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Characteristic features of Orissa super cyclone of 29th October, 1999 as observed through CDR Paradip

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सार – इस शोध–पत्र में 29 अक्तूबर, 1999 में उड़ीसा के तट पर आए महाचक्रवात के क्रमिक विकास के रेडार से प्राप्त हुए अभिलक्षणों को प्रलेखित करने का प्रयास किया गया है। 280800 यू. टी. सी. और 290200 यू. टी. सी. के मध्य लिए गए 18 घंटे की अवधि के पी. पी. आई. चित्रों से तैयार किए गए ध्रुवीय आरेखों के विश्लेषण से इस महाचक्रवात के क्रमिक विकास के रोचक पहलुओं का पता चला है। इस विश्लेषण से प्राप्त हुए प्रबलीकरण के संकेत प्रेक्षण की अन्य प्रणालियों के उपयोग से प्राप्त हुए विश्लेषणों के अनुरूप पाए गए हैं।

ABSTRACT. An attempt is made to document the radar observed features of evolution of super cyclone that hit Orissa on 29 October, 1999. Analysis of polar diagrams comprising of hourly PPI images taken between 280800 UTC and 290200 UTC reveals interesting aspects of development of this Super Cyclone in terms of waxing and waning of eye size in relation to intensification process. The smallest radius of maximum reflectivity is in conformity with the colossal death toll observed close to the track of the super cyclone. Structural changes observed through radar images are in conformity with intensify changes as seen through other observing systems.

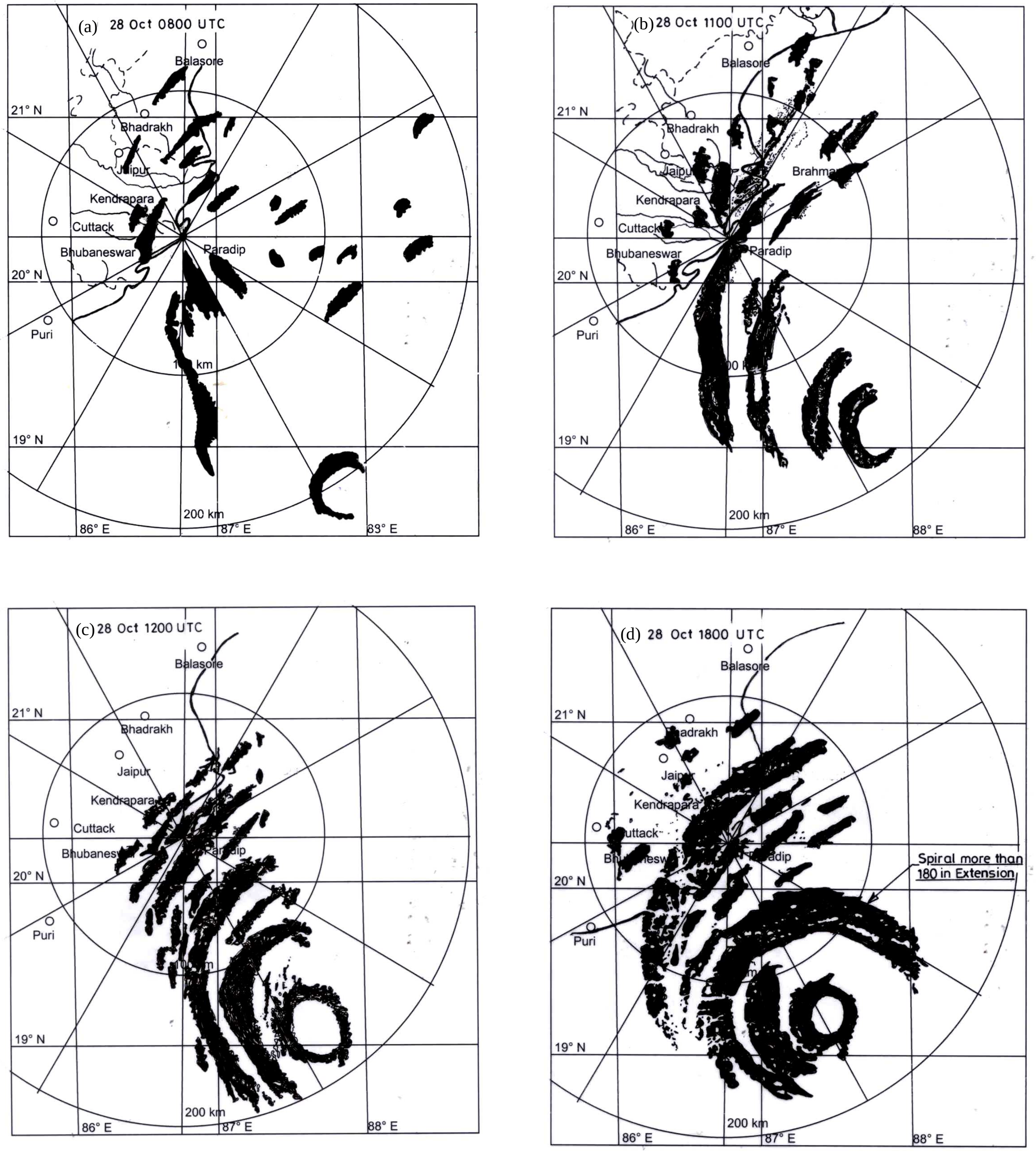
Key words − Cyclone detection radar, Plan position indication, Spiral bands, Double eyewalls, Radius of maximum reflectivity, Eye diameter.

1. Introduction

Radar has contributed significantly to our understanding of tropical cyclone development process. Taking cognizance of this fact, India Meteorological Department (IMD) had installed a set of 10 Cyclone Detection Radars (CDRs) along the vulnerable sections of the coastline of India. CDR imagery has been extensively utilized in IMD for analysis of tropical cyclones (Raghavan, 1997). The super cyclonic storm that lashed coastal Orissa on 29 October, 1999 was tracked operationally among other observing systems by CDR Paradip that provided very important signals for its location and structure. Unfortunately the original film containing the radar images was washed out in the immense rain and the subsequent flood that entered the radar room. Highly useful signals emanated from CDR Paradip and were used on real-time basis in the Cyclone Warning Centres at Bhubaneswar and Kolkata and also at Delhi to advise the Govt. at the apex level. It is considered desirable to document this information which has been derived operationally for the analysis of the super cyclone development for posterity. Hence, an attempt is made here to make use of the manual sketches derived from the faxes received at the forecast offices to study the evolution of this super cyclone. For the sake of continuity the history of development is included in Section 2. Performance of CDR Paradip during the epoch of super cyclone is very briefly touched upon in Section 3 whereas the broad radar observed features are discussed in Section 4. Radar track is discussed in Section 5. Discussion on eye size fluctuation and radius of maximum reflectivity is included in Section 6. The structural changes in the inner core area are discussed in Section 7.

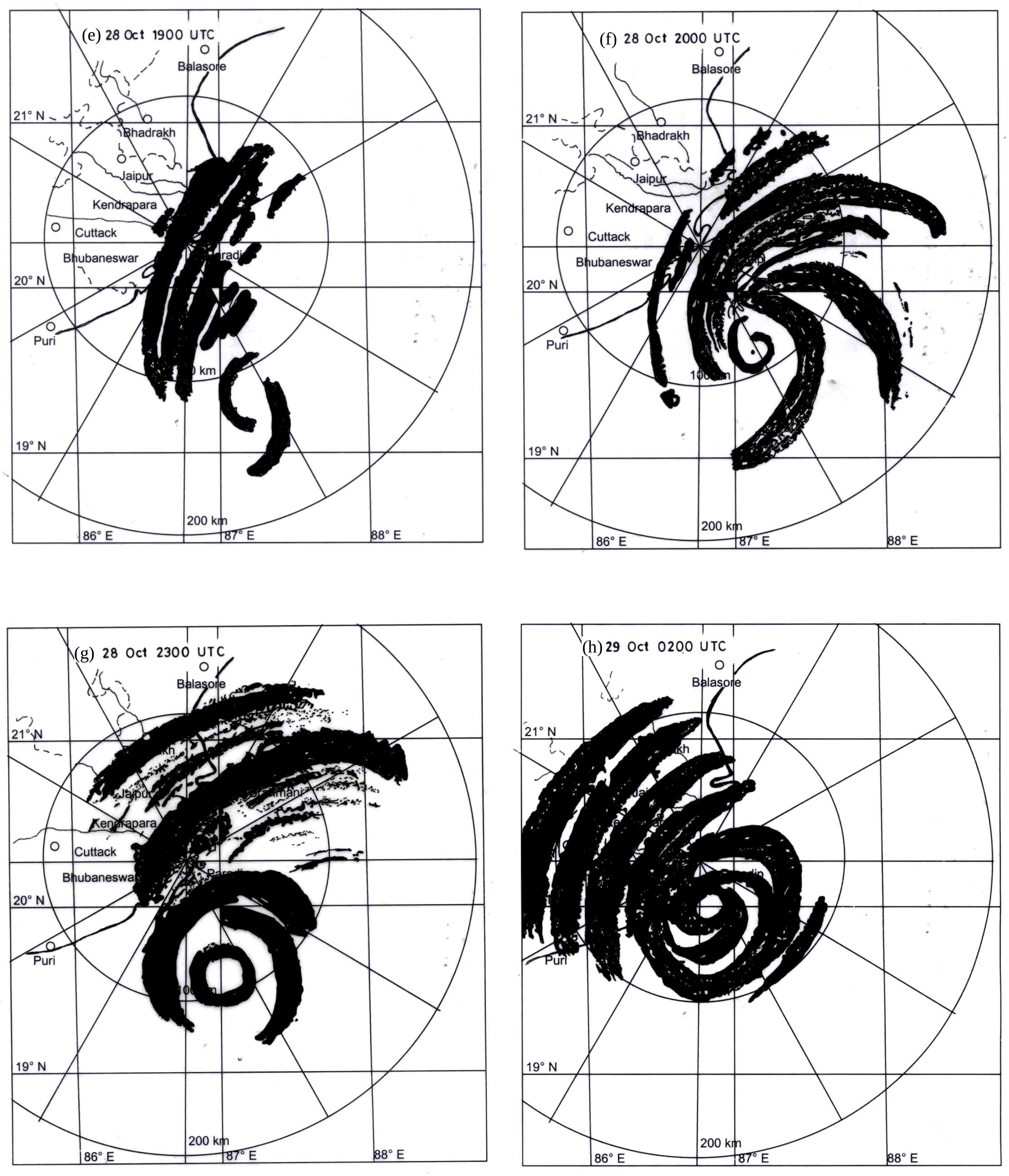
2. History of development

The best track of this cyclone is given in the paper by Kalsi (in this volume). As per Regional Specialised Meteorological Centre (RSMC) Report the remnant of the tropical cyclone "TS 9921 EVE' in the South China Sea moved westwards across Malaysian peninsula and emerged in the North Andaman Sea on 25 October, 1999. As shown in Kalsi (2002 & 2005) it evolved rapidly on 28 October when it slowed down its forward motion and acquired the super cyclonic storm stage at 281800 UTC when the estimated Maximum Sustained Wind (MSW) speed was of the order of 127 knot. At this time the storm



Figs. 1(a-d). CDR Paradip PPI images. See Section 4 for details

was located about 150 km southeast of Paradip. MSW rose to 140 knot at 290300 UTC. Vital signals about development of this cyclone defining intensity at each stage were captured mostly from the satellite imagery. The system came within the surveillance range of CDR Paradip at noon of 28 October when as per the satellite imagery in the paper in this volume, the system had acquired maximum sustained wind speed of 90 knot corresponding to T 5.0 as per Dvorak (1984) technique. Radar data was available only upto 290200 UTC as the



Figs. 1(e-h). CDR Paradip PPI images (Contd.)

operations came to a halt with snapping of power supply and flooding of station and subsequently the system was tracked using land-based surface and upper air network and also by the satellite systems. Operationally, development of this cyclone over the sea beyond the range of CDR Paradip was monitored using mainly the INSAT-1D satellite imagery which was received on hourly basis. CDR at Paradip tracked the approaching cyclone from noon of 28 October till 290200 UTC. Therefore, the discussion on development is restricted by and large upto 290200 UTC up to which radar observations are available.

3. Performance of CDR Paradip

A conventional analog S-band weather radar has been in use at Paradip since 1973. The initial Plessy 435 system was replaced by GRS-440 BEL radar in 1986. Despite the numerous shortcomings it was employed to track the super cyclone. The performance of this radar was satisfactory and its receiver sensitivity and transmitted power were optimum. However, 1500 UTC observation of 28 October could not be recorded due to technical snag in the system. The sweep was not normal in 200 kms range. So observations could not be recorded with the selection of this range. Sweep was appearing only in *Y*-axis and was absent in *X*-axis. All observations were recorded for 500 km range. However, when the cyclone was very close to the coast, there was total disruption of the power-supply and stand-by generator also failed due to water-logging upto knee level. Glass-panes of many windows in the rooms were smashed by the strong force of wind. Air-conditioners of display room (1st floor) and transmitter room (2nd floor) were pushed inside allowing copious entry of rain water in these rooms. VSAT antenna and RT mast fell down in the early hours of 29 October. Stream of water of approximately two feet was flowing in all the rooms housing transmitter, display and other units. In view of the above, the radar observations could not be carried out after 290200 UTC.

4. Broad structural features

As the radarscope photographic film was destroyed by the flooding of the station, only the faxed polar diagrams were available. These have revealed very interesting features that have been analysed to document the structure of the super-cyclone in relation to its intensification process.

Development process of this cyclonic storm can be visualised through Figs. 1(a-h), which depicts PPI images taken at different hours with the help of CDR Paradip. The cyclone first marked its presence on radar display in the form of an open eye at 0800 UTC of 28 October [Fig. 1(a) with centre of eye at Latitude 18.8 deg N and Longitude 87.9 deg E]. There are some pre-cyclone lines in the form of line and broken echoes over coastal Orissa far away from the cyclone centre. The invisible part of the eyewall is more than 200 km away from radar site at this stage and it is possible that the radar beam is overshooting the wall at that range. Subsequent radar images from 280900 UTC to 281000 UTC (Fig. not given) continued to show absence of a part of the eyewall though a slight cyclonic rotation of the visible part of the eyewall was noticed. It is obvious that a gap in the eyewall existed until 281200 UTC when a closed eyewall is seen. This was the stage when the associated sustained wind speed exceeded 100 knots (Kalsi, 2002 & 2005).

The strong horizontal winds in the inner regions of hurricanes advect the individual cumulus cells at about the speed of low-level winds (Parrish *et al*. 1984). Though some bands remain stationary with reference to the storm centre as happened in the case of hurricane Fredric (Parrish *et al.* 1982), the mesoscale rainbands in hurricane David rotated cyclonically completely round the centre (Willoughby *et al*. 1984). At such high wind speeds, the echoes associated with the visible part of the eyewall could be expected to rotate anticlockwise (cyclonically) and close the echo free eye area. Satellite imagery does show the eye and also the tall eyewall clouds in the sector in which it is not seen in the radar imagery. Radar Observer here has taken pains to map out all the features. Since, the estimated diameter at this stage ranged between 30-40 km, the length of missing eyewall (roughly one third of the circumference of circle with 15-20 km radius) was not more than 40 km which could be easily covered by the rotating echoes in less than 15 minutes. It is, therefore, interesting to see the missing part of eyewall at this intense stage. The visible part of the eyewall is mostly in the western sector. It may be of interest to add here that the cyclone was moving westnorthwestwards towards which major part of the eyewall is seen. Though it is quite difficult to explain the missing part of the eyewall at such high intensity, it may not be out of place to add here that there are instances of severe cyclones having a poorly formed eyewall or no eye at all (Weatherford and Gray, 1988 a&b). However, there are numerous cyclones, some not even severe, for which closed eyewalls have been seen in the past in PPI images.

As the system tracked further to the northwest and came closer to the radar station, the eye was seen as a closed one at 281200 UTC with three spiral rain bands of thickness approximately 20 km, 10 km and 10 km running ahead in northwest of it as seen in [Fig. 1(c)]. The banded structure of tropical cyclones has since long been recognised [(Simpson (1956), Raghavan (1985) and Willoughby (1988)]. A significant increase is noticed in the number and curvature of bands at 281200 UTC. Since the two surrounding bands have widened and also enlarged from 1100 UTC to 1200 UTC, it is the partial eyewall ring of more than 180° extension in Fig. 1(b) that has completed itself in this case. Eye structure is maintained upto 1800 UTC [Fig. 1(d)] though it is waxing and waning in size. The intensity of the system was assessed as T 6.5 at 1800 UTC of 28 October on the basis of Dvorak (1984) technique that uses visible and infrared satellite images for tropical cyclone intensity analysis. It may be of interest to add here that a convective burst had taken place around mid-night in the core area of the cyclone as seen in satellite imagery (Kalsi, 2002) and the cyclone evolved rapidly to super cyclone intensity.

As seen in Fig. 1(e) there is a sea change in the organisation of eyewall convection at 281900 UTC when the closed eye seen at 281800 UTC is breaking into two asymmetric crescent shaped open eyewalls. Eyewall is better developed but still not complete at 282000 UTC but the stationary band complex appears to have developed at this stage which may be acting like a barrier to further intensification [Fig. 1(f)]. It may be worthwhile to add here that the intensity of the super cyclone has increased very little after 281800 UTC. The band closest to the eye at 281800 UTC seems to have impacted the eyewall. Further discussion on eyewall changes is deferred for a subsequent section. Observation of 282300 UTC reproduced in Fig. 1(g) shows inner eyewall surrounded by thick spiral bands with opening to the south. These have circular extension of more than 180° and approximately 180° and thickness of 20 km and 10 km respectively. This is a structure closest to double eyewall. In addition, two more spiral bands are seen on land. One of the spiral bands had thickness of 20 km and lay over Paradip.

The closed eyewall at 290000 UTC and 290100 UTC (Fig. not shown) was engulfed by spiral band having circular extension of more than 270 degrees thus maintaining double eyewall-like structure. The last observation of 290200 UTC in Fig. 1(h) showed the most intense form of storm as seen by the radar. This was very close to the time when the system acquired intensity of T 7.0 with MSW of 140 knot. In addition to asymmetric double eyewall-like structure there are two connecting bands which are joining these two eyewalls.

As the cyclone intensified, the thickness (width) of spiral bands around the eye increased. The thickness of spiral bands consisting of highly convective clouds was about 20-30 km after 290000 UTC. These outermost bands over northeast Orissa seen in the last image in Fig. 1(h) at 290200 UTC are interesting. Though these bands originated earlier over the sea area, it is interesting to note that the total extent of these bands is only over land. They start just at the coast, extend southwestwards in the northwest sector over land and dissipate before emerging into the sea. This asymmetrical organization with reference to the centre of eye is apparently in relation to enhanced frictional convergence, diurnal variation and motion of the cyclone. These spiral bands were sweeping the affected area for a long time and resulted in copious rainfall over the coastal belt of Orissa (Kalsi, 2005).

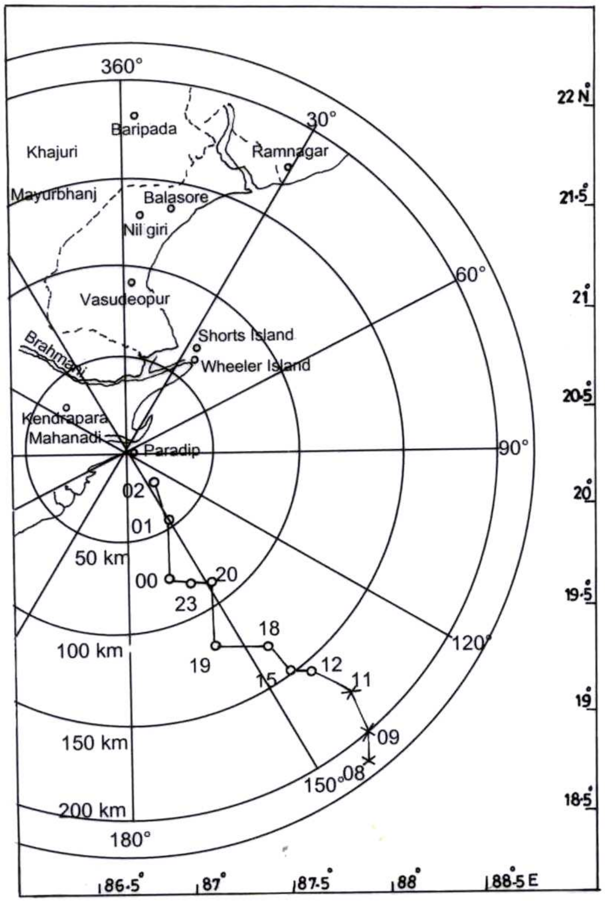


Fig. 2. Radar track of Super Cyclone

5. Radar track of Super Cyclone

Radar has been widely used for fixing the tropical cyclone tracks and with varying degrees of success for short term track forecasts. The centre of the super cyclone was fixed by examining the eye wall reflectivity patterns. Subjective/human errors in viewing or superposing overlays can not be ruled out from the analogue radar fixes. We have compared the best track positions determined by IMD with radar fixes. The system was far away from other CDRs and no useful inputs could be obtained from them. The positioning difference was of the order of 40 km initially at 280800 UTC when the eye was only partially visible. As the cyclone approached the coast the positioning difference had come down at times to 10 km. But the most striking position difference of 40 km is encountered at 281800 UTC when the eye is seen as very well organized. Since excellent satellite data sets were available and have also been used for building best track in IMD, this rather large position difference may be result of meandering of the cyclone track over short period. As per Raghavan (2003), the short period oscillation in the cyclone track is captured better in radar rather than satellite imagery.

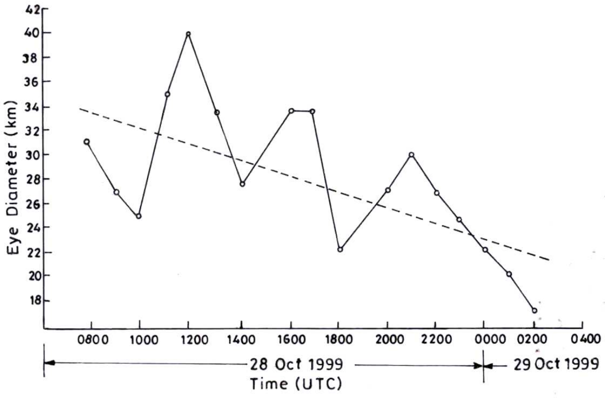


Fig. 3. Eye diameter as estimated from CDR imagery

Fig. 2 shows the radar track of the cyclone. It is seen that the path of the cyclone is a zigzag as monitored on the basis of hourly radar observations. However, it maintained a steady northwesterly trend in its total journey as observed by radar. The zigzag motion could be due to trachoidal motion in which centre of the eye rotates cyclonically around the centre of the cyclone [Rao (1967) Subramanian (1981) and Muramatsu (1986)]. Some authors have linked trachoidal motion with change in shape of the eye. The shape of the eye was monitored on hourly basis and it was found that except for four hours, the shape of the eye was elliptical. The change in shape as we note here may be one of the reasons for track fluctuations

6. Eye size and radius of maximum reflectivity

The size of the eye was measured by placing radar beam at the centre of the cyclone and then adjusting the mobile range marker. The width of the eyewall clouds was also measured for few hours. Initially, at 0800 UTC on 28 October, the eye diameter was measured as 31 km. The hourly plot of the eye-diameter of the cyclone is shown in Fig. 3. The eye-diameter shows cycles with a periodicity of about 4 hours from about 1000 UTC to 2100 UTC. However, a decreasing trend of the eye-diameter is very conspicuous after 2100 UTC of 28 October. At 290200 UTC [Fig. 1(h)], it contracted to 18 km *i.e.* less than half of the maximum eye-size attained at 1200 UTC of 28 October. It is worthwhile to mention that at 281800 UTC [Fig. 1(d)], when the system's intensity was upgraded to super-cyclone by IMD, diameter of the eye contracted abruptly to 23 kms from 34 km recorded at 1700 UTC observation. However, in the very next hour it again showed increasing trend. Bell (1975) found statistically that smaller eyes were associated with lower central pressures in the Pacific. The decrease of eye size along with intensification was noticed by Raghavan and Veeraraghavan (1979) in the case of a Bay of Bengal cyclone. Shea and Gray (1973) had found similar inverse relationship between radius of maximum winds (RMW) and tropical cyclone intensity. But, the correlation coefficient presented by Schwerdt *et al.* (1979) between RMW and the central pressure never exceeded 0.40. Hence, in the absence of the pressure or winds measurement in the eyewall, it is not possible to infer the intensity of a cyclone simply from the knowledge of eye diameter measurements.

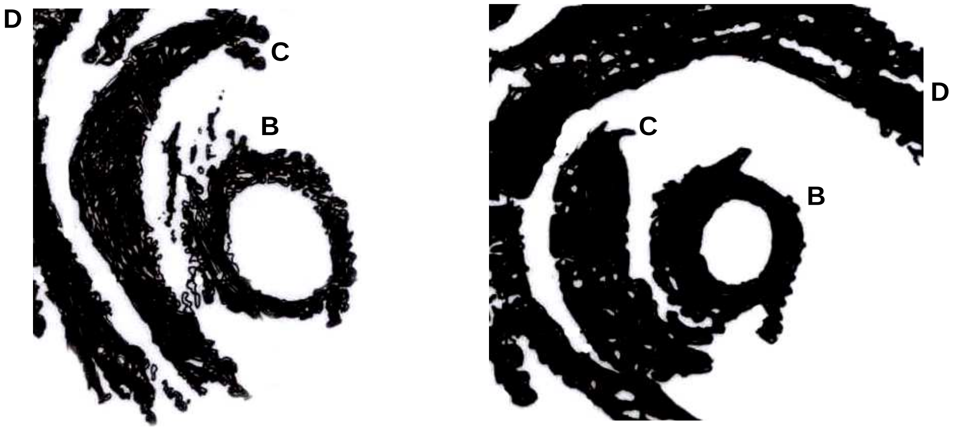
As stated earlier breaks in the eyewall were conspicuous at 281900 UTC & 282000 UTC despite the fact that the cyclone had already acquired super cyclonic storm stage. One of the possible causes cited for variation of eye size and structure is the interaction between two eyewalls noticed in double walled structure of cyclones (Willoughby *et al.* 1982; Raghavan *et al.* 1980 and Kalsi 2002). Gupta and Mohanty (1997) also talked of interactions between asymmetric double eyewalls in May 1990 cyclone that also had intensity of a super cyclone. In fact, in that case also the inner eyewall was punctured at 2051 UTC on 8 May, 1990 [Fig. 6(i) in Gupta and Mohanty, 1997]. Though the break in the inner eyewall had more or less continued in that cyclone, but in the current case a complete ring surrounded by numerous bands is reappearing after 2300 UTC of 28 October.

As noticed in Kalsi (2002) though there were no such kinds of walls noticed in INSAT imagery, a NOAA pass on 28 October, 1999 showed signatures similar to double eyewall. It appears that in the present case surrounding bands seem to be interacting with the eye in the same manner. The internal structural changes noticed during span of about 18 hours of radar scan are large and frequent with a periodicity of 4 hours. Since nothing else is discernible, the eye size changes appear to have been forced by these interactions. Though the radar scans were taken on hourly basis it may still be impossible to keep proper track of features that have meso spatial and temporal domains which probably may require more frequent scanning. In the event when the spiral band nearest to the eye replaces the earlier eyewall, the size and shape of the eye could change and this is what is happening in this case as well. In the absence of reconnaissance aircraft observations, intensity estimated using satellite imagery in terms of maximum wind speed or central pressure has usually been kept somewhat constant for the north Indian Ocean cyclones at the time of landfall.

Another possible measure of the size of the eye is the radial distance from the cyclone centre to the point of maximum reflectivity in the eyewall. Raghavan *et al.* (1989) defined it as the Radius of Maximum Reflectivity

(a) 28 Oct 0800 UTC (b) 28 Oct 1100 UTC

(c) 28 Oct 1200 UTC (d) 28 Oct 1800 UTC



(e) 28 Oct 1900 UTC (f) 28 Oct 2000 UTC

(g) 28 Oct 2300 UTC (h) 29 Oct 0200 UTC

Fig. 4. Structural details in the inner core

(RMR). According to them RMR changes with time are better related with intensification of any cyclone. This was also observed in an another Bay cyclone that landed at Kakinada in 1996 (Sharma, 1999). Incidentally so far as this cyclone is concerned the lowest RMR of 8 km was observed at 290200 UTC, very close to the time when the cyclone acquired the maximum intensity T 7.0 as per the RSMC, New Delhi Report on Cyclonic Disturbances of the North Indian Ocean for 1999. But there were some variations hour to hour in the RMR. In most other hourly radar observations RMR was around 15 km. This value was taken as the RMW for computing storm surge profile along the Orissa coast (IMD, 2004). CDRs have provided realistic estimates of RMW through their estimation of RMR. In the absence of any estimate of RMW, in most of storm surge models [Das *et al.* (1974), Ghosh (1977) and Dube *et al.* (1985)], RMW has been taken as 50 km. As seen in Kalsi (2005), CDR Paradip yielded important information on the location of peak surge and also its magnitude which was controlled by RMW.

7. Structural changes in the inner core

To examine the structural changes taking place in the inner core area we have reproduced features within one degree from the centre of the eye from 281200 UTC onward and marked them as band A, B, C, D etc. in Fig. 4. It appears that as discussed earlier band A at 281100 UTC that defines partial eyewall is getting closed at 281200 UTC. Band B gets first fragmented at 281300 UTC and then a part of it towards the south has apparently disappeared in the next hour (Fig. not given). Unfortunately there was no radar observation carried out at 281500 UTC due to technical snag. The system had acquired maximum intensity at 281500 UTC as per digital and objective Dvorak Technique (ODT) algorithms (Kalsi, 2002). The small diameter at 281400 UTC is in tune with this intensification phase. As discussed and seen earlier there is increase in the number of bands at 281200 UTC between the storm centre and the coast towards which the super cyclone is heading. Therefore, it may be expected that within one degree of the centre, band D is new addition at 281200 UTC with band C coming closer and band B supplanting the inner eyewall which is enclosing larger echo free area. The increase in diameter of the eyewall is reason sufficient to infer that the eyewall replacement has occurred at 281600 UTC. The eye seen at this stage then shrinks and becomes small in size at 281800 UTC. But the big change in structural configuration mentioned earlier becomes distinct at 281900 UTC and 282000 UTC. Apart from the fragmentation of the eyewall at 281900 UTC, the relative displacement of earlier bands to the northwest away from the storm centre and appearance of band X in the east defined as the stationary band are the most conspicuous features. This has to be kept in mind that all this is happening when the storm is almost in peak stage of intensification. The band C has come so close to the eyewall at 281800 UTC that it again interacts with the eyewall which gets broken into two crescent shaped bands at 281900 UTC. Raghavan and Veeraghavan (1979) have reported breaking up of wall clouds of Nagapattinam cyclone of November, 1977 when the eye was close to the land but still out at sea. Remnant of its eyewall could be seen up to 4 hours after landfall. As already stated break in the inner eyewall was also encountered in May 1990 case (Gupta and Mohanty, 1997). However, In the present case a complete ring reappears at 282200 UTC which persists and shrinks in size consistently upto 290200 UTC. Eye had shortest diameter of 18 km at this stage and it was almost half of what it was at 281200 UTC.

Unfortunately there is no observation other than satellite derived intensity estimate. Kalsi (2002) brought it out that a short period intensification might have occurred as the eye got warmed up thereby increasing the intensity as per Dvorak (1984). As done in most other cyclones, near the time of landfall the satellite derived intensity estimate is kept almost constant here as well except half a T. No. increase from T 6.5 at 281800 UTC to T 7.0 at 290300 UTC. This is consistent with radar observed improvement in the eye structure. The digital algorithm and objective Dvorak techniques have yielded slight re-intensification tendency in the morning around 290300 UTC. Without detailed reconnaissance aircraft observations intensity changes on short term scale, having linkages with eyewall configurations and their changes, can not be determined. However, research programmes are already in the offing in the United States of America such as hurricane Rainband and Intensity change Experiment (RAINEX), and also Intensity Forecasting Experiment (IFEX). US Scientists have collected plenty of observations in respect of hurricanes such as Katrina, Ophelia and Rita that battered US coast during August and September 2005 (Schrope, 2005). These experiments may help improve understanding and prediction of intensity and track of tropical cyclones.

As a tropical cyclone approaches land, on account of land interaction, the outer winds which first encounter the land begin to get modified due to increased friction in response to the frictional convergence in the onshore winds (Parrish *et al.* 1982). The asymmetric heating due to this convergence induces a track acceleration towards the enhanced convection. As this cyclone approached the land, a clockwise rotation in the spiral band structure also appeared at 282000 UTC indicating northward deflection of the course of cyclone that actually was experienced. Development of bands along and off the coast and also over land is basically in response to increased friction and also because of northwestward movement of the super cyclone. Since major structural change has occurred within six hours of the landfall when the super cyclone was just within 100 km of the coast, land interaction also seems to have played role in shaping this development. Willoughby (1990) has reported frequent coincidence of outer eyewall with landfall.

8. Conclusion

The PPI images of CDR Paradip which were available on near real-time basis to cyclone forecast offices were of immense interest and use in monitoring development process for a limited duration of time when the cyclone was under its range of detection. Analysis has revealed a lot of eyewall structural changes that were associated with intensification process. Eye size fluctuations had a periodicity of about 4 hours. Though the reconnaissance aircraft data is lacking to figure out the corresponding intensity changes, the eye size fluctuations have links with intensity changes seen through satellite analysis. A slight re-intensification tendency in the early morning on 29 October is in tune with improvement in internal structure seen through CDR Paradip. The small estimate of RMR is in confirmity with maximum deaths that have occurred near the track and indicates the compact and intense structure of the eyewall. The structural changes mentioned in Section 7 may also be partly due to land interaction as the same are occurring very close to the coast.

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