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Satellite and radar study of Sriharikota severe cyclonic storm of November 1984

M. K. PANDEY, JAGADISH SINGH, P. C. SHARMA and S. NIRANJAN

Meteorological Office, New Delhi

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सार — इनसेट-1 बी वी.एच.आर.आर. एवं नोआ-6 तथा नोआ-7 ए. वी. एच. आर. आर. के दृश्य और अवरक्त चैनलों में प्राप्त आँकड़ों का प्रयोग करके 9–14 नवम्बर 1984 की अवधि के दौरान श्रीहरिकोटा चक्रवात का अध्ययन किया गया है। मौसम उपग्रह आंकड़ों के साथ-साथ मद्रास, मछलीपट्नम और करईकल स्थित समुद्र तटीय चक्रवात संसूचन रेडारों के प्रेक्षणों का भी उपयोग किया गया है। इस भीषण चक्रवाती तूफान के क्रोड़ क्षेत्र के निकट चक्रवात-केन्द्र-स्थिति, तीव्रता आकलन और मेघ अभिलक्षण से संबंधित उपग्रह और रेडार आँकड़ों के विश्लेषण द्वारा प्राप्त परिणाम आपस में अच्छा मेल खाते हैं। उपग्रह मेघ संरूपण से डीवोराक की तकनीक और रेडार आँकड़ों से डुचेंग विधि का प्रयोग करते हुए इस मौसमतंत्र की तीव्रता को आकलित करने का प्रयास किया गया है। मौसम विज्ञान आँकड़ा उपयोग केन्द्र (एम. डी. यू. सी.), नई दिल्ली में उपलब्ध आंकड़ा अनुप्रयोग और अन्योन्य प्रदर्श (डी. ए. आई. डी.) सुविधा का प्रयोग करते हुए मेघ क्षेत्र के शीर्षस्थ भाग में तापीय कन्टूर खींचे गये हैं। इस चक्रवाती तूफान के क्षेत्र में ऐसा देखा गया कि प्रबल तापीय प्रवणता दक्षिणपश्चिम/दक्षिणी भाग में अधिकतम-दीर्घकालिक-पवन-गति से संबंधित थी।

ABSTRACT. A study of Sriharikota cyclone during the period 9-14 November 1984 has been made using INSAT-IB VHRR, NOAA-6 and NOAA-7 AVHRR data in visible and IR channels together with radar observations of coastal radar stations, *viz.*, CDR Madras, CDR Machilipatnam and CDR Karaikal. The inferences drawn from satellite and radar data are in good agreement with regard to location, intensity estimates and the cloud characteristics near the core region. An attempt was made to estimate the intensity of the system using Dvorak's technique from satellite cloud configuration and Ducheng's method from radar data. Thermal contours corresponding to the top of the cloud field have been drawn using Data Application and Interactive Display (DAID) facility of Meteorological Data Utilisation Centre (MDUC), New Delhi. The strong thermal gradient was observed in the southwest/south sector of the cyclonic storm associated with the maximum sustained wind speed over the region.

1. Introduction

The meteorological satellites and cyclone detection radars (CDRs) are the two independent versatile remote sensing tools for cyclone structure analysis and its tracking. There has been reasonable correspondence in the two modes of observations with regard to the information derived by them. Geostationary and polar orbiting satellites are the only reliable observation platforms for indicating the location and the intensity of the cyclones when they are far out in the open seas/oceans, as conventional meteorological observations from ships, in and around cyclone fields are generally not available. Cyclone detection radars provide an excellent source of observation on the location and intensity of cyclones when the systems are within the tracking range of the radars, which is generally about 400 km all around the coast. Radars provide more precise information within their tracking range than the satellites because of their better resolution. In view of the relative merits of these two modes of observations during the life span of the cyclone, the present study was undertaken to carry out detailed analysis of the structure at various stages of its formation, development, dissipation and the intensity analysis using Dvorak's technique (1975, 1984) from satellite data in terms of T-number and also using Zhou Ducheng's method (1985) from radar data.

Sriharikota cyclone during the period 9-14 November 1984 was one of the severe cyclones of this century in the Bay of Bengal. The disturbance originated as a well marked low pressure area over southeast Bay and adjoining Andaman Sea on 9th morning which concentrated into deep depression in the same day evening. It intensified into cyclonic storm in the morning of 11 November and further intensified into severe cyclonic storm in the evening of the same day. The storm attained peak intensity in the afternoon of the 13 November and crossed south Andhra coast in the morning of the 14 November close to Sriharikota. The storm track using satellite and radar data is shown in Fig. 1.

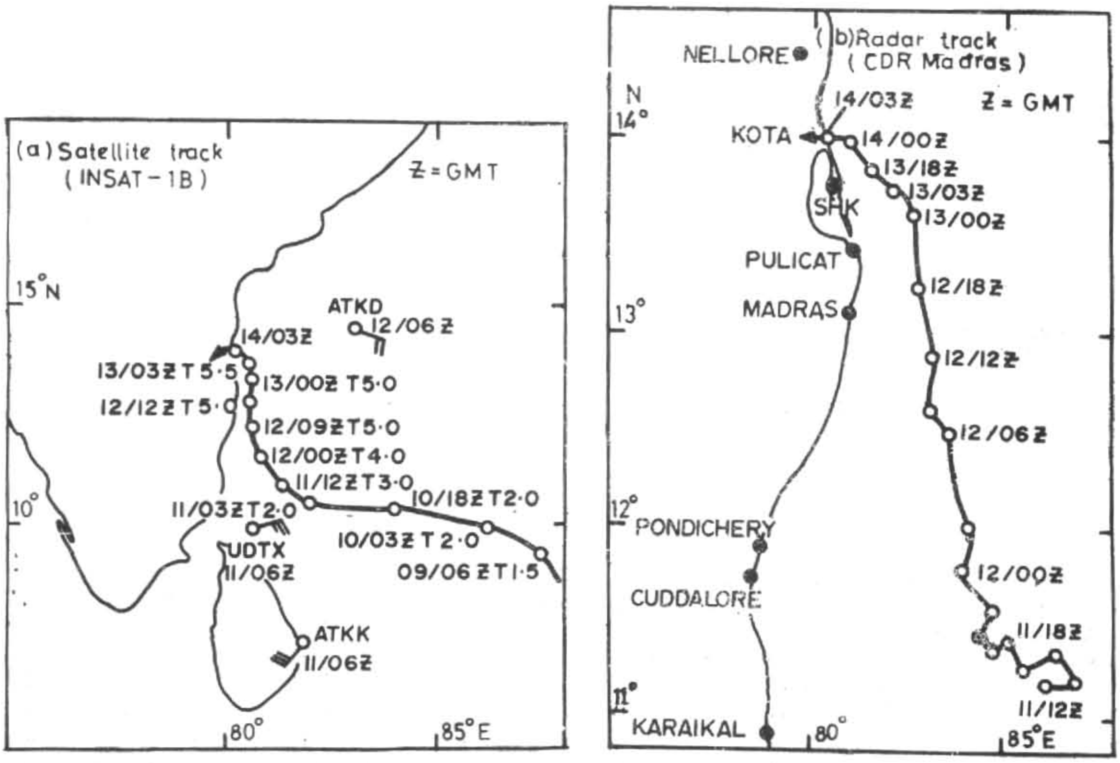

Fig. 1. Tracks of Sriharikota severe cyclonic storm (9-14 Nov 1984) using satellite and radar data

2. Data used

INSAT-1B satellite Very High Resolution Radiometer (VHRR) imagery of 2.75 km resolution in visible channel and 11 km in thermal IR channel and NOAA-6 and NOAA-7, Advanced Very High Resolution Radiometer (AVHRR) imagery of 1.1 km in visible channel have been used to analyse cloud features and estimate the intensity of the cyclone. Thermal contours of the cloud tops in the cyclone field have been drawn for different temperature intervals using the Data Application and Interactive Display (DAID) facility available in Meteorological Data Utilisation Centre (MDUC), New Delhi. Radar photographs taken from cyclone detection radars at Madras, Machilipatnam and Karaikal have been utilised. Surface and upper air data of Tamil Nadu and Andhra coasts and available ships observations have been used.

3. Observational features

3.1. *Analysis of satellite data*

The cloud analysis system centre location and the intensity estimates of the storm were made right from the inception till the landfall using INSAT-IB, NOAA-6 and NOAA-7 visible and thermal IR imagery. The location of the system and its intensity from 9 to 14 November 1984 are shown in Table 1. The cyclone developed as a curved band pattern in the southwest Bay of Bengal on 9th morning and its intensity was estimated as T1.5. The system assumed intensity T2.0 in the afternoon of the same day. On 10 November when the system was organising it covered an extensive area of about 7-degree diameter with two intense convective cloud bands to the east and northeast of the centre. The INSAT-IB visible picture of 03 and 06 GMT of 10 November are shown in Fig. 2. Although the intensity of the system on this day at 03 and 06 GMT was same but there was considerable increase in the convective cloud area to the east and northeast. The system maintained intensity T2.0 till 03 GMT of 11th. At 0530 GMT of 11th, the system intensified to T2.5 and further attained intensity T3.0 in the afternoon. It maintained practically the same intensity till 21 GMT of date. INSAT-IB visible pictures of 0300 GMT and 0600 GMT of 11th are shown in Fig. 3. The comparison of the two pictures indicates considerable changes taking place in the system organisation. At 0300 GMT the system centre is surrounded by a distinct cloud band width 1.5 to 2 degrees to the east where as at 0600 GMT there are two prominent curved convective cloud bands emerging from south separated by about 2.5 degrees. An extensive broken band of about one degree width encircling about three-fourth to the west/north/northeast of the system is seen across the outer boundary of these two bands. The anticyclonic cirrus outflow is also observed. By 11th evening, an irregular Central Dense Overcast (CDO) started forming.

The system showed rapid development since early morning of 12th. At 22 GMT of 11th, the intensity was T3.5. At 00 GMT and 03 GMT of 12th it became T4.0 and T5.0 respectively. The INSAT-IB visible pictures of 03 GMT and 06 GMT, of 12th are shown in Fig. 4. At 03 GMT, INSAT imagery showed a clear eye within a well defined CDO of about 2.5 deg. diameter. The two convective cloud bands as seen on 11th appear to have merged into a single prominent band about 2.5 to 3 deg. wide from south. The cirrus outflow also became prominent and extensive. At 06 GMT, two

TABLE 1

Location and intensity of Sriharikota cyclone 1984 (9 Nov to 14 Nov) using INSAT-1B, NOAA-6 and NOAA-7 data

Time (GMT)	Location Lat. (°N)	Long. (°E)	Intensity (T. No.)	Estemated maximum mean wind speed (kt)
9 November 1984				
06	9.5	87.5	1.5	25
09	9.5	87.5	2.0	30
12	9.5	87.2	2.0	30
15	10.0	87.0	2.0	30
18	9.5	86.5	2.0	30
21	9.5	86.5	2.0	30
10 November 1984				
00	10.0	86.3	2.0	30
03	10.0	86.2	2.0	30
06	9.8	85.8	2.0	30
09	10.0	84.6	2.0	30
12	10.0	84.5	2.0	30
15	10.2	84.3	2.0	30
18	10.5	84.0	2.0	30
21	10.6	83.8	2.0	30
11 November 1984				
00	10.4	82.8	2.0	30
03	10.5	82.1	2.0	30
0530	10.5	82.0	2.5	35
09	10.8	81.5	3.0	45
12	11.0	81.3	3.0	45
15	11.2	81.3	3.0	45
18	11.2	81.3	3.0	45
21	11.3	81.0	3.0	45
12 November 1984				
00	11.6	80.6	4.0	65
03	12.0	80.6	5.0	90
06	12.4	80.7	5.0	90
09	12.5	80.7	5.0	90
12	12.8	80.7	5.0	90
15	13.2	80.7	5.0	90
18	13.2	80.7	5.0	90
21	13.3	80.7	5.0	90
13 November 1984				
00	13.6	80.6	5.0	90
03	13.8	80.3	5.5	102
06	13.8	80.3	5.5	102
09	13.9	80.3	5.5	102
12	13.9	80.4	6.0	115
15	13.9	80.5	6.0	115
18	13.9	80.5	6.0	115
21	13.9	80.1	5.0	115
14 November 1984				
00	14.0	80.1	4.5	90
03	14.0	80.1	4.0	65

bands, one encircling the CDO and the other surrounding the system at a distance of about 3 degrees from the cyclone centre, are observed. NOAA-7 AVHRR visible imagery of 1023 GMT of 12th and NOAA-6 (VIS) imagery of 0109 GMT of 13 Nov 1984 is shown in Fig. 5 in which a sharp round eye of the cyclone is clearly seen.

INSAT-IB visible imagery of 03 GMT and 06 GMT of 13th are shown in Fig. 6. INSAT-IB visible imagery of 0900 GMT and NOAA-7 AVHRR visible imagery of 1011 GMT of 13th are shown in Fig. 7. 03 and 06 GMT INSAT imagery show very prominent band to the east of the centre. The eye at 03 GMT in INSAT and 0109 GMT in NOAA-6 visible pictures is more clearly defined as compared to that at 06 GMT in INSAT visible picture. At 09 GMT, the band to the east became less important and the CDO became more circular and tight. At this stage the system showed intensification and the intensity was T 5.5. The system further intensified at 12 GMT to T 6.0 and maintained the same intensity till around mid-night. The system showed signs of weakening since 21 GMT of 13th and the eye started filling up later.

3.2. *Analysis of radar data*

On 9 Nov 1984, the radar pictures taken by CDR Madras showed scattered convective cloud cells in southwest Bay and adjoining area organising into SW-NE oriented squall lines. The appearance of spiral bands was noticed in the morning of 11 November but due to poor organisation it was not possible to locate the centre prior to 10 GMT of 11th. Fig. 8 shows the radar photographs of the cyclone taken at 1024 GMT and 1242 GMT of 11 November respectively. At 1024 GMT of 11th, radar observation showed formation of an eye, which became nearly complete at 1242 GMT of 11th. showing gradual increase in the intensity of the system. Fig. 9 shows the radar photographs of the cyclone taken at 0500 GMT and 1146 GMT of 12 November respectively. At 05 GMT of 12th a new inner eyewall formed inside the eye leading to an effective decrease in eye size which is one of the characteristics of the intensification of the system. Fig. 10 shows the radar photographs of the cyclone taken at 0603 GMT, 1207 GMT, and Fig. 11 shows photographs taken at 1811 GMT of 13 Nov and 0258 GMT of 14 Nov. On 13 Nov the storm was at peak intensity in the afternoon as seen in 1207 GMT radar photographs with tightness in the banding and perfectly clear eye. From photographs taken after mid-night of 13 November, it is seen that the eye of the cyclone widened and became poorly defined, showing the weakening of the cyclone. Table 2 shows the details of radar fixes at significant hours of observations during the period from 11 to 14 November 1984.

The intensity of the cyclone on 12 and 13 November was computed using an empirical formula given by Zhou Ducheng (1985) and is presented in Table 3. The intensity of the tropical cyclone according to Ducheng (1985) depends upon the diameter (in km) of the eye (X_{1t}), height (in km) of the eyewall (X_{2t}), width (in km) of eyewall (X_{3t}) and minimum crossing angle (in deg.) of the rain band (X_{4t}). It is given by the equation :

$$Y_t = 31.6613 - 0.1501\ X_{1t} + 1.4710\ X_{2t} + 0.1033\ X_{3t} - 0.3375\ X_{4t},$$

where Y_t is cyclone intensity (m/sec).

TABLE 2

The details of radar fixes at significant hours of observation during the period 11-14 Nov 1984

Date (Nov 1984)	Time (GMT)	Azimuth (deg.)	Range from Madras (km)	Lat. (°N)	Long. (°E)	Remarks
11	1024	154	265	11.0	81.4	Eye seen
11	1242	149	250	11.2	81.3	Almost complete eye
12	0500	150	120	12.2	80.8	A small inner eye formed
12	1146	120	055	12.8	80.6	—
12	2104	047	055	13.4	80.6	—
13	0603	008	069	13.7	80.3	—
13	1207	012	067	13.7	80.3	A perfect clear eye seen
13	1811	012	078	13.8	80.4	—
13	2045	002	088	13.9	80.2	—
14	0258	354	097	14.0	80.1	—
14	0644	337	082	13.8	79.9	—
14	0855	328	082	13.7	79.8	—
14	1234	323	060	13.5	79.8	—

TABLE 3

Computation of cyclone intensity Y_t (m/sec) using Zhou Ducheng's method and comparison with satellite intensity estimates

Time (GMT)	X_{1t} (km)	X_{2t} (km)	X_{3t} (km)	X_{4t} (°)	Y_t (m/sec)	Satellite intensity estimates (m/sec)
12 November 1984						
0500	18	14	10	12	46.5	46.5
1146	20	15	12	10	48.6	46.5
2104	22	15	11	10	48.2	46.5
13 November 1984						
0603	14	18	18	10	54.5	51.0
1207	13	18	20	8	55.6	58.8
1811	18	16	15	5	52.4	58.8

4. Thermal distribution at the top of the cloud field in the cyclonic storm

Thermal contours were drawn using INSAT VHRR infrared data received in the wavelength interval 10.5-12.5 μm. The satellite derived cloud top temperature distribution showed a highly asymmetric intense convection shown in Fig. 12. Thermal gradient was found to be more in southwest/south sector as compared to other areas in the storm field. Thermal gradient was very steep in eyewall and eye temperature was about —20°C at 0900 and 1200 GMT of 13 Nov (Fig. 12). The analysis of the thermal contours on 12 and 13 November indicated that the thermal distribution at the top of the cloud field was asymmetric throughout, even at the peak intensity attained in the afternoon of 13 November. The temperature of the eye and wallcloud were computed using DAID facility of NDUC during the period from 18 GMT of 11 Nov to 18 GMT of 13 Nov 1984. There was marked variation in the eye temperature during this period whereas the thermal variation in the eyewall was small (Fig. 13).

5. Results and discussion

5.1. The satellite and radar photographs (Figs. 2–11) show that the storm had small horizontal extent. The precipitating area in the radar picture was less than 2 deg. across. As seen in radar picture, even after crossing the coast, the system exhibited the characteristics of a cyclone with an eye and eyewall. The cloud configuration around the eye as well as the increase in the eyewall size were indicative of the reduction of the organisation of the system.

5.2. One of the striking features of the storm was that there was a rapid development between 11 November and 12 November morning from intensity T2.0 [maximum mean wind speed (MWS) 30 kt] to T5.0 (MWS 90 kt). The cyclone remained practically stationary throughout the day on 13 November.

5.3. Synoptic observation and satellite observation appear to be in close agreement. Sriharikota recorded pressure 984.2 mb at 0710 GMT on 13 November. The maximum sustained wind speed (kt) computed using Mishra and Gupta formula (1976) :

$$V_{max} = 14.2 \sqrt{(P_n - P_0)}$$

P_0 = Central pressure of cyclone in mb

P_n = Peripheral pressure (taken as 1013 mb)

comes out to be 76.2 kt which is equivalent to T4.5 in Dvorak's classification, whereas the intensity estimated using INSAT-1B imagery of 0600 GMT of 13 November was T5.5 with corresponding estimated maximum mean wind speed (MWS) 102 kt. Further, it was seen that Sriharikota reported very high wind speed in gustiness from 0530 GMT of 13th to 0600 GMT of 14 Nov. The highest wind speed reported at 0700 GMT of 13th was 94 kt which is in close agreement with the wind estimated from satellite cloud organisation.

5.4. The surface wind observations at Vakadu and Durgarajupatnam (located about 25 km north of Sriharikota) indicated veering from northeast to east between 0230 GMT and 0330 GMT on 14 Nov, which suggested that the storm crossed the coast around 0300 GMT on 14 Nov. to the just north of Sriharikota.

5.5. The satellite derived thermal contours using INSAT VHRR infrared data showed strong thermal gradient on the cloud top of the storm field in the southwest/south sector. As mentioned in para 5.3, it is seen that maximum sustained mean wind speed (MWS) happens to be in the southwest sector which is the area of strong thermal gradient. It may be inferred that such observations in other cases of tropical cyclones may serve as a vital clue for locating the area of MWS. A graph showing the variation in temperatures of eye and

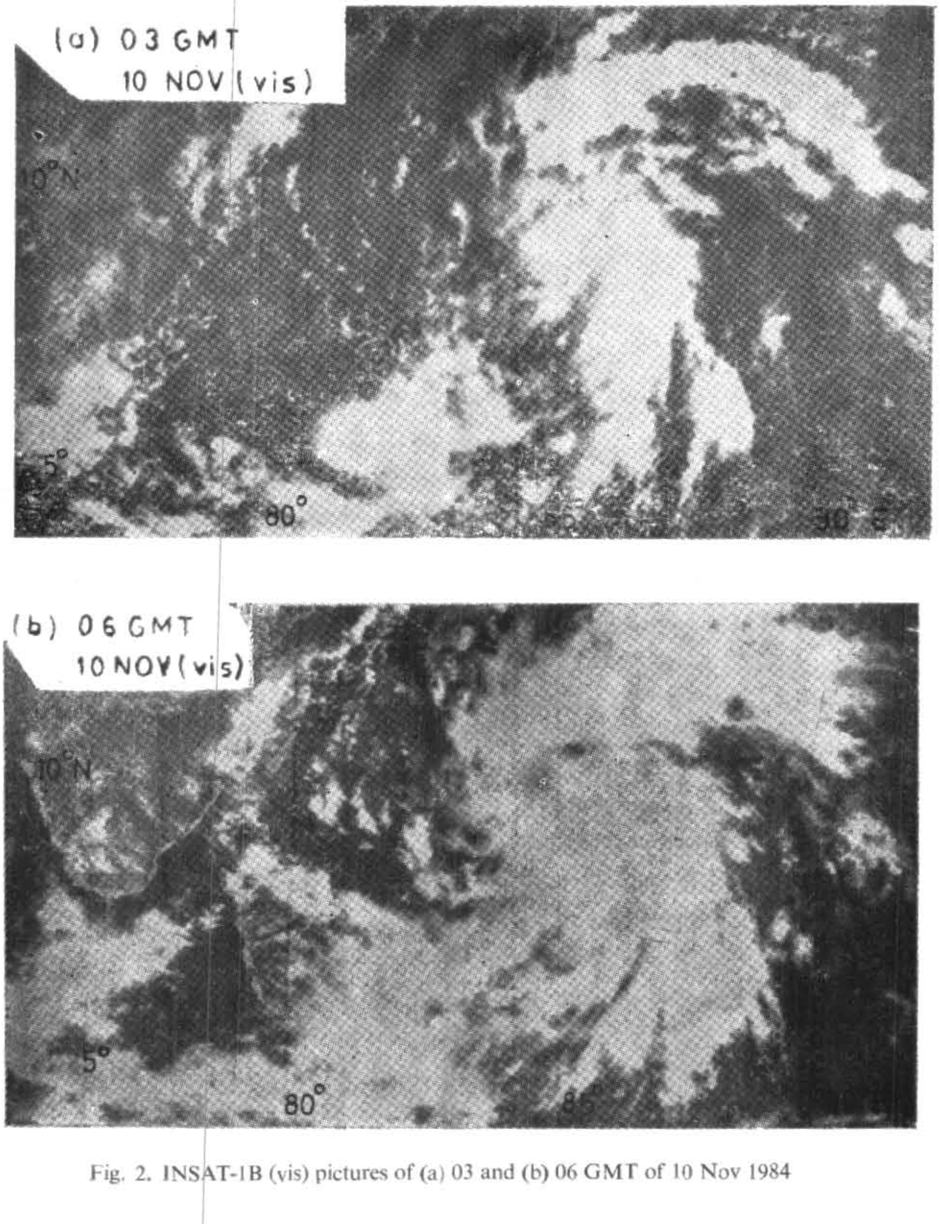

Fig. 2. INSAT-1B (vis) pictures of (a) 03 and (b) 06 GMT of 10 Nov 1984

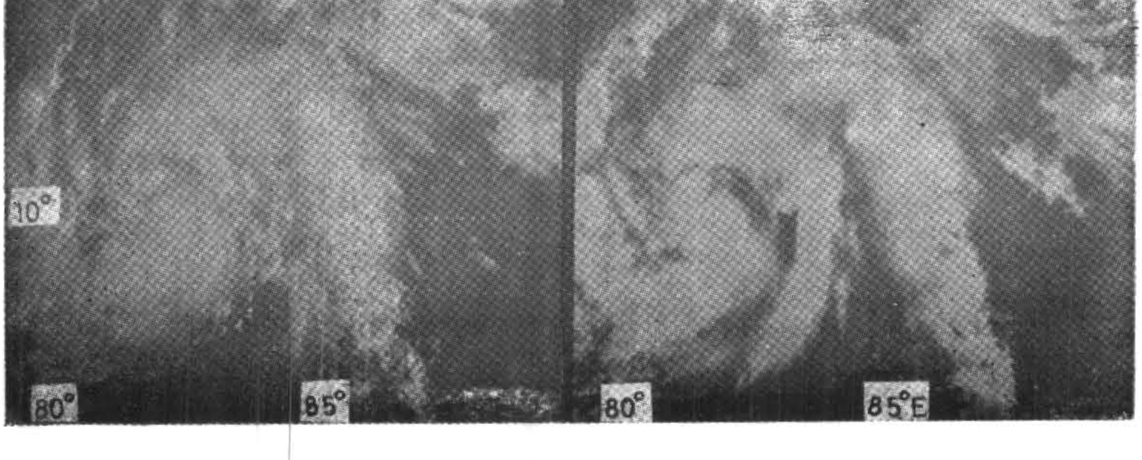

Fig. 3. INSAT-1B (vis) pictures of 03 and 06 GMT of 11 Nov 1984

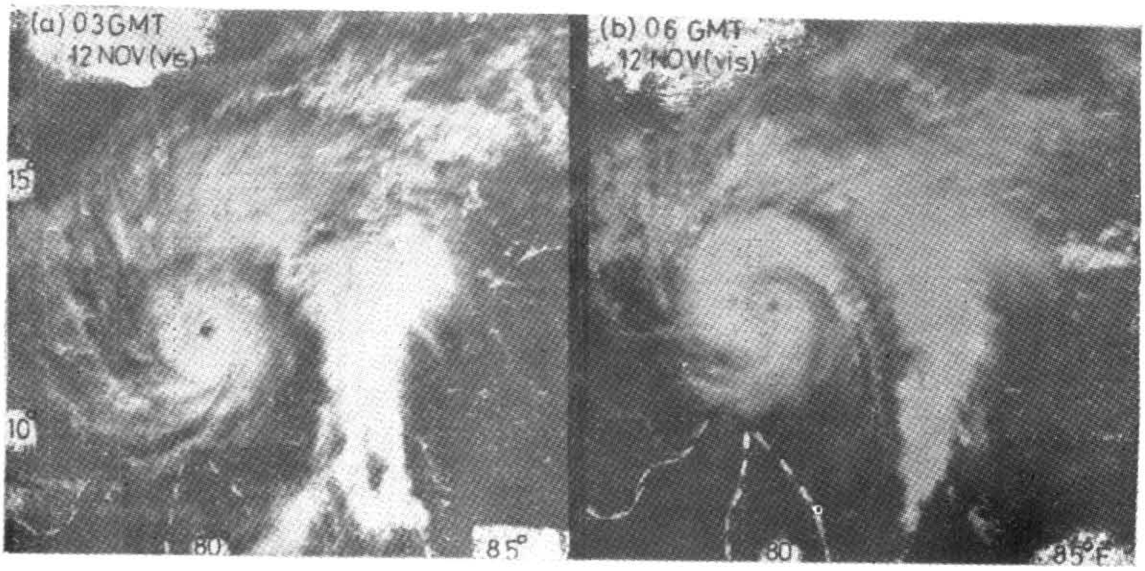

Fig. 4. INSAT-1B (vis) pictures of 03 and 06 GMT of 12 Nov 1984

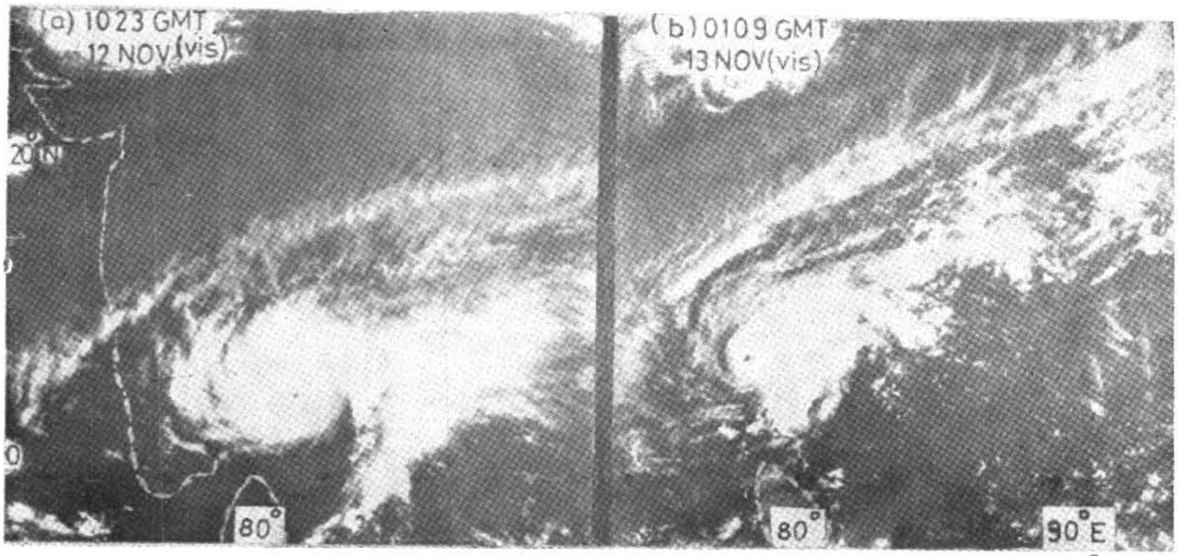

Fig. 5. NOAA-7 AVHRR (vis) imagery of 1023 GMT of 12th & NOAA-6 (vis) imagery of 0109 GMT of 13 Nov 1984

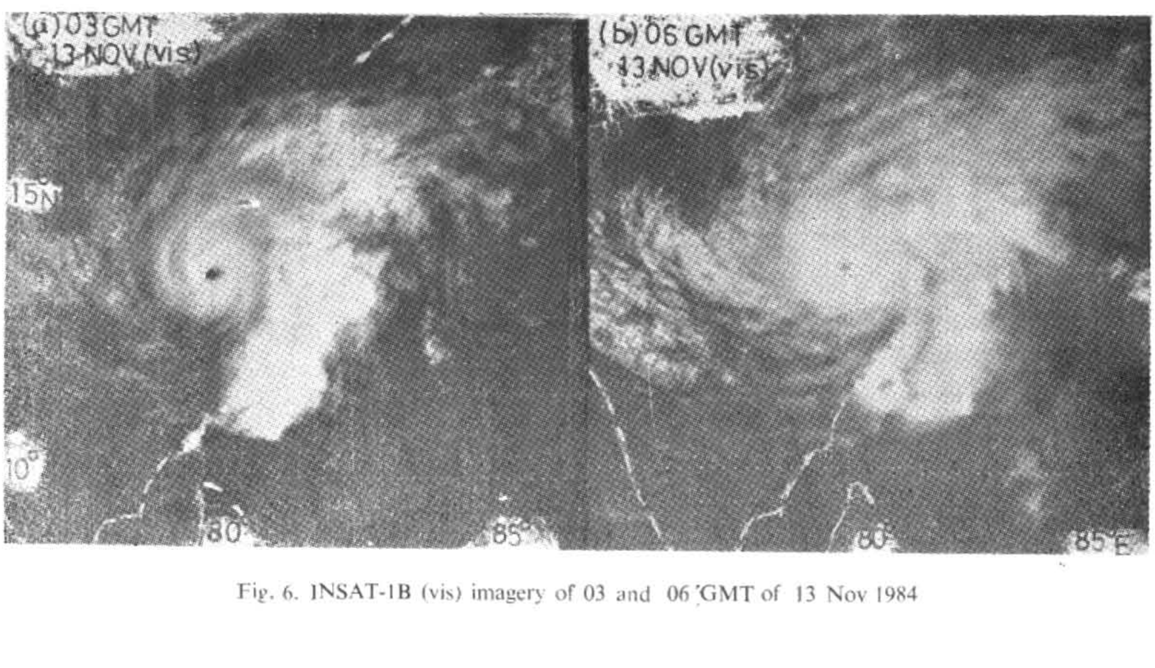

Fig. 6. INSAT-1B (vis) imagery of 03 and 06 GMT of 13 Nov 1984

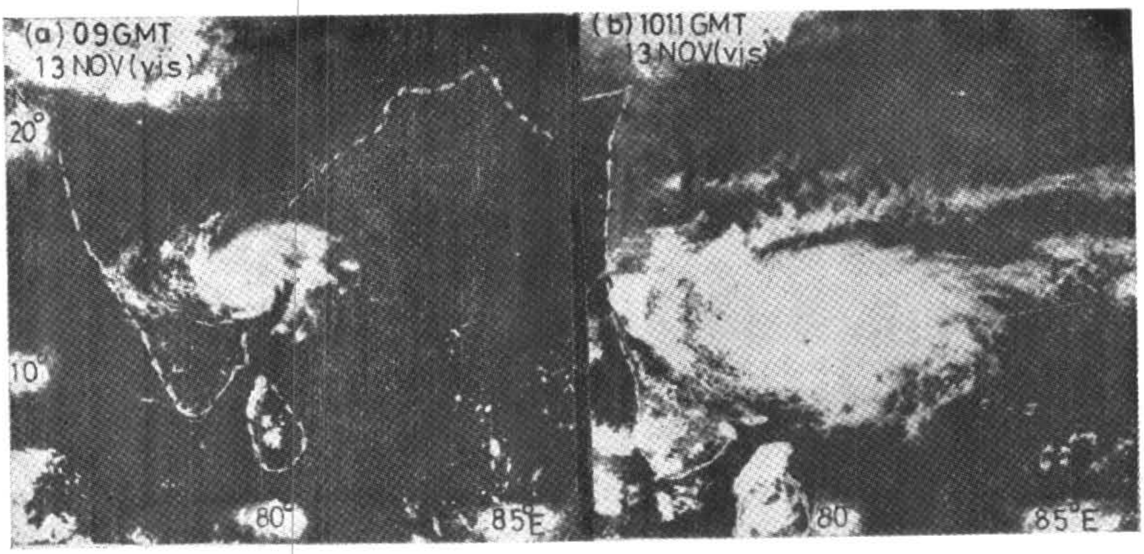

Fig. 7. INSAT-1B (vis) imagery of 09 GMT and NOAA-7 AVHRR visible imagery of 1011 GMT of 13 Nov 1984

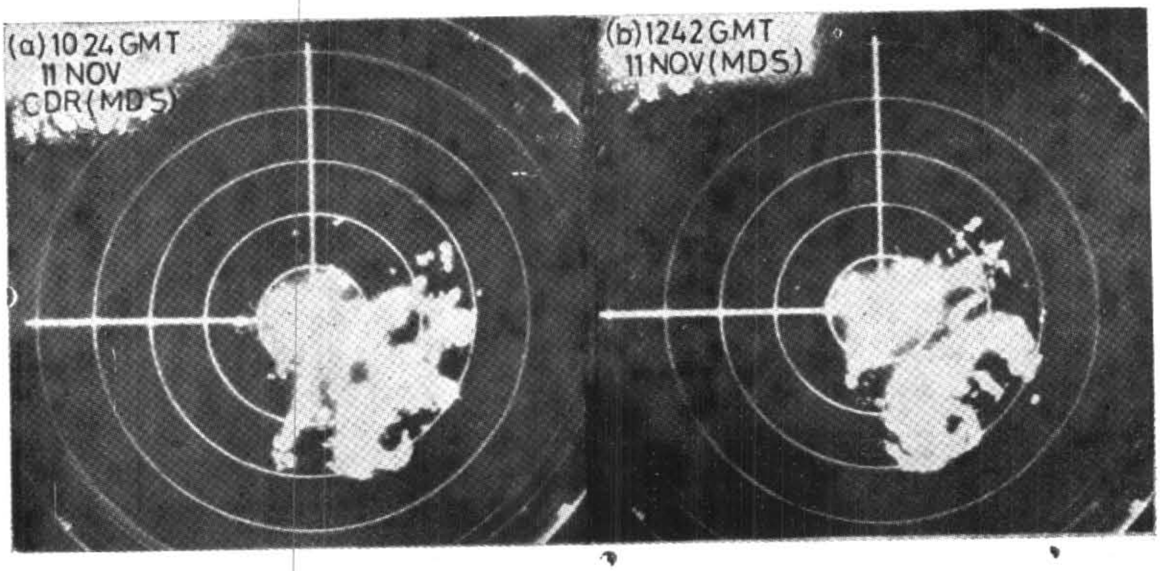

Fig. 8. CDR Madras photographs of the cyclone taken at 1024 and 1242 GMT of 11 Nov 1984

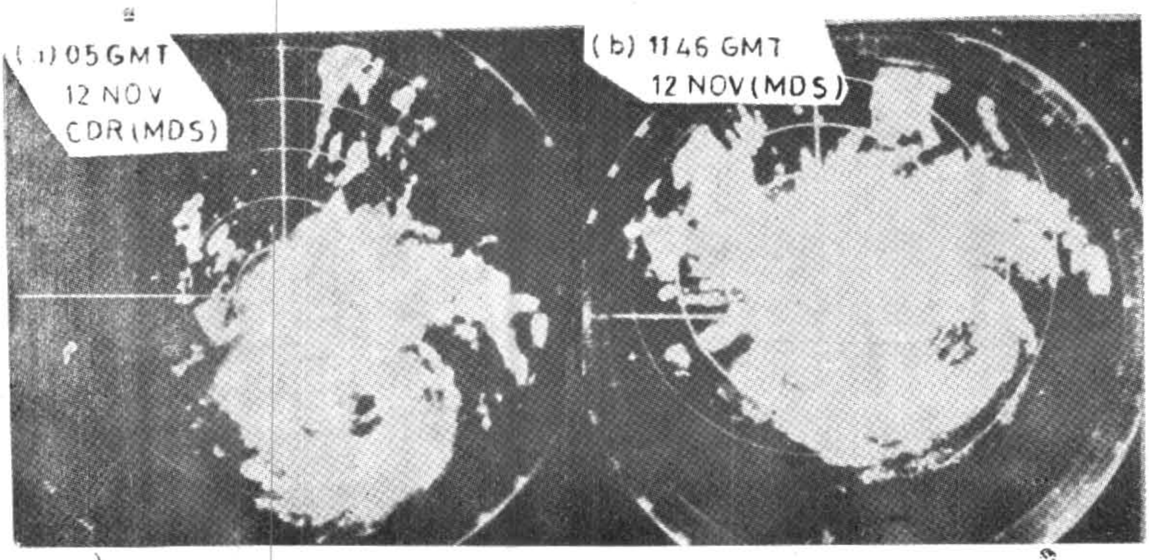

Fig. 9. CDR Madras photographs of the cyclone taken at 0500 and 1146 GMT of 12 Nov 1984

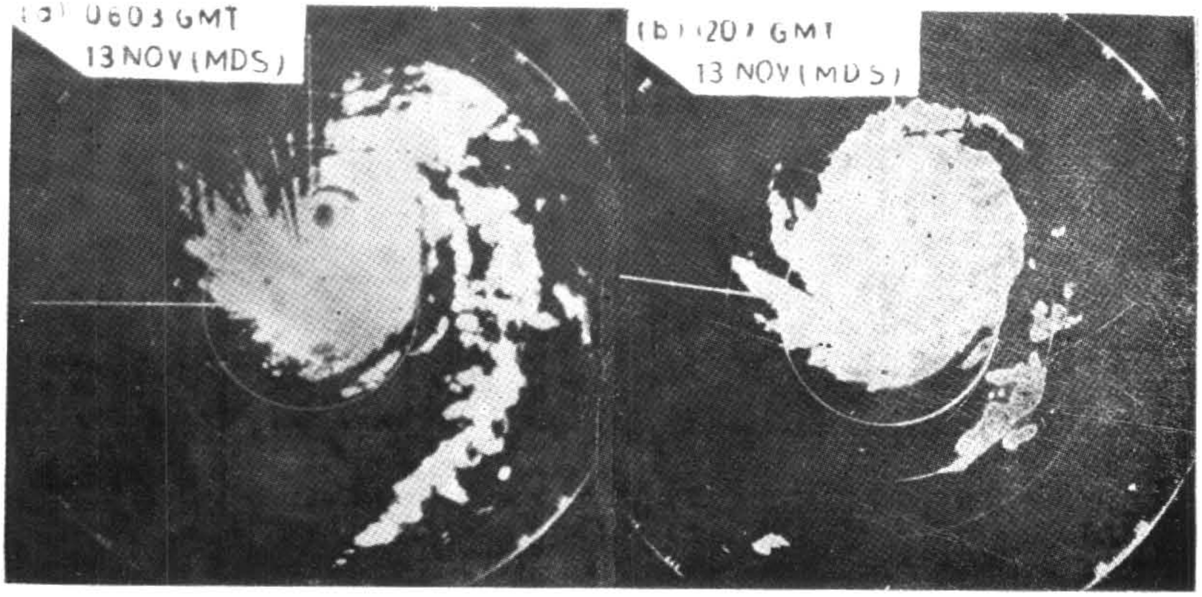

Fig. 10. CDR Madras photographs of the cyclone taken at 0603 and 1207 GMT of 13 Nov 1984

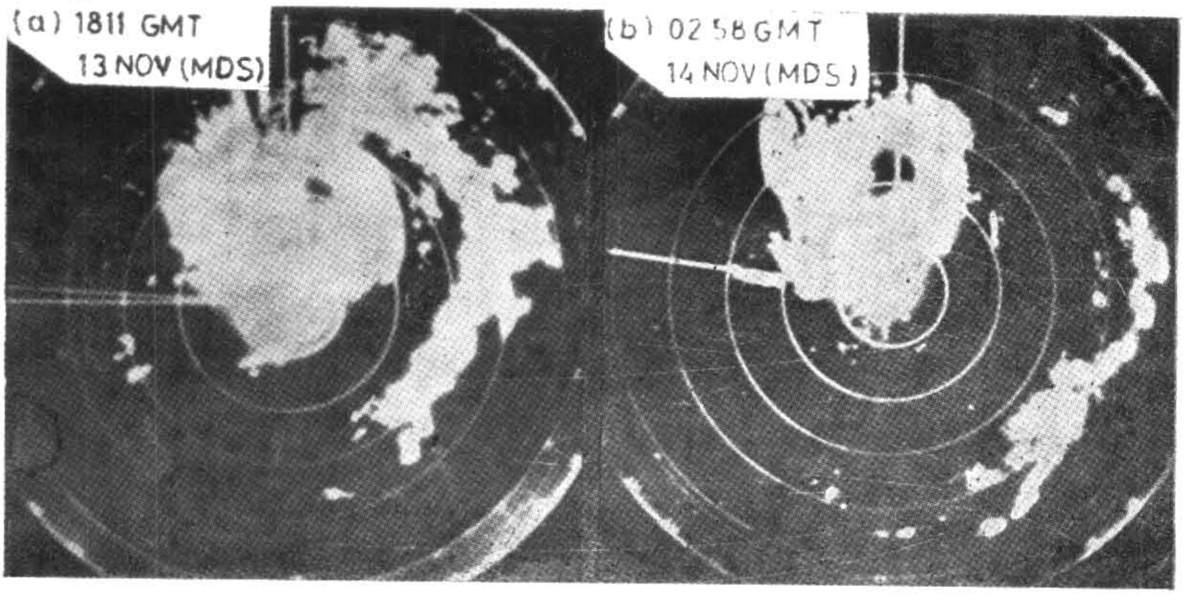

Fig. 11. CDR Madras photographs of cyclone taken at 1811 GMT of 13 Nov 1984 and 0258 GMT of 14 Nov 1984

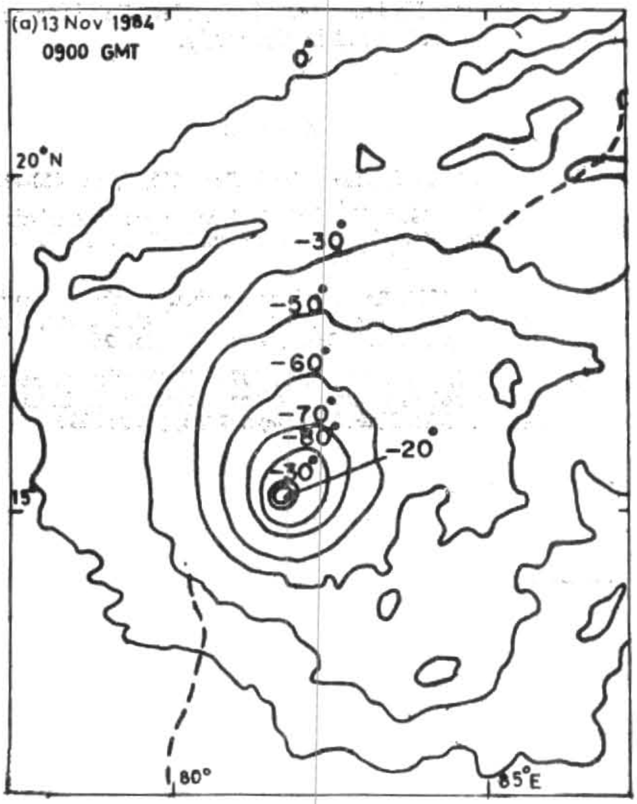

Fig. 12(a). Satellite derived cloud top temperature (°C) distribution (INSAT-1B, 0900 GMT of 13 Nov 1984)

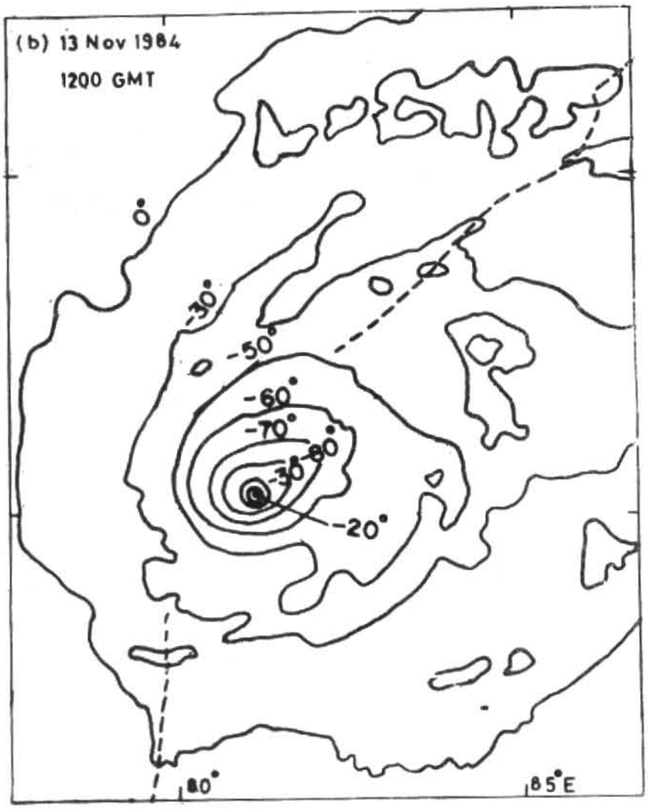

Fig. 12(b). Satellite derived cloud top temperature (°C) distribution (INSAT-1B, 1200 GMT of 13 Nov 1984)

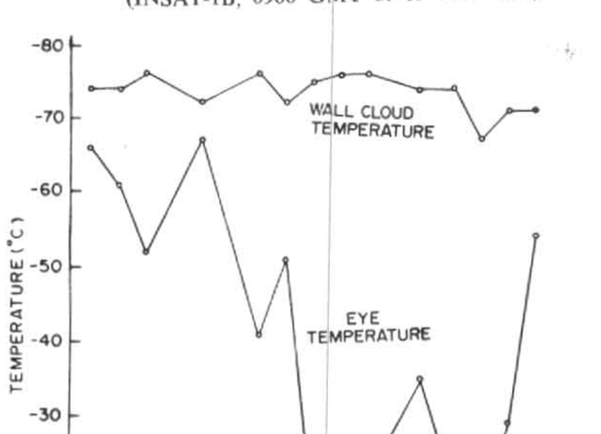

Fig. 13. Temperature variation on the top of the wall-clouds and in the eye during the period, 18 GMT of 11 Nov 1984 to 18 GMT of 13 Nov 1984

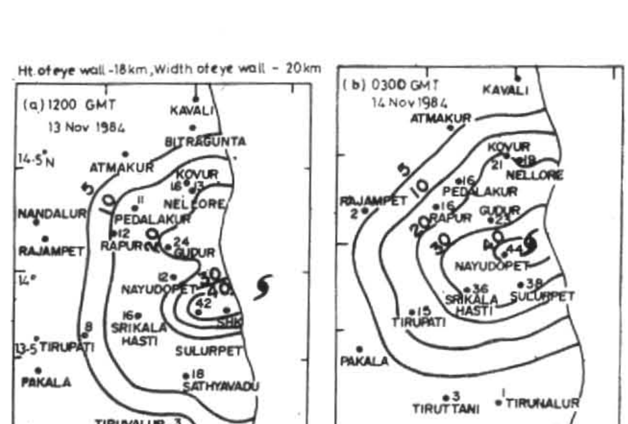

Fig. 14. Rainfall distribution over south Andhra Pradesh and north Tamil Nadu (a) at 03 GMT of 14 Nov 84 *vis-a-vis* cyclone characteristics at 12 GMT of 13 Nov 84 and (b) at 03 GMT of 15 Nov 84 *vis-a-vis* cyclone characteristics at 03 GMT of 14 Nov 84

eyewall is shown in Fig. 13. The eye was considerably warmer at 18 GMT of 12 Nov and 12 GMT of 13 Nov 1984. The variation in the temperature of the eye is an indicative of the extent of subsidence in the eye region whereas the temperature variation in the eyewall during 12-13 Nov 1984 shows that the height of the clouds in the eyewall did not change appreciably.

5.6. Rainfall distribution at 03 GMT of 14 and 15 Nov 1984 over south Andhra Pradesh and north Tamil Nadu *vis-a-vis* characteristic features of the cyclone have been depicted in Figs. 14 (a) & (b). Under the influence of cyclone heavy to very heavy rain was experienced in Chingleput district of Tamil Nadu and Chittoor, Cuddapah, Nellore and Prakasam districts of Andhra Pradesh. The rainfall at Sulurpet 42 cm on 14th and at Nayudupet 44 cm on 15 Nov are most significant and indicate great hydrological potential of the system. These amounts are due to passage of the western portion of the eyewall having dense very intense convective clouds with tops reaching 18 km or more.

Acknowledgements

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