown in Table 1 from Raghavan (1991). [The threshold for the echo is the Minimum Detectable Signal (MDS) of the radar]. The average ratio is 1.5. Table 1 also shows the extent of rainfall of 2 cm per day or more in the coastal strip on either side of the track (rain gauge estimates). The tracks in these cases were east to west or southeast to northwest. As noted earlier, rainfall extends farther to the right of the track than to the left. The ratio of the total extent of rainfall (X1) to the echo dimension should be unity if the radar sees all the precipitation. The average ratio in the Table 1 is 1.2.

7. Storm surge prediction

7.1. *Storm surge*

In India, for operational prediction of storm surge location and peak height, a model which takes account of the intensity of the cyclone, its radius of maximum winds (RMW), the ocean bathymetry near the point of landfall and the angle of the storm track with reference to the coast, is used (Das *et al.* 1974, Ghosh 1977). A nomogram is available for a "standard" TC with assumed parameters, $P_0 - P$ = 50 hPa, RMW = 50 km, Latitude = 20°N, Speed of TC motion = 25 kmph, track normal to coast; P and P_0 are the central and peripheral surface atmospheric pressures. Departures from these values are corrected for from other nomograms. Hence to predict the peak storm surge height, its location and its time of occurrence a knowledge of the pressure deficit, the RMW, the anticipated landfall point and time of landfall and the angle of track with reference to the coastline are needed well in advance of the landfall of the TC.

7.2. *Radar-derived parameters*

Radar can contribute the following inputs for storm surge prediction.

(1) Maximum wind in the eyewall (which can be converted by suitable relationships to a figure of pressure deficit in the TC). A Doppler radar is needed and is subject to the limitations already discussed. At present the intensity estimate is obtained from satellite imagery.

(2) Radius of Maximum Winds (RMW) set equal to the Radius of Maximum Reflectivity (RMR) from the radar reflectivity pattern (Raghavan

1987). In future this may be obtainable from the Doppler velocity pattern.

(3) Expected track and therefrom the landfall point, time of land fall and the angle of track with reference to the coast.

(4) The position of peak surge one RMW away from the predicted landfall point and to its right.

8. Future prospects

8.1. *Operations*

It has been mentioned above that IMD proposes to induct highly automated Doppler weather radars for operational cyclone observations. This step will hopefully improve the operational monitoring of cyclones both in terms of accuracy of tracking as well as estimation of intensity of the cyclone. It should however be recognised that the range of these radars will be limited in the case of some outputs. Networking of the radars and integration of their outputs along with satellite imagery and surface and upper air data at workstations is a very desirable step. Hopefully other observational systems such as wind profilers may become available.

8.2. *Research*

It appears unlikely that weather radars exclusively dedicated to research will be available in India in the near future. But we can hope to derive a considerable amount of research results from the data of an augmented operational radar network. It may be possible to mount campaigns during some cyclone situations with radar, surface, upper air and possibly airborne observations. Some important areas where our understanding of cyclones can be improved by studies with radar in conjunction with other observations are listed below.

(1) Kinematics of the storm using Doppler radar.

(2) Thermodynamic and microphysical retrievals in systems approaching close to the radar.

(3) Identification of the relative proportion of convective and stratiform precipitation and their influence on storm development.

(4) Asymmetries in the core region and outside and their relation to motion of the cyclone.

(5) Landfall effects including correlation of winds measured over the sea with surface wind over land.

8.3. *Longer term developments*

Polarimetric radar is emerging as a powerful research tool. It can identify the phase of hydrometeors and can hopefully improve the rainfall estimates. It may take some more years to be regarded as an operational device.

Other areas of technology development such as faster scanning radars, electronically switched antennas, improved algorithms for derived outputs, better networking and integration with other observations may be expected to improve our operation and research capabilities in the long term.

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