MAUSAM, **57**, 1 (January 2006), 1-20

551.515.2 (541.5)

Orissa super cyclone – A Synopsis

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सार – 29 अक्तूबर 1999, को पारादीप के निकट आए महाचक्रवातीय तूफान ने उड़ीसा को तहस नहस कर डाला जिसके कारण पारादीप के निकट एक लैन्डफाल बन गया इसके कारण अंदरूनी क्षेत्रों में लगभग 260 से 270 कि.मी. प्रतिघंटा की तीव्रगति से हवाएँ चलने से समुद्र में ऊँची–ऊँची तरंगें उठीं और समुद्र के जल का स्तर 20 फीट से भी अधिक बढ़ गया। इस महाचक्रवातीय तूफान के कारण लगभग 10,000 लोगों को अपने बहुमूल्य जीवन से हाथ धोना पड़ा। इसके साथ–साथ असाधारण भारी वर्षा हुई जिसके कारण प्रलयंकारी बाढ़ आने से राज्य का समूचे देश से संपर्क कट गया। इस शोध–पत्र में रेडार और उपग्रह के चित्रों, पारम्परिक आँकड़ों, संख्यात्मक मॉडलों से इस चक्रवात के उत्पन्न होने और उसके आगे बढ़ने के विभिन्न लक्षणों का विवेचन किया गया है। इस शोध–पत्र में चक्रवात से हुए विनाश के लिए राज्य और केन्द्रीय अभिकरणों द्वारा आपदा प्रबंधन के रूप में वास्तविक समय पर किए गए राहत कार्यों पर विशेष बल दिया गया है।

ABSTRACT. Orissa was battered by a Super Cyclonic Storm on 29 October, 1999 that made landfall near Paradip (43976). The estimated maximum wind speed reached 260-270 kmph in the core area which produced a huge storm surge that led to sea-level elevation of more than 20 feet and took away valuable lives of nearly 10,000 people. It was accompanied with exceptionally heavy rains which led to devastating floods and cut off the State from the rest of the country. An attempt is made to describe the various features of development and movement of this cyclone through radar and satellite imageries, conventional data and numerical models. Emphasis is laid on the real-time handling of this event, impacts made by the cyclone and the services rendered in relation to disaster management by the State and Central Agencies.

Key words − Super cyclone, Gale force winds, Microwave images, RMR, QLM, Storm surge, Disaster management.

1. Introduction

In the recorded history of cyclones for the State of Orissa, the Super Cyclone of 29-30 October, 1999 was undoubtedly the most intense one. It had some unique features such as rapid intensification, small radius of eyewall confining the large surge close to the point of landfall and relatively long life after landfall. Climatologically there is a high frequency of dissipation of cyclones in October because of strong easterly winds aloft. Cyclogenesis usually terminates at the stage of marginal cyclones (Kalsi & Jain, 1989). Occasionally development of cyclones to hurricane force winds and higher occurs in September and October as it happened in 1831 and 1885.

The author had brought out an exhaustive review for India Meteorological Department (IMD) on this Super Cyclone (Kalsi, 2003). This synopsis is brought out on the lines of the same review. History of development is included in Section 2 whereas analysis of wind and rainfall observations received mostly from the operational networks is given in Section 3. Emphasis is laid on the satellite data for the cyclone intensity analysis and other structural details in Section 4. Cyclone Detection Radar (CDR) at Paradip was of immense help in real-time handling of this super cyclone. Useful signals from CDR data regarding its development are described in Section 5. In addition to conventional pattern recognition techniques followed in synoptic approach, IMD has been using Numerical Weather Prediction techniques for tropical cyclones. Some details of outputs from Quasi Lagrangian Model (QLM) such as model track forecast are presented in Section 6. IMD has been using nomograms for storm surge prediction (Das, 1972; Ghosh, 1977). IMD (2004) has carried out a detailed review of estimate of storm surge encountered in this super cyclone using different models. It is briefly described in Section 7. Reports on damages encountered in this cyclone were available from different sources. These have been briefly included in Section 8. IMD took the lead in mobilizing all the disaster management agencies both at the Central as well as State levels. Initiatives taken by IMD in providing the timely warnings are included in Section 9. Actions taken on the preparedness, relief and rehabilitation soon after the event are summarized in Section 10. Finally the conclusions with suitable recommendations appear in Section 11.

TABLE 1

Evolutionary characteristics of super cyclonic storm

Date	Hour	T. No.	Estimated wind (knots)	Category	Movement during previous 24 hrs
25 Oct 1999	1200 UTC	1.5	25	D	-
26 Oct 1999	0000 UTC	2.0	30	DD	-
26 Oct 1999	1200 UTC	3.0	45	CS	WNW/447 km
27 Oct 1999	0000 UTC	3.0	45	CS	WNW/403 km
27 Oct 1999	1200 UTC	3.5	55	SCS	WNW/430 km
28 Oct 1999	0000 UTC	4.0	65	VSCS	WNW/361 km
28 Oct 1999	1200 UTC	5.5	102	VSCS	WNW/291 km
29 Oct 1999	0000 UTC	6.5	127	SuCS	NW/366 km
29 Oct 1999	1200 UTC	-	90	VSCS	NW/283 km
30 Oct 1999	0000 UTC	-	50	SCS	NW/135 km
30 Oct 1999	1200 UTC	-	35	CS	Practically stationary
31 Oct 1999	0000 UTC	-	30	DD	Practically stationary

Legend : D-Depression, DD-Deep Depression, CS-Cyclonic Storm, SCS-Severe Cyclonic Storm, VSCS-Very Severe Cyclonic Storm, SuCS-Super Cyclonic Storm

Sources : Report on Cyclonic Disturbances over North Indian Ocean during 1999-RSMC Tropical Cyclones, New Delhi, Report 2000 and the data available with Cyclone Warning Division O/o Director General of Meteorology, Mausam Bhawan, Lodi Road, New Delhi

2. Development

Fig. 1 shows the track of this cyclone. Remnant of an initial vortex which lay over the Gulf of Thailand, emerged in the North Andaman Sea where it concentrated into a depression on 25 October evening with its centre about 550 km east of Port Blair. The depression moved in a west – northwesterly direction and intensified into a cyclonic storm on 26 October about 350 km northeast of Port Blair.

While maintaining more or less northwesterly movement throughout its life history, it evolved through several stages and acquired the stage of super cyclone maximum (maximum sustained winds 120 kt) at 281800 UTC when it was centred about 150 km southeast of Paradip. The surface pressure estimated following Mishra and Gupta (1976) was 912 hPa on 29 October. It fell by 66 hPa during the preceding 24 hours. This indicates it was a case of rapid development. The central pressure in this case was almost same as in the case of Nagapattinam cyclone of November 1977 where it was 911 hPa. The current system attained its peak intensity (lowest pressure 912 hPa) at 0300 UTC of 29 October.

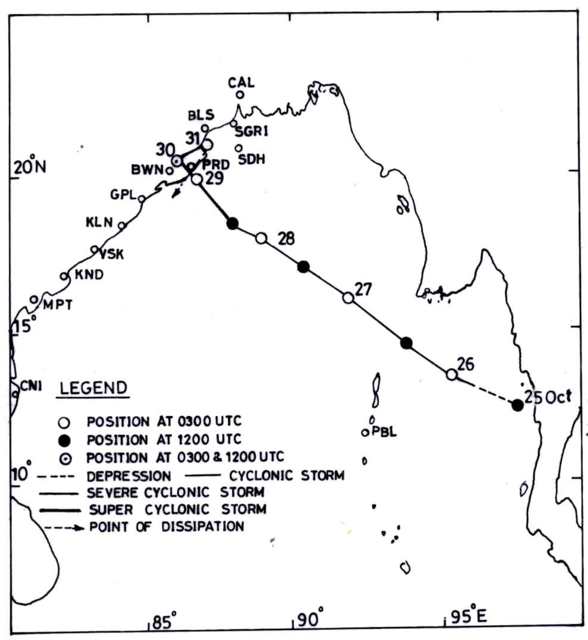
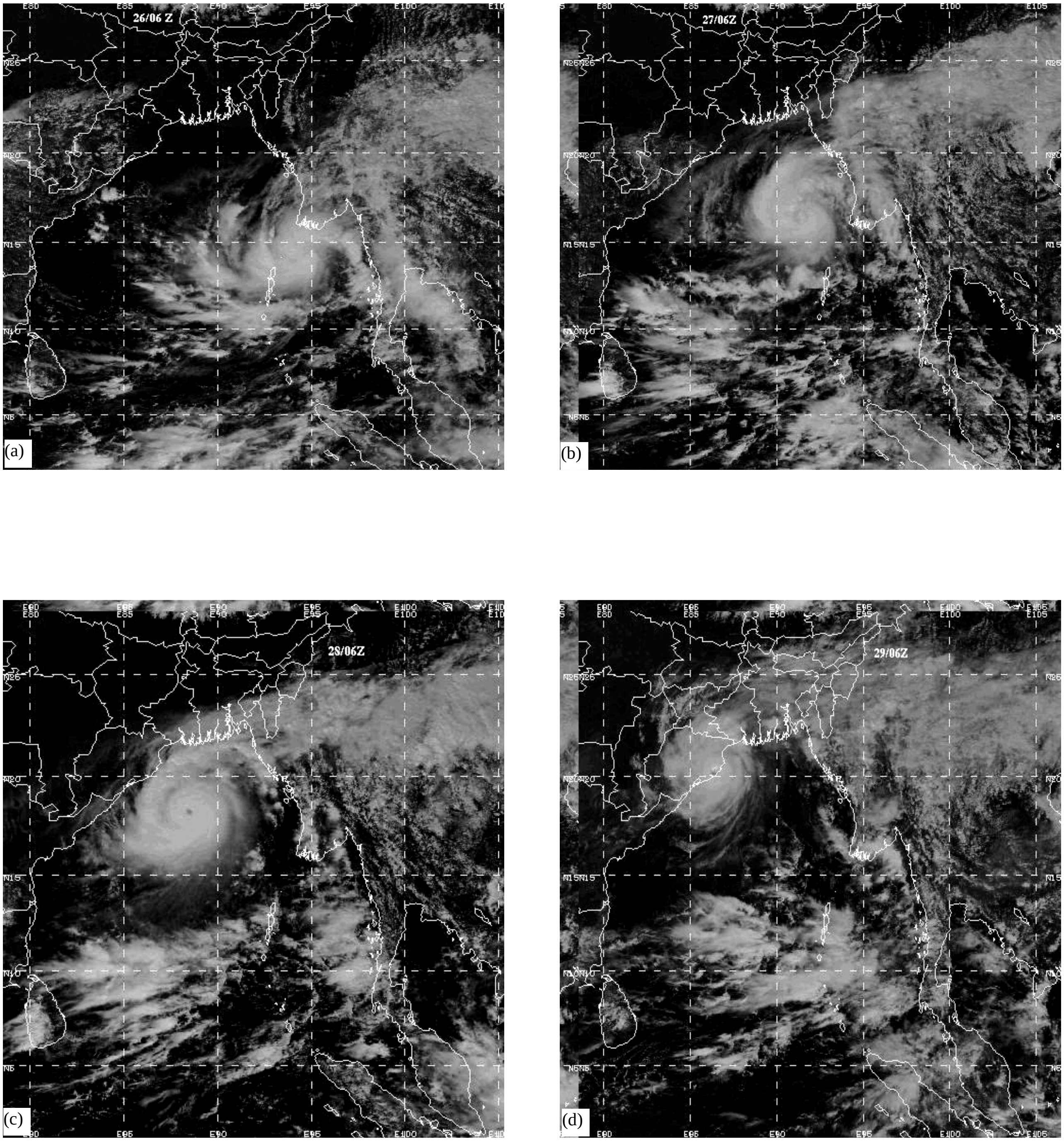


Fig. 1. Track of the super cyclonic storm in the Bay of Bengal that struck Orissa on 29 October 1999

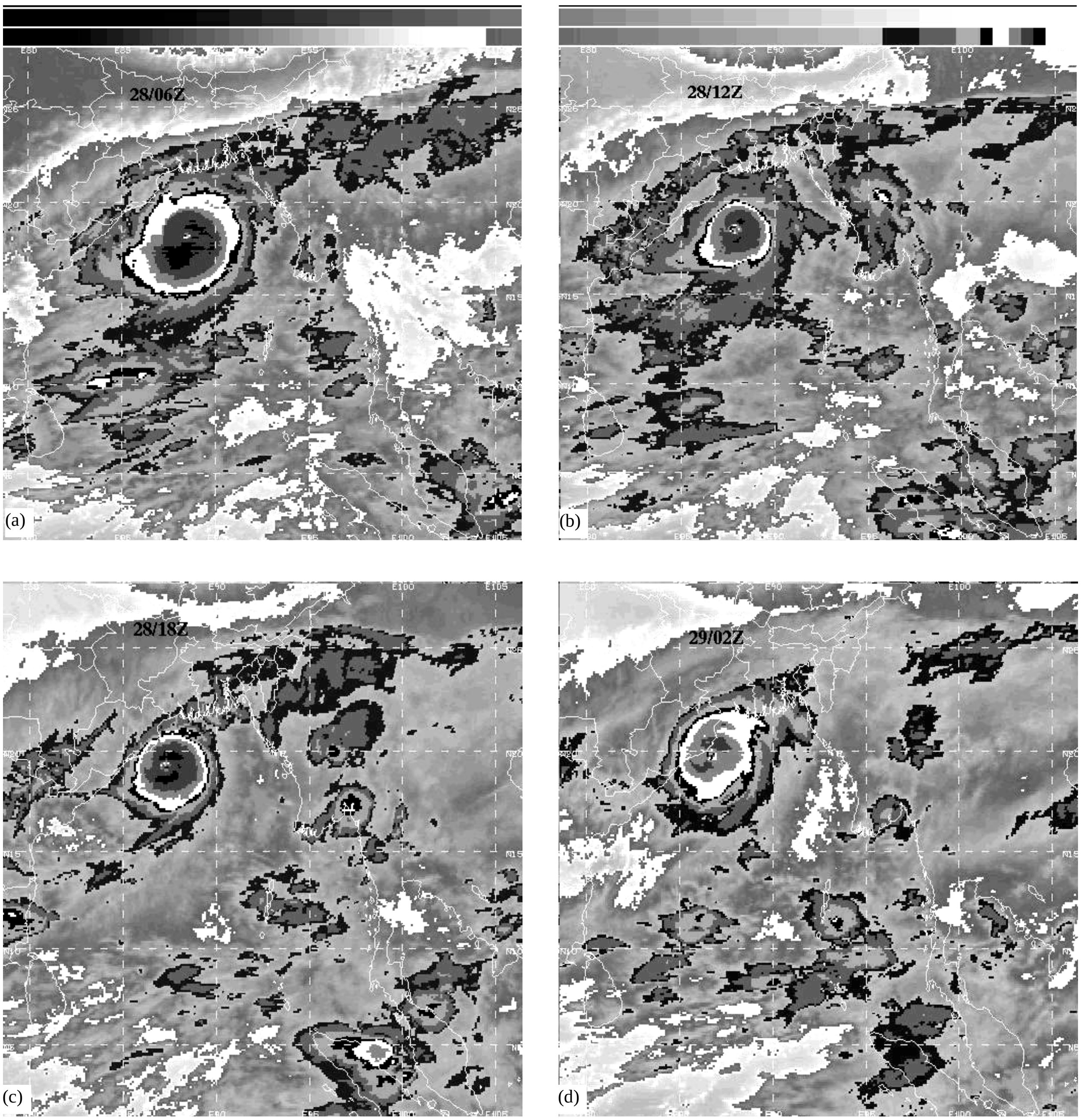
After crossing coast the system moved very slowly a little further to the northwest, weakened and lay centered in the evening of 29 October near Cuttack as a very severe cyclonic storm. Very heavy rains accompanied with strong winds for two days lashed coastal Orissa. The storm was stuck up in eastern Orissa near Bhubaneswar for want of any steering current as it was sandwitched between two upper air anticyclones. It weakened slowly, took a clockwise turn and appeared as a depression near Chandbali on 31 October morning. Thereafter its remnant drifted southwestwards as a low pressure area that dissipated off south Orrisa coast on 1 November 1999. The life history of development of this Super Cyclone is given in the Table 1.



Figs. 2(a-d). 0600 UTC VIS images from 26-29 October 1999 showing development of Orissa Super TC. (a) Solid looking CDO on 26 October with weakly organized bands. (b) The cloud spirals tighten and concentrate convection. Banding eye structure on 27 October. (c) Eye encircled by solid eyewall convection on 28 October. Rapid intensification observed and (d) Convective structure weakens at the time of landfall. Eye getting filled up. Radius of core convection reduced. Current intensity T 7.0 from EIR analysis continuity

3. Analysis of winds

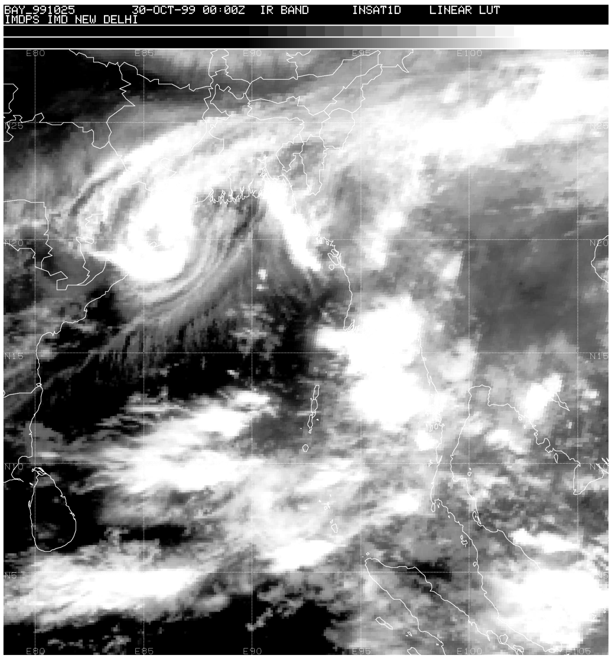
Cyclones developing over the oceans have been analysed over the years using data from ships of opportunity. There was hardly any ship observation available for the analysis of this cyclone. The buoys deployed under National Data Buoy Program (NDBP) of Department of Ocean Development were not of much



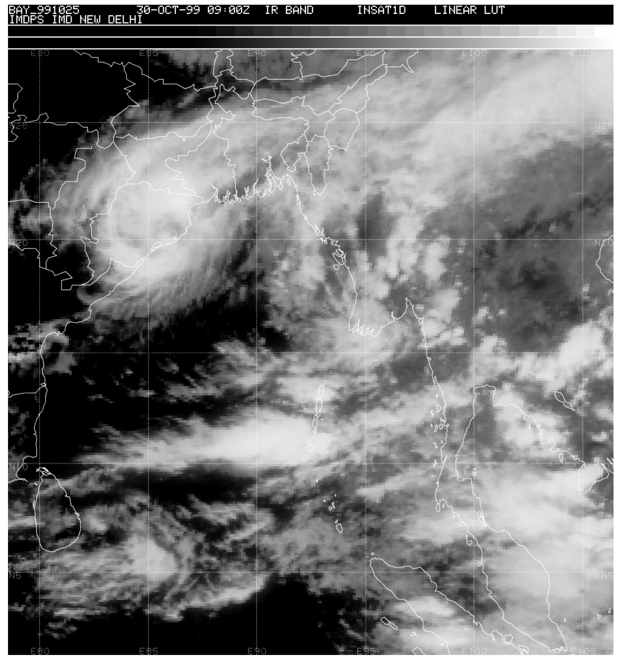
Figs. 3(a-d). 6 hourly EIR images from 0600 UTC of 28 October to 0000 UTC of 29 October, 1999. Intensity (a) Surr. Gray shade CMG and eye gray shade also CMG, intensity T 6.5-1.0 = 5.5. (b) Surr. Gray shade CMG and eye gray shade off-white, intensity T 6.5 + 0.5 = 7.0, (c) & (d) Same gray shades for Surr. and eye as in (b), intensity T 7.0
(Definition of grey shades as in Dvorak technique)

help to provide any useful data except a significant wave height of 8.2 m by a buoy that was stationed off Paradip. Surface observatories in the coastal areas provided some response when the cyclone started affecting them. The wind speed recorders at Paradip became unserviceable after recording 80 kt winds around 0200 UTC on October 29. A maximum wind of south-westerly 97 kt was reported at about 0700 UTC on 29 October from Puri (43053). Though as per the memorandum submitted by the Govt. of Orissa, the impact of the wind fury was so great that telecom links of districts with capital became unserviceable by 0730 hr (IST) on 29 October roughly four hours before landfall, it is estimated that strongest winds that had radius of only 15 km, as discussed later, reached about one to two hours before landfall as the cyclone was translating at this speed. The extensive

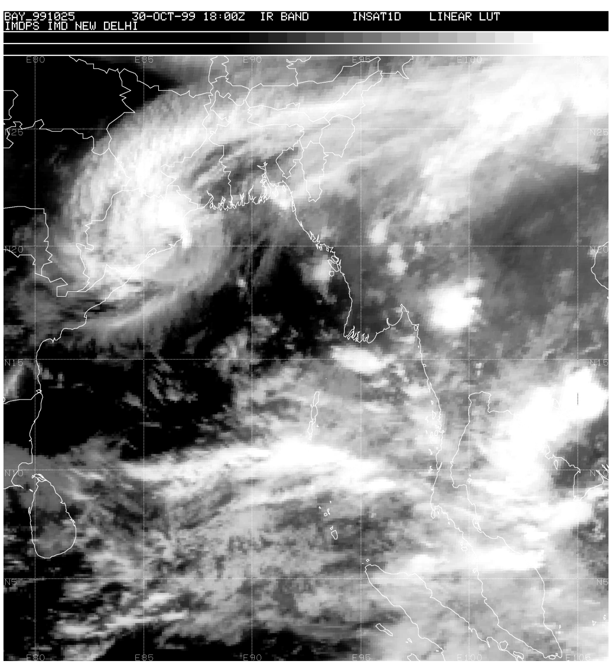
(a) 30 Oct 1999 0000 UTC



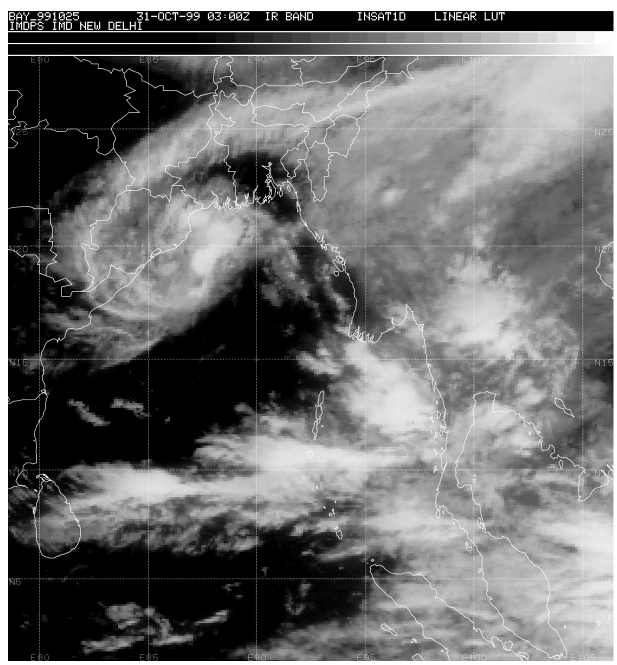
(b) 30 Oct 1999 0900 UTC



(c) 30 Oct 1999 1800 UTC



(d) 31 Oct 1999 0300 UTC



Figs. 4(a-d). INSAT-1D Satellite imagery showing the decaying phases of Orissa Super TC (a) and (b) a sharp band originating over southeast Orissa. Dry air is intruding and filling the core area. (c) considerable decrease in the core convection and (d) Complete destruction of vortex structure in the IR image on 31 October, 1999

damages in the state are attributable to larger radius of gale force winds as we see later. It is quite in order to keep in mind the views of Merrill (1984) who differentiated between inner core intensity of the tropical cyclone, defined as the maximum sustained wind speed encountered in the cyclone and its outer core strength

(OCS), as the spatially averaged wind speed in the outer core defined as the annulus between 100 and 250 km from the cyclone centre after Weatherford and Gray (1988). Though the inner core intensity is primarily responsible for the surge induced havoc which is highly localised, it is the size and strength rather than the intensity that determine the area of damage. The Disaster Managers must be aware of this important aspect of tropical cyclone. The gale force wind field arrived at the coast roughly 9 hours before landfall when the cyclone was about 150 km from Paradip. The cyclone fury over some parts of Orissa coast continued for about 45 hours (9 hours before landfall and 36 hours after landfall) and thereafter residual depression lasted for another 9 hours.

4. Satellite data application

Satellite data was of tremendous help in analysis and forecasting of development of this super cyclone. In addition to use of visible and infrared imagery data through Dvorak algorithms, data from few other payloads was also taken into consideration for this purpose.

4.1. *Dvorak (1984) Technique*

Satellite imagery has been used very extensively for over three decades for analysis of tropical cyclones. Dvorak (1975, 1984) technique is employed widely over the world for tropical cyclone intensity analysis and is in vogue at IMD also. Using this technique Kalsi (2002) made detailed study of this super cyclone development using Visible and Enhanced Infrared (EIR) imagery and digital IR algorithm. The same is reproduced in the following paragraph.

Satellite picture in top left in Figs. 2(a-d) indicates solid looking persistent convection in the form of Central Dense Overcast (CDO) of about 1.5° which means that the disturbance had intensity of T-2.5 at this stage. As the system moved northwest, the spiralling band became tight around the centre and covered it completely. Banding eye structure is seen in the top right frame for 27th when the intensity is just reaching the minimum hurricane wind force (very severe cyclonic storm). However, the intense convection increased in size around the centre as seen in the EIR images [Figs. 3(a-d)] indicating convective burst in the core area. 6 hourly EIR images from 0600 UTC of 28 October to 0000 UTC of 29 October are included in Figs. 3(a-d). There are indications of double out flow channels particularly at 0600 and 1800 UTC of 28 October. Sharpening and warming of eye continued throughout the day and the eye was warmest around 1500 UTC when its temperature was -8° C and the surrounding overcast was colder than -85° C. Digital IR technique would give us intensity estimate of this TC in excess of

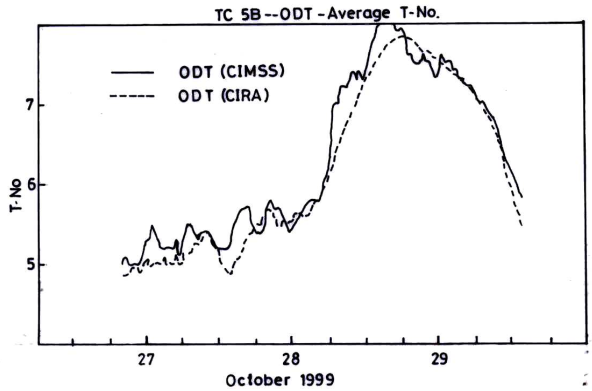


Fig. 5. ODT intensity estimates, Bay of Bengal super cyclone (TC 5B) (from Kalsi *et al.* 2002)

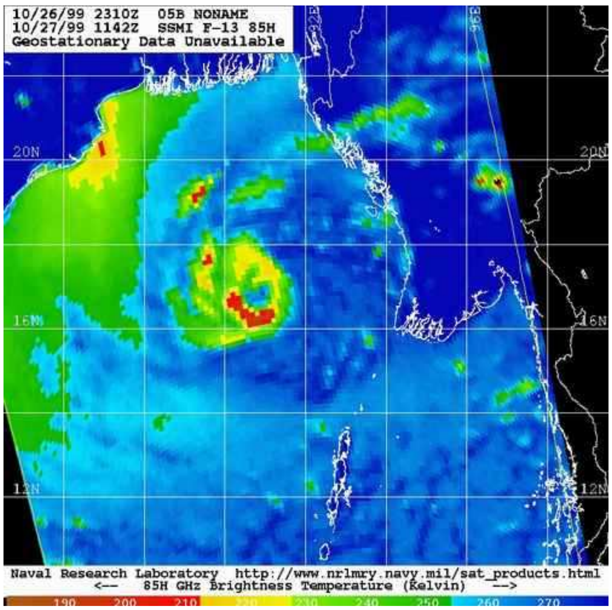
T-7.5 at 1500 UTC of 28 October though with EIR we get T-7.0. Since it was a very well defined pattern throughout the day and the embedded distance of eye in the afternoon was of the order of one degree, Data T-No. defined as DT in Dvorak (1984) technique was 7.0 at 0900 UTC which is confirmed by the more objective EIR analysis. Data T-No has to be seen in conjunction with Model Expected T-No (MET) and then averaging over previous 3-6 hours is required for realistic intensity estimates which are include in Table 1.

After crossing coast the system tracked very slowly a little further to the northwest, and its associated MSW decreased exponentially with time after landfall (Kalsi *et al.*, 2003). The central dense overcast associated with the super TC which had a wind force of 90 knots at 1200 UTC of 29 October decreased in size. Dry air intruded into the cloud mass from the western side at this stage. In fact an opening in the cloud mass started in the southwest sector at 1800 UTC of 29 October and almost whole of the core area was devoid of clouds by 0300 UTC of 30 October. Figs. 4 (a-c) shows a band over south Orissa which continued to persist here and a cloud cluster at 0900 UTC of 30 October over northeastern Orissa. After the weakening of the core convection, thin curved bands reappeared at 1800 UTC of 30 October. With further weakening of the TC this structure also vanished on 31 October.

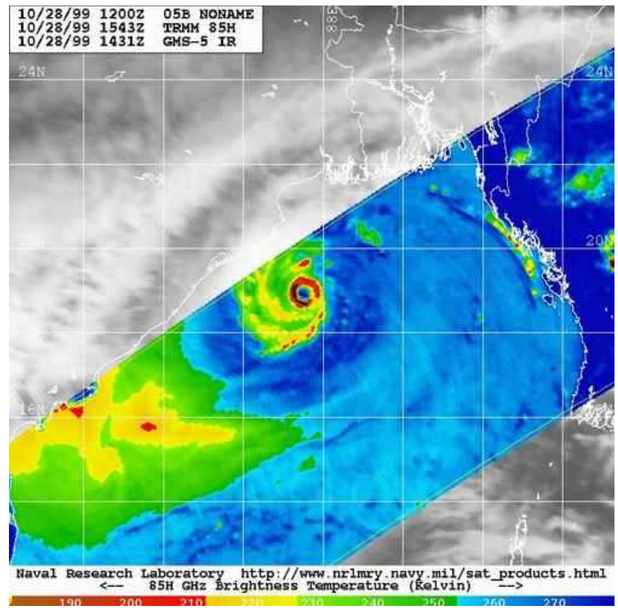
4.2. *The Objective Dvorak Technique (ODT)*

The Objective Dvorak Technique (ODT) algorithm was originally developed by Dvorak (1984), based on the IR eye temperature and a surrounding ring temperature at 55 km. ODT has since been modified, utilizing automated computer-based algorithms developed at the Cooperative Institute for Research in the Atmosphere (CIRA) to objectively calculate the eye/convection temperatures, apply multi-radius and time averaging computations to derive intensity estimates (Zehr, 1989). This will be

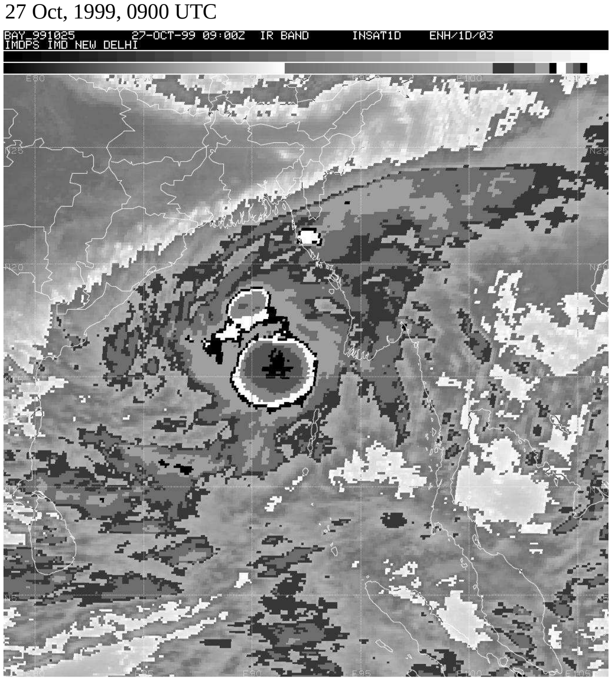
SSM/I 85 H GHz 271142 UTC



TRMM 85 H GHz 281543 UTC



27 Oct, 1999, 0900 UTC



28 Oct, 1999, 0900 UTC

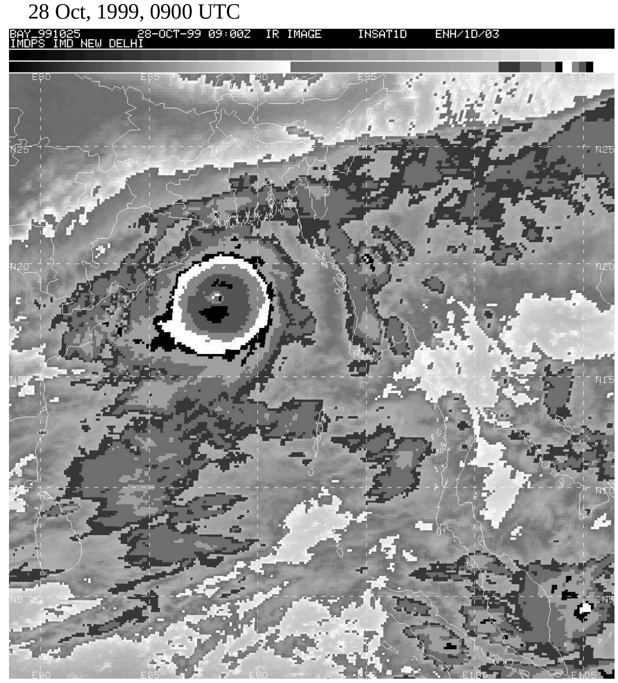


Fig. 6. Microwave and EIR images of 27 & 28 October 1999. Eye structure is seen in SSM/I imagery of 27 October but it is absent in INSAT –1D imagery on this day. For details see text

hereafter called as ODT- CIRA. ODT has since been modified further with the work of Velden *et al*. (1998).

After identifying the eye and surrounding temperatures, the basic original ODT (ODT-CIRA) utilizes a lookup table (Dvorak, 1995) to estimate the intensity. The T numbers (and intensity estimates) increase as the eye temperature gets warmer and also as the surrounding temperature gets colder. Selected empirically determined constraints are imposed upon the final derivation of the estimate, such as confining the minimum T number to be no less than 3.5 and limiting the maximum intensity of no-eye storms (CDO patterns) to a T number of 5.0. In addition, those cases that have a maximum eye temperature less (colder) than the surrounding temperature (*e.g.*, a strongly sheared environment) are automatically set to a T number of 4.5. Upon determination of the T number value (in this application, T number and CI number are considered equal), TC intensity is estimated either in terms of maximum wind speed or pressure deficit at the centre.

In the re-modified ODT technique developed in the Co-operative Institute of Meteorological Satellite Studies, hereafter called ODT-CIMSS, the lookup table is replaced with an integration (coded approximation) of the original Dvorak EIR rules for various cloud patterns (Dvorak, 1995). Determination of the cloud pattern is performed objectively by examining areal histograms of cloud-top temperatures and corresponding Fourier analysis for the eye region and surrounding cloud region (as defined earlier). Based on this analysis, four scene patterns are categorised: eye, central dense overcast, embedded centre, and shear.

The initial T number is then based on the scene pattern type and surrounding temperature, with the eye temperature used only in the adjustment of the T number in certain situations (Dvorak, 1984). In very special cases, the surrounding temperature is replaced with the temperature of the histogram bin that contains the maximum number of surrounding cloud top temperature values. The ‘‘peak histogram temperature’’ is used only when certain thresholds are exceeded. ODT-CIMSS (Velden *et al*., 1998) includes this modification in order to emphasize those cases with an eye and a significant amount of very cold surrounding cloud temperatures that are not sufficiently captured by the basic ODT ‘‘ring’’ methodology (which chooses the warmest pixel on each ring).

The ODT plots for this TC are included in Fig. 5 from Kalsi *et al.* (2002). There is a good synchronization of the development process seen in the two techniques. Though the ODT-CIRA estimate does not reach T - 8.0, it is very close to that. The point of interest here is that the estimate of maximum intensity is about 1 T - No. higher than the operational estimate. A part of this difference may be real as the authors feel that the ODT techniques are capturing the time and intensity of maximum intensity as they are using more frequent (half hourly satellite images). Like the original Dvorak technique, they are also designed for the Atlantic storms for which a lot of reconnaissance data was available. IR cloud top temperatures, in general, with tropical weather systems in the Bay of Bengal are slightly colder than with Atlantic systems. Therefore, the possibility of ODT techniques giving slightly higher estimate of the intensity is not ruled out.

4.3. *Gale force winds and QuikScat data*

The new microwave-sounding units on NOAA-15 polar orbiting satellite have the ability to see through the upper level cirrus and provide insight into the environment around and within the tropical cyclone. Techniques have been developed at CIMSS (Velden *et al*., 1998) and CIRA (Demuth *et al*., 2000) to assess wind fields and improve numerical specification of a tropical cyclone vortex and intensity. Kalsi *et al*. (2002) used these techniques to figure out the structural details of this system. Data from NOAA passes of 27 October and 28 October (forenoon pass) were used in this study. Against the analysed intensity of 105 knots on 28 October forenoon, this technique yielded 88 knots as an estimate of intensity with corresponding radii of 35, 50 and 64 knots as 126, 73 and 35 nautical miles. As shown in Kalsi *et al*. (2002), the intensity as well as these wind radii increased from 27 to 28 October. Therefore, the intensification of the inner core as well as strengthening of the outer core was nicely brought out. Although no data corresponding to afternoon of 28 and morning of 29 October was available, it seems clear that further strengthening had taken place.

QuikScat wind field was also available for the Super Cyclone of October 1999. QuikScat is a sun synchronous polar orbiting satellite and has an 1800 km wide swath on the earth surface. Sea winds is a radar instrument on the QuikScat that sends pulses to the ocean surface and measures the echoes that bounce back to the satellite. The directional ambiguity was evident in some of the analyses. Gale force wind radii were computed manually in different quadrants. The average gale force radius increased from 167 km on 27 October to about 216 km on 28 October. This is in conformity with observations made above regarding the expansion of radius of gale force winds using AMSU data.

4.4. *Microwave imagery for TC analysis*

The passive microwave imagery from the SSM/I can alleviate many of the inherent limitations encountered in VIS/IR imagery. Microwave channel is particularly useful in the rather common situation because the cloud and rain bands beneath the cirrus shield can be seen.

Fig. 6 shows images of SSM/I of 27 October and TRMM image of 28 October, 1999 for the Orissa Super cyclonic storm. The SSM/I 85H GHz on 27 October 1999 image gives strikingly clear picture of formation of eye which was absent in the concomitant INSAT-lD satellite image. A compact eye is seen in the TRMM 85H GHz image on 28 October. It gives us an impression of great strength. According to Kalsi *et al*. (2002), the eyewall

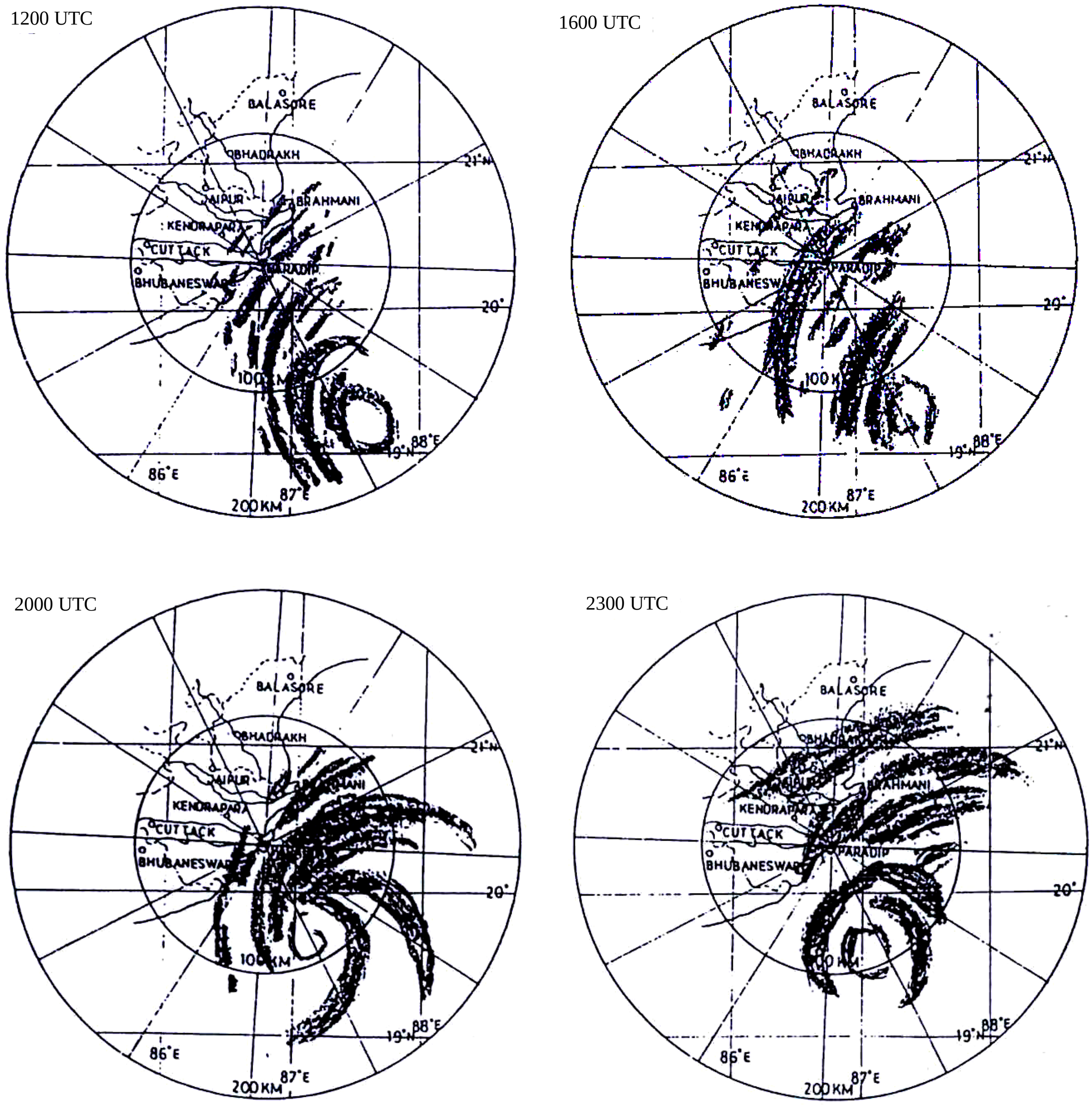


Fig. 7. CDR Paradip images on 28 October. Eyewall seen in all frames. Clockwise rotation of secondary bands indicates possible change in the course of the cyclone towards north

contracted in the afternoon on 28 October confirming rapid intensification. As seen by Huntrakul (1992), the infrared scene in the INSAT-1D imagery is dominated by the extensive stratified anvils. In fact much of the structural details of microwave images are being obscured in the infrared images.

5. CDR Paradip observations

Special radar observations were available from 0800 UTC of 28 October to 0200 UTC of 29 October. Thereafter radar observations had not been recorded due to Power Supply failure. CDR Paradip provided only analog images. There was no digital output available. The photographic film was also washed out in the intense rain and subsequent flood. A few sketches of rain bands/eyewall observed in these fax messages are reproduced in Fig. 7. Since it was a well organized system before it came under surveillance, a partial 'eye' with centre near Lat. 18.8° N / Long. 87.5° E was seen in the CDR Paradip radar imagery at 280800UTC (not shown). The estimated 'eye' diameter was 31 km. At 281200 UTC

TABLE 2

Date	Eye diameter	Eye Structure & change	RMR
280800 UTC	31	Open eye seen	
281000 UTC	25	Smaller eye with no significant change	14 km
281200 UTC	40	Closed eye more distinct & increased in size	20 km
281400 UTC	28	Small eye, no other significant change	16 km
281600 UTC	34	No significant change	15 km
281800 UTC	22	Eye more distinct & decreased in size	14 km
282000 UTC	28	Eye more distinct & increased in size	8 km
282200 UTC	28	No significant change	15 km
290000 UTC	23	Decrease in size	14 km
290200 UTC	18	Smallest eye with no other significant change	8 km

the 'eye' became more distinct and closed but its size increased at this time. Though there was hour to hour change in the structure of the Cyclone as observed by CDR Paradip, Kalsi and Srivastava (2005) observed cycles with 4 hour repeativity in eye diameter measurements. The centre of the 'eye' was located near Lat. 19.2° N / Long. 87.6° E at 281400 UTC. The 'eye' diameter increased to 34 km at 281600 UTC but again decreased to 22 km at 281800 UTC. By 282200 UTC the 'eye' again became more distinct though the diameter increased to 28 km. The storm became stationary with its centre near Lat. 19.6° N / Long. 87.0° E till 282300 UTC as per the radar reports and diameter of the eye decreased again to 18 km at 290200 UTC. The Radius of Maximum Reflectivity (RMR) also showed fluctuations somewhat similar to the 'eye' diameter.

The eye was seen surrounded by spirals mostly to the northwest of the centre of the eye before 281200 UTC. The principal spiral band became distinct only from 282000 UTC. A number of curved bands indicating rain spirals at 281200 UTC which have spread right upto the coast have rotated clockwise from 1600 UTC to 2000 UTC giving impression of change of course of the cyclone towards north. This is confirmed from Best-Track data that shows northward movement from 281800 UTC to 290000 UTC. Some of these bands shifted northwards by 282300 UTC alongwith the super cyclone. The eyewall, the principal band and the secondary bands all underwent some change in their organisation. The overall stationary band complex (Willoughby *et al*. 1984) structure was, however, maintained in most of these radar image time frames. Almost a similar structure was modelled by Raghavan (1985) by compositing echoes of a number of cyclones of Bay of Bengal. Secondary bands seen over coastal Orissa started developing over sea areas west to northwest of the centre at 281000 UTC. Though these bands rotated and were seen more towards north of centre, in the absence of either the digital data or even the photographic film, it is difficult to infer much on the nature of these bands. They appeared to be embedded in the area of central dense overcast seen in the satellite imagery. From the analysis of rainfall data, it appears that they were not as convective as the eyewall.

Evolutionary characteristics of the cyclone seen through CDR Paradip are included in Table 2. Waxing and waning of eye diameter and of Radius of Maximum Reflectivity (RMR) indicate interactions within the 'eye walls' which are usually seen in super hurricanes and super typhoons [Kalsi and Srivastava (2005)]. Second complete concentric ring is not seen in this cyclone's radar images, though a part of the 2^{nd} ring is seen. Kalsi (2002) showed a structure similar to concentric eyewall structure in the NOAA satellite imagery of this cyclone.

The lowest RMR of 8 km was reported at 282000 UTC and 290200 UTC. Huge lose of life of about 7,000 people in Erasma block very close to the track of super cyclone confirms that this super cyclone had a small radius of maximum winds.

6. Numerical models

IMD has been running operationally a limited area multilevel primitive equation model (LAM). For want of adequate observations synthetic observations are generated and included in the GTS observational data base to correct the initial analysis for proper representation of cyclone vortex at the initial stage. The analysis is obtained *via* a 3-dimentional multivariate optimum interpolation (OI) procedure. The LAM is adapted from the Florida State University (Krishnamurti *et al*., 1990). Prasad *et al*. (2000) made detailed evaluation of LAM performance in handling cyclones of 1998 and established its skill. Performance of limited area model in respect of Kandla cyclone of June 1998 was also studied by Kalsi (1999a). Recently another limited area model, a Quasi Lagrangian Model (QLM) specially designed for cyclone track prediction, has also been implemented in IMD. The latter is an adapted version of the hurricane prediction model of the National Centre for Environmental Prediction (NCEP – erstwhile National Meteorological Centre), Washington (Mathur, 1991).

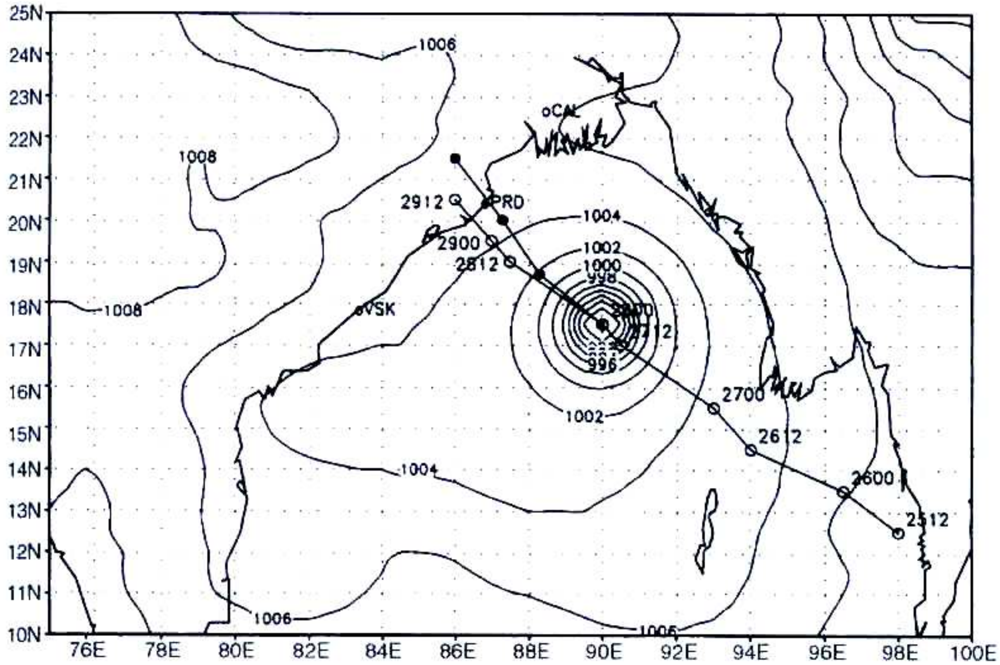


Fig. 8. MSL pressure (hPa) analysis and predicted cyclone track (Initial date 28 October 1999/0000 UTC) (open circle : observed location : filled circle : predicted location)

A special feature of the QLM is prescription of an idealised vortex and a steering current. The idealised vortex is created from the three dimensional structure of a cyclone *via* empirical functions. The construction of idealised vortex is done from the current observed structure of the storm and needs information like the present location of the storm, the central pressure, the value of the outermost closed isobar, size of the storm etc. which are gathered from the preliminary synoptic analysis and satellite imagery. The vortex so generated is nearly symmetric with size and intensity close to that of the observed storm. This idealised vortex is merged with the analysis on the QLM grid to obtain the final initial analysis for running the model.

6.1. *Performance of QLM*

Operational runs were carried out with the model to produce track forecast on the initial conditions of each day (0000 UTC and 1200 UTC map times) beginning from the stage when the disturbance was declared as a cyclonic storm (26 October 0000 UTC). Fig. 8 shows the mean sea level pressure analysis on 28 October 1999/0000UTC. The analysis shown here is after the merger of the idealised vortex with the OI analysis fields. It is interesting to see the packing of isobars in the core area roughly between 50 to 150 km belt. The strongest pressure gradient should have been in the 10 - 50 km belt from the centre. The strong pressure gradient near the centre has apparently not been resolved with the horizontal resolution of 40 km used here. Mean Sea Level Pressure (MSLP) gradient in the outer core is consistent with the observed intensity of the storm on the days under consideration. Side by side we also examined the structural pattern in the wind field. Here, the stream flow and isotach pattern at 850 hPa have been depicted for October 29, 0000 UTC when the storm was at its peak intensity (Fig. 9). The isotach pattern shows an elongated maxima of peak wind speed about a degree away from the storm centre which is not realistic as we have seen earlier that the radius of maximum winds was much smaller. The maxima lies in the northeast quadrant on October 29 to the right of the direction of storm movement. This asymmetry in the wind field is brought about by superimposing the storm motion on the symmetric vortex and is consistent with the actual storm movement. The central core region of the storm vortex has a speed minima. Strong speed gradients are seen to exist in the core region of the vortex.

The observed track of the storm from the initial date up to the 36 hours and the corresponding 12 hourly predicted positions starting from the respective initial conditions on 28 October 1999/0000UTC is shown superimposed on the MSLP analysis in Fig. 8. Operationally the model was run only upto 36 hour

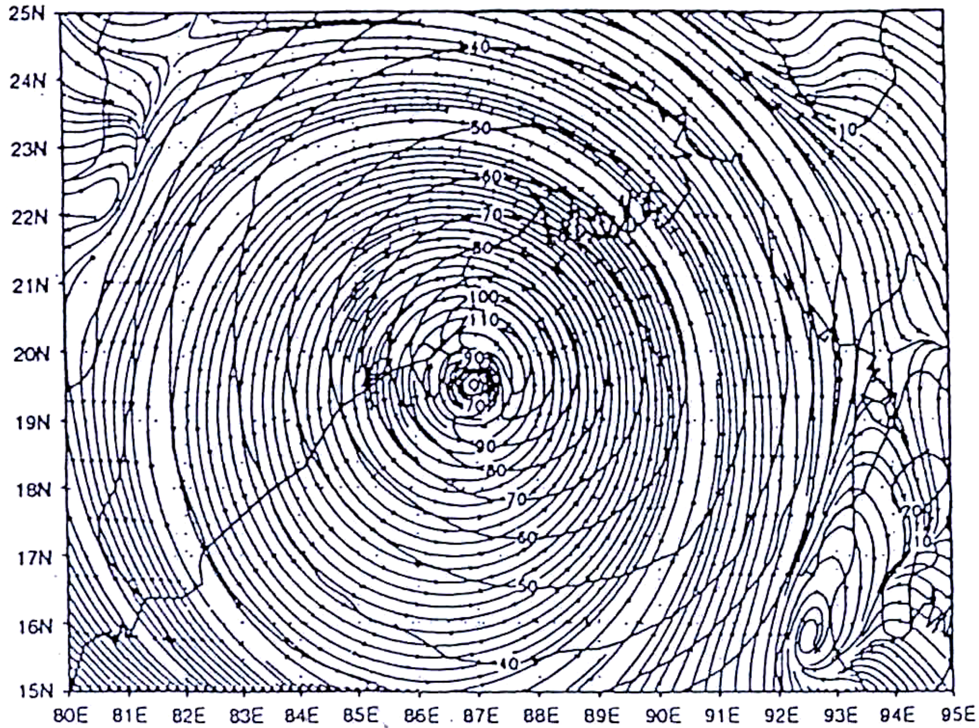


Fig. 9. Flow analysis 850 hPa (intial date : 29 October 1999/0000 UTC) (isotaches/wind speed in knots)

forecasts time frame. One may conclude that the track forecast is reasonably accurate in this case. While deviations of the observed track from the predicted track no doubt exist, the northwestward movement in the October 28 case is well captured by the model. As far as the landfall point is concerned, the deviation between the observed and the predicted positions is about 100 km in the 24 hour forecast. The October Super Cyclone made its landfall just south of Paradip. It may not be out of place to add here that though UK Met Office forecast made on the initial conditions of 26 October was quite realistic, the forecast made available on 27th indicated looping in the track of the super cyclone before landfall.

A large number of studies have appeared on numerical simulation of Orissa super cyclone. NCAR MM5 has been used by many researchers in connection with Orissa Super Cyclone simulation. MM5 has been running at National Centre for Medium Range Weather Forecasting (NCMRWF) on real time basis for mesoscale prediction. It is triply nested at 90, 30 and 10 km. resolutions. The model has been used for several applications including Orissa Super Cyclone by Das (2002) who used initial and boundary conditions from T80 to simulate its track. Storm Showed recurvature with T80 initial conditions of 25th October 1999. Considerable improvement in the track was however made using synthetic vortex observations that improved the initial conditions. Mohanty *et al*. (2004) simulated the Orissa Super Cyclone using NCAR MM5 with a horizontal resolution of 30 km and with analysis nudging for 12 hrs prior to the model integration starting at 0000 UTC of 26 October 1999. Their model could predict the intensity of the storm fairly well up to 48 hrs in advance, but underestimated it between 48 hrs and 72 hrs. The study also reported delayed landfall which is reflected as overestimation of the intensity [Refer paper by Mandal & Mohanty (2005) published in this volume]. Rao and Bhaskar Rao (2003) attempted to simulate the Orissa super cyclone using NCAR MM5 with the options of a number of parameterisation schemes of convection, planetary boundary layer and explicit moisture. The Orissa super cyclone was well simulated but with an underestimate of cyclone intensity. Trivedi *et al*. (2002) reported the improvement of track prediction and the characteristics of Orissa super cyclone due to the assimilation of synthetic vortex in the initial analysis. IMD has started integrating QLM upto 72 hours. Rama Rao *et al*. (2005) in this volume have presented the results of this model and shown that average track forecast errors for 72 hours of the order of 420 km are comparable to those of the other global centres.

7. Storm surge

For the super cyclonic storm of Orissa, there is no recorded surge information available. The super cyclone had devastated the entire infrastructure in its core area on

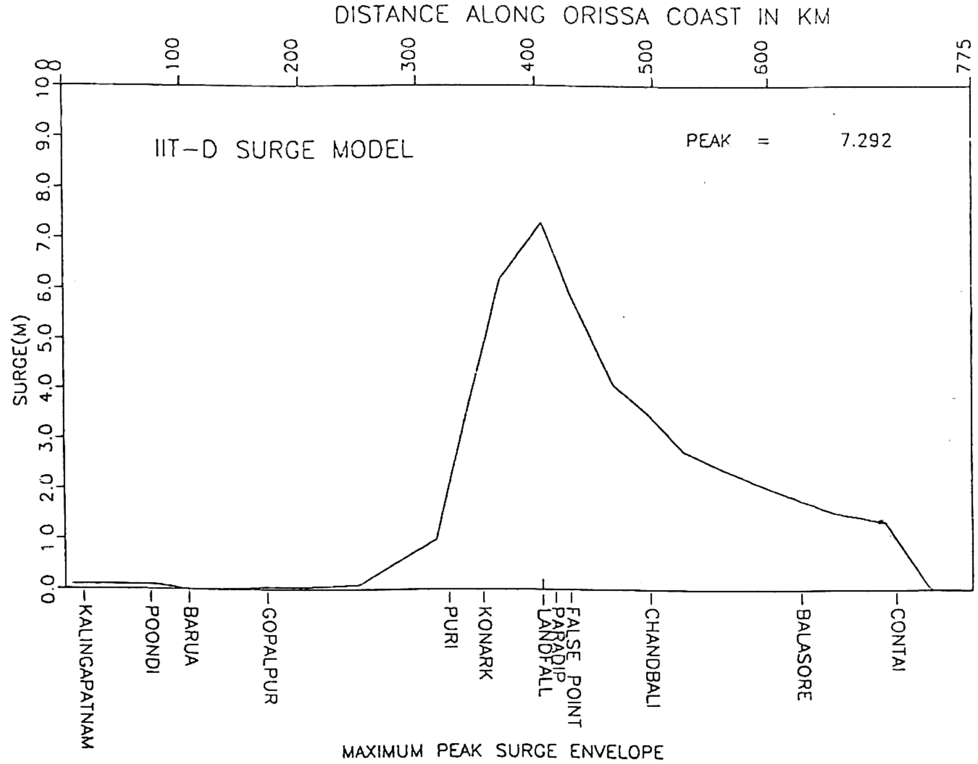


Fig. 10. Peak surge (m) envelop with IIT Delhi location specific fine grid model (Radius of maximum wind as 40 km)

29 October 1999. There are couple of reports available on the useful survey done on damages encountered in association with this cyclone. The National Center for Disaster Management (NCDM) brought out in its appraisal report that the probable maximum storm surge was up to 7.95 m which they apparently meant as total sea level elevation. The Structural Engineering Research Centre (SERC) Madras has also given the storm surge of about 7 m. A realistic assessment of the storm surge has been provided by the task force instituted by the Ministry of Urban Development for the assessment of the damages encountered in this super cyclone. They have given a storm surge of 7.5 m, which apparently contains the astronomical tide of about 0.8 m at the time of landfall. According to the State Government of Orissa total sea elevation was about 20 feet (6.5 m). The pioneering work on storm surge encountered in association with landfall of tropical cyclones over Indian coast line was started by Das (1972). A numerical surge prediction model was developed by Das *et al.* (1974) for the north Bay of Bengal. Ghosh (1977) used Jalesnianski (1972) scheme for estimation of storm surges on the east coast of India. Pre-computed nomograms were prepared relating peak surge with storm parameters such as pressure drop, radius of maximum winds, vector motion of the cyclone, and the off-shore bathemetry of the coast near the landfall point. Extensive work on the PC based storm surge prediction models developed at IIT-Delhi has been reviewed by Dube *et al.* (1997).

Tropical cyclone track forecast as well as forecast of intensity and radius of maximum winds are the important meteorological inputs for storm surge forecast. The fierce winds that are responsible for the storm surge are usually comprehended through the pressure deficit at the centre. Radius of maximum winds cannot be easily defined from the satellite imagery. Moreover we require an accurate prediction of the distribution of winds in the cyclone field at the time of landfall. Satellite imagery has also occasionally helped in this regard. There have been a couple of occasions in which internal structure of tropical cyclone has been revealed in visible imagery (Kalsi, 1999b). The input on radius of maximum winds has been usually extracted from the radar imagery (Raghavan, 1997). In the absence of any realistic inputs on this parameter, an estimate of 50 km has been often taken in all the techniques for storm surge forecasting / estimation (Das *et al.* 1974; Dube *et al.* 1985, and Ghosh *et al.* 1983).

Building Material Technology Promotion Council (BMTPC) vulnerability atlas gives probable maximum surge of about 5.5 m for that part of Orissa coast line where maximum surge occurred. Ghosh (1983) computed probable maximum storm surge (PMSS) for different segments of west and east coasts of India and also of Bangladesh coast line by taking Δp = 100 hPa (for east coast), radius of maximum winds of about 50 km and speed of propagation as 24 kmph. The PMSS estimate of 4.5 m for Paradip as given in Mandal (1991) appears to be an overestimate of it as it is based on Ghosh's nomograms. The estimate of storm surge for this cyclone provided by IIT Delhi was more than 7 m as seen in Fig. 10.

Radial distance from the cyclone centre to the point of maximum reflectivity in the eyewall is a measure of the size of the eye. Raghavan *et al*. (1989) called it as Radius of Maximum Reflectivity (RMR). According to Marks and Houze (1987), the tangential wind maxima was 4 km radially outward from reflectivity maxima. Though RMR had gone down upto 8 kms, since it was close to 15 km in several observations, this value has been used for purpose of storm surge calculation. Therefore, when the IIT model is run with radius of maximum winds close to 15 km, the peak surge becomes 5.9m (IMD, 2004). This appears to be closer to the estimates provided by many governmental agencies. The short radius of maximum winds is in close conformity with the colossal death toll of more than 7000 in Erasma block during the day light hours. Certain amount of awareness and preparedness has definitely gone a long way in reducing the death toll which was earlier much higher with storms of equal or even less intensity.

8. Damage

Sources : Government of Orissa, Indian Institute of Public Administration, New Delhi & Report of the Task Force on Repairs and Reconstruction of the Housing in the Areas Affected by Super Cyclone in Orissa prepared by Ministry of Urban Development, Govt. of India.

The Orissa coast with a length of 550 km coast line spreading from Andhra Pradesh to West Bengal is one of the longest coast lines. It is a stretch in the Indian peninsula that has more than a dozen major cyclones; but the super cyclone was the severest one the century has ever experienced with wind speed exceeding 250 km per hour. It struck the Orissa coast in the early hours of Friday on 29 October 1999 uprooting large number of trees, electric poles, devastating houses, human settlement and created wanton destruction. The districts of Kenderpara and Jagatsinghpur which were along and close to the track of the super cyclone were the most hit districts where alone 3.5 lakh houses collapsed. 2.5 lakh houses collapsed partially. The cyclone affected 120 Blocks covering 14 districts and damaging a total of 19 lakh houses. The worst affected district was Jagatsinghpur which accounted for a death toll of more than 8000 persons mainly because of the surge induced havoc in the Erasma Block. More than 6 villages were completely washed away and 59 villages were partly washed out. Tidal waves and intrusion of the sea were experienced while heavy rain continued for more than 2 days. The 14 districts affected by the super cyclone marooned 2.5 million people besides leaving agricultural land unfit for cultivation due to salinity and more than 2 lakhs live stock perished.

It was observed that buildings with RCC sheet roof in general have withstood the wind gales of 250 km per hour and almost none of the houses have completely collapsed even being under submergence of water for long. The severe damage also occurred in the districts of Puri and Kenderpara nearer to sea coast where fierce winds have damaged the electrical lines, uprooted even the large trees more than 50 years old and infrastructure services like water supply, road, electricity were badly affected.

The super cyclone that devastated 14 districts and marooned a large number of buildings, cut off Orissa's communication link from rest of the world for more than 24 hours. The whole State reeled under darkness due to power failure and snapping of power lines. The communication link between various villages and districts snapped and roads were washed away, railway's link of Southern Railway disrupted due to breach.

The Paradip port had suffered massive damage such as extensive damage to the conveyor belt and power transmission system, warehouses and roads but core infrastructure was reported to be intact. On receipt of the cyclone warning on 28 October twelve ships docked at Paradip port were ordered out to sea in order to keep them clear of the cyclone track. Bhubaneswar Air Port was closed for operations with severe damage to air traffic control equipments. It resumed operations from 2 November 1999.

The super cyclone had severely affected Research Institutes and facilities situated in the coastal belt of the State. A few coastal installations of the Department of Ocean Development and India Meteorological Department including IMD's Cyclone Detection Radar (CDR) at Paradip have also been damaged.

The super cyclonic storm caused exceptionally heavy rains over some stations in Orissa. Heavy rainfall also occurred in adjoining districts of Gangetic West Bengal. Intense precipitation that lashed Orissa in association with

TABLE 3

Rainfall in Orissa in association with super cyclonic storm

Station	Rainfall in cm				
	29 October	30 October	31 October	1 November	Total
Oupada	12.0	34.5	40.0	9.0	95.5
Bhadrak	3.1	36.1	44.6	2.9	86.7
Anandpur	1.5	39.6	30.0	1.2	72.3
Paradip	15.0	53.0	26.0	-	94.0
Chandbali	4.4	24.8	36.3	3.5	69.0
Bhubaneswar	2.6	42.6	10.4	0.54	56.1
Udala	-	31.0	13.0	3.5	47.5
Gopalpur	0.2	25.0	15.0	3.2	43.4
Puri	4.8	18.0	12.0	0.4	35.2
Kamakhyanagar	-	10.0	19.0	0.8	29.8
Daitary	15.0	12.0	-	-	27.0
Dhenkanal	-	15.0	11.0	0.5	26.5
Cuttack	1.5	25.5	2.5	1.2	30.7
Rajghat	2.0	9.4	25.0	1.3	37.7
Nilgiri	4.3	23.0	9.2	6.3	42.8
Suneidam	2.2	33.0	29.2	14.0	78.4
Akhuapada	2.6	35.0	16.7	7.8	62.1
Astarang	-	30.0	22.0	8.0	60.0
Kakatpur	28.0	18.0	8.7	-	54.7
Kujang	6.5	35.5	5.5	-	47.5
Jenapur	3.7	25.9	12.6	2.3	44.5
Hadgarh	0.7	19.1	46.8	2.4	69.0

the super cyclone gave rise to catastrophic floods particularly in the coastal areas. The extension of the floods and their fury was highly pronounced in and around Balasore area much to the north of the point of landfall. This flooding was the result of intense rains in this area and occurred far away from Erasma block which witnessed a huge storm surge. The super cyclonic storm associated heavy rainfall ranging from 400 mm to 955 mm spanning over period of 4 days resulted in high flood in Baitarani, Salandi, Budhabalanga Kharasua and Brahmani rivers (Table 3). This caused 20,005 number of breaches in the flood embankments. A large number of structures had also been damaged and 454 public buildings have partially/fully collapsed. Head works of 6 dams suffered structural distress. Distribution channels in major projects have been damaged due to heavy rain and flood.

The super cyclone had caused extensive damage. The impact was more pronounced because it struck just 11 days after a very severe cyclone that had ravaged 4 southern coastal districts of the State. The sectors of Agriculture, Livestock, Village Industries, Infrastructure and Environment were badly devastated. According to a UN based EM-DAT data base kept in Belgium of all disasters in the world total damage incurred in this cyclone amounted to $2.5 billion. Besides the economic problem, it also created a number of sociological problems that provided a challenge to the Central and State Government to tackle the existing problems and to revive the socio-economic condition of the State. It had taken a toll of 9893 human lives and left 7507 persons injured. As per the estimate, about 7,000 lives were lost due to tidal surge, about 2,000 lives due to cyclonic flood and the rest by falling objects and/or being blown away due to high speed winds. 8119 lives were reported lost from Jagatsinghpur district alone.

9. Forecasts and warnings provided by India Meteorological Department

Since the system developed in the Andaman Sea to the east of Andaman Islands on 25 October, 1999, the Andaman and Nicobar (A&N) Administration was informed by IMD Head Quarters Office about the formation of a depression, its likely intensification into a cyclonic storm and the occurrence of associated adverse weather (Strong winds and heavy to very heavy rainfall) over A&N islands on 25 October, 1999. As soon as the depression intensified into a cyclonic storm, Cyclone Warning Bulletins were sent by IMD's Area Cyclone Warning Center (ACWC), Kolkata to the Chief Secretary, A&N Islands starting from the afternoon of 26 October. The warning bulletins indicated strong gale wind speed reaching 70-80 kmph, uprooting tree branches and damaging kuchha houses in the Andaman and Nicobar Area. The bulletins contained advice to fishermen not to venture into sea. Six cyclone warning bulletins were issued by ACWC, Kolkata to A& N administration. 6th warning issued at 0915 hrs (IST) of 27 October indicated that adverse weather was no longer expected over the A&N islands.

As the cyclone proceeded further westnorth-westwards, it posed threat to the east coast from north Andhra coast to West Bengal coast. First indication of the same was made in the bulletin issued on 26 October from HQ, IMD. Thereafter, Director General of Meteorology (DGM), IMD issued daily fax messages to all senior functionaries of the Government of India and Chief Secretaries of the States of Andhra Pradesh, Orissa and West Bengal. Thus the fact that the system posed a potential threat to the Indian coastline was brought to their notice three days in advance. In view of greater uncertainty in the beginning, a large part of the coast line covering north Andhra, Orissa and West Bengal coasts had to be alerted from 27 October forenoon onwards. Cyclone alerts were issued for West Bengal, Orissa and north Andhra Pradesh coasts by India Meteorological Department (IMD's) ACWC, Kolkata and Cyclone Warning Centres (CWCs) at Bhubaneswar and Visakhapatnam on 27 October morning indicating commencement of adverse weather in the form of heavy rainfall and strong winds by the afternoon of 28 October in these areas. Regular cyclone warning bulletins by ACWC, Kolkata and CWC, Bhubaneswar commenced from the late evening of 27 October. The bulletins indicated further ongoing intensification of the cyclonic storm, occurrence of gale winds varying from 100 kmph to 200 kmph depending on intensity and OCS of the system, heavy to very heavy rainfall in the coastal districts, state of sea being high to phenomenal and advice to fishermen not to venture into the sea. As the system approached Orissa coast and intensified into a super cyclonic storm, the warnings were upgraded to indicate gale wind speeds reaching 240-260 kmph, storm surge reaching 4-5 metres above the astronomical tide level at the time and near the point of landfall. 14th Cyclone Warning message issued at 2115 hrs (IST) of 29 October from ACWC, Kolkata was dewarning message for West Bengal coastal areas. It indicated that gale speeds were no longer expected on the coastal districts of West Bengal where warning for same were in vogue earlier. In fact heavy rains and gale speed winds were experienced in these areas in association with the super cyclone that crossed into Orissa near Paradip on 29 October. Warnings were continued for Orissa until 31 October, 1315 hrs (IST).

The IMD officials personally interacted with the senior functionaries of the State Governments at Kolkata, Bhubaneswar and Visakhapatnam. IMD's warnings were widely disseminated through the print media, Doordarshan and AIR. DG and Dy DG (cyclone warning), IMD were in close touch with Cabinet Secretary and other functionaries of the Govt. of India throughout the storm period and provided regular updates at the meeting of the National Crisis Management Committee (NCMC). On 30 October, 1999, DG, IMD briefed the Union Cabinet at its emergency meeting chaired by the Hon'ble Prime Minister. India Meteorological Department's forecasts were very accurate and given well in advance.

10. Response to cyclone warnings

10.1. *Government of India*

Department of Agriculture and Co-operation (DAC) in the Ministry of Agriculture functioned as the nodal agency for relief and rehabilitation measures in the wake of natural calamities. On receipt of the first information from the IMD on 26 October, 1999 regarding the cyclonic storm, DAC requested the chief Secretaries and Relief Commissioners of Orissa and West Bengal and Andhra Pradesh to take all preparatory measures including evacuation of the vulnerable people. The Cabinet Secretary, Secretary, DAC and other senior officers remained in constant touch with the above State Government authorities. NCMC under the Chairmanship of Cabinet Secretary had reviewed the status of preparedness in the meetings held at 2200 hrs (IST) on 27 October, 1999 and 1600 hrs (IST) & 2300 hrs (IST) on 28 October 1999. The representatives of various ministries and Departments of GOI *i.e.*, Defence, Home affairs, Power, Telecom, Shipping, Road Transport, Railways, Petroleum and Natural Gas, Information & Broadcasting, IMD and Resident Commissioners of the concerned states were present in this meeting. Various preparatory measures taken at the central level were reviewed during the NCMC meetings.

The preparatory measures were :

(*i*) Cancellation of rail services in some routes and diversion of trains in other routes in order to eliminate the loss of life.

(*ii*) The Armed forces and paramilitary forces were alerted to remain in readiness and to be available to the State Govt. for the help.

(*iii*) A team of senior authorities at Paradip , Calcutta and Haldia were alerted to take all preparatory measures.

(*iv*) The Dept. of Power alerted to remain in state of readiness.

(*v*) The Dept. of Telecom informed all its local Organisations.

(*vi*) The Doordarshan and the All India Radio were informed to issue special Cyclone Warning bulletins in various languages including local languages.

(*vii*) The Ministry of Petroleum was advised to ensure availability of Kerosene and other petroleum products.

(*viii*) A decision was taken to send a Rapid Action Team comprising the officials of the Ministries of Agriculture, Power, Roads, Telecom, Defence and Shipping.

After the NCMC meeting, the Secretary, Department of Agriculture & Co-operation sent a communication to the Chief Secretary of Orissa, appraising him about the latest position of the cyclonic system and requested to take necessary preparatory measures including evacuation of the people, stopping of trains in the vulnerable areas.

From 28 October onwards Doordarshan and All India Radio also arranged dissemination of special cyclone bulletin (both in local and national languages) on hourly basis.

10.2. *Government of Orissa*

The Cyclone Warning Centre, Bhubaneswar had issued a warning in the afternoon of 26 October, more than 48 hours before the killer cyclone hit the state.

The State Government communicated the warning to district collectors and alerted Army. Over the next two days the collectors were kept posted about the cyclone's movement and were asked to evacuate people residing within 10 km of the sea. Nearly 150000 people were shifted in Puri, Bhadrak, Jagatsinghpur, Kendrapara and Balasore districts. There were as many as 35 Cyclone Warning Dissemination Systems (CWDS) all along the Orissa coast. This system was successfully used for dissemination of warnings. In addition, the 23 permanent Cyclone Shelters constructed by the Red Cross Society in 6 coastal districts of Orissa also came very handy in protecting about 30000 people from the fury of the cyclone. Local volunteers, who were trained by the Red Cross, helped the local people in securing shelters during this cyclone. On 28 October evening, the State Cabinet reviewed the state of preparedness.

The United Nations has launched a massive relief and rehabilitation programme in the State. A coordinated effort to provide relief materials and aid to the cyclone victims has been put into operation by United Nations Organisation. The intensity of the cyclone required a large scale intervention from all quarters including National / International agencies / NGOs, Civil Societies, Donor aid agencies.

11. Conclusions

IMD did a commendable job in providing necessary advance information in the form of bulletins and warnings to help the disaster managers to take timely action to reduce loss of life and property. Very highly useful signals on the development of its various phases were provided to the Disaster Management Agencies at the Central and State level. It is however very unfortunate that despite these excellent efforts, death toll of about ten thousand valuable lives was witnessed in the coastal Orissa mainly due to lack of preparedness. Therefore, there is a need for investment in cyclone preparedness related activities.

There is a strong requirement for strengthening of observational network, surface and upper air both, including high wind speed recording instruments. In view of the failure of the observatories to respond to the situation, there is a strong need to deploy sturdy and reliable observing and recording systems. There is an imperative need for augmentation of ocean observing systems (Ocean Data Buoys) in the high seas. Also, there is a need to deploy high performance tide recorders at vulnerable point along the east coast.

Deployment and networking of adequate number of Doppler Radars would facilitate improvement in analysis and prediction of cyclones. IMD has since deployed four Doppler Weather Radars and is in the process of deployment of few more Doppler Weather radars in the east coast of India. It is equally important to modernise the computerised weather forecasting system by introducing very fine resolution numerical models for tropical cyclone predictions. Action for same is in the offing.

Training and education to the people in the cyclone prone areas is also very important component of disaster management machinery so as to prepare them to mitigate the disaster by themselves.

A reliable communication system based on state-of-the-art-technology is an essential requirement for an effective warning system. For the dissemination of the warning messages, communication systems which have very broad public reach such as radio, television, community warning (Cyclone Warning Dissemination System - CWDS) should be used. The communication facility can be provided immediately in case of total communication failure by satellite telephone, mobile telephone if tower is not affected. It was apparently the lack of preparedness/awareness that was instrumental in the deaths of so many people. According to Dash (2002) valuable time (roughly 24 hours) was lost before the advisory/warning could catch the attention of the people.

According to WMO (2003), the meteorological services are becoming increasingly concerned with the end to end approach that characterizes the Total Warning System. These services are finding that the socio–economic issues affecting the response to the warnings are a huge challenge. It was suggested that large gains in the effectiveness of warning systems are to be found in this area. This is very relevant in the context of Indian sub-continent.

Acknowledgements

Author is highly indebted to Dr. R. R. Kelkar, Director General of Meteorology (Retd.), who has been the source of inspiration for the author to produce the original Review. He would be failing in his duty if he does not acknowledge the critical comments that were made by Shri S. Raghavan, Deputy Director General of Meteorology (Retd.) on that Review. He also thanks his colleagues in the Cyclone Warning Offices and Sat. Met. Division for fruitful discussion on many aspects of development of this super cyclone.

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