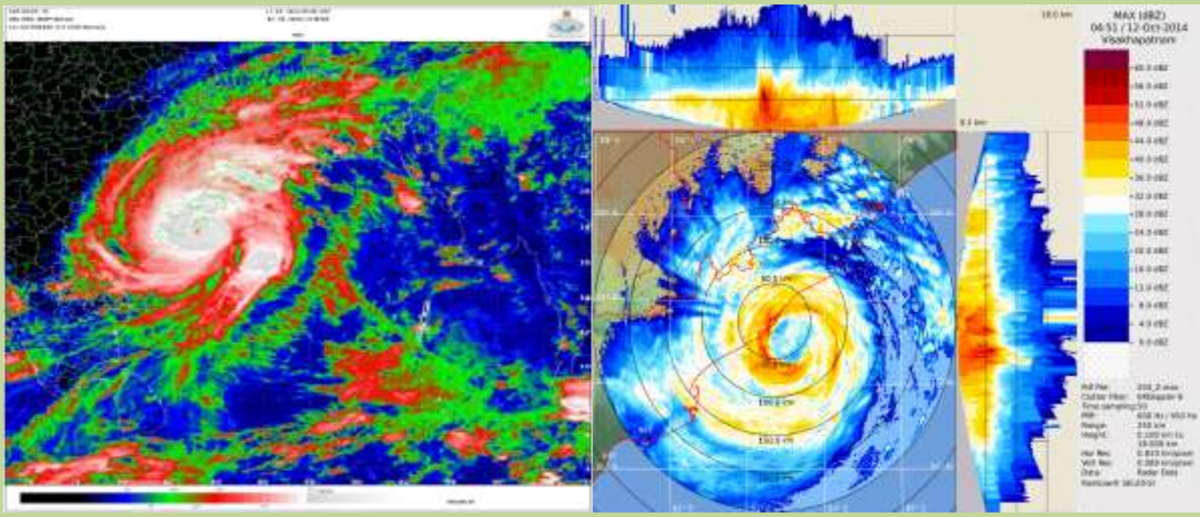
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
EARTH SYSTEM SCIENCE ORGANISATION
INDIA METEOROLOGICAL DEPARTMENT

Very Severe Cyclonic Storm, HUDHUD over the Bay of Bengal (07-14 October 2014): A Report



Satellite imagery and Doppler Weather Radar imagery of VSCS HUDHUD

Cyclone Warning Division

India Meteorological Department

New Delhi

October 2014

Very Severe Cyclonic Storm (VSCS) HUDHUD over the Bay of Bengal (07-14 October 2014)

1. Introduction

The Very Severe Cyclonic Storm 'HUDHUD' (07-14 Oct. 2014) developed from a low pressure area which lay over Tenasserim coast and adjoining North Andaman Sea in the morning of 6th Oct. 2014. It concentrated into a *Depression* in the morning of the 7th Oct. over the North Andaman Sea. Moving west-northwestwards it intensified into a *Cyclonic Storm (CS)* in the morning of 8th Oct. and crossed Andaman Islands close to Long Island between 0830 and 0930 hrs IST of 8th Oct.. It then emerged into Southeast Bay of Bengal and continued to move west-northwestwards. It intensified into a *Severe Cyclonic Storm* (SCS) in the morning of 09th Oct. and further into a *Very Severe Cyclonic Storm* (VSCS) in the afternoon of 10th Oct.. It continued to intensify while moving northwestwards and reached maximum intensity in the early morning of 12th with a maximum sustained wind speed (MSW) of 180 kmph over the West Central Bay of Bengal off Andhra Pradesh coast. It crossed north Andhra Pradesh coast over Visakhapatnam (VSK) between 1200 and 1300 hrs IST of 12th Oct. with the same wind speed. After landfall, it continued to move northwestwards for some time and weakened gradually into *SCS* in the evening and further into a *CS* in the same midnight. It then, weakened further into a *Deep Depression* in the early morning of 13th and weakened into a depression in the evening of 13th. Thereafter, it moved nearly northward and weakened into a well-marked low pressure area over East Uttar Pradesh and neighbourhood in the evening of 14th Oct. 2014.

The salient features of this system are as follows.

i. HUDHUD is the first cyclone that crossed Visakhapatnam coast in the month of Oct., after 1985 and it made landfall on the same day as VSCS Phailin did in 2013.

ii. At the time of landfall on 12th Oct, the estimated maximum sustained surface wind speed in association with the cyclone was about 100 Knots.

iii. The estimated central pressure was 950 hPa with a pressure drop of 54 hPa at the centre compared to surroundings.

iv. It caused very heavy to extremely heavy rainfall over North Andhra Pradesh and South Odisha and strong gale winds leading to large scale structural damage over North Andhra Pradesh and adjoining districts of South Odisha and storm surge over North Andhra Pradesh.coast

v. Maximum 24 hour cumulative rainfall of 38 cm ending at 0830 hrs IST of 13 October was reported from Gantyada (dist Vizianagaram) in Andhra Pradesh. Maximum of storm surge of 1.4 meters above the astronomical tide has been reported by the tide gauge at Visakhapatnam.

vi. The numerical weather prediction (NWP) and dynamical statistical models provided good guidance with respect to its genesis, track and intensity. Though there was divergence in model guidance with respect to landfall point and time in the initial stage, the consensus among the models emerged as the cyclone moved closer to the coast.

viii. India Meteorological Department (IMD) accurately predicted the genesis, intensity, track and point & time of landfall and also the adverse weather like heavy rainfall, gale wind and storm surge 4-5 days in advance.

Brief life history, characteristic features and associated weather along with performance of numerical weather prediction models and operational forecast of IMD are presented and discussed in following sections.

2. Monitoring of VSCS HUDHUD

The VSCS HUDHUD was monitored & predicted continuously since its inception by the IMD. The forecast of its genesis on 7th Oct., its track, intensity, point & time of landfall, as well as associated adverse weather like heavy rain, gale wind & storm surge were predicted exceedingly well with sufficient lead time which helped the disaster managers to maximize the management of cyclone in an exemplary manner.

At the genesis stage, the system was monitored mainly with satellite observations, supported by meteorological buoys and coastal and island observations. As the system entered into the east central Bay of Bengal moving away from Andaman & Nicobar Islands, it was mainly monitored by satellite observations supported by buoys. From 11th Oct. early morning, as the system lay within the range of the Doppler Weather Radar (DWR) at Visakhapatnam, continuous monitoring by this radar started from 0330 hrs IST of 11th Oct. when the system was at about 350 km east-southeast of Visakhapatnam coast and continued till 1020 hrs IST of 12th Oct. when the DWR Visakhapatnam products were not accessible due to disruption of telecommunication in association with the wall cloud region entering into North Andhra Pradesh. In addition, the observations from satellite and coastal observations, conventional observatories and Automatic Weather Stations (AWS) were used. While coastal surface observations were taken on hourly basis, the half hourly INSAT/ Kalpana imageries and every 10 minute DWR imageries, available microwave imageries and scatterometry products were used for monitoring of cyclone HUDHUD. DWR Machilipatnam was also utilized for monitoring this system when VSCS HUDHUD was lying close to the Visakhapatnam coast on 12th Oct.

Various national and international Numerical Weather Prediction (NWP) models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models, dynamical statistical models for genesis and intensity were utilized to predict the genesis, track and intensity of the storm. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation.

3. Major initiatives during VSCS, HUDHUD

Following are the major initiatives taken by IMD for monitoring, prediction and warning services of VSCS, HUDHUD.

(i) Observations:

- The products of INSAT-3D satellite were fully utilised for the first time with the development of new products like enhanced IR imageries and colored enhanced imageries and were made available through an exclusive page for cyclone images in IMD website (www.imd.gov.in). The satellite data was also ingested in model runs at NCMRWF.
- All the existing High Wind Speed Recorders (HWSR) were made operational around the path of cyclone HUDHUD. 1-min wind data from HWSR were recorded alongwith 1 second peak gust.

(ii) Monitoring and analysis:

- In addition to existing 3 hourly monitoring, hourly monitoring and analysis was carried out on the date of landfall.

(iii) Prediction Technique:

- During VSCS HUDHUD, Hurricane Weather Research Forecast (HWRF) model was run by IMD and IIT Delhi with 27/9/3 km resolution based on 00 and 12 UTC observations and products were made available to Cyclone Warning Division.

(iv) Operational Forecasting:

- Hourly updates on the movement and intensity of VSCS HUDHUD were made available to the National and State level disaster managers and media persons on the day of landfall from 0530 hrs IST of 12th till landfall.

(v) Warning bulletins and Products:

- In view of the improvements in operational track forecast during last five years, the cone of uncertainty has been reduced by about 20-32 % for 24-120 hr forecast period w.e.f. VSCS HUDHUD. The new radii of cone of uncertainty are 120, 200, 270, 320 and 360 km for 24-, 48-, 72-, 96- and 120- hrs respectively.

(vi) Warning Dissemination:

- During VSCS HUDHUD Agricultural Meteorology Division, IMD, Pune in coordination with Agromet Field Units and Cyclone Warning Division, IMD, New Delhi disseminated Alert and Agromet Advisory in the affected districts of Andhra Pradesh, Odisha from 9th October onwards and for the states of Telangana, Bihar, Chattisgarh, Jharkhand, East Uttar Pradesh, East Madhya Pradesh and Gangetic West Bengal from 11th onwards. Overall 1,91,4872 SMSs were sent to the farmers and local people of affected states.
- INCOIS, Hyderabad disseminated warnings through SMS and Electronic Display Boards (EDB) to coastal population especially meant for fishermen. Cyclone Warnings issued by IMD were also incorporated in the bulletins issued by INCOIS.
- SMS to Disaster Managers at National level and upto District Collector level
- A new dedicated website for cyclone (www.rsmcnewdelhi.imd.gov.in) has been developed and was fully operational during VSCS HUDHUD.
- The Direct to Home (DTH) service through cable service operators has been installed at 178 places out of proposed 500 stations for cyclone warning communication in the coastal regions.

- Internet Lease Line Bandwidth was upgraded from 60mpbs to 100 mpbs during the cyclonic storm ‘HUDHUD’ failure-free accessibility of IMD website.

4. Brief life history

4.1. Genesis

The VSCS HUDHUD originated from a low pressure are over Tenasserim coast and adjoining North Andaman Sea on 6th Oct. 2014. It concentrated into a depression over North Andaman Sea on 7th Oct. morning over the North Andaman Sea while moving west-northwestwards.

On 7th Oct. morning, scatterometry data indicated the cyclonic circulation over the region and associated wind speed was about 25-30 knots. The wind speed was relatively higher in northern sector of the system. According to satellite observation, intense to very intense convection was seen over Andaman Sea and adjoining area between lat 9.0^0N to 16.0^0N and east of long 90.0^0E to Tenasserim coast at 0830 hrs IST of 7th Oct. The associated convection increased gradually with respect to height and organisation during previous 24 hrs. The lowest cloud top temperature (CTT) was about -70^0C. The convective cloud clusters came closer and merged with each other during past 24 hrs ending at 0830 hrs IST of 7th Oct. According to Dvorak’s intensity scale, the intensity of the system was T 1.5. The system showed curved band pattern with convection dominating in the southwest area of low level circulation centre. The SSMIS microwave imagery depicted increased banding features along the southern periphery of the low level cyclonic circulation (LLCC). Considering all these, the low pressure area was upgraded as a depression over the north Andaman Sea at 0830 hrs IST of 7th with its centre near latitude 11.5^0N and longitude 95.0^0E, about 250 km east-southeast of Long Island. Maximum sustained surface wind speed was estimated to be about 25 knots gusting to 35 knots around the system centre. A buoy located near 10.5^0N and 93.9^0E reported southwesterly winds of 25 KTs supporting the upgradation of the system to depression on 7th morning. The observed track of the system is shown in fig.1.

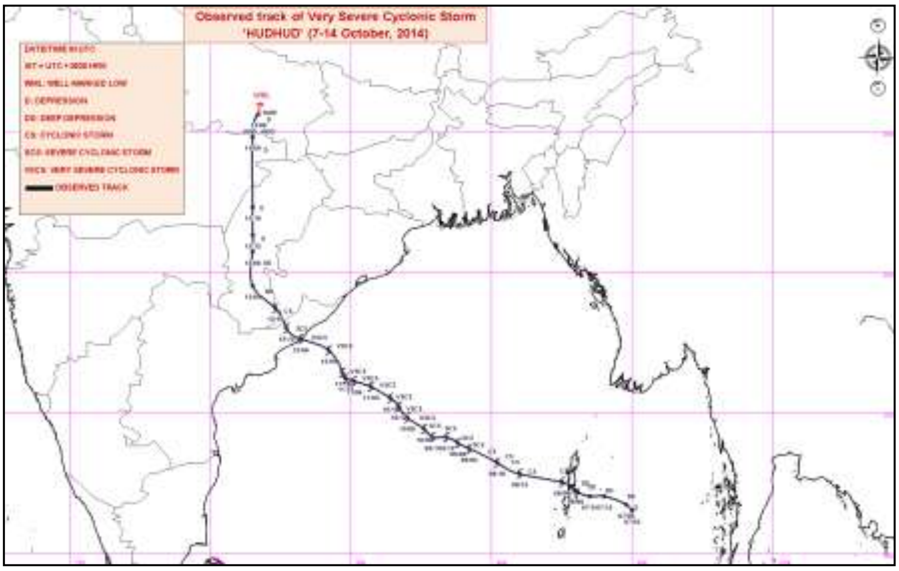


Fig.1 Observed track of VSCS HUDHUD during 7th-14th Oct. 2014.

4.2. Intensification and movement

On 7th Oct. morning, the upper tropospheric ridge at 200 hPa level ran along 19^0N and was providing poleward outflow in association with the anticyclonic circulation located to the northeast of the system centre. Hence upper level divergence was favourable for intensification. The low level convergence along with low level relative vorticity increased in the previous 24 hrs ending at 0830 hrs IST of 7th Oct.. The sea surface temperature based on satellite and available buoys and ships observation was about 30-32^0C and ocean thermal energy was about 60-80 KJ/cm^2. The vertical wind shear of horizontal wind was about 10-20 knots (low to moderate). The Madden Jullian oscillation (MJO) index lay over phase 6 with amplitude greater than 1. All these environmental, atmospheric and oceanic conditions suggested further intensification. Accordingly the depression moved west-northwestwards and intensified into a deep depression at 1730 hrs IST of 7th Oct. over North Andaman Sea near 12.0^0N and 94.0^0E about 130 km east-southeast of Long Island. It further intensified into a cyclonic storm HUDHUD at 0830 hrs IST of 8th Oct. and crossed Andaman Islands close to Long Island (near latitude 12.4^0N and longitude 92.9^0E) between 0830-0930 hrs IST of 8th Oct. with maximum sustained wind speed of 70-80 kmph gusting to 90 kmph. Port Blair reported 88 kmph at 0835 hr IST of 8th Oct. It then continued to move west-northwestwards and intensified into a severe cyclonic storm (SCS) and lay centered at 0830 hrs IST of 9th Oct. over eastcentral Bay of Bengal (BoB) near 13.8^0N and 89.0^0E about 750 km east-southeast of Visakhapatnam. On 9th the vertical wind shear slightly increased and became moderate (15-20 Kts) about the system centre which inhibited the rapid intensification of the system, though predicted by most of the NWP models. However, the SCS continued to intensify gradually while moving slowly west-northwestwards and intensified into a VSCS at 1430 hrs IST of 10th Oct. due to favourable poleward outflow leading to increase in upper level divergence and favourable lower level inflow coupled with warmer sea surface temperature (SST) and moderate ocean thermal energy. It lay centered at 1430 hrs IST of 10th Oct. over westcentral BoB near 15.0^0N and 86.8^0E, about 470 km east-southeast of Visakhapatnam. Thus the VSCS moved slowly with an average translational speed of about 10 kmph from 9th to 10th Oct. It further slowed down thereafter and moved west-northwestwards with a speed of about 5 kmph till midnight of 11th Oct.. It remained almost stationary around early hrs. of 12th Oct..Thereafter the northerly component of the movement and the translational speed increased gradually. Since the morning of 12th, the translational speed of the cyclone was about 15 kmph with northwestward movement. It also gained intensity and maximum sustained wind speed picked up in the early hrs. of 12th Oct. to about 100 kts gusting to 110 kts. Thereafter, as the system came closer to the coast it experienced relatively lower ocean thermal energy with some pockets of the area reporting less than 50KJ/cm^2 and the system interacted with land surface, with its outer spiral band engulfing north Andhra Pradesh & South Odisha coast. As a result, the VSCS did not intensify further & crossed north Andhra Pradesh over Visakhapatnam (near latitude 17.7^0N and longitude 83.3^0E) with a maximum sustained wind speed of 100 kt gusting to 110 kt between 1200 & 1300 hrs IST of 12th Oct.. After the landfall, the system continued to move northwestward for some time and weakened into a SCS at 1730 hrs

IST of 12th Oct. over North Andhra Pradesh close to South Odisha near latitude 18.0^0N and longitude 82.7^0E. It then moved north-northwestward and weakened into a CS at 2330 hrs. IST of 12th in the border of South Chhattisgarh and South Odisha near latitude 18.7^0N and longitude 82.3^0E. It then recurved northwards and weakened into a deep depression at 0530 hrs IST of 13th Oct. over South Chhattisgarh and further into a depression at 1730 hrs IST of 13th Oct. over central part of Chhattisgarh and neighbourhood. It continued to move northward upto the morning of 14th Oct. across east Madhya Pradesh and then north-northeastwards across east Uttar Pradesh and weakened into a well-marked low pressure (WML) area at 1730 hrs. IST of 14th Oct. over East Uttar Pradesh and neighbourhood (Fig.1). The best track parameters of VSCS 'HUDHUD' are shown in Table 1.

Table 1: Best track positions and other parameters of the Very Severe Cyclonic Storm, 'HUDHUD' over the Bay of Bengal during 07-14 October, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
07-10-2014	0300	11.5/95.0	1.5	1004	25	3	D
	0600	11.7/94.8	1.5	1004	25	3	D
	1200	12.0/94.0	2.0	1000	30	5	DD
	1800	12.0/93.5	2.0	1000	30	5	DD
08-10-2014	0000	12.2/93.0	2.0	1000	30	5	DD
	0300	12.3/92.9	2.5	998	35	7	CS
	The system crossed Andaman & Nicobar island near Long island (near lat. 12.4^0N and long. 92.9^0E) between 0300-0400 UTC						
	0600	12.5/92.5	2.5	996	40	8	CS
	0900	12.7/91.7	2.5	996	40	8	CS
	1200	12.8/91.0	2.5	996	40	8	CS
	1500	13.0/90.5	2.5	996	40	8	CS
	1800	13.2/90.2	3.0	994	45	9	CS
	2100	13.5/89.6	3.0	992	45	10	CS
09-10-2014	0000	13.7/89.2	3.0	990	45	12	CS
	0300	13.8/89.0	3.5	988	55	16	SCS
	0600	13.9/88.8	3.5	988	55	16	SCS
	0900	14.0/88.6	3.5	988	55	16	SCS
	1200	14.1/88.4	3.5	988	55	16	SCS
	1500	14.1/88.1	3.5	988	55	16	SCS
	1800	14.1/87.9	3.5	988	55	16	SCS
	2100	14.3/87.7	3.5	988	60	16	SCS
10-10-2014	0000	14.4/87.6	3.5	988	60	16	SCS
	0300	14.7/87.2	3.5	988	60	16	SCS

	0600	14.8/87.0	3.5	986	60	18	SCS
	0900	15.0/86.8	4.0	984	65	22	VSCS
	1200	15.2/86.7	4.0	982	70	26	VSCS
	1500	15.4/86.5	4.0	980	75	28	VSCS
	1800	15.5/86.4	4.0	978	75	30	VSCS
	2100	15.7/86.1	4.0	974	75	30	VSCS
11-10-2014	0000	15.9/85.7	4.0	970	75	30	VSCS
	0300	16.0/85.4	4.5	968	80	34	VSCS
	0600	16.1/85.1	5.0	966	90	40	VSCS
	0900	16.1/85.0	5.0	964	90	42	VSCS
	1200	16.2/84.8	5.0	962	95	44	VSCS
	1500	16.2/84.8	5.0	960	95	46	VSCS
	1800	16.4/84.7	5.0	954	100	50	VSCS
	2100	16.7/84.4	5.0	952	100	52	VSCS
12-10-2014	0000	17.2/84.2	5.0	950	100	54	VSCS
	0300	17.4/83.8	5.0	950	100	54	VSCS
	0600	17.6/83.4	5.0	950	100	54	VSCS
	The System crossed Andhra Pradesh coast over Visakhapatnam (near lat. 17.7^{0}N and long.83.3^{0}E between 0630-0730 UTC						
	0900	17.8/83.0	-	960	90	42	VSCS
	1200	18.0/82.7	-	982	60	20	SCS
	1500	18.3/82.5	-	986	45	15	CS
	1800	18.7/82.3	-	987	40	14	CS
	2100	18.7/82.3	-	988	40	13	CS
13-10-2014	0000	19.5/81.5	-	994	30	8	DD
	0300	20.5/81.5	-	996	30	6	DD
	0600	20.7/81.5	-	998	30	5	DD
	1200	21.3/81.5	-	998	25	4	D
	1800	22.3/81.5	-	1000	25	4	D
14-10-2014	0000	24.8/81.5	-	1000	25	4	D
	0300	25.1/81.6	-	1000	20	3	D
	0600	25.6/81.7	-	1000	20	3	D
	0900	26.3/81.8	-	1000	20	3	D
	1200	Weakened into a well marked low pressure area over East Uttar Pradesh and neighbourhood.					

4.3 Landfall point and time

The place and time of landfall was determined through monitoring of hourly observations from the coastal stations as shown in Fig. 2. The veering of wind over Visakhapatnam and backing of wind over Tuni along with the lowest pressure and maximum sustained surface wind over Visakhapatnam clearly suggested the landfall over Visakhapatnam between 1200 and 1300 hrs IST of 12th Oct. Similar was the case considering the landfall near Long Island on 8th Oct. between 0830 and 0930 hrs IST of 8th Oct. 2014 as Long Island reported lowest mean sea level pressure and veering of wind.

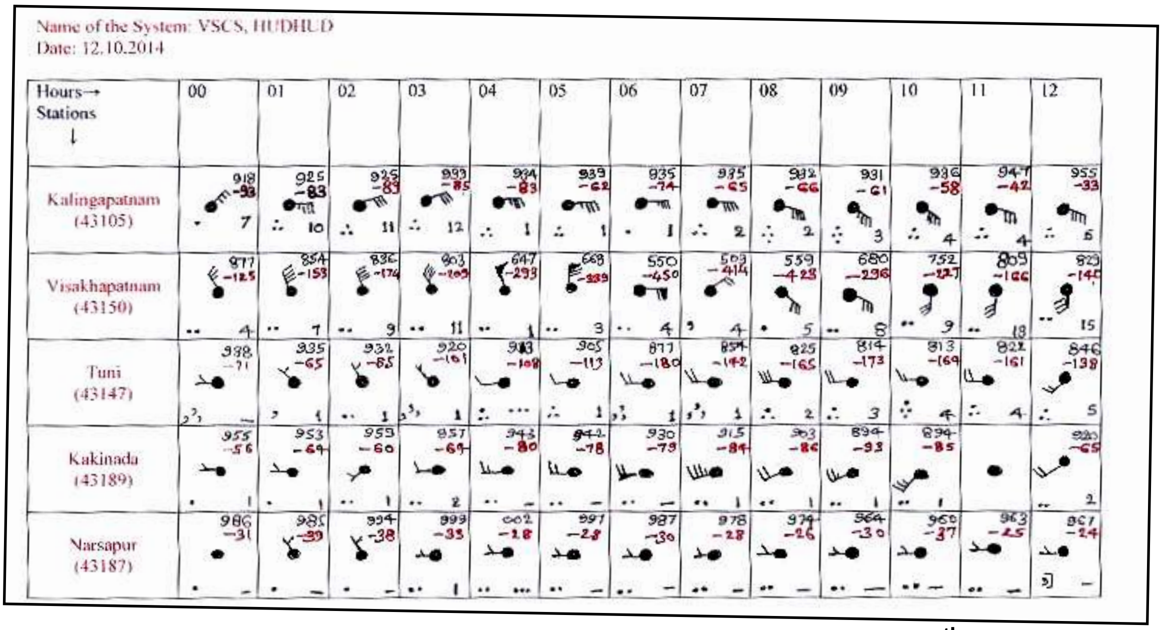


Fig. 2: Hourly observations from coastal stations on 12th October 2014.

5. Maximum Sustained Surface Wind speed (MSW) and estimated central pressure at the time of landfall:

The MSW in association with a cyclone affecting Indian coasts is defined as the average surface wind speed over a period of 3 minutes measured at a height of 10 meters. The MSW is either estimated by the remotely sensed observations or recorded by the surface based instruments. As the VSCS, Hudhud crossed Andhra Pradesh coast over Visakhapatnam, the MSW in its association at the time of landfall has been observed and recorded by the High Wind Speed Recorder (HWSR) located at the Cyclone Warning Centre (CWC), (IMD), Visakhapatnam. It has also been observed by an Automatic Weather Station (AWS) installed in a ship located near Visakhapatnam port by the Indian National Centre for Ocean Information System (INCOIS), Hyderabad.

The Doppler Weather Radar (DWR) of IMD at Kailasagiri, Visakhapatnam also continuously monitored the VSCS, Hudhud and measured the MSW in terms of radial velocity. Based on satellite imagery, an empirical technique known as the Dvorak technique is utilized worldwide to estimate the intensity of cyclone and hence the associated MSW. Further, the IMD observatory at the CWC, VSK continuously monitored the Mean Sea Level Pressure (MSLP) during the landfall of cyclone, Hudhud. Based on the observation of the pressure drop at the centre, MSW can also be estimated using the empirical pressure-wind relationship (MSW= 14.2* √ pressure drop at the centre). These are the basic standard methods used worldwide to estimate the MSW or intensity of the cyclone.

5.1 Estimated central pressure of VSCS, HUDHUD

The hourly MSLP as recorded by Visakhapatnam is shown in Fig.3a which clearly indicates that the pressure fell gradually from 11th onwards and fall became rapid from the early morning of 12th Oct. As a result, 24-hour. pressure fall ending at 0600 UTC of 12th was 45 hPa and the lowest pressure was 950.3 hPa as recorded at 0700 UTC over Visakhapatnam (time of landfall). Thereafter the pressure rose sharply as the VSCS crossed coast and filled in due to increase in surface pressure and cut off from moisture supply.

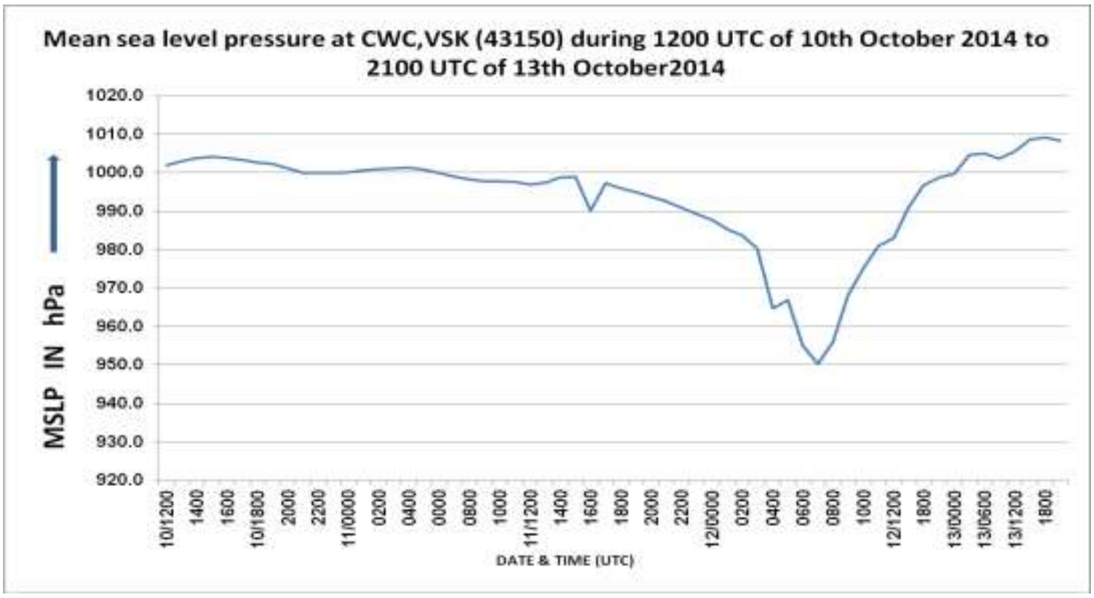


Fig.3a: Hourly MSLP recorded at Visakhapatnam during 10-12th Oct. 2014

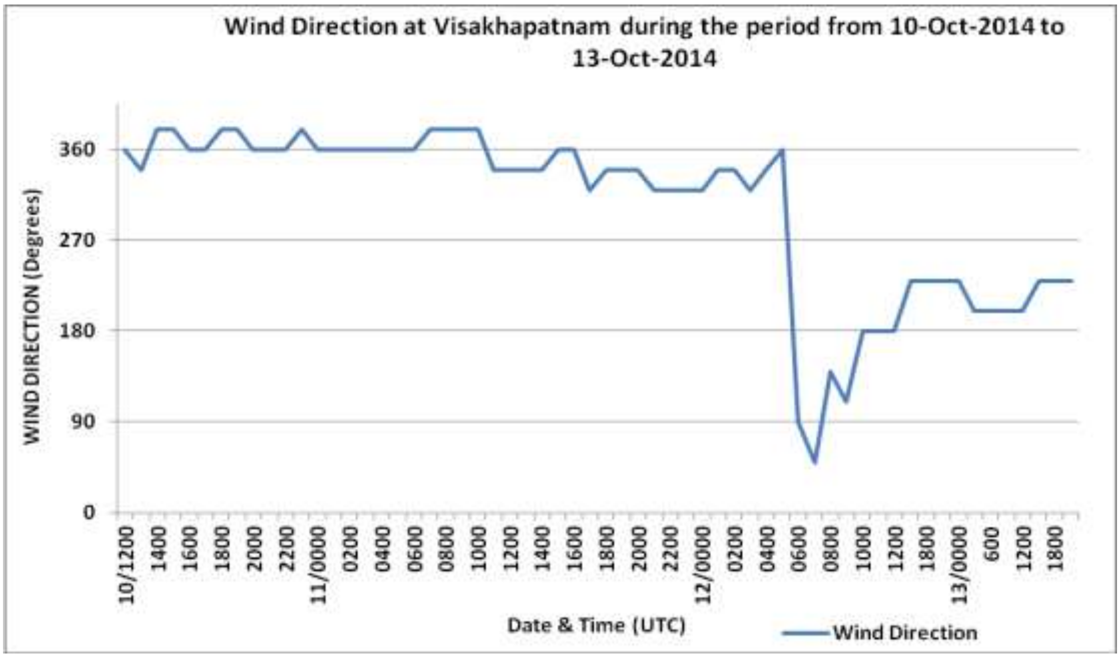


Fig.3(b) : Hourly wind direction reported by Visakhapatnam Observatory during the period from 1200 UTC of 10th October 2014 to 2100 UTC of 13th October 2014.

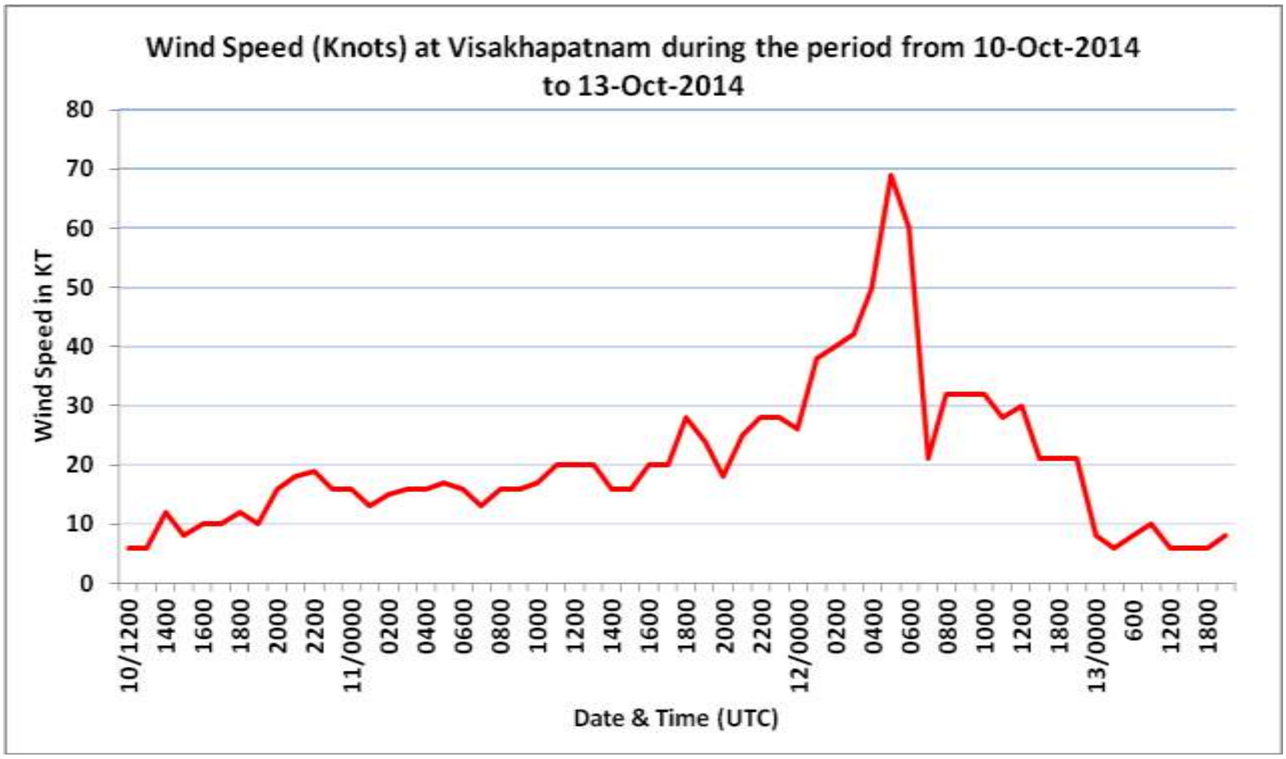


Fig.3(c) : Hourly wind speed reported by Visakhapatnam Observatory during the period from 1200 UTC of 10th October 2014 to 2100 UTC of 13th October 2014.

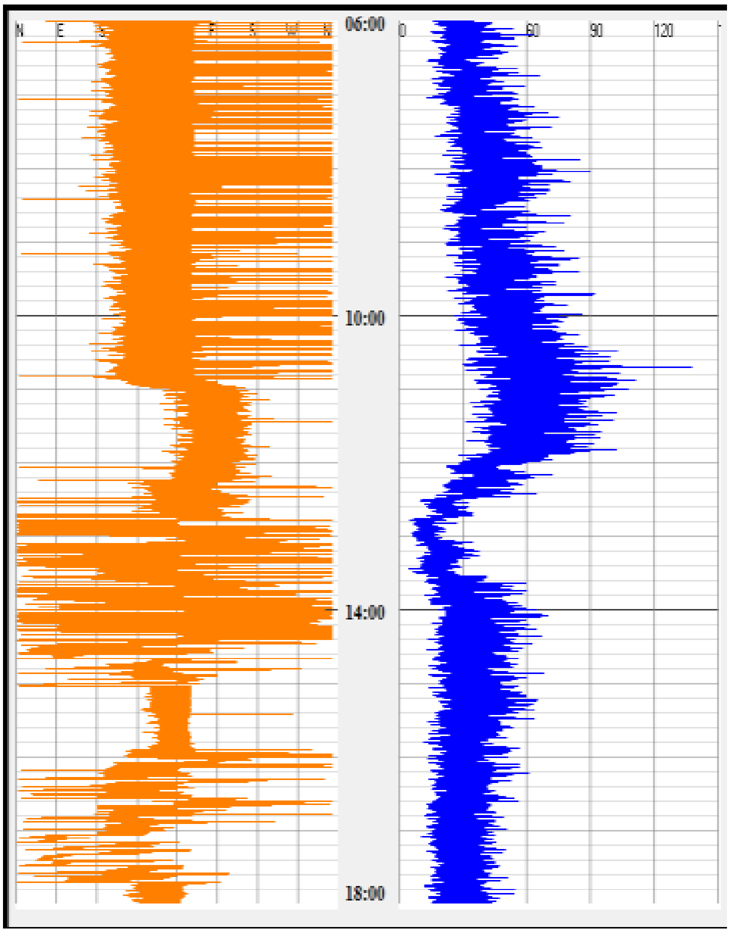


Fig.3d: Wind speed and direction recorded by HWSR, Visakhapatnam on 12 October 2014

5.2. MSW over Visakhapatnam as measured by HWSR:

According to HWSR located at the CWC, IMD, Visakhapatnam, one -minute average MSW was about 74 knots (137kmph) at 1101 hours IST and the 3-minute average MSW which is the standard practice of the IMD was about 69 knots (128kmph) at 1103 hours IST of 12th October, 2014 (Fig.3b).

5.3 MSW based on observation by the AWS:

The AWS installed at a ship near Visakhapatnam port recorded one-minute average MSW of 181.6kmph around the time of landfall on 12th October 2014.

5.4. Satellite based MSW over Visakhapatnam:

According to interpretation of satellite imageries, as per Dvorak technique by the IMD, the tropical cyclone intensity was T5.0 on intensity scale. T5.0 corresponds to an MSW of about 90-100 knots (167-185 kmph).

5.5. MSW over Visakhapatnam based on radar:

The DWR, VSK recorded 67 meters per second or 130knots (241kmph) at a height of about 200 meters. When converted or reduced to the surface level, it is estimated to be around 90 knots. (167kmph)

5.6. MSW based on pressure drop:

According to the observation taken in the IMD observatory at Visakhapatnam, the lowest central pressure of 950.3hPa was recorded at Visakhapatnam at the time of landfall. Hence, the lowest central pressure can be considered as 950hPa. Thus, the pressure drop at the centre was 54hPa as the outermost pressure in the cyclone was 1004hPa. According to Mishra and Gupta formula, the MSW=14.2*SQRT (pressure drop) = 14.2*SQRT (54) = 104knots. (193kmph)

Considering all these observations and estimates, it can be concluded that the MSW at the time of landfall of Hudhud was about 170-180kmph. The gust which is a sudden rise in wind speed in association with a cyclone can reach upto a factor of 1.2 times the MSW, according to the standard specified by the WMO, Geneva. However, according to the HWSR, Visakhapatnam, the one second peak gust wind speed was 140.6 knots (260 kmph) at 1042 hours IST of 12th October, 2014.

6. Features observed through satellite

Monitoring of the cyclone was mainly done by using half hourly Kalpana-1, INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 and MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical satellite INSAT-3D imageries of VSCS HUDHUD representing the life cycle of the cyclone are shown in Fig. 4-6.

According to INSAT-3D imageries and products, a low level circulation developed over Tenasserim coast in the morning of 6th Oct. 2014. It intensified into a vortex with intensity T1.0 and centre near 11.5°N/95.2°E at 0530 hrs IST of 7th October over north Andaman Sea. The pattern was of shear type at this stage. Initially it moved in westerly direction. The system intensified again at 1700 hrs IST of 7th October with centre near 11.5°N/94.7°E and intensity T1.5. The shear pattern changed to curved band pattern with maximum cloud mass in southern sector. Moving in the westwards direction it intensified with intensity of T2.0 and centre 11.5°N/94.2°E at 1730 hrs IST of 7th Oct. The curved band pattern with maximum cloudiness in southern sector continued. However, the convection became more compact and organized around the low level cyclonic circulation centre. The intensity became T 2.5 at 0830 hrs IST of 8th October with centre near 12.4°N/92.5°E. At this time it was of curved band pattern and the band wrapped 0.5 degree in the logarithmic spiral. It remained with intensity of T2.5 for 11 hours and intensified to T3.0 at 2030 hrs IST of 8th Oct. It further intensified to T3.5 at 0830 hrs IST of 9th Oct. corresponding to SCS intensity and lay centered near 13.7°N/89.2°E. The curved band pattern changed to Central Dense Overcast (CDO) pattern. The intensification to T4.0 occurred at 1430 hrs IST of 10th October and centre at this time was located near 15.0°N/87.0°E. The spiral bands were more organized and well defined CDO was observed. It further intensified into T4.5 at 0830 hrs IST of 11th and further to T5.0 at 1130 hrs IST of 11th near 16.1°N/85.2°E. The eye was clearly visible at 0530 hrs IST of 11th and continued to be distinct till the morning of 12th. VSCS HUDHUD maintained its intensity of T5.0 till the time of landfall. According to satellite imagery, the VSCS HUDHUD crossed Andhra Pradesh coast near 17.9°N/83.2°E.

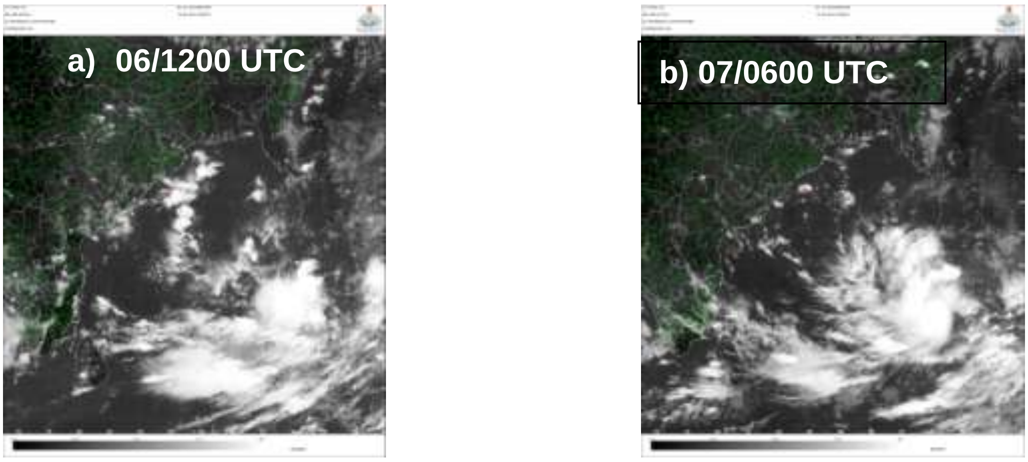


Fig. 4: Typical INSAT-3D Infra-red (IR) imageries based in association with VSCS HUDHUD during 06-14 October 2014

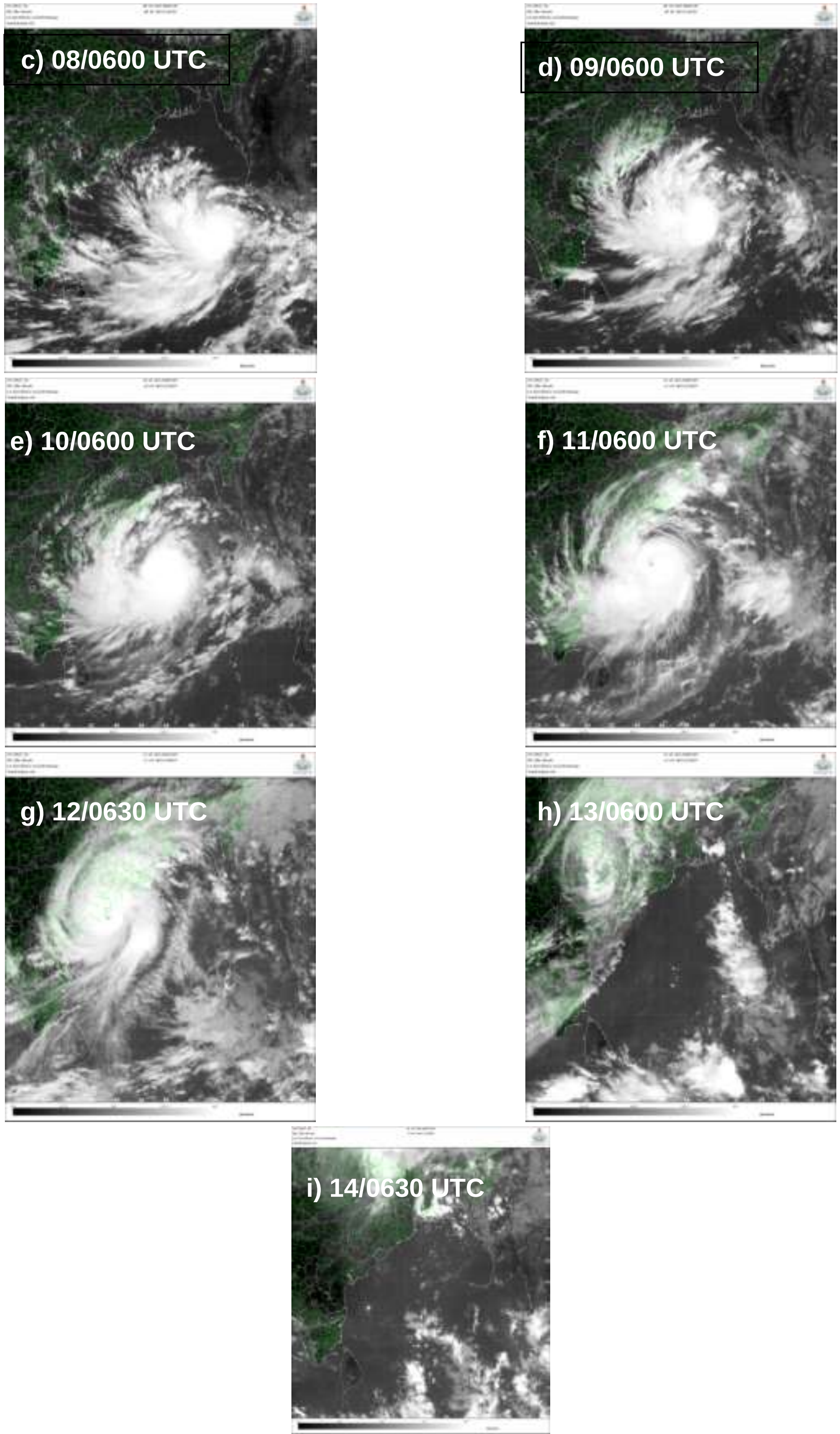


Fig. 4 (contd.): Typical INSAT-3D IR imageries based in association with VSCS HUDHUD during 06-14 October 2014

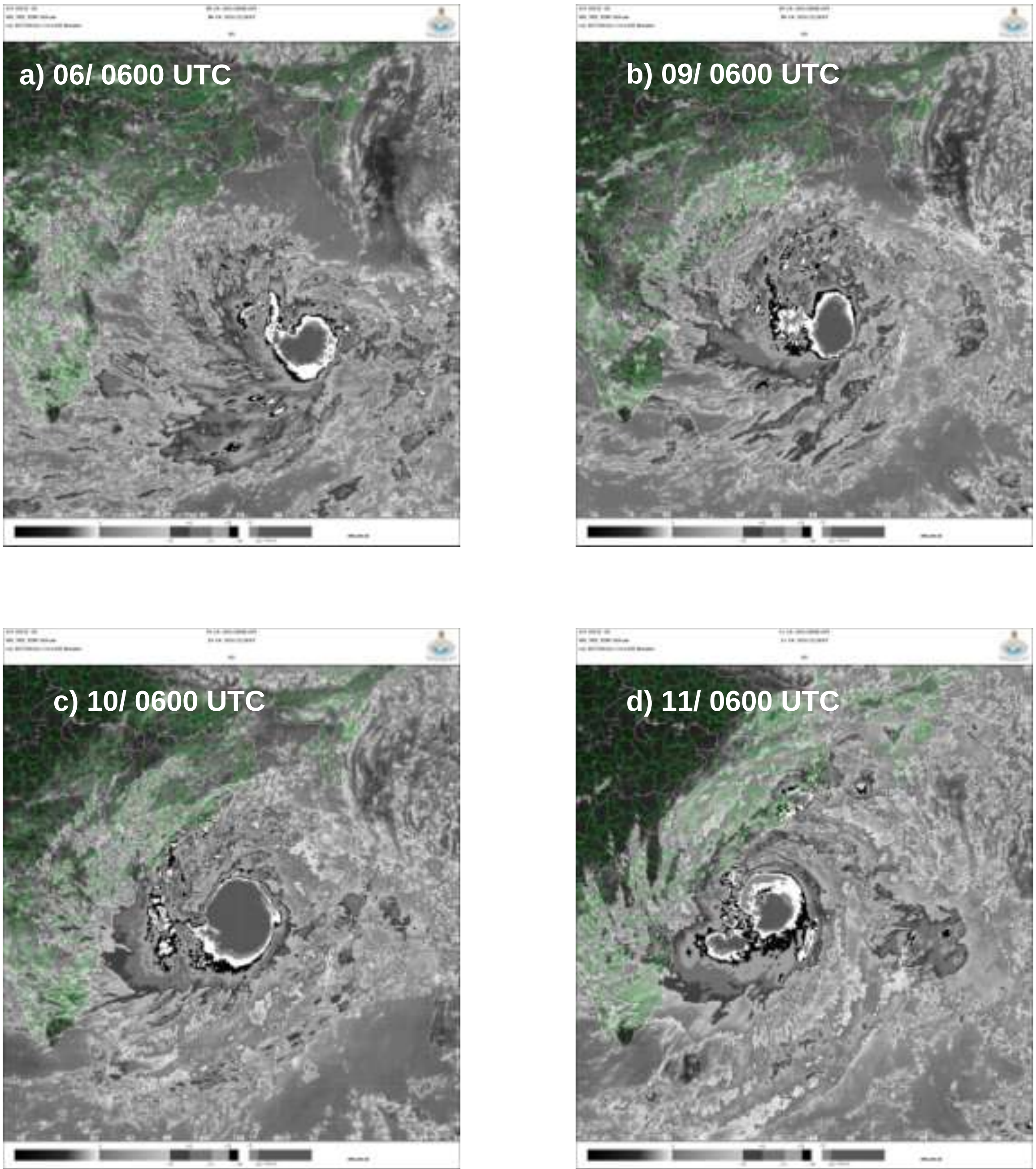


Fig. 5: INSAT-3D enhanced IR imageries in association with VSCS HUDHUD during 08-14 October 2014

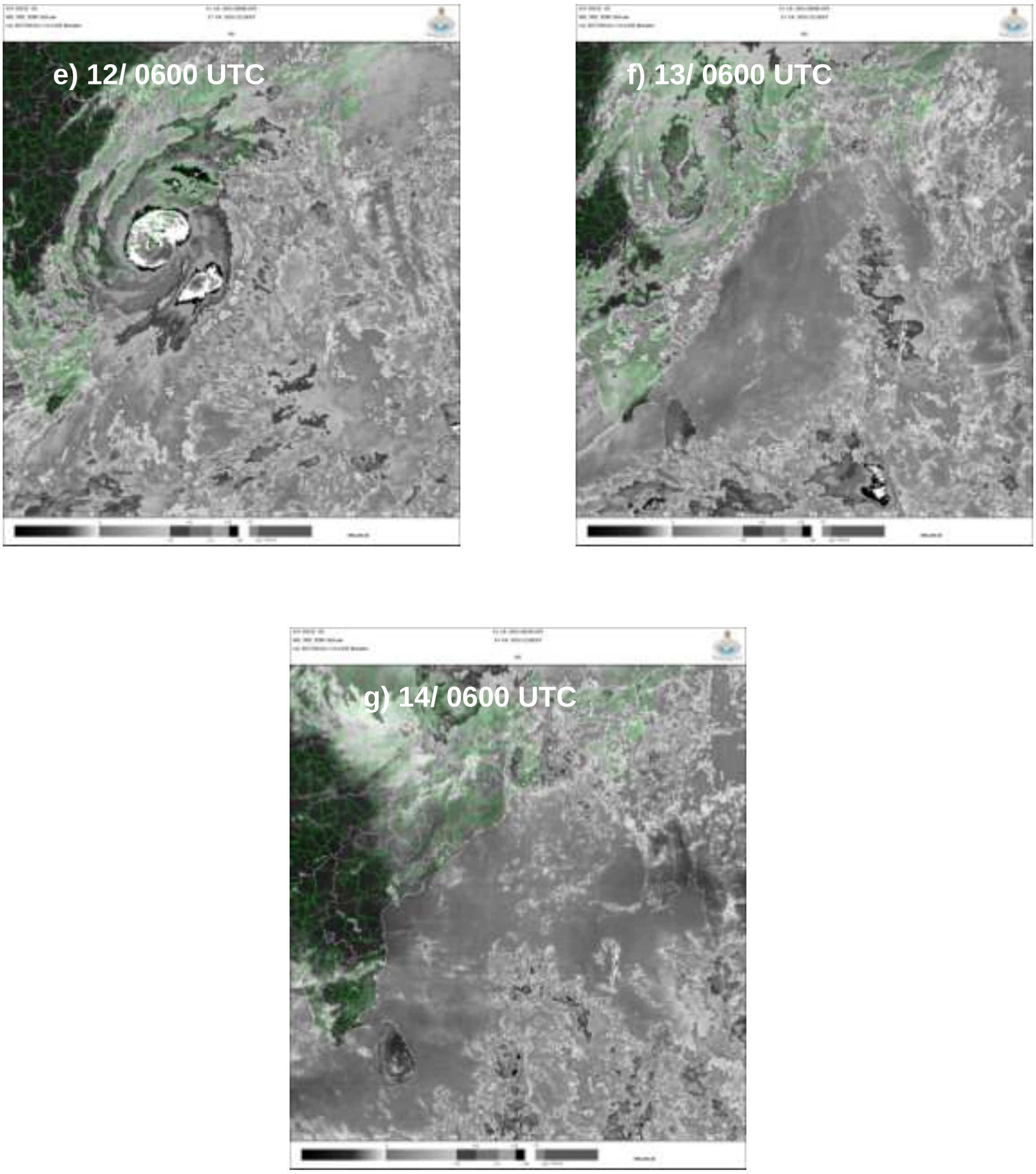


Fig. 5 (cotd.): INSAT-3D enhanced IR imageries in association with VSCS HUDHUD during 06-14 October 2014

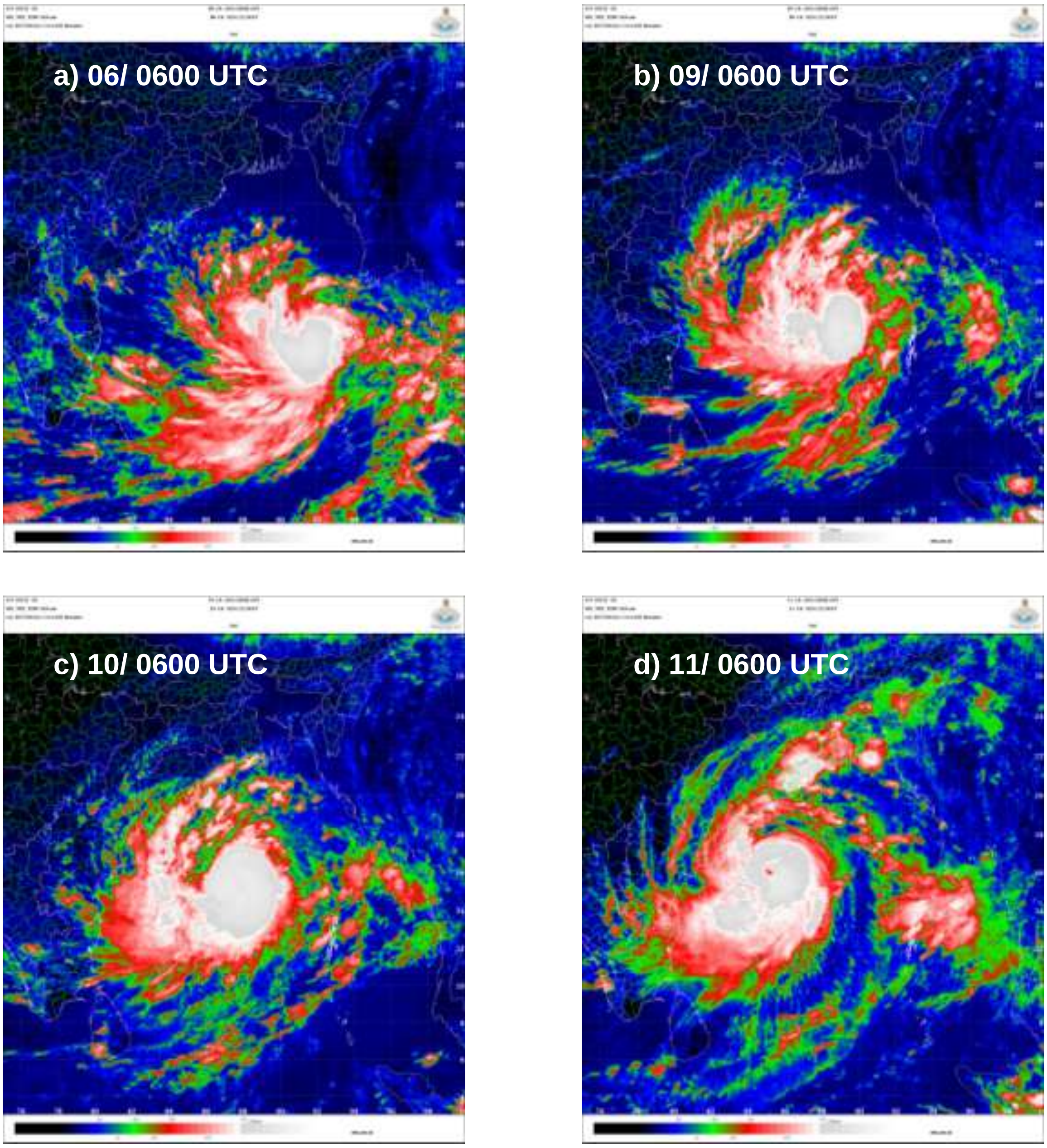
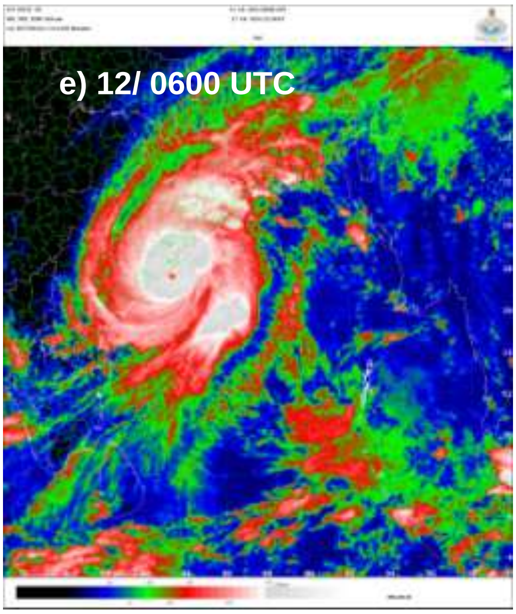
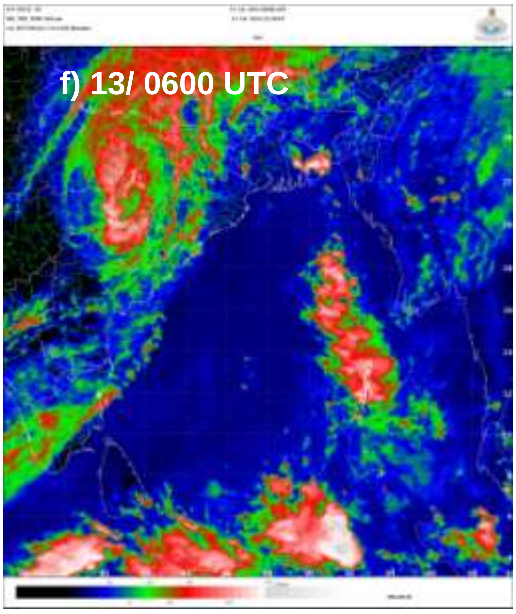


Fig.6.: INSAT-3D colored enhanced IR imageries based on 0600 UTC in association with VSCS HUDHUD during 06-14 October 2014





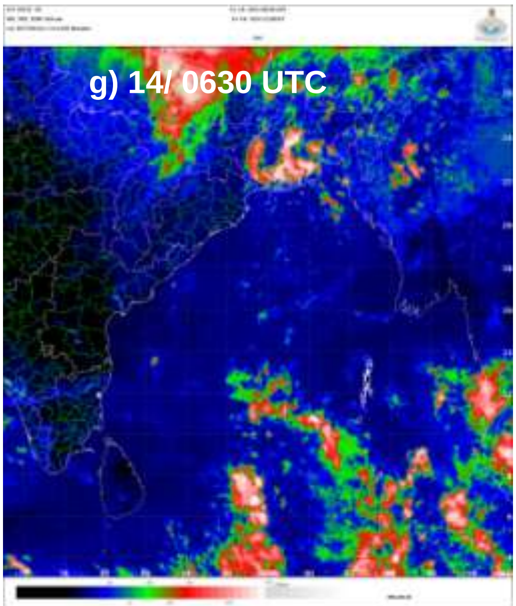


Fig.6 (contd).: INSAT-3D colored enhanced IR imageries based on 0600 UTC in association with VSCS HUDHUD during 06-14 October 2014

7. Features observed through Radar

VSCS HUDHUD was monitored by DWR Visakhapatnam continuously and observations were taken every 10 min. and bulletins were issued hourly till 1020 hrs IST of 12th. After that telecommunication was disrupted and the issue of bulletins was stopped. However, the observations from DWR Machillipatnam were used to monitor the cyclone till 12th evening. The initial cloud echoes were observed at 0330 hrs IST of 11th October, 2014 in Special 400 PPI Scan when the first half eye was observed with an estimated diameter of about 30 km located at a distance of about 334 km. The bulletins were issued based on maximum reflectivity (Max. Z) product and radial velocity. The Maximum wind speed of 67mps (130kts) at 200 m height was reported near Visakhapatnam at 0830 hrs IST of 12th (Table 2). When reduced to surface level, it is about 90 kts. The half eye of the cyclone was visible till 0630 hrs IST of 11th Oct. By 0730 hrs IST, it became closed with a diameter of 52 km. The closed eye was present for a temporary period and became open eye again during 1530-1930 hrs IST of 11th. By 1630 hrs IST of 11th, it was again a closed eye and the same continued till 0530 hrs IST of 12th. It became a weak eye during 0530-0730 hrs IST and became elliptical at 0730 hrs IST of 12th. The eye became ill defined from 0830 hrs IST onwards. The eye diameter increased initially reaching the maximum of 52 km at 0730 hrs IST of 11th Oct. Thereafter, it decreased upto 1030 hrs IST and then increased again till 1630 hrs IST of 11th. Thereafter, it decreased slightly and varied between 36-46 km. The detailed position of the VSCS HUDHUD along with the eye characteristics and radial velocity are shown in Table 2. A few DWR imageries are shown in Fig. 7 to illustrate the structural characteristics of VSCS HUDHUD including eye, wall cloud, spiral bands as observed through reflectivity imageries. The maximum convective band in the wall cloud region was limited to northwest sector and adjoining southwest sector around the centre initially on 11th. It encircled the complete southern sector by 1000 hrs IST of 12th Oct. The outer band caused rainfall activity along the coast of north Andhra Pradesh and adjoining coastal Odisha from the afternoon of 11th.

Table-2. Position of VSCS HUDHUD based on DWR, Visakhapatnam

SN	Date and time (UTC)	Lat deg N	Long deg E	Range kms	Azimuth deg	Radial wind speed/Maximum Velocity (mps) in any other area	Diameter of Eye(km)	Shape of eye
1	10.10.14 2200	15.7	85.7	334.2	131.1	-/30.5	30.4	Half eye
2	10.10.14	15.8	85.7	334.2	131.0	35.0	38.0	Half eye
3	11.10.14 0000	15.8	85.7	334	131	-/35.0	42.7	Half eye
4	11.10.14 0100	15.8	85.6	325	131	-/35.0	50.0	Half eye
5	11.10.14 0200	15.83	85.51	314	132.3	-/44.0 at 3.81 km asl	52.0	Closed eye
6	11.10.14 0300	15.86	85.41	303	133.3	/40.8 at 3.70 km	41.0	Closed eye

7	11.10.14 0400	15.86	85.38	301	133.3	42.2 at 4.0 kmasl/-	47.0	Closed eye
8	11.10.14 0500	15.7	85.7	334	131.1	/30.5	30.4	Half eye
9	11.10.14 0500	15.8	85.7	334	131	/30.5	38.0	Half eye
	11.10.14 0600	16.00	85.230	279.4	133.6	42.2 at 3.2 km asl/-	43.0	Closed eye
10	11.10.14 0700	16.0	85.20	281.9	133.6	42.2 at 2.9 km asl/-	42.0	Open eye
11	11.10.14 0800	16.13	85.12	260.4	133.0	42.5 at 2.4 km asl/-	45.0	Open eye
12	11.10.14 0900	16.12	85.01	252.9	135.0	46.0 at 2.6 km asl/-	41.3	Open eye
13	11.10.14 1000	16.15	84.92	243.7	136.5	46.0 at 4.6 km asl/-	42.1	Open eye
14	11.10.14 1100	16.17	84.86	238.2	137.2	46.0 at 4.3 km asl/-	48.7	Closed eye
15	11.10.14 1200	16.15	84.83	237.6	138.1	43.0 at 4.1 km asl/-	31.0	Closed eye
16	11.10.14 1300	16.19	84.79	232.0	138.1	46.0 at 3.9 km asl	40.4	Closed eye
17	11.10.14 1400	16.198	84.77	230.7	138.9	46.0 at 3.8 km asl/-	36.1	Closed eye
18	11.10.14 1500	16.23	84.80	229.7	137.3	46.0 at 3.5km asl/-	38.1	Closed eye
19	11.10.14 1600	16.32	84.8	221.0	135.9	46.0 at 3.9 km asl/-	46.0	Closed eye
20	11.10.14 1700	16.43	84.81	212.6	133.9	49.0 at 3.6 km asl/-	41.8	Closed eye
21	11.10.14 1800	16.57	84.75	198.8	131.1	48.6 at 2.8 km asl/-	40.6	Closed eye
22	11.10.14 1900	16.71	84.66	180.8	129.4	51.8 at 3.0 km asl/-	40.1	Closed eye
23	11.10.14 2000	16.77	84.57	170.0	129.8	48.2 at 3.1 km asl/-	38.7	Closed eye
24	11.10.14 2100	16.86	84.47	155.1	129.5	49.8 at 1.9 km asl/-	40.8	Closed eye
25	11.10.14 2200	16.99	84.41	140.3	126.6	49.5 at 1.7 km asl/-	37.2	Closed eye
26	11.10.14 2300	17.17	84.29	118.7	122.3	49.0 at 1.2 km asl/-	44.2	Closed eye

27	12.10.14 0000	17.26	84.17	103.1	121.1	54.0 at 1.0 km asl/-	66.0	Closed eye
28	12.10.14 0100	17.17	84.05	98.3	130.9	57.0 at 0.8 km asl	30.1	Weak eye
29	12.10.14 0130	17.34	83.93	77.0	126.6	58.6 at 0.6 km asl/-	27.518.5	Weak eye
30	12.10.14 0200	17.27	83.83	73.8	136.4	52.0 /-	24.2/21.8	Weak elliptic eye
31	12.10.14 0230	17.38	83.78	61.5	130.6	65.0/-	41.0	Weak elliptic eye
32	12.10.14 0300	17.39	83.8	61.5	132.7	67.0	-	Ill defined eye
33	12.10.14 0330	17.33	83.67	57.8	136.1	65.0/	-	Ill defined eye
34	12.10.14 0400	17.37	83.71	57.3	138.0	65.0/	-	Ill defined eye

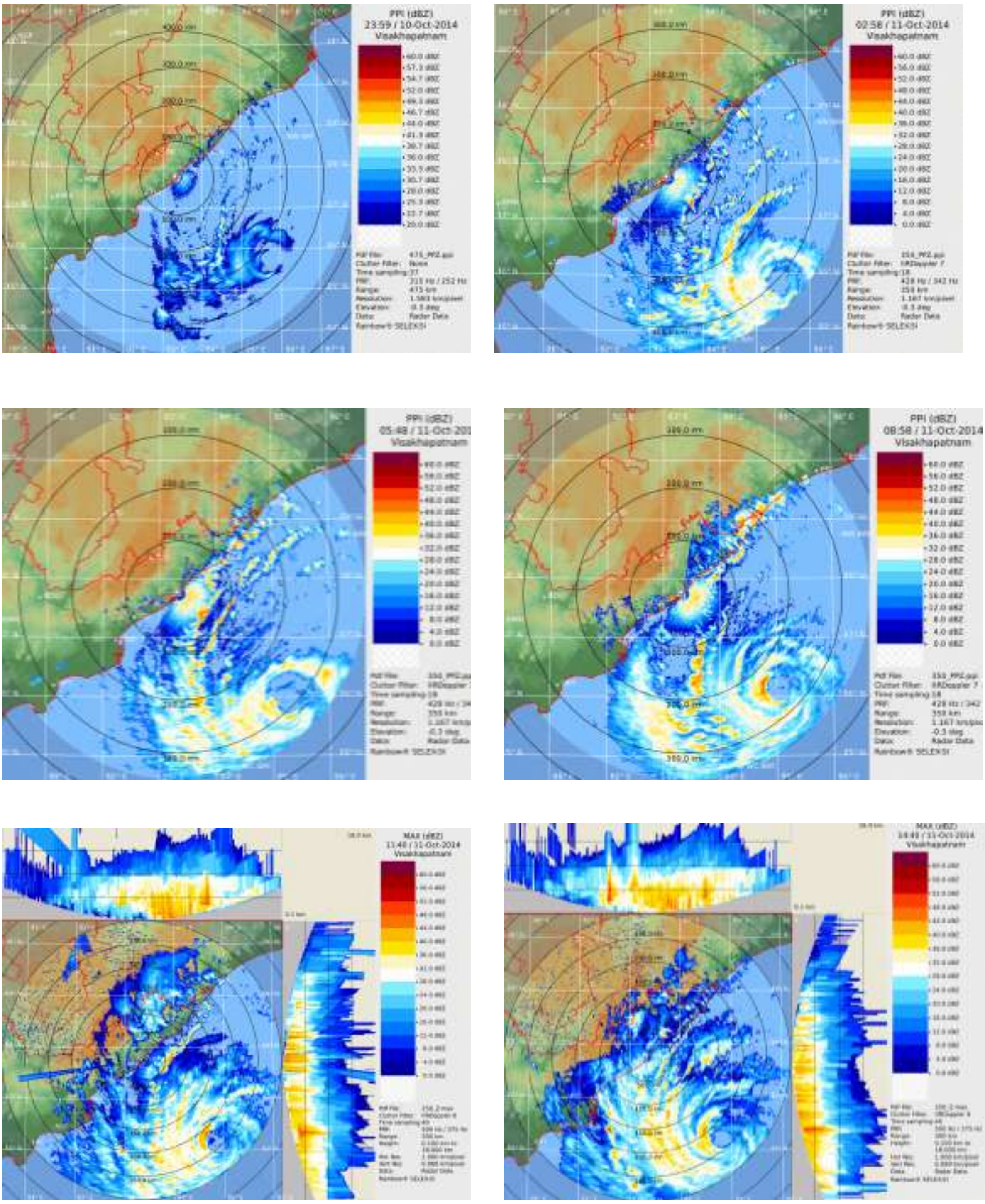


Fig. 7 : Visakhapatnam RADAR imageries based on 0000 UTC to 1500 UTC of 11th October 2014

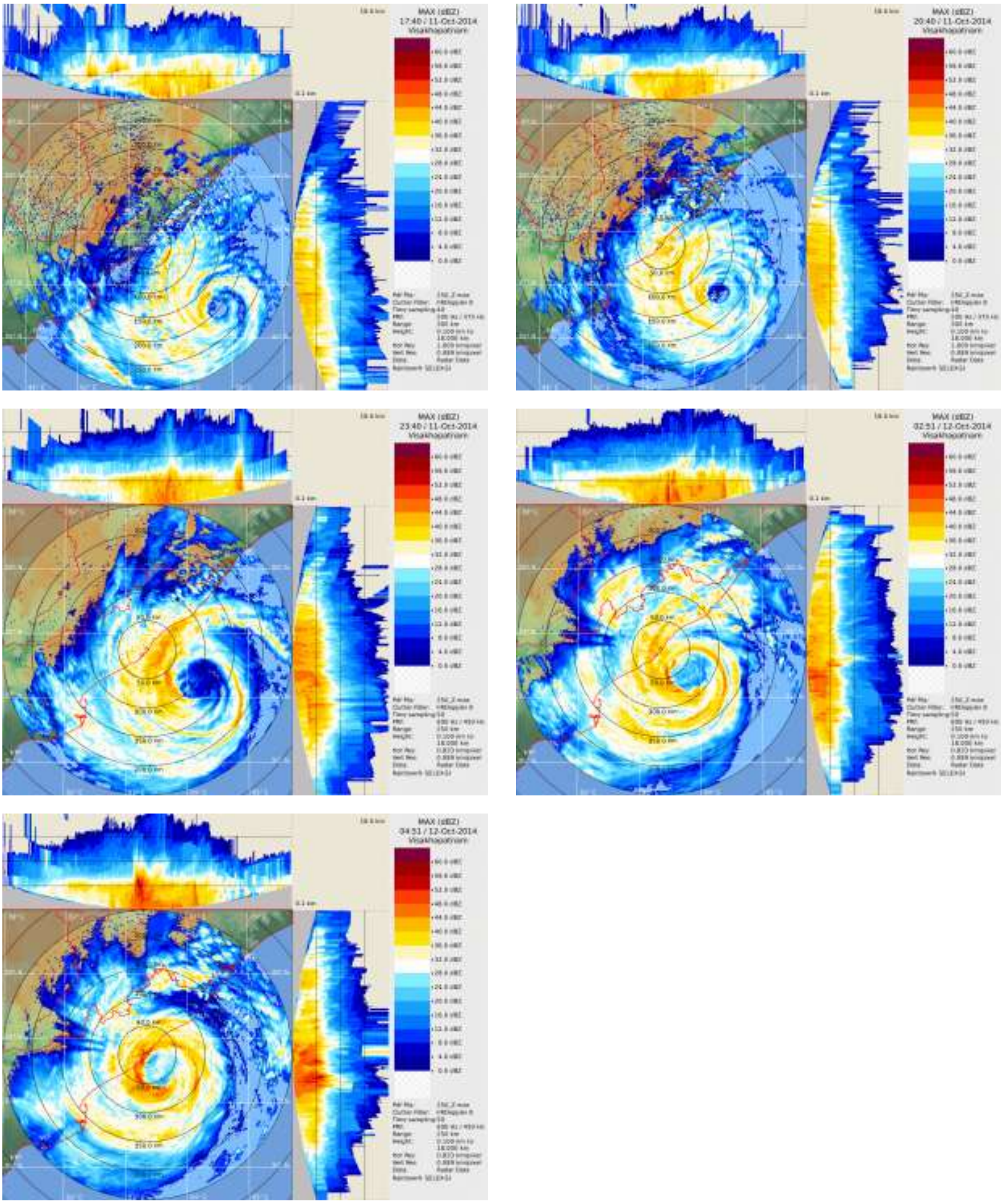
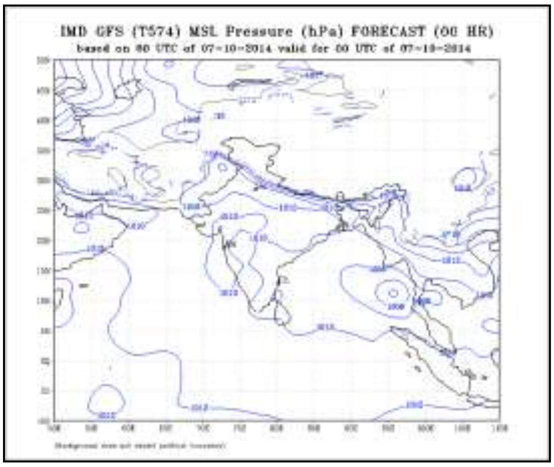


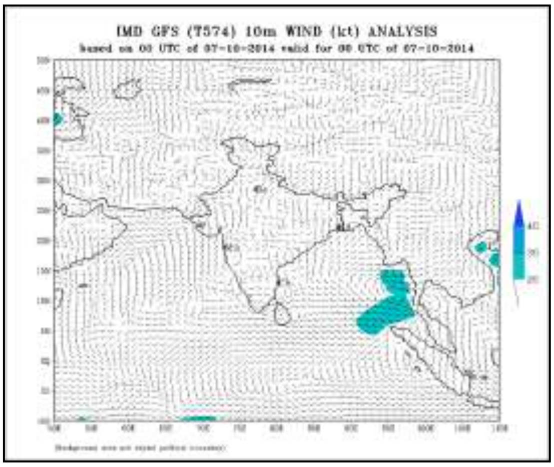
Fig. 7 (contd): Visakhapatnam RADAR imageries based on 1800 UTC of 11th October 2014 to 0500 UTC of 12th October 2014

8. Dynamical features

To analyse the dynamical features, the Mean Sea Level Pressure (MSLP), surface winds at 10 m height and winds at 850 hPa, 500 hPa and 200 hPa levels during the period 7 – 14 October 2014 are presented in Fig. 8. based on IMD-GFS analysis.



(a)



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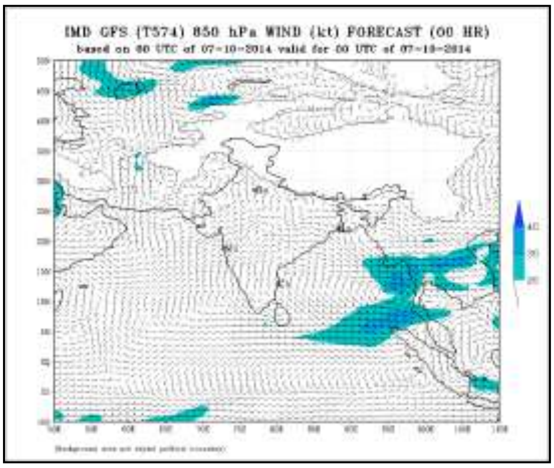

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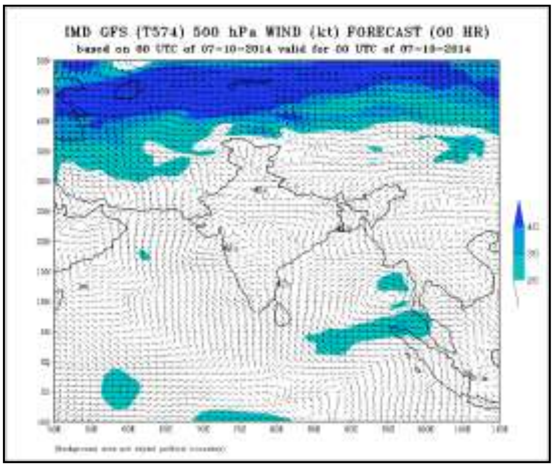

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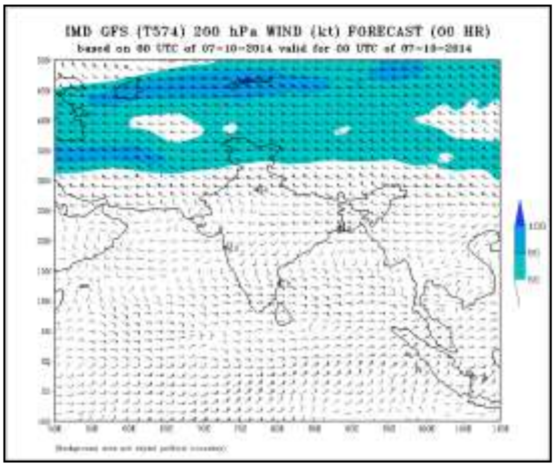
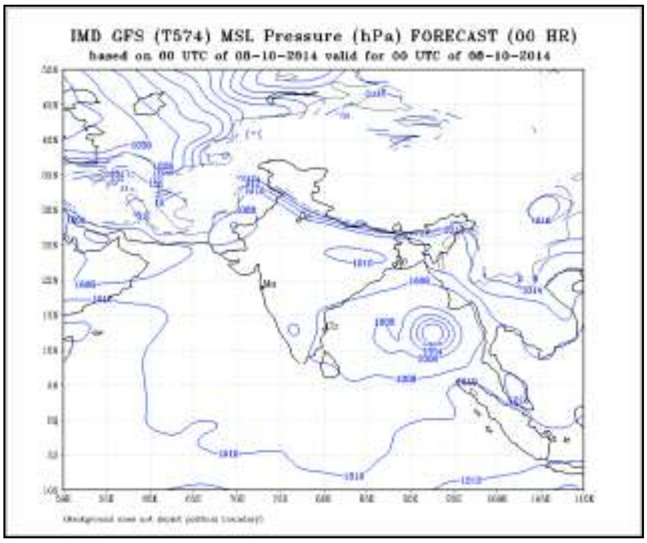


(e)

Fig 8 : IMD-GFS Analysed charts on 7th October 2014

(a) MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



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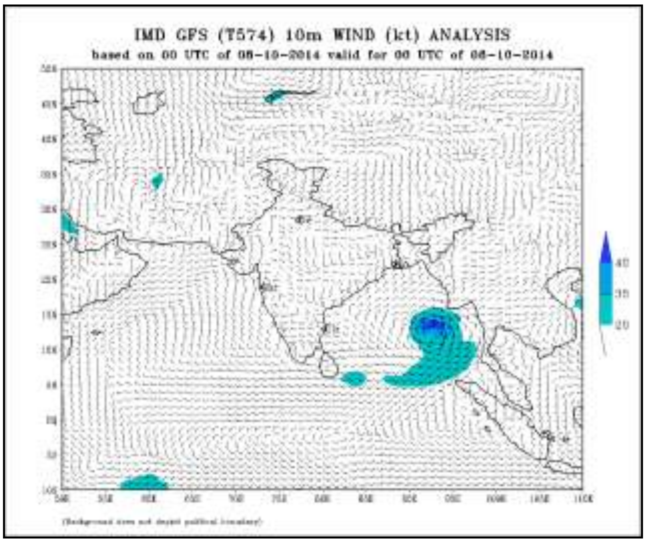

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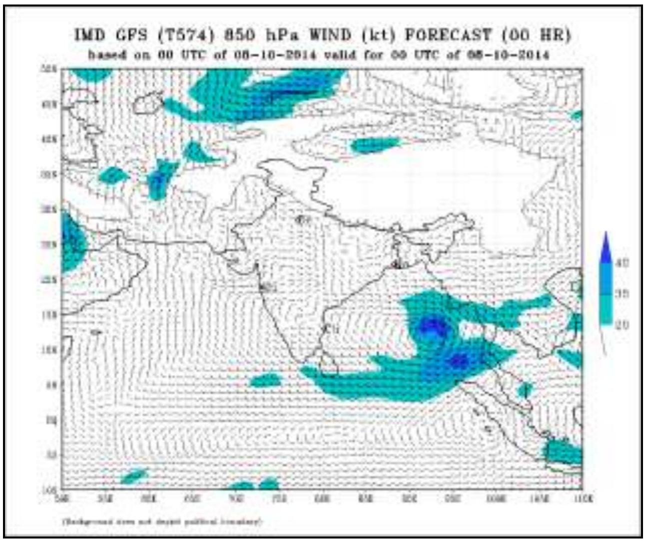

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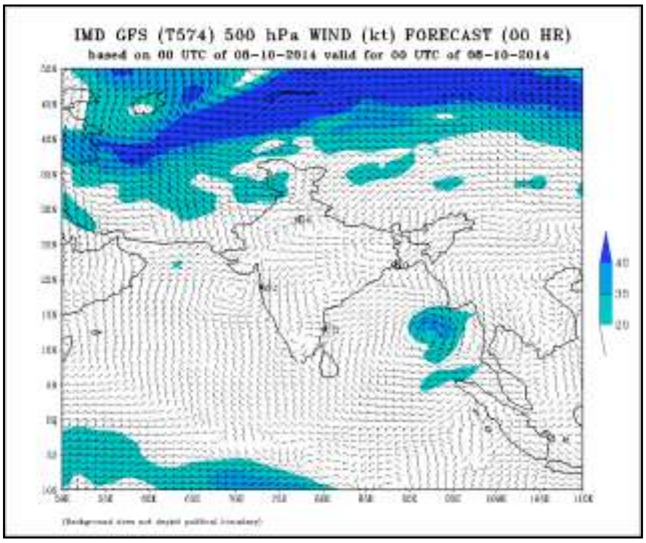

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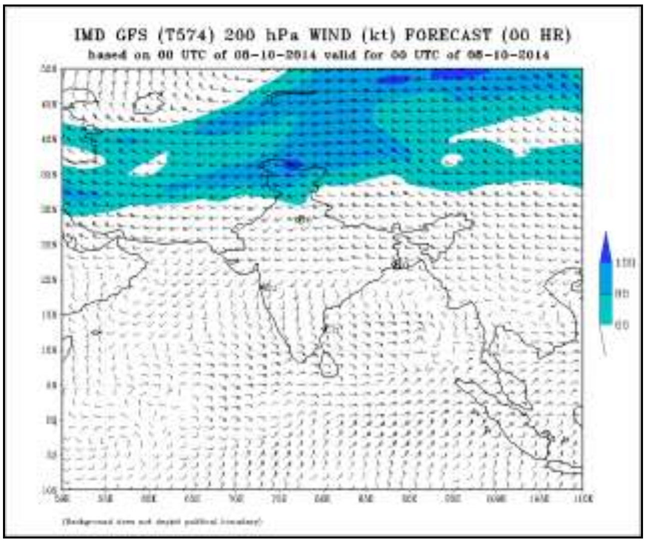
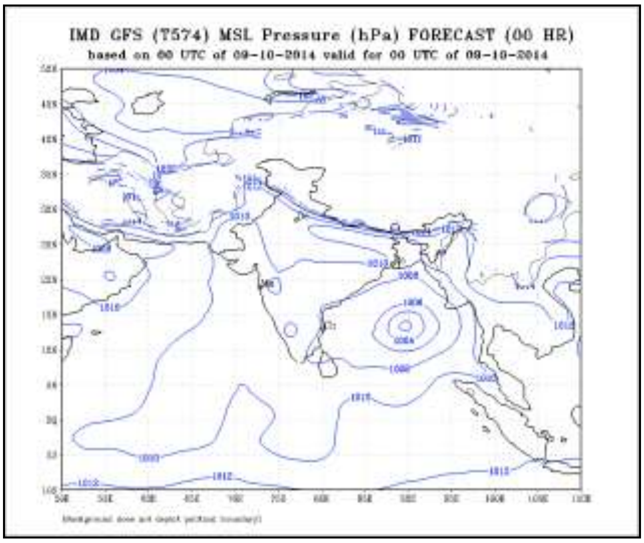


(e)

Fig. 8 (contd): IMD-GFS Analysed charts on 8th October 2014

(a) MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



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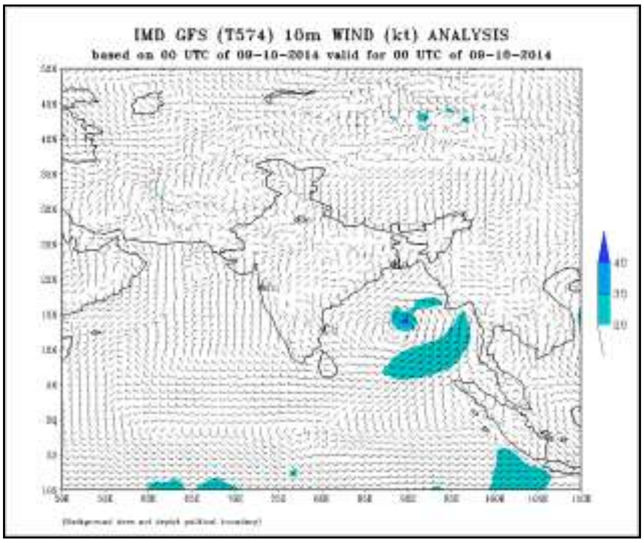

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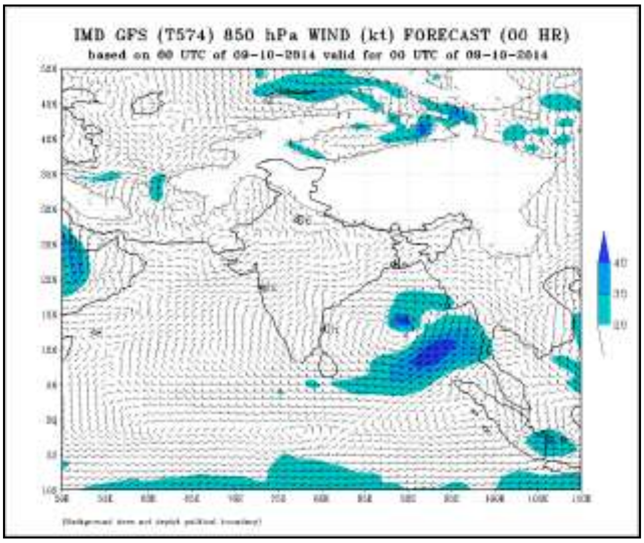

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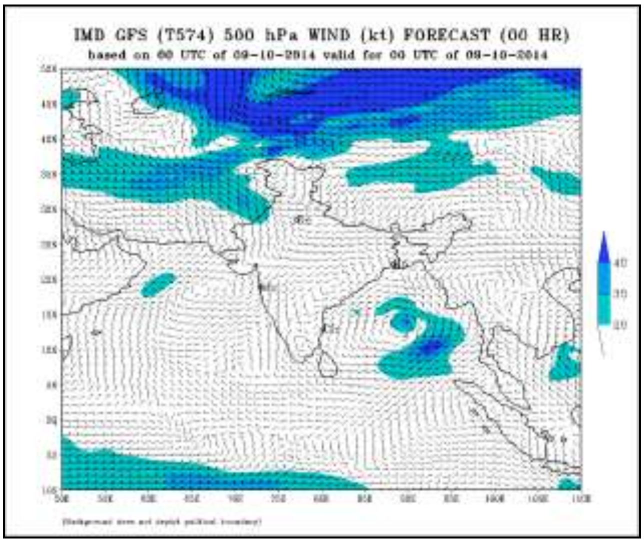

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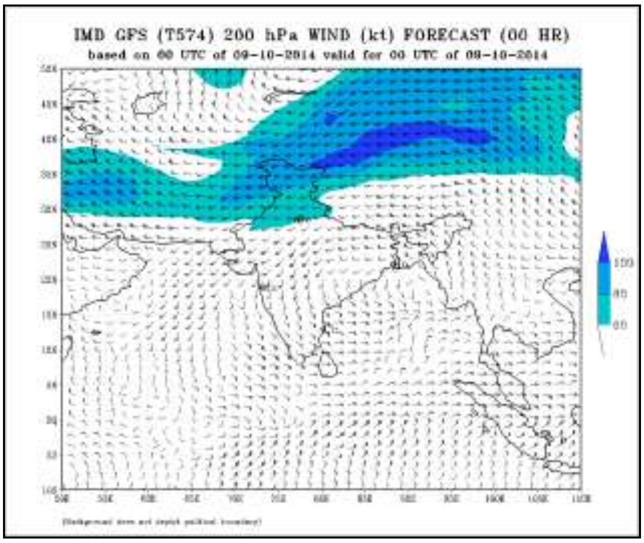
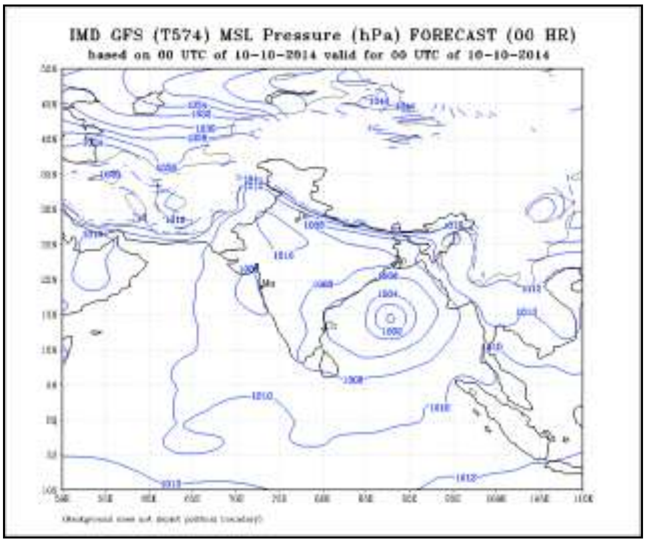


(e)

Fig. 8 (contd): IMD-GFS Analysed charts on 9th October 2014
(a) MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



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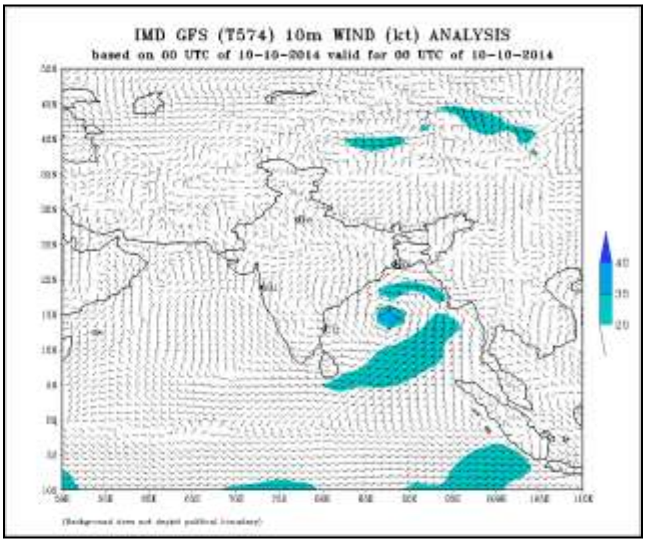

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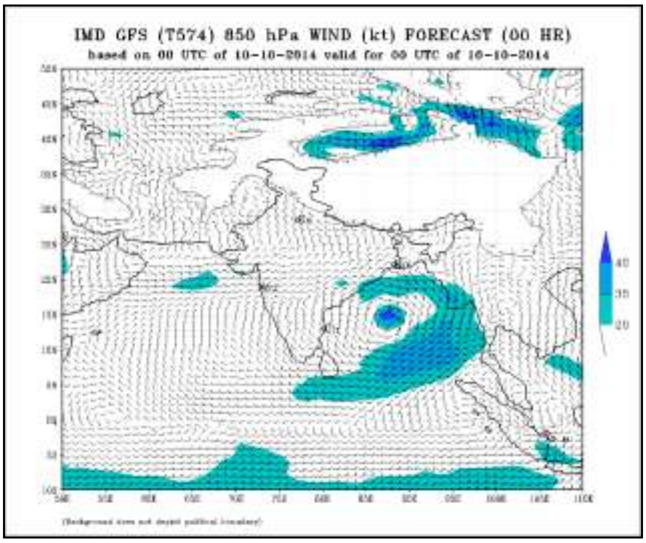

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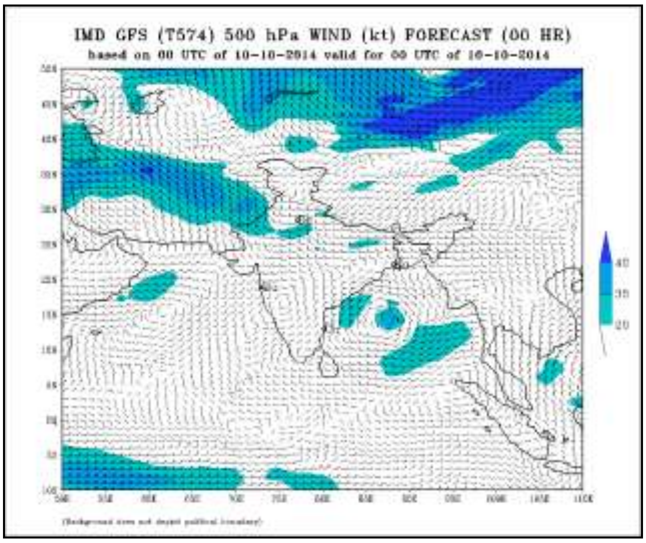

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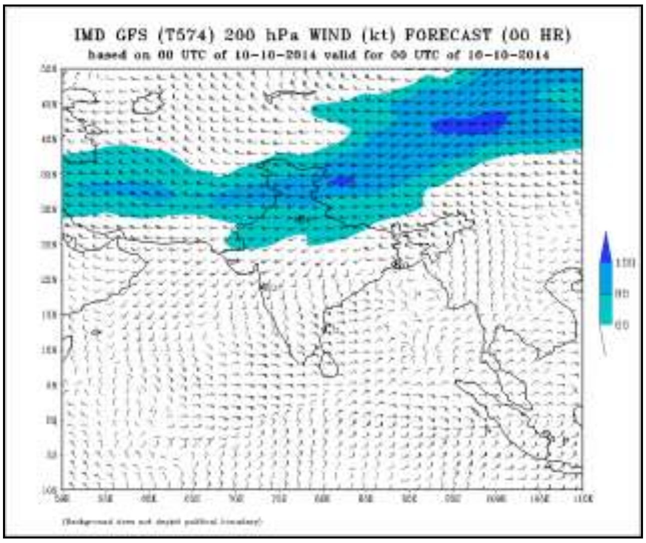
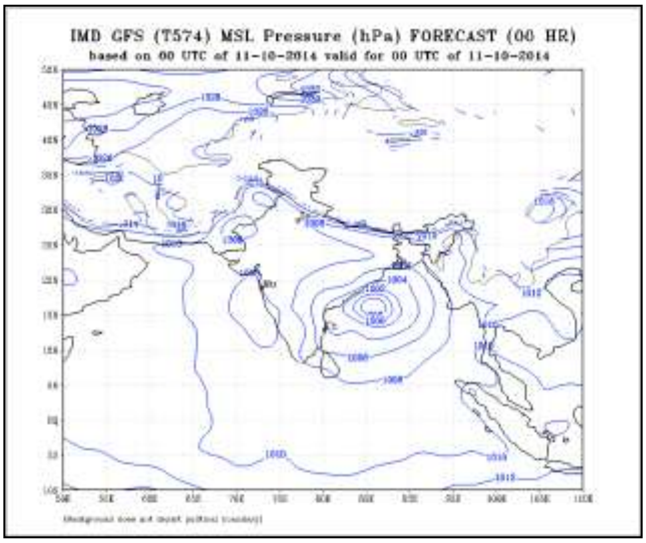


(e)

Fig. 8 (contd): IMD-GFS Analysed charts on 10th October 2014

(a) MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



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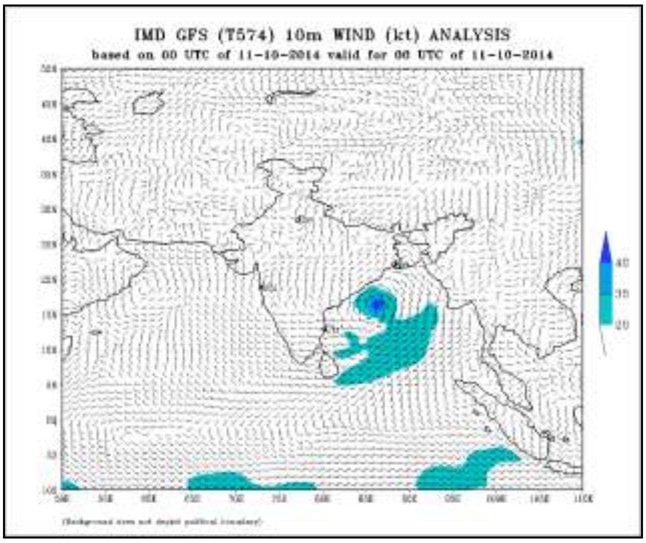

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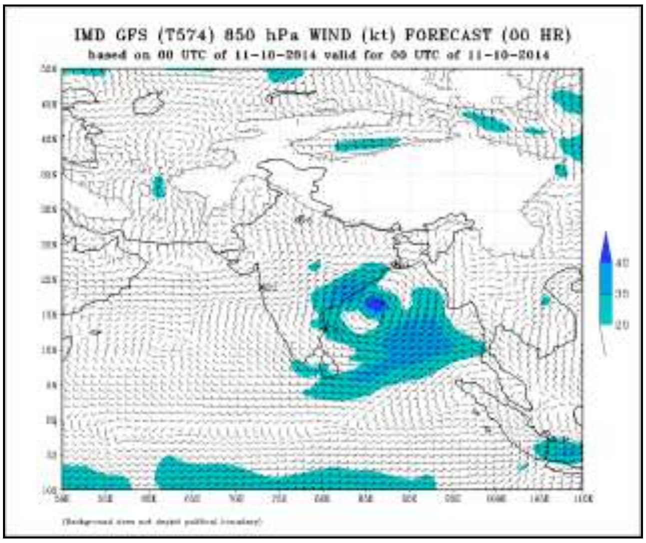

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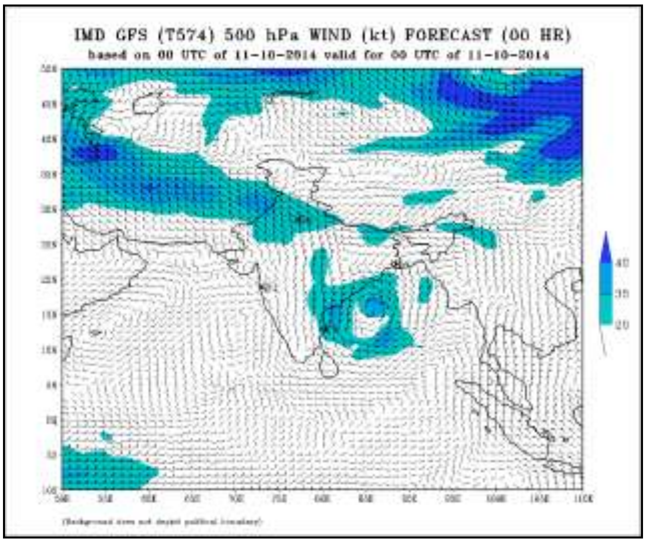

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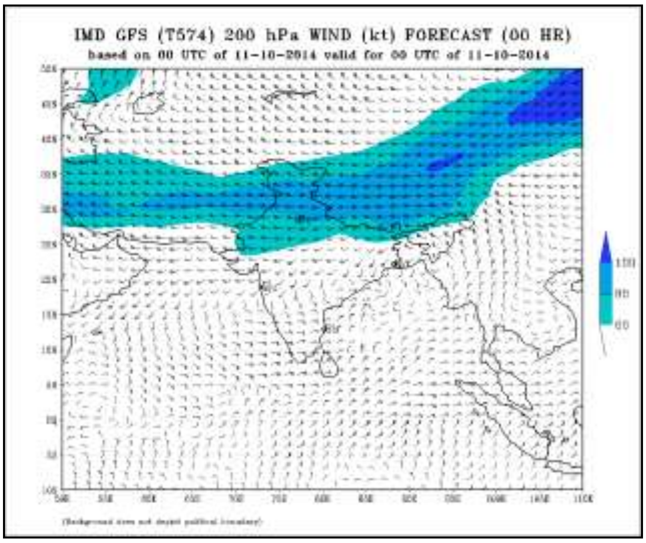
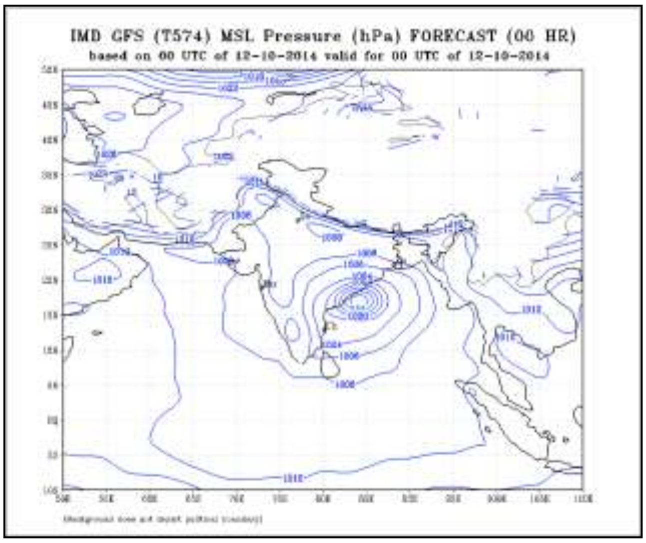


(e)

Fig. 8 (contd): IMD-GFS Analysed charts on 11th October 2014

(a) MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



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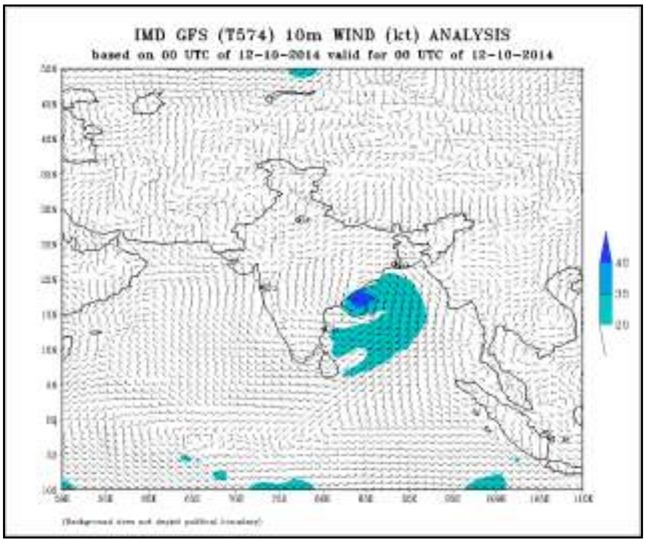

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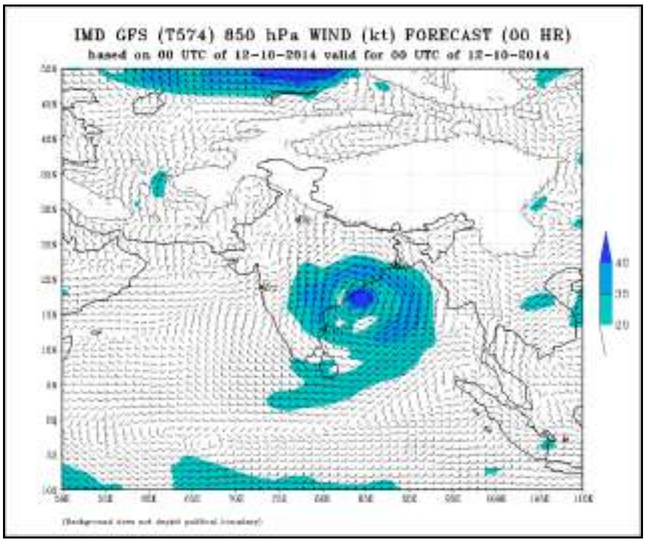

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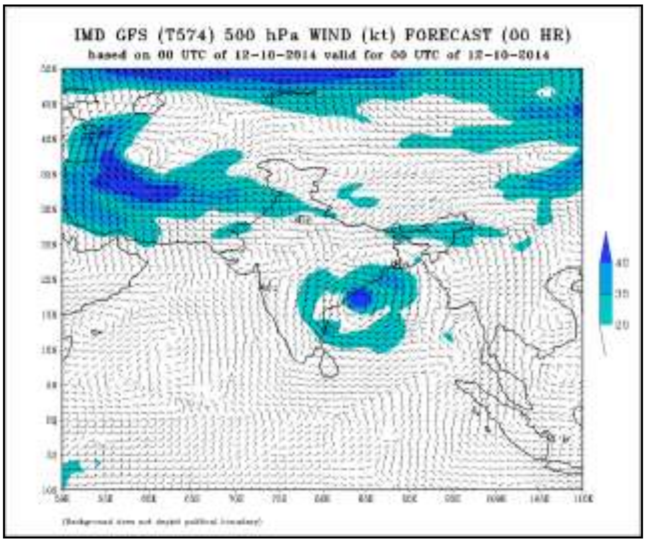

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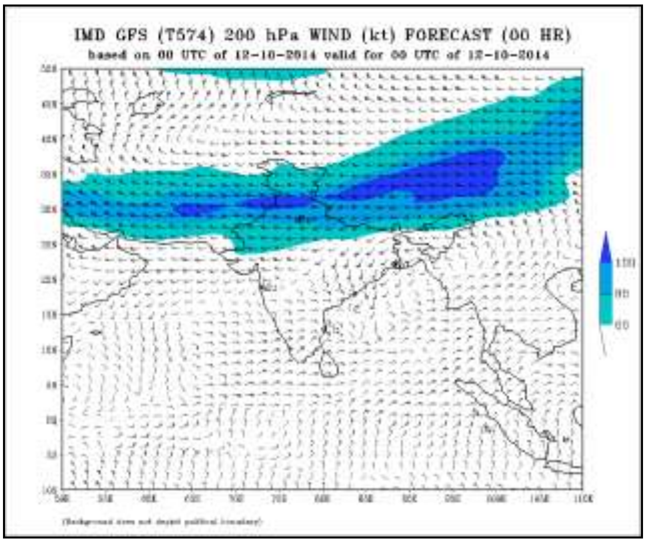

(e)

Fig. 8 (contd): IMD-GFS Analysed charts on 12th October 2014

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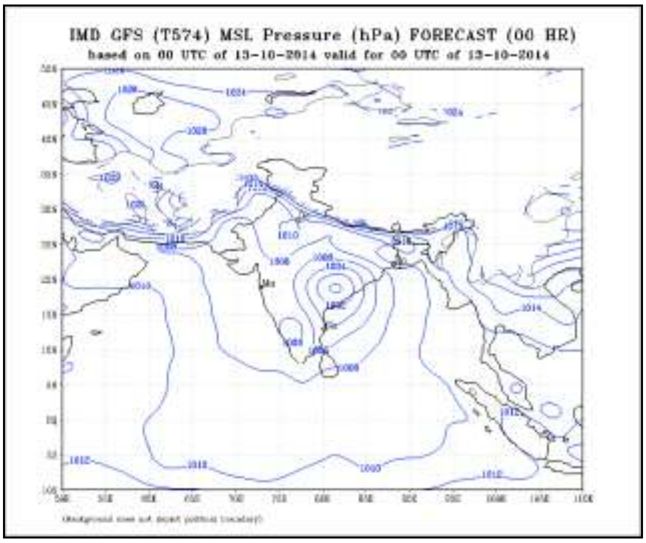

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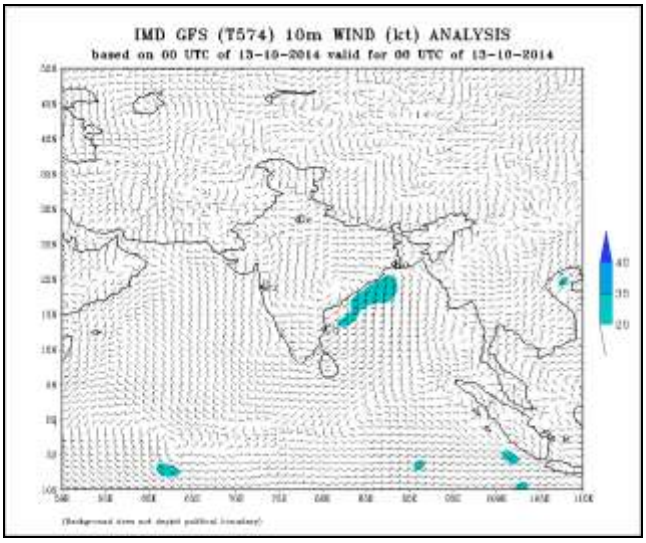

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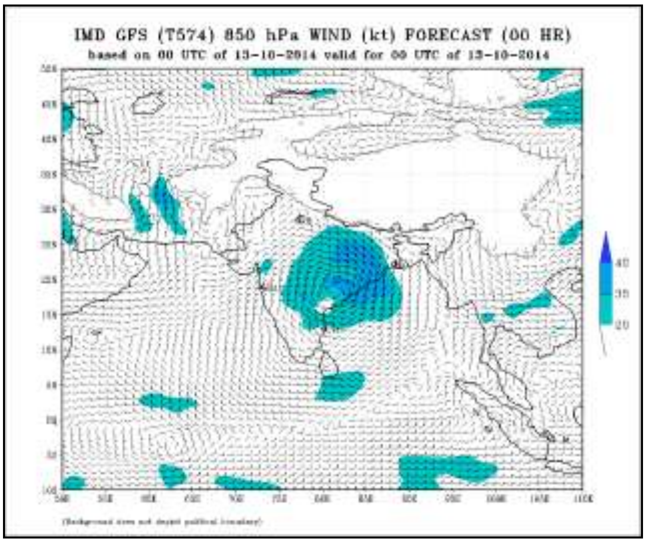

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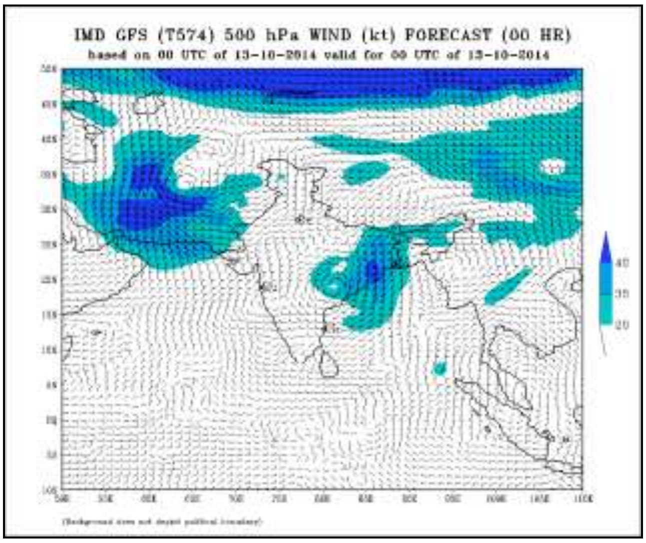
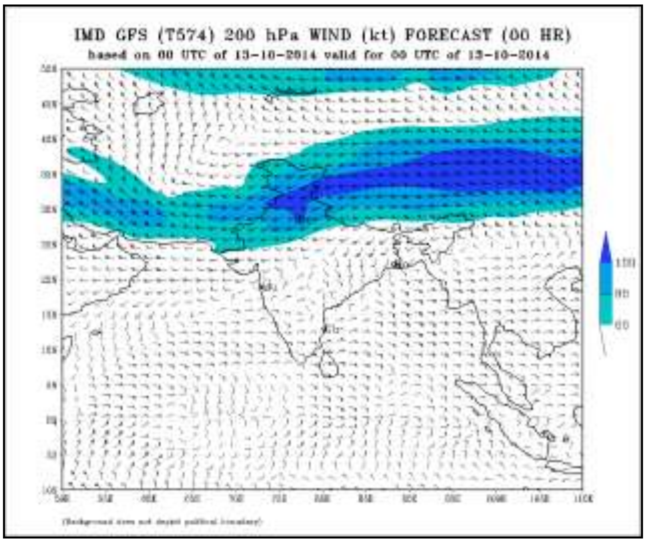


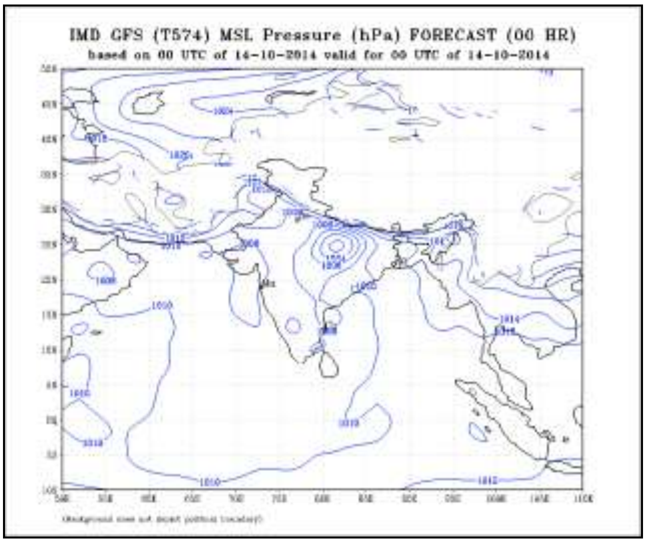
(d)



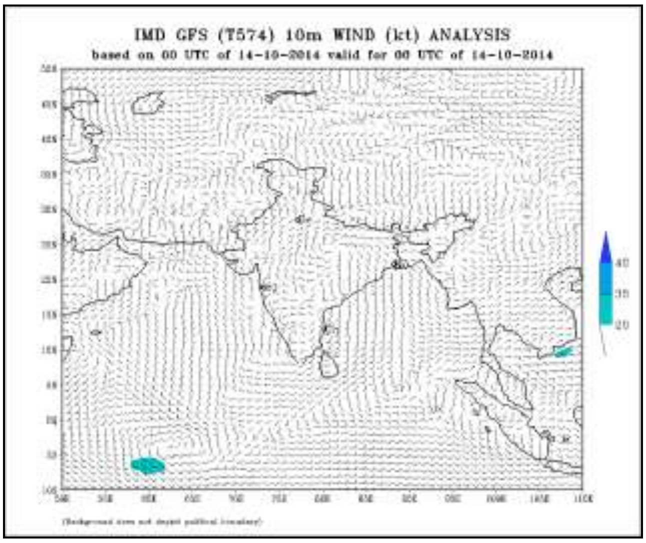
(e)

Fig. 8 (contd): IMD-GFS Analysed charts on 13th October 2014

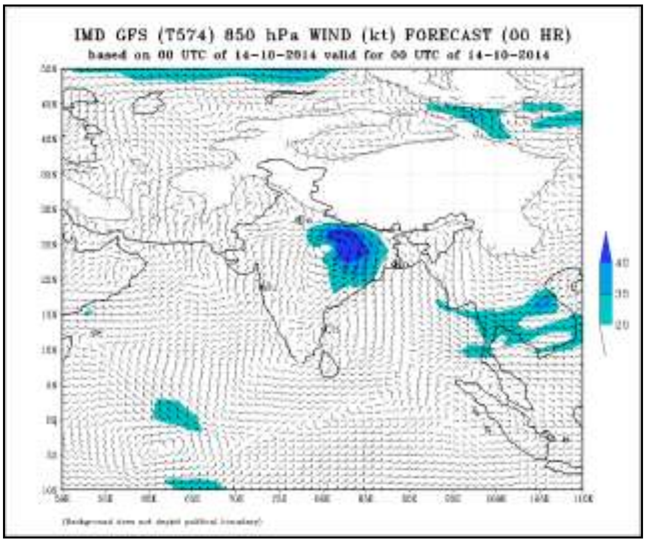
(a) MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



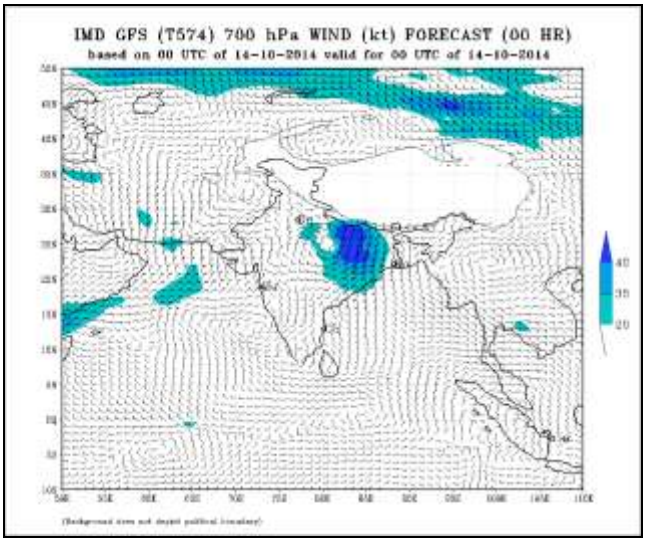
(a)



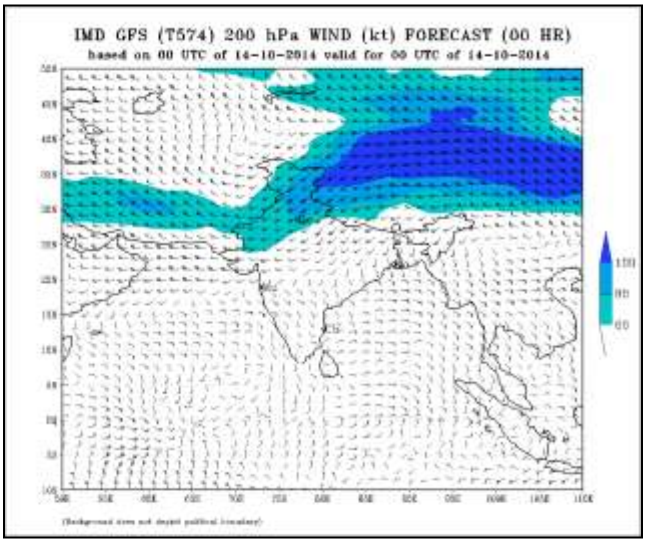
(b)



(c)



(d)



(e)

Fig. 8 (contd): IMD-GFS Analysed charts on 14th October 2014

(a) MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds

As it can be observed, the wind speed was higher on the northeastern and the southern sectors at the time of genesis of Depression. With the intensification of the system into Cyclonic Storm on 8th October 2014, wind was significantly higher in the northern sector. Thus, the model could capture the initial condition as discussed in section 4.1. Similar conditions continued on 9th October 2014. However, the size of the gale wind relatively increased in the northeastern and the southeastern sector on 9th and 10th. On 11th October 2014, when it was VSCS, the core wind became almost symmetric around the centre. However, the gale wind had maximum radial extent in the southeastern sector. On 12th October 2014, the day of landfall when the system was lying near to the coast asymmetry also increased in the northeastern sector with the extension of gale winds whereas the core wind remained symmetric around the centre, with slight increase in size. The cyclonic circulation in association with the system extended vertically upto 300 hPa during the genesis phase and upto 200 hPa in the mature stage on 11th and 12th. The analysis could very well capture the genesis and track of the system. However, the intensity was underestimated.

9. Realized Weather:

9.1 Heavy rainfall due to HUDHUD:

The VSCS, HUDHUD caused *isolated heavy to very heavy rainfall* over Andaman & Nicobar Islands, *heavy to very heavy rainfall* at a few places with *isolated extremely heavy rainfall* over North Andhra Pradesh and South Odisha, *heavy to very heavy rainfall over a few places* of Chhattisgarh, East Uttar Pradesh, East Madhya Pradesh, *isolated heavy to very heavy rainfall* over Jharkand and Bihar and *isolated heavy rainfall* over Sub-Himalayan West Bengal (Description of rainfall terminologies: ***Heavy***: 64.5 to 124.4 mm; ***Very Heavy***: 124.5 to 244.4 mm and ***Extremely Heavy***: ≥244.5 mm) as well as spatial distribution [***Isolated (ISOL)***: (1-25% of stations reporting rainfall); ***Scattered (SCT / A few places)*** : 26-50% of stations reporting rainfall; ***Fairly WideSpread (FWS/ Many places)***: 51-75% of stations reporting rainfall; ***Widespread (WS/ Most places)***: 76-100% of stations reporting rainfall during the last 24 hours ending at 0300 UTC of every day).

The chief amounts of past 24 hr rainfall realised (≥ 7 cm) ending at 0830 IST of date during the period of VSCS HUDHUD are furnished below:

8 October 2014
ANDAMAN AND NICOBAR ISLANDS: Port Blair-21 cm, Long Islands-15.

11 October 2014
ANDHRA PRADESH: Bestavaripeta (dist Prakasam) 5,

12 October 2014
ANDHRA PRADESH: Itchapuram (dist Srikakulam) 14, Visakhapatnam Ap (dist Vishakhapatnam) 12, Kalingapatnam (dist Srikakulam) 12, Visakhapatnam (dist Vishakhapatnam) 11, Pusapatirega (dist Vizianagaram) 10, Vizianagaram (dist

Vizianagaram) 10, Ranasthalam (dist Srikakulam) 10, Nellimarla (dist Vizianagaram) 9, Tekkali (dist Srikakulam) 9, Palasa Mandal(arg) (dist Srikakulam) 9, Sompeta (dist Srikakulam) 8, Palasa (dist Srikakulam) 8, Cheepurupalli (dist Vizianagaram) 8, Mandasa (dist Srikakulam) 7, Denkada (dist Vizianagaram) 7, Garividi (dist Vizianagaram) 7, Palakonda (dist Srikakulam) 6, Bhimunipatnam (dist Vishakhapatnam) 6, Araku Valley(arg) (dist Vishakhapatnam) 5, Pathapatnam (dist Srikakulam) 5, Therlam (dist Vizianagaram) 5,

ODISHA: Mahendragarh-12, Basudevpur (AWS)-11, Tihidi (ARG)-10, Marsaghai (ARG)-10, Garadapur (ARG)-9, Paradeep-9, Paralakhemundi-8, Udala-8, Tirtol (ARG)-7, Jaipur-7, Berhampur-7, Nischintakoili (ARG)-7, Bhuban (ARG)-7

13 October 2014

ANDHRA PRADESH: Gantyada (dist Vizianagaram) 38, Srungavarapukota (dist Vizianagaram) 34, Nellimarla (dist Vizianagaram) 24, Gajapathinagaram (dist Vizianagaram) 22, Pusapatirega (dist Vizianagaram) 19, Bondapalle (dist Vizianagaram) 19, Garividi (dist Vizianagaram) 19, Palakonda (dist Srikakulam) 19, Denkada (dist Vizianagaram) 19, Anakapalle(a) (dist Vishakhapatnam) 18, Salur (dist Vizianagaram) 18, Vepada (dist Vizianagaram) 16, Mentada (dist Vizianagaram) 15, Seethanagaram (dist Vizianagaram) 14, Merakamudidam (dist Vizianagaram) 14, Araku Valley(arg) (dist Vishakhapatnam) 13, Vizianagaram (dist Vizianagaram) 13, Parvatipuram (dist Vizianagaram) 13, Jiyyamma Valasa (dist Vizianagaram) 12, Bobbili (dist Vizianagaram) 12, Palasa (dist Srikakulam) 12, Ranasthalam (dist Srikakulam) 11, Cheepurupalli (dist Vizianagaram) 11, Veeragattam (dist Srikakulam) 11, Garugubilli (dist Vizianagaram) 11, Balajipeta (dist Vizianagaram) 9, Therlam (dist Vizianagaram) 9, Pathapatnam (dist Srikakulam) 9, Mandasa (dist Srikakulam) 9, Tekkali (dist Srikakulam) 9, Komarada (dist Vizianagaram) 8, Palasa Mandal(arg) (dist Srikakulam) 8, Tuni (dist East Godavari) 8, Kurupam (dist Vizianagaram) 7, Kalingapatnam (dist Srikakulam) 7,

ODISHA: R.Udaigiri-26, Pottangi-24, Kalinga-24, Mahendragarh-23, Mohana-22, Similiguda (AWS)-21, Malkangiri-18, Tikarpara-17, Nuagada (ARG)-17, Chandanpur-17, G Udayagiri (AWS)-17, Daringibadi-17, Belaguntha (ARG)-16, Khandapara-16, Kashipur-15, Jhorigam (ARG)-15, Raikia (ARG)-15, Barmul-15, Tikabali-14, Banki (ARG)-13, Rayagada-13, Jhumpura-12, Bhanjnagar-11, Digapahandi (ARG)-11, Ghatagaon-11, Danagadi (ARG)-11, Nayagarh-11, Tentulikhunti (ARG)-10, Kantapada (ARG)-10, Jagannath Prasad (ARG)-10, Madhabarida-10, Keonjhargarh-10, Banpur-10, Daspalla-10, Narsinghpur-9, Phiringia (ARG)-9, Rajkishorenagar-9, Odagaon (ARG)-9, Hindol-9, Bissem-Cuttack-9, Aska-9, Paralakhemundi-9, Nawana-9, Joda (ARG)-9, Koraput-9, Betanati (ARG)-9, Sorada-9, Jeypore-8, Angul-8, Bangiriposi-8, Gunupur-7, Rairakhol-7, Kashinagar-7, Gania (ARG)-7, Chandahandi (ARG)-7, Harabhanga-7, Tigiria (ARG)-7, Umarkote-7, Sukinda-7, Talcher-7, Naktideul-7, Samakhunta (AWS)-7

CHHATTISGARH: Sukma- 17, Narayanpur- 8, Jagdalpur- 8, Kondagaon- 7.

JHARKHAND: Jamshedpur-15, Hazaribagh-12, Jamshedpur Aero-12, Ramgarh-9, Ghatsila-9, Ranchi Aero-8, Chandil-8

14 October 2014

ANDHRA PRADESH: Denkada (dist Vizianagaram) 19, Cheepurupalli (dist Vizianagaram) 12, Garividi (dist Vizianagaram) 10, Pathapatnam (dist Srikakulam) 9

ODISHA: R.Udaigiri-19, Paralakhemundi-11, G Udayagiri (AWS)-8, Nuagada (ARG)-8

CHHATTISGARH: Manendragarh- 17, Pendra Road-17, Pali- 15, Kawardha- 12, Janakpur-11, Katghora-11, Simga- 9, Mungeli- 9, Bilaspur-8, Bemetara- 8, Janjgir- 7, Durg- 7.

EAST UTTAR PRADESH: Patti-13, Pratapgarh-13, Chhatnag-13, Bara-12, Koraon-12, Salempur-12, Karchhana-12, Phoolpur-11, Kunda-11, Allahabad Sadar-11, Akbarpur-11, Allahabad -10, Soraon-9, Mau Tehsil-9, Handia-9, Meja-9, Sultanpur Obsy-9, Faizabad-8, Varanasi/Bab Aero-8, Jaunpur (CWC)-8, Haraiya-8, Rae Bareli (CWC)-7, Beberu-7, Fursatganj-7, Ayoadhya-7, Sultanpur (CWC)-7, Tarabganj-7

EAST MADHYA PRADESH: Amarkantak-28, Sidhi (AWS)-19, Kotma-18, Hanumana-18, Pushpajgarh-16, Maihar-16, Anuppur (AWS)-13, Rewa (AWS)-11, Sohagpur (AWS)-11, Gudh-11, Jaithari-10, Bichhia-10, Satna (AWS)-10, Dindori (AWS)-9, Malanjkhand-8, Nagode-7, Umaria (AWS)-7,

15 October 2014

BIHAR: Tribeni/Balmiki-18 cm, Sheohar-17, Sonbarsa-16, Dhengbridge-15, Gaunaha-14, Lalbegiaghat-12, Saulighat-12, Ramnagar-11, Chanpatia-11, Kamtaul-10, Chatia-10, Jainagar-7, Ahirwalia-7

EAST UTTAR PRADESH: Maharajganj-15, Bansi (CWC)-12, Regoli-12, Pharenda-12, Gorakhpur-11, Hata-11, Kakrahi-11, Birdghat-10, Domeriaganj-9, Basti (CWC)-9, Utarala-9, Bansgaon-9, Khalilabad-8, Sardanagar-8, Chanderdeepghat-8, Ayoadhya-7, Mukhlispur-7, Chandauli-7, Katerniaghat-7

SUB-HIMALAYAN WEST BENGAL & SIKKIM: Bagdogra - 8

(AWS: Automatic Weather Station; ARG: Automatic RainGauge Station; CWC: Central Water Commission; IAF: Indian Air Force)

The daily rainfall figures in terms of actual, normal and percentage departures from normal over the meteorological sub divisions of Coastal Andhra Pradesh, Odisha, Telangana, Chhattisgarh, Jharkhand, East Uttar Pradesh, Bihar and East Madhya Pradesh during the period 12-15 October 2014 are presented in the Table-3 . The district-wise distribution of daily rainfall over Andhra Pradesh during 13-14 October 2014 is presented in Fig. 9.

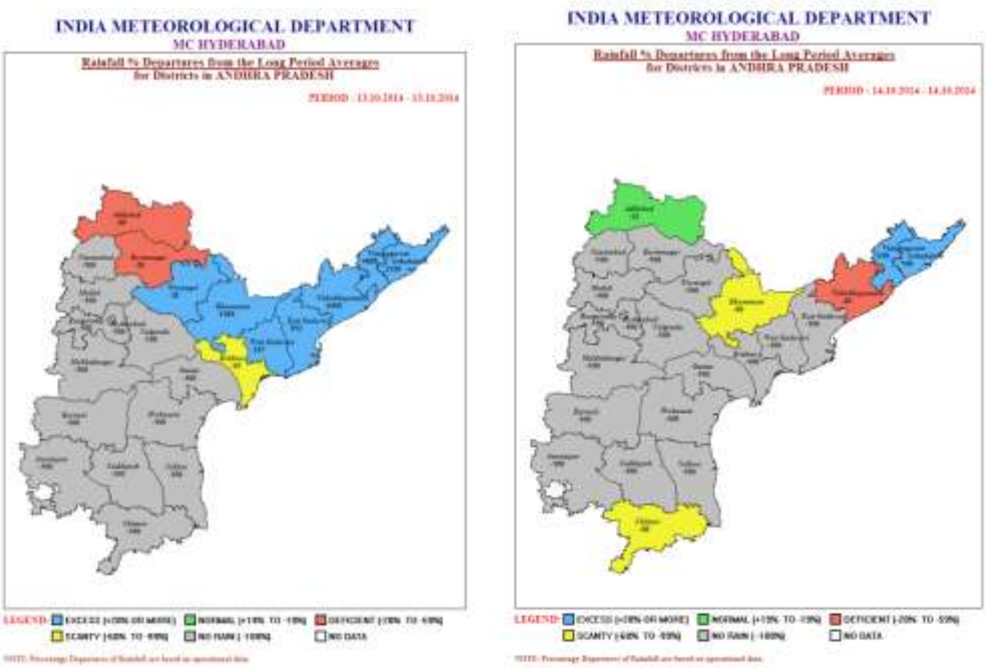


Fig. 9: District-wise distribution of daily rainfall over Andhra Pradesh during 13-14 October 2014

Table3: Excess rainfall figures over various meteorological sub divisions in association with passage of VSCS HUDHUD

Date		CAP	ODISHA	TELANGANA	CHHATTISGARH	JHARKHAND	BIHAR	EMP	EUP
	ACT (mm)	13.3	17.3						
	NOR (mm)	3.7	3.7						
	PDN	259%	369%						
12.10.2014									
	ACT (mm)	30.9	63.4	2.3	33.0	26.3	5.6		
	NOR (mm)	3.0	2.5	1.2	1.6	1.7	1.6		
	PDN	931%	2437%	92%	1964%	1446%	252%		
13.10.2014									
	ACT (mm)		5.5		32.6	3.0	7.0	49.5	41.9
	NOR (mm)		2.8		1.5	1.7	1.7	0.5	1.8
	PDN		98%		2070%	75%	310%	9792%	2225%
14.10.2014									
	ACT (mm)						30.5		27.8
	NOR (mm)						1.4		0.6
	PDN						2078%		4535%
15.10.2014									

Act: Actual; Nor: Normal; PDN: Percentage Departure From Normal; CAP: Coastal Andhra Pradesh; EMP: East Madhya Pradesh; EUP: East Uttar Pradesh

Rainfall associated with the cyclone when it was out in the sea is also determined based on satellite-gauge merged rainfall dataset generated by IMD and NCMRWF (Mitra et al, 2009) for the North Indian Ocean region from 2013 onwards using the TRMM data. 24-hour accumulated rainfall associated with the VSCS HUDHUD during the period 08-14 October 2014 as well as the 7-day average rainfall during the same period are furnished in the Fig. 10.

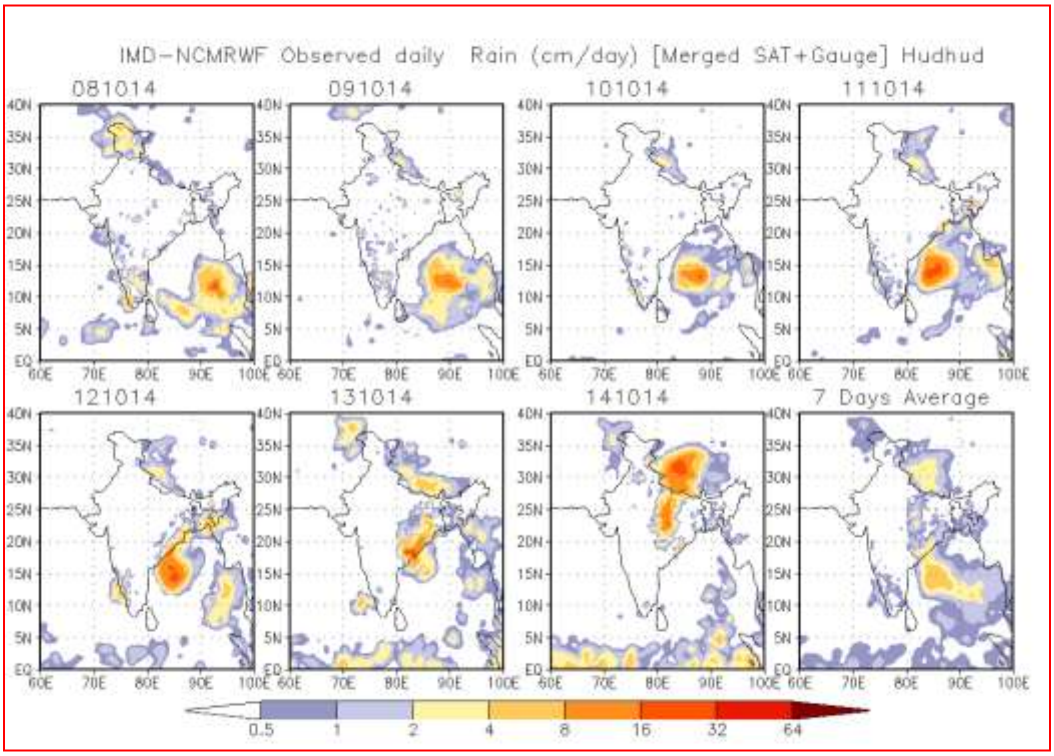


Fig. 10 IMD-NCMRWF satellite-gauge merged daily rainfall (in cm) during the period 08-14 October 2014 and the 7-day average rainfall during the same period.

The above rainfall figures indicate that rainfall was high in the southwest sector of the TC when it was over the sea. During landfall, the maximum rainfall region shifted to northeast sector leading to high rainfall figures over North Andhra Pradesh and South Odisha. This shift in the maximum rainfall regime is associated with gradual recurvature of the TC from west-northwestward movement over the sea to northwest movement during landfall and northward movement thereafter. This spatial pattern of rainfall distribution was in expected lines as it has occurred in a similar fashion in earlier cases also including the VSCS Phailin (2013). Apart from North Andhra Pradesh and South Odisha, there has been good rainfall activity over Chhattisgarh, East Uttar Pradesh Bihar and over Nepal.The rainfall over Nepal on 14th October has been significantly higher under the influence of (i) orographic effect of the Himalayas and (ii) interaction with mid-laittude westerly trough lying to the west of the cyclone. Intensity of rainfall in the inner storm region has been of the order of 16 cm/day and above and in the outer storm region, it has been of the order of 2-16 cm/day.

9.2 Gale Wind

Maximum gale wind of 180 kmph prevailed over Visakhapatnam district and adjoining areas at the time of landfall. It was about 70-80 gusting to 90kmph over Andaman Islands during first landfall

9.3. Storm Surge

Observed Storm Surge recorded by the tide gauge (INCOIS) at Visakhapatnam was 1.4m as recorded by the tide gauge at Visakhapatnam port against the forecast of 1-2m.

10. Damage due to Cyclone 'HUDHUD'

The VSCS, 'HUDHUD' mainly affected North Andhra Pradesh and adjoining south Odisha. Details of the damages in Andhra Pradesh are given in Table 4. As per the report of the Government of Andhra Pradesh.

Table -4 Damages associated with VSCS Hudhud

S No.	ITEM	
1	Districts Affected	4
2	Block Affected (Nos.)	65
3	Village Affected(Nos.)	4484
4	Families affected	20,93,508
5	Persons evacuated	135262
6	Persons rescued	**146**
7.	Human Loss/Injured	
	(a) Number of Deaths(no.)	46
	(b) Number of injured (no.)	43
8.	Loss of livestock	
	(A) Number of animal perished (no.)	2831
	(B) poultry/duck	2443701
9.	Agriculture	237854 Hect
	Expected production loss (tons)	
	(a) Food Grains & Cash crops	2214000 in Tons
	(b) Horticultural crops	6.89 Tons
10.	Housing	
	Number of Affected houses (no.)	41269
	(i) kuchha	18886
	(ii) pucca	12264
	(iii) Hut	10119
11.	Infrastructure	
	(A) Roads	
	(a) Road length damaged (km)	
	(i)National highway	Not estimated
	(ii)state highway	2250.00
	(iii)P.R. Road	3176.7 km
	(iv)others(municipal Roads)	648.73 km

	(b) Villages disconnected to transportation facility	
	(i) Number	73
	(ii) Days	2
	(B) Water supply system	
	(a) pipe line	
	(i) Trunk (Fully/ Partially damaged no)	194 No /39.40 km
	(ii) Distribution (Fully/ Partially damaged no)	35
	(b) pumping station (no.)	102
	(c) overhead reservoirs(Fully damaged)	197
	(e) Drinking water (Tanks Partially damaged no.)	7
	(f) Drinking water wells Fully/ Partially damaged (no.)	33
	[E] IRRIGATION	
	(a) breach of canal damaged (No.)	55
	(b) breaches to dams(No.)	1847
	(d) irrigation wells damaged(No.)	16
	[F] Eletrctricity supply*	27041 poles
	(a) high tension lines damaged (km)	506 km
	(b) low tension lines damaged (km)	7500 km
	(c) transformers damaged (No.)	7300
	(d) substation damaged	1526
	[G] Building	455 Nos.
	(a) Primary schools (Partially/Fully no.)	80
	(b) Secondary schools (Partially/ully no.)	237
	(c) Community Center (Partially no.)	23
	(e) Other Government Building (Partiall)	8
	(H) Shops and others commercial building damaged	
	(a) shops (Partially)	70
	(b) other commercial buildings(Partially)	73
	[I] Other utilities	
	(a) Land telephone disrupted(no. of days)	2
	(b) Mobile phones disrupted (no. of days)	1
	(c) villages disconnected to communication facilities	
	(i) Number	73
	(ii) days	2
8	Handlooms	
	i) Damaged looms	15
	ii) Loss of raw materials / Goods in process / finished goods	32
9	Fisheries	
	i) Loss of Boat/missing	1110
	ii) Catamaran	698
	iii) Net	2129
10	Street vendors	10
	Loss of push carts(number)	85
11	Artisans'	70

The ravaged Visakhapatnam Airport

A boat was turned turtle at Visakhapatnam Port

Gushing waves, whiplashes and splashes near Visakhapatnam

The Visakhapatnam beach-front was eroded by surge and waves

The collapsed telephone tower near Visakhapatnam

Overturned college bus and up-rooted electric pole at Visakhapatnam

A fallen tree damaging house in Jeypore town of Koraput district of Odisha

Fig. 11: Few Damage photographs associated with VSCS Hudhud

11. NWP model forecast performance

India Meteorological Department (IMD) operationally runs a regional models, WRF for short-range prediction and one Global model GFS (T574L64) for medium range prediction (7 days). The WRF-Var model is run at the horizontal resolution of 27 km, 9 km and 3 km with 38 Eta levels in the vertical and the integration is carried up to 72 hours over three domains covering the area between lat. 25^o S to 45^o N long 40^o E to 120^o E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 23 km. The boundary conditions are updated at every six hours interval. IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency). Hurricane WRF (HWRF) model and Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

In addition to the above NWP models, IMD also run operationally "NWP based Objective Cyclone Prediction System (CPS)". The method comprises of five forecast components, namely (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) Predicting decaying intensity after the landfall. Genesis potential parameter (GPP) is used for predicting potential of cyclogenesis and forecast for potential cyclogenesis zone. The multi-model ensemble (MME) for predicting the track (at 12h interval up to 120h) of tropical cyclones for the Indian Seas is developed applying multiple linear regression technique using the member models IMD-GFS, IMD-WRF, GFS (NCEP), ECMWF and JMA. The SCIP model is used for 12 hourly intensity predictions up to 72-h and a rapid intensification index (RII) is developed and implemented for the probability forecast of rapid intensification (RI). Decay model is used for prediction of intensity after landfall. Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. Apart from the observations that are used in the earlier system, the new observations assimilated at NCMRWF include (i) Precipitation rates from SSM/I and TRMM (ii) GPSRO occultation (iii) AIRS and AMSRE radiances (iv) MODIS winds. Additionally ASCAT ocean surface winds and INSAT-3D AMVs are also assimilated. NCUM (N512/L70) model features a horizontal resolution of 25km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. At NCMRWF the Global Ensemble Forecast System (NGEFS) provides analysis and forecast run out to 10 days based on 20 perturbed forecasts. Additionally verification and intercomparison is also provided for the forecast tracks from the Met Office UK (UKMO) and the Australian Bureau of Meteorology model ACCESS-TC. The model forecast integration are carried out at respective centers and the only forecast output is analyzed for verification and intercomparison. The results of these models guidance are presented and discussed herewith. The track forecast of MME and HWRF models are shown in fig.12 and 13 respectively. The average track forecast errors (Direct Position Error) in km, Landfall point forecast errors (km) of NWP Models at different lead time (hour) and Landfall time forecast errors (hour) at different lead time (hr) are given in Table 5, Table

6 and Table 7 respectively. The Average absolute errors and Root Mean Square (RMSE) errors of intensity forecast by SCIP and HWRF model are given in Tables 8 and 9 respectively. NCMRWF forecast tracks and forecast track errors are presented in Table 10 and figs. 14 and 15.

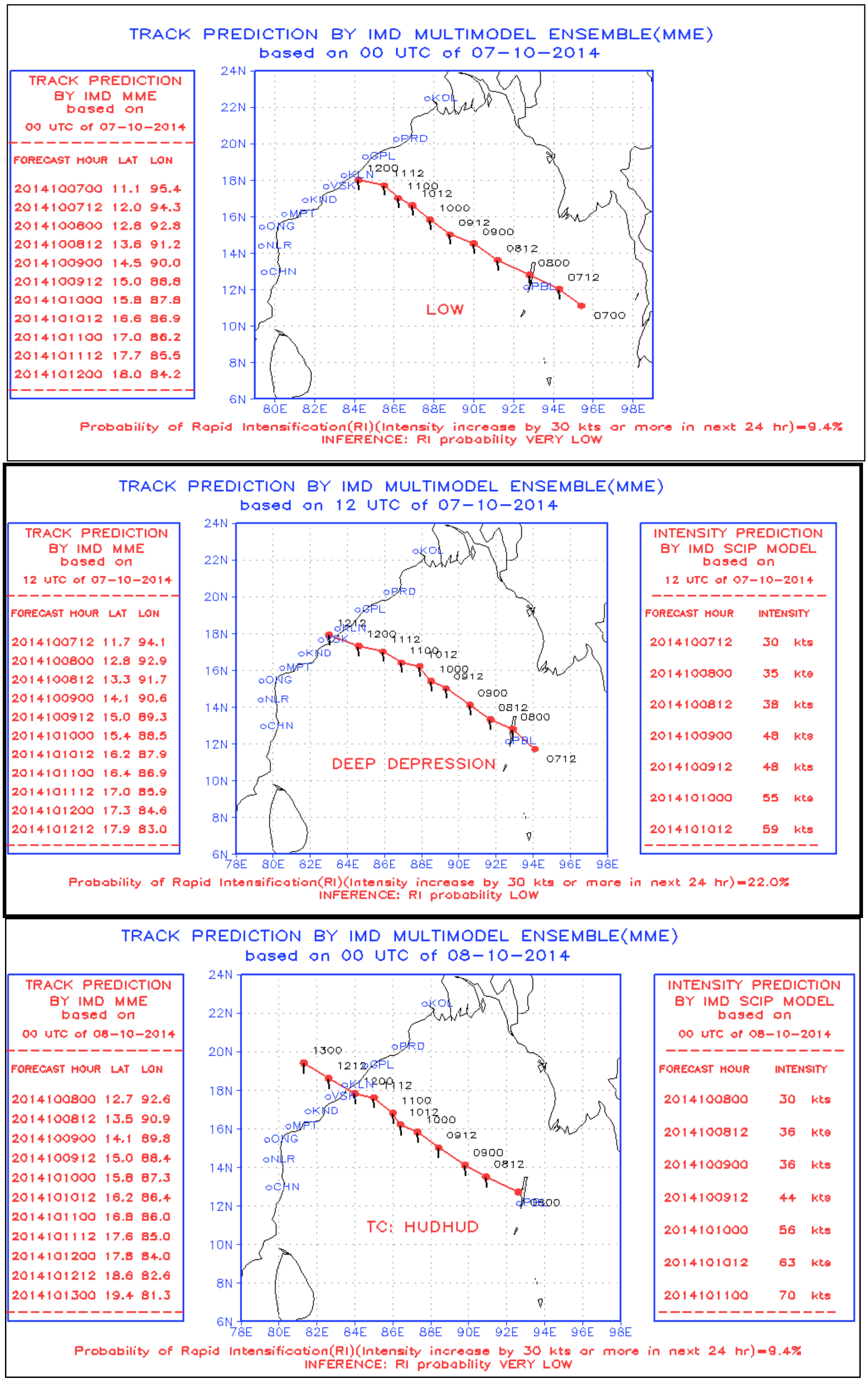


Fig.12. MME track forecast based on 0000 1200 UTC of 07 and 0000 UTC of 8 October 2014

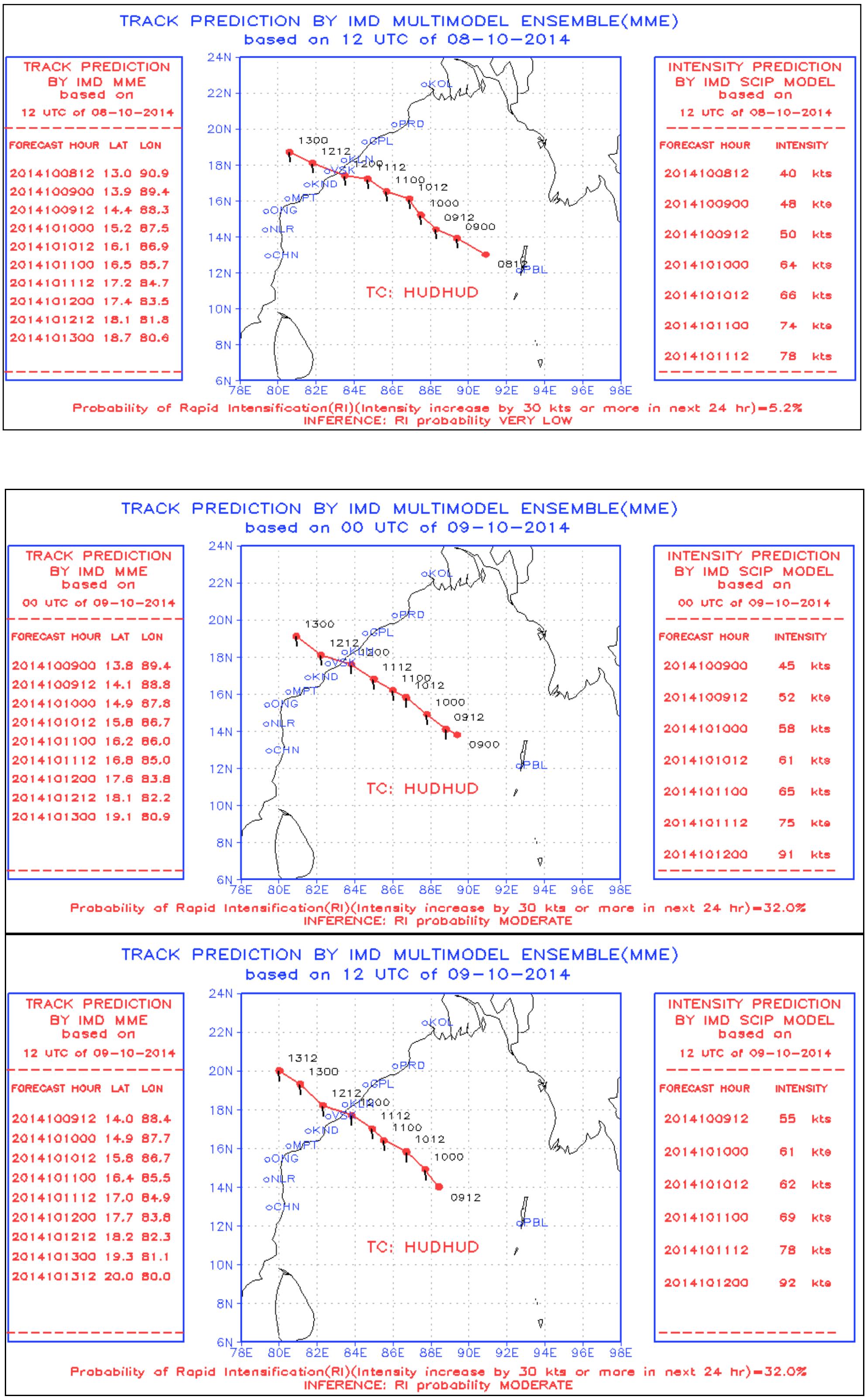


Fig.12 (Contd). MME track forecast based on 1200 UTC of 08 and 0000 and 1200 UTC of 9 October 2014

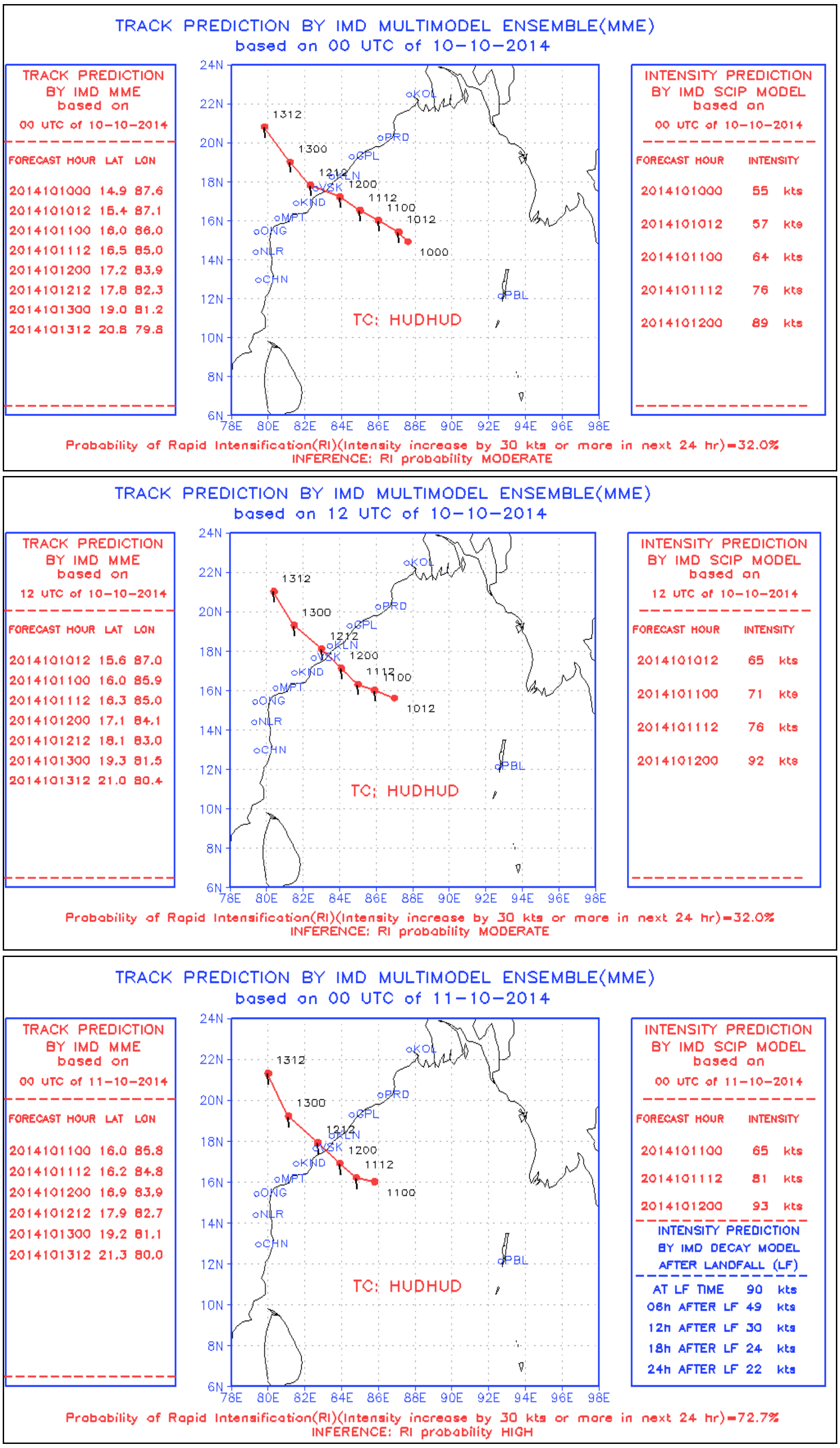


Fig.12(contd). MME track forecast based on 0000 and 1200 UTC of 10 and 0000 UTC of 11 October 2014

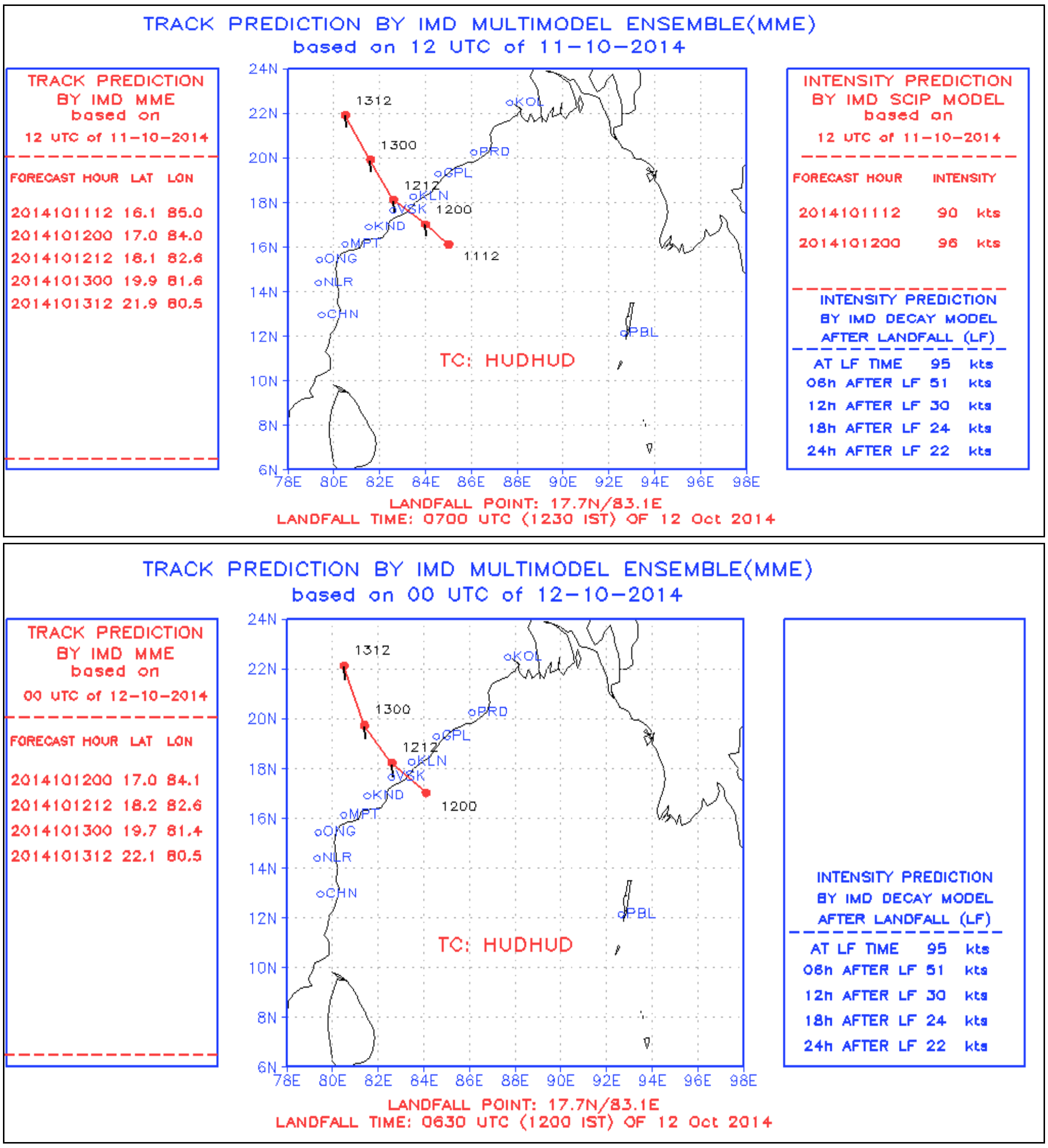


Fig.12(contd). MME track forecast based on 1200 UTC of 11 and 0000 UTC of 12 October 2014

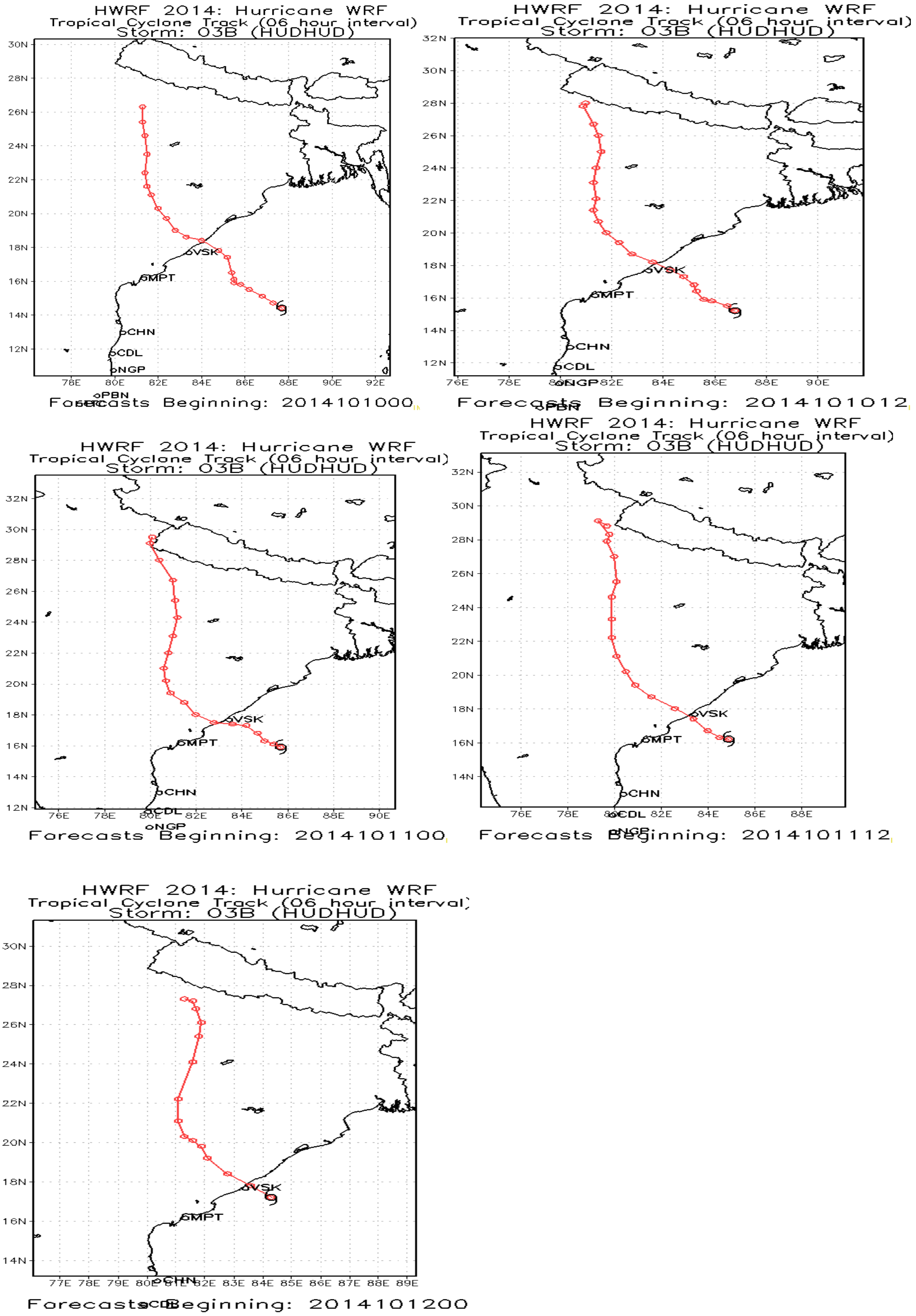


Fig. 13. Predicted tracks of HWRF model based on 00 UTC of 10th to 00 UTC of 12th October 2014

Table-5. Average track forecast errors (Direct Position Error) in km (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	47(11)	66(11)	105(11)	175(10)	228(9)	262(8)	289(7)	294(6)	302(4)	279(3)
IMD-WRF	46(11)	109(11)	150(11)	155(10)	197(9)	222(8)	-	-	-	-
JMA	56(11)	79(11)	86(11)	105(10)	114(9)	126(8)	144(7)	-	-	-
NCEP-GFS	63(11)	82(11)	96(11)	130(10)	110(9)	108(8)	137(7)	126(6)	145(4)	88(3)
UKMO	51(11)	60(11)	83(11)	103(10)	138(9)	153(8)	161(7)	159(6)	172(4)	146(3)
ECMWF	39(11)	66(11)	82(11)	83(10)	95(9)	121(8)	120(7)	145(6)	123(4)	135(3)
IMD-HWRF	34(5)	30(5)	75(5)	108(4)	126(3)	107(2)	123(1)	-	-	-
IMD-MME	40(11)	50(11)	74(11)	90(10)	89(9)	104(8)	117(7)	123(6)	106(4)	49(3)

Table-6. Landfall point forecast errors (km) of NWP Models at different lead time (hour) ('+' for north of observed landfall point, '-' for south of observed landfall point)

Forecast Lead Time (hour) →	7 h	19 h	31 h	43 h	55 h	67 h	79 h	91 h	103 h	115 h
IMD-GFS	11	-72	-39	84	39	161	268	306	336	252
IMD-WRF	-34	21	84	21	-	-	-	-	-	-
JMA	11	11	-24	11	-78	-15	-	-	-	-
NCEP-GFS	11	-78	11	55	-123	46	46	-46	77	11
UKMO	11	46	-78	-11	11	11	11	25	25	11
ECMWF	11	11	11	11	11	-34	-78	-78	39	-
IMD-HWRF	31	-22	-72	64	107	-	-	-	-	-
IMD-MME	21	21	-24	11	-24	25	11	11	46	11

Table-7. Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	7 h	19 h	31 h	43 h	55 h	67 h	79 h	91 h	103 h	115 h
IMD-GFS	1	8	11	8	17	11	16	5	-5	1
IMD-WRF	0	11	11	11	-	-	-	-	-	-
JMA	-6	6	8	7	6	5	-	-	-	-
NCEP-GFS	1	6	1	6	3	1	1	-1	-5	3
UKMO	2	-6	2	-3	-4	-10	-9	11	11	-9
ECMWF	0	1	0	0	-6	-5	-1	-1	5	-
IMD-HWRF	0	0	4	5	5	-	-	-	-	-
IMD-MME	0.5	0	0	1	-1	-4	-4	-4	-4	2

Table-8 Average absolute errors of SCIP and HWRF model (Number of forecasts verified is given in the parentheses) (Intensity forecasts prior to landfall (0600 UTC of 12.10.2014) are considered.

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
IMD-SCIP	3.3(9)	6.1(8)	7.3(7)	8.0(6)	8.2(5)	10.5(4)
IMD-HWRF	8.3(4)	9.3(3)	6.0(2)	1.0(1)	-	-

Table-9 Root Mean Square (RMSE) errors of SCIP and HWRF model (Number of forecasts verified is given in the parentheses)

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
IMD-SCIP	4.0(9)	7.2(8)	8.4(7)	9.2(6)	10.4(5)	11.4(4)
IMD-HWRF	10.6(4)	9.6(3)	6.3(2)	1.0(1)	-	-

Table 10. Forecast Track Errors in km for the model products of NCMRWF

	00hr	**24hr**	**48hr**	**72hr**	**96hr**
NGFS	**40**	**156**	**229**	**288**	**111**
NCUM	**41**	**81**	**161**	**237**	**295**
UKMO	**51**	**64**	**97**	**140**	**155**
ACCESS-TC	**32**	**112**	**154**	**189**	
NGEFS	**33**	**95**	**203**	**272**	**170**
No. of Cases	*5*	*4*	*3*	*2*	*1*

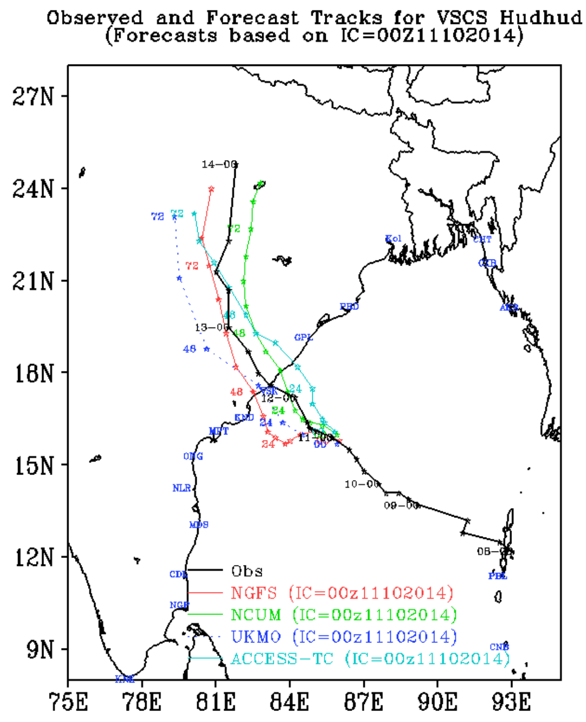


Fig. 14. Track forecasts of the models run at NCMRWF

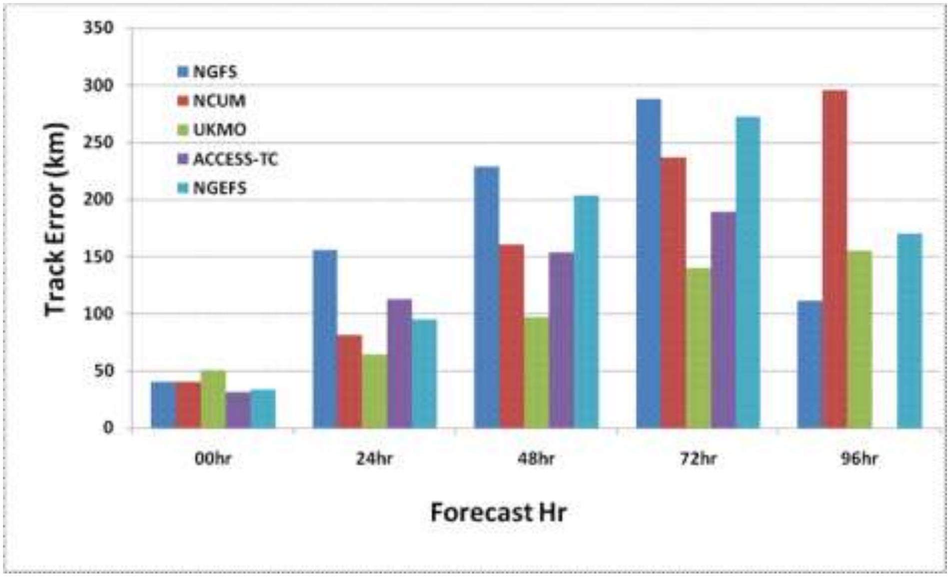


Fig.15 . Track forecast errors of different models run at NCMRWF

From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors was minimum for MME track. It was less than 100 km upto 60 hour forecast and about 100-120 km for higher lead periods. Considering the individual deterministic models, the performance of ECMWF was the best with track forecast error being 66 km, 53 km, 121 km, 145 km and 135 km respectively for 24 hour, 48, hour, 72 hour, 96 hour and 120 hour.

Considering the landfall point forecast error, the performance of MME and ECMWF models was the best among the deterministic models.

7.5. Heavy rainfall

The heavy rainfall guidance from various models was also used for heavy rainfall warning. An example of HWRF model is shown in Fig.16 and that of IMD-GFS and WRF in Fig.17(a-b) and 18(a-b) respectively.

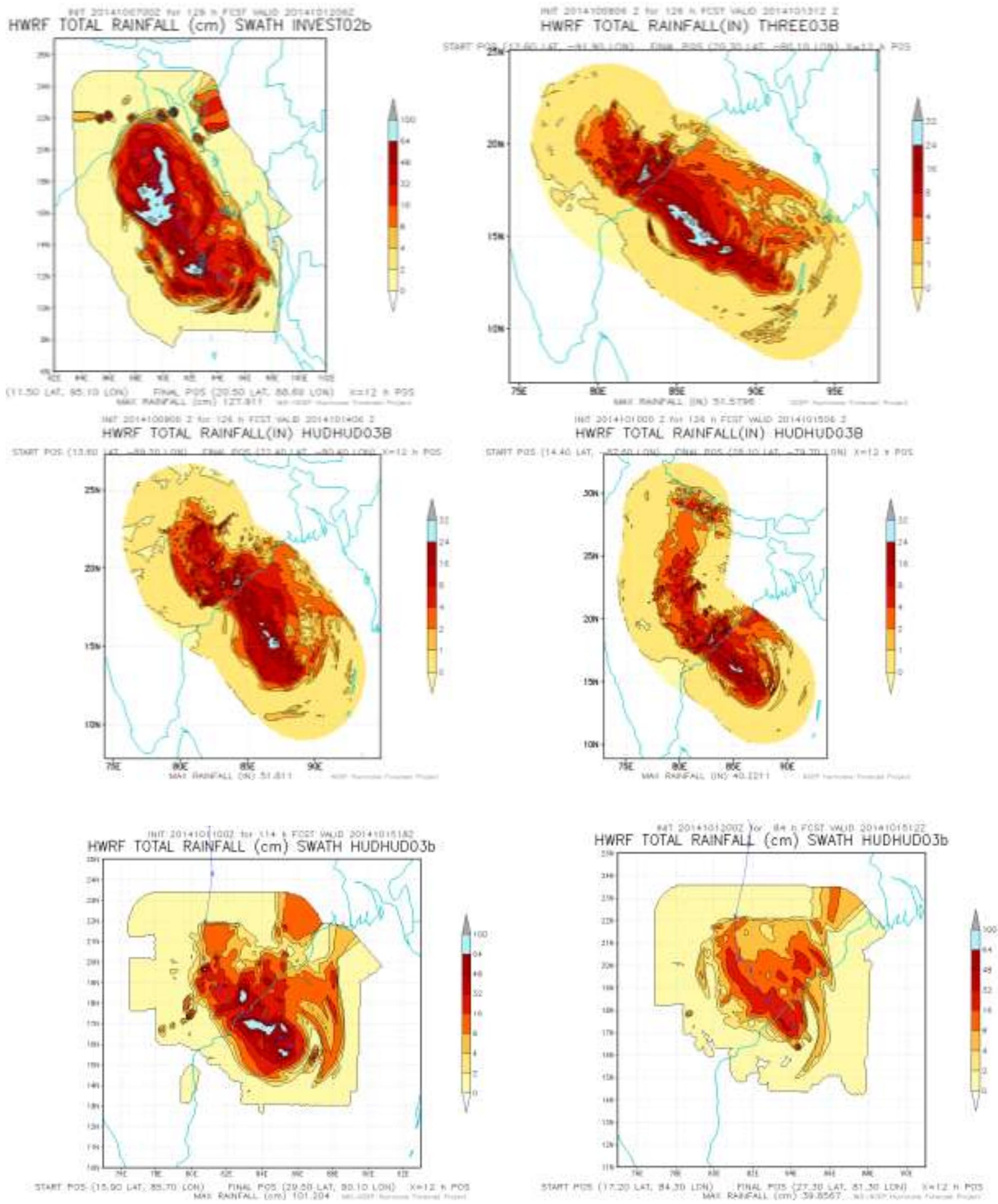


Fig.16 IMD-HWRF rainfall guidance based on 07/00, 08/06, 09/00, 10/00, 11/00 and 12/00 UTC of October 2014

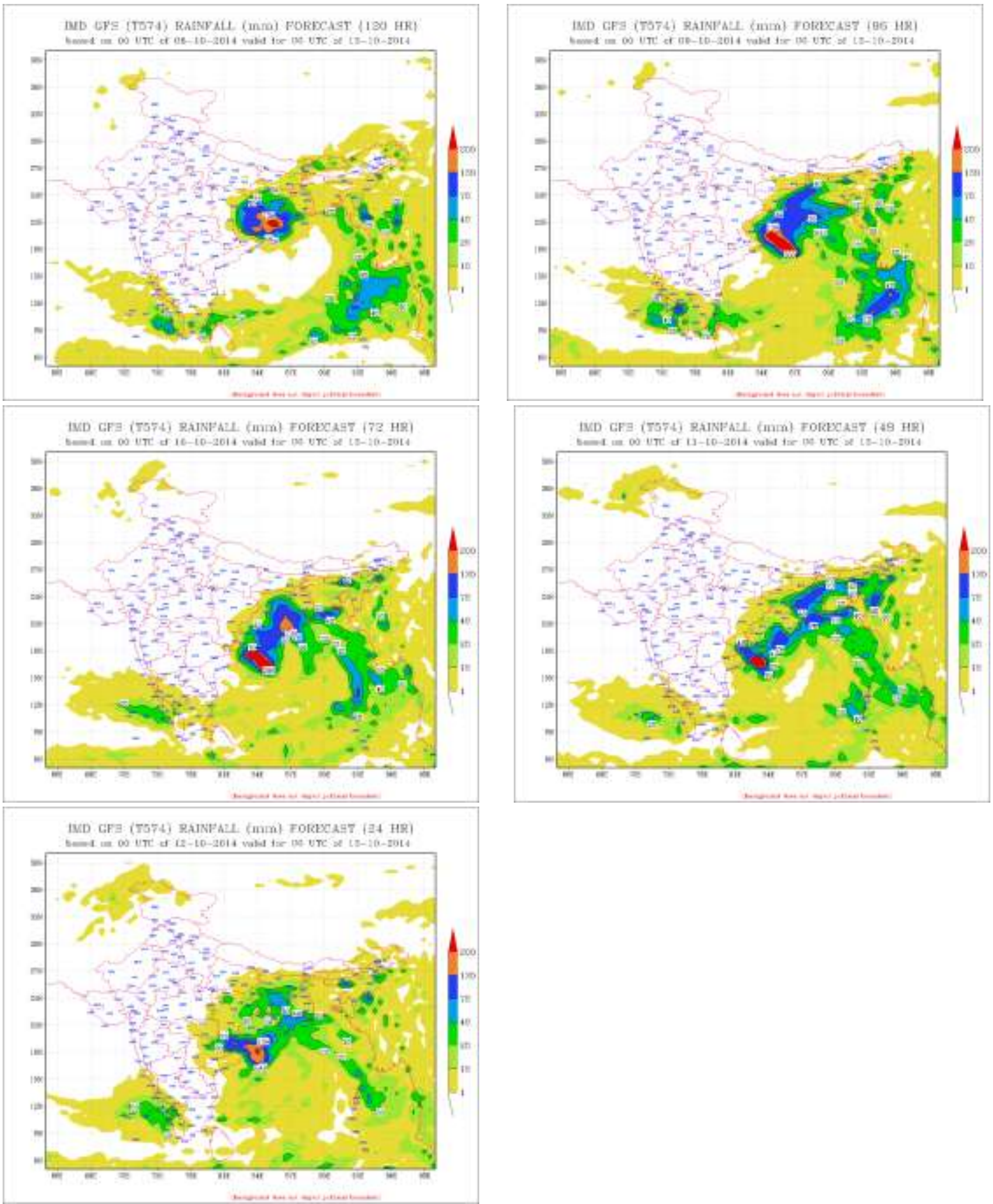


Fig.17a IMD-GFS rainfall forecast for 13th october 2014 based on 8th, 9th, 10th, 11th and 12th / 0000UTC initial conditions.

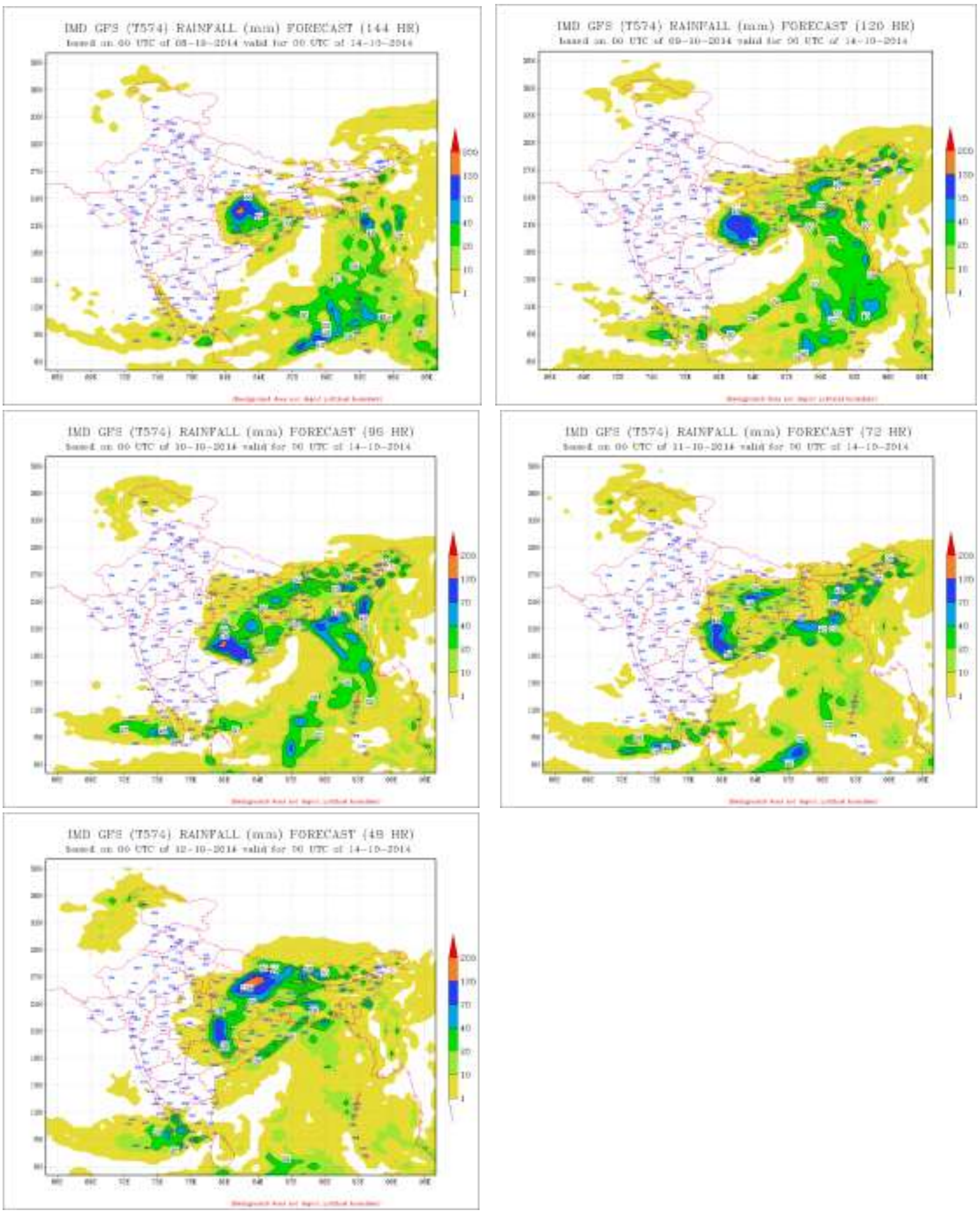


Fig.17b   Same as Fig.14a but for 14th October 2014.

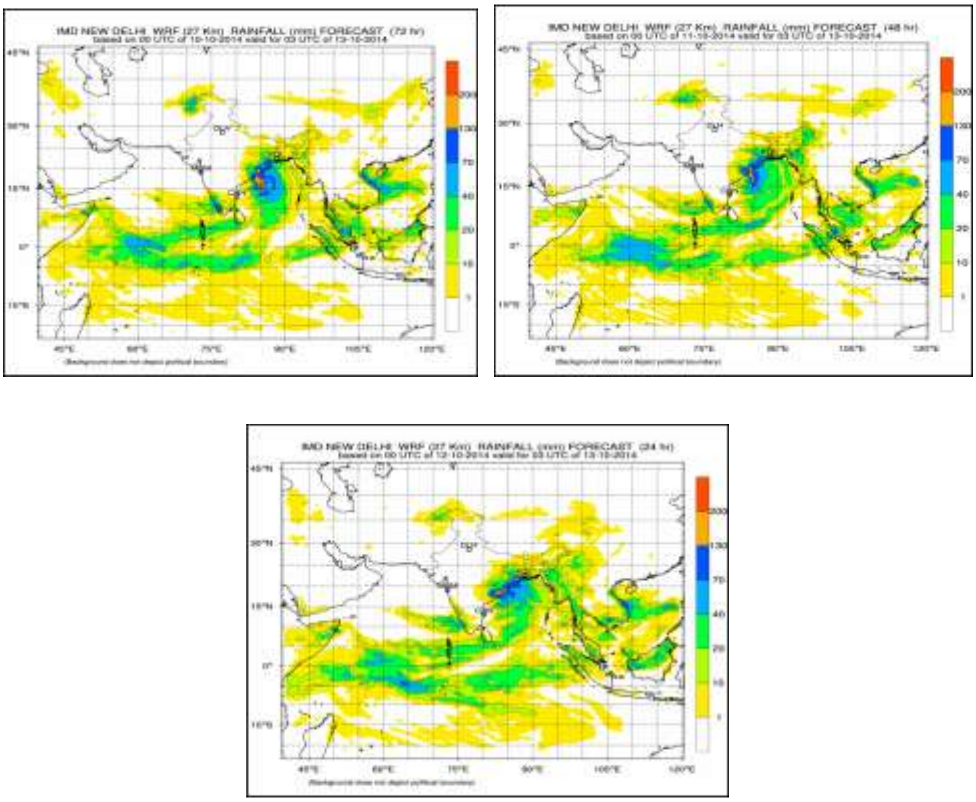


Fig.18a IMD-WRF rainfall forecast for 13th october 2014 based, 10th, 11th and 12th / 0000UTC initial conditions.

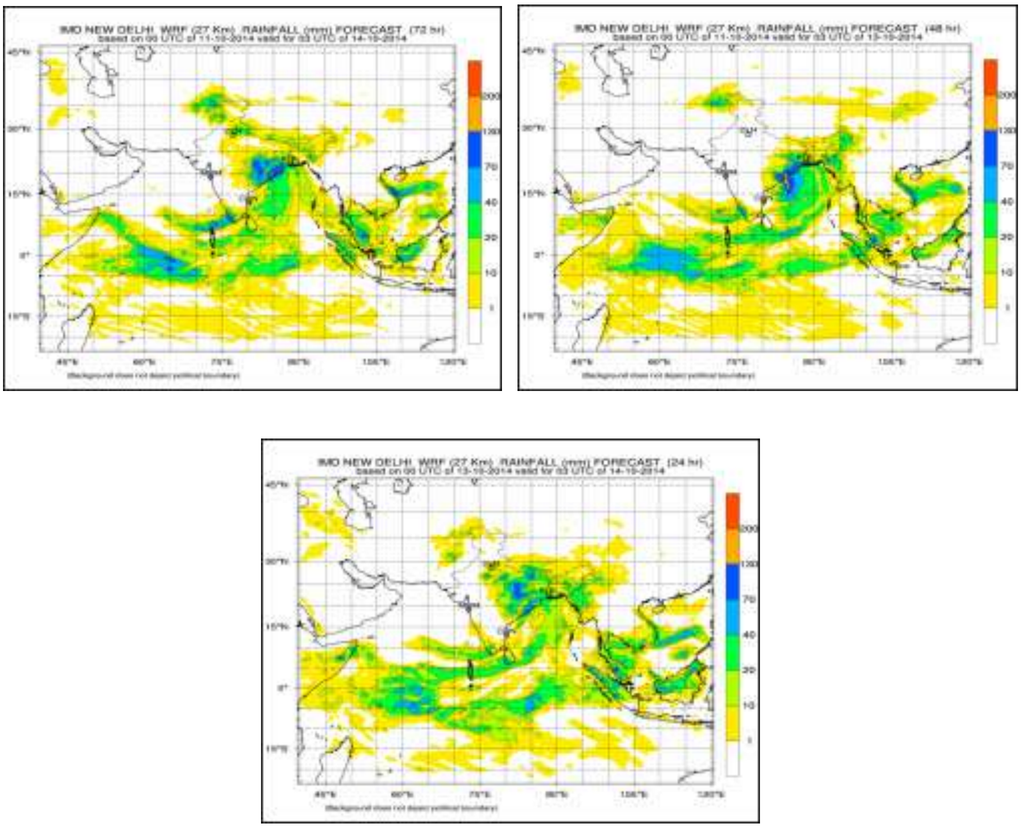


Fig. 18b Same as Fig.15a but for 14th October 2014.

7.6. Storm surge forecast

The storm surge models of INCOIS and IIT, Delhi provided prediction of storm surge of 1-2.5 meters. Maximum Storm Surge forecast by INCOIS model based on 11th October 2014, 1430 IST data was 2.5 m at Chepaluppada, Bheemunipatnam mandal and Visakhapatnam district of North Andhra Pradesh. Storm surge predicted for Visakhapatnam city was 1.6 m. Based on 12th October, 1130 IST conditions, IIT Delhi model predicted 2.1 m at 17.65°N, 83.50°E. Fig.19 presents the storm surge prediction products of INCOIS and IIT Delhi.

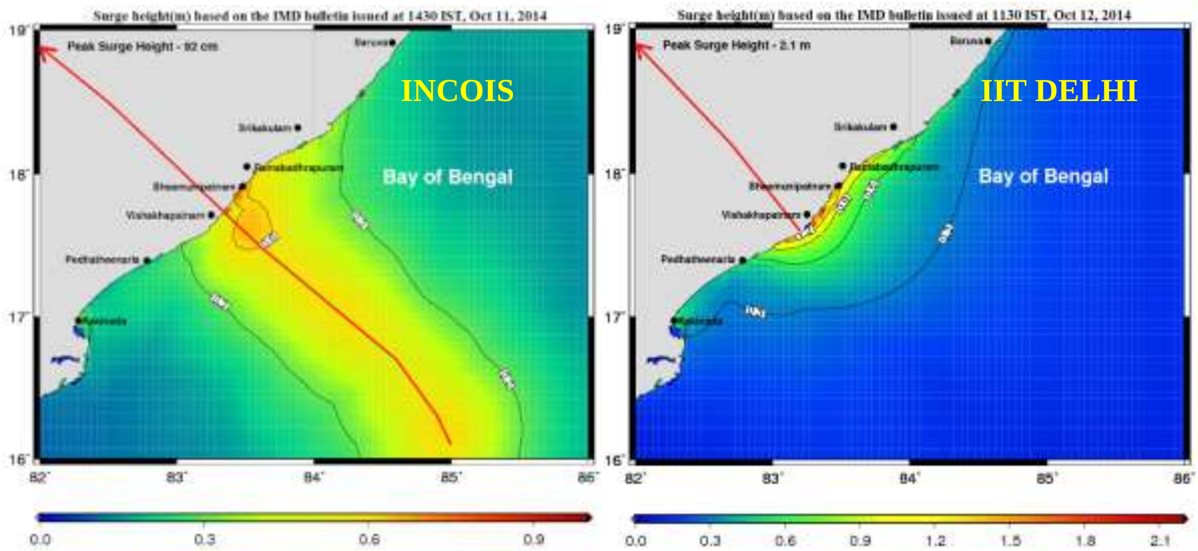


Fig.19 Storm surge prediction guidance based on INCOIS (11th/1430 IST)and IIT Delhi (12th/ 1130 IST) models

12. Bulletins issued by IMD

IMD continuously monitored, predicted and issued bulletins containing track & intensity forecast at +06, +12, +18, +24, +36, +48, +60, +72, +84, +96, +108 and +120 hrs or till the system weakened into a low pressure area. The above structured track and intensity forecasts were issued from the stage of deep depression onwards. The cone of uncertainty in the track forecast was also given for all cyclones. The radius of maximum wind and radius of ≥ 28 knots, ≥34 knots, ≥50 knots and ≥64 knots wind in four quadrants of cyclone was also issued for every six hours. The graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were uploaded in the RSMC, New Delhi website (http://rsmcnewdelhi.imd.gov.in/) regularly. The storm surge forecast was given based on INCOIS and IIT, Delhi model. The prognostics and diagnostics of the systems were described in the RSMC bulletins and tropical cyclone advisory bulletins. The TCAC bulletin was also sent to Asian Disaster Risk Reduction (ADRR) centre of WMO at Honkong like previous year. Tropical cyclone vitals were prepared every six hourly from deep depression stage onwards to various NWP modeling groups in India for bogusing purpose. Bulletins issued by Cyclone Warning services of IMD in association with VSCS HUDHUD are given in Tables 11-14.

Table 11: Bulletins issued by Cyclone Warning Division, New Delhi

Bulletins issued by Cyclone Warning Division, New Delhi in association with Very Severe Cyclonic Storm "HUDHUD" during the period 07-14 October 2014			
S.No.	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	55	1. IMD's website 2. FAX to Control Room NDM, Cabinet Secretariat, Minister of Sc. & Tech, Secretary MoES, DST, HQ Integrated Defence Staff, DG Doordarshan, All India Radio, DG-NDRF, Dir. Indian Railways, Indian Navy, IAF, Chief Secretary-Govt. of Andhra Pradesh, Puducherry, Andaman & Nicobar Islands, West Bengal, Chhattisgarh, Jharkhand, Odisha, Bihar, Sikkim, Uttar Pradesh, Madhya Pradesh, Met. Office Visakhapatnam. 3. Email's to a. Modelling Groups- IIT-DLH & BBN, NCMRWF, INCOIS. b. MC-Patna, Raipur, Ranchi, Lucknow. c. Chief Secretary-Govt. of Andhra Pradesh, Puducherry, Andaman & Nicobar Islands, West Bengal, Chhattisgarh, Jharkhand, Odisha, Bihar, Sikkim, Uttar Pradesh
2	RSMC Bulletin	35	1. IMD's website 2. All WMO/ESCAP member countries through GTS and E-mail. 3. Indian Navy, IAF, by E-mail
3	Press Release	02	1. Put up on IMD's website 2. Emails to : a. Senior Officers of NDMA, NDM, NDRF, Ministry of Home Affairs, b. Senior Officers of MoES, IMD c. Modelling Groups- IIT-DLH & BBN, NCMRWF, INCOIS.
4	DGM's Bulletin for High Government Officials	08	FAX and E-mail to Cabinet Secretary, Principal Secretary to PM, P.S. to Hon'ble Minister for S &T and MoES, Secretary- Ministry of Home Affairs, Ministry of Defence, Ministry of Agriculture, Ministry of I & B, MoES, DST,

			Ministry of Shipping & Surface Transport, Director General, Shipping, Central Relief Commissioner, Ministry of Home Affairs Control Room, NDM, Ministry of Home Affairs, Director Of Punctuality, Indian Railways, Director Central Water Commission, Director General, Doordarshan, AIR, Chief Secretary-Govt. of Andhra Pradesh, Chief Secretary-Govt. of Odisha, Govt. of Puducherry, Andaman & Nicobar Islands.
5	No. of Press Conferences	04	Press &Electronic Media at National level.
6	Personal Briefings At National level		Crisis Management Committee, Cabinet Secretaries, Chief Secy. Andhra |Pradesh, Odisha Special Relief Commissioner / Commissioner for Disaster Management, Andhra Pradesh, Odisha. MHA, NDMA for Disaster Management, Central Water Commission etc. Press, Electronic Media & Public.
7	Personal Briefings At State level		Crisis Management Committee, Chief Commissioners Briefings to Chief Secretary, State Relief Commissioner, Chief Disaster Management , District Collectors
8	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	23	1. IMD's website 2. Meteorological Watch Office for International Civil Aviation
9	ADRR Bulletin to Hong Kong website	22	(Through ftp) to ADRR HongKong
10	TC vitals For creation of synthetic vortex in NWP Models	22	(Through ftp) To: modelling group-NCMRWF, IIT, INCOIS, IMD NWP (Through E-mail).To: NCMRWF, IIT, INCOIS, IMD NWP
11	Quadrant Wind – radial forecast	22	E-mail to modelling group- NCMRWF, IIT, INCOIS, IMD NWP.
12	Hourly Updates on 12 th October 2014 From 05:30 IST to 13:30 IST	09	E-mails to all addresses as mentioned in SNo.1
13	SMS to Senior		1. IMD Group. A officers

	Govt. Officials		2. Disaster Management Officers, at National level. 3. Chief Secretary, Relief Commissioner / Revenue Secretary/ Commissioner of Disaster Management, Andhra Pradesh and Odisha.

Table 12: Bulletins issued by Cyclone Warning Centre Visakhapatnam:

1.	Type of Bulletin	**Number**
2.	Port Warnings	19
3.	Fisherman Warning issued	16
4.	Coastal Weather Bulletin	14
5.	Special Weather Bulletin issued to State Government Officials	02
6.	Cyclone Alert Bulletin	05
7.	Cyclone Warning Bulletin	14
8.	CWDS Bulletins	14
9.	All India Radio Bulletins	06
10.	All India Radio News cycle	14
11.	Press Bulletin	06
12.	Heavy Rainfall Warning	01
13.	Gale /Strong Wind Warnings	02

Table 13: Bulletins issued by Cyclone Warning Centre Bhubaneswar

1.	Type of Bulletin	**Number**
2.	Port Warnings	41
3.	Fisherman Warning issued	28
4.	Informatory messages	04
5.	Coastal Weather Bulletin	03
6.	Cyclone Alert Bulletin	16
7.	Cyclone Warning Bulletin	16
8.	Post Land fall Warning	06
9.	Press / All India Radio Bulletin	43
10.	Heavy Rainfall Warning	05
11.	Meetings with Chief Minister of State / Senior Government Officers	10

Table 14: Bulletins issued by Area Cyclone Warning Centre, Kolkata

	Type of Bulletin	Number
1.	Port Warnings	I. 25 for Port Blair port II. 17 for Hooghly Port
2.	Fisherman Warning	I. 10 for West Bengal Coast II. 13 for Andaman Coast
3	Coastal Weather Bulletin	I. 10 for West Bengal Coast II. 13 for Andaman Coast
4	Heavy Rainfall Warnings	09
5	Gale /Strong Wind Warnings	I. 6 for West Bengal Coast II. 13 for Andaman Coast

13. Operational Forecast Performance

Following are the salient features of the bulletins issued by IMD.

(i) 6th October (morning): Forecast for intensification of low into depression by 7th Oct over Andaman Sea and subsequently into a cyclonic storm on 8th Oct near Andaman Islands.

(ii) 7th October (morning): Depression formed in the morning of 7th Oct. over north Andaman Sea and regular special bulletin commenced. Forecast was issued for further intensification into a deep depression within 24 hours and further into a cyclonic storm on 8th October and to cross Andaman & Nicobar Islands close to Long Island by 8th forenoon. It was further predicted that it would intensify further and move towards north Andhra Pradesh-Odisha coast during subsequent 72 hrs.

(iii) 7th October (evening): With the formation of deep depression, it was predicted in the evening of 7th October that it would become VSCS and cross between Visakhapatnam and Gopalpur coast a s depicted in the track forecast graph maximum wind speed of 130 to 140kmph gusting to 155kmph would prevail along and off across Andhra Pradesh coast on 12th October.

(iv) 8th October (morning): Forecast was issued for Cyclonic Storm to intensify further to a severe cyclonic storm by 9th and further into a VSCS by 10th evening. Further it was stated that it would cross north coastal Andhra Pradesh and south Odisha coast between Visakhapatnam and Gopalpur around noon of 12th October with wind speed of 130 to 140 gusting to 155kmph. However, in the track forecast graphics, the landfall was indicated to be near Visakhapatnam.

(v) 9th October morning: It was predicted that cyclone would cross north Andhra Pradesh coast around Visakhapatnam by the forenoon of 12th October.

(vi) 10th evening: Further intensification of the system with MSW of 140-150 kmph gusting to 165 kmph by 11th evening, was predicted. Further it was stated that it would cross north Andhra Pradesh coast around Visakhapatnam by the forenoon of 12th October.

(vii) 11th morning: Further intensification of the system with MSW 170-180 kmph gusting to 195 kmph by 12th morning was predicted. Further, it was forecast that it would cross north coastal Andhra Pradesh coast around Visakhapatnam around noon of 12th October.

13.1. Operational landfall forecast error

The operational landfall forecast error varied from 2 to 20 km for 12 to 72 hrs forecast (Table 15). Considering the diameter of the eye of the cyclone as 40 km, the landfall error was negligible for all forecast time scales. The landfall time error was also very less varying from 1 to 4 hrs. An example of forecast & actual track showing accurate prediction of landfall point & time is shown in Fig.20.

Table 15. Operational landfall point and time forecast errors of VSCS 'HUDHUD'

Lead Time (Hrs)	Landfall Point Error (km)	Landfall Time Error (hrs)	Long period average landfall point error(km)	Long period average landfall time error(hrs)
19	10	0 h	38.8	2.3
31	20	0 h	75.0	4.2
43	17	4 h early	94.5	7.8
55	04	4 h early	97.5	6.9
67	08	3 h early	83.8	3.5
79	02	1 h early	123.7	1.9
91	24	3 h early	-	-
103	40	3 h early	-	-

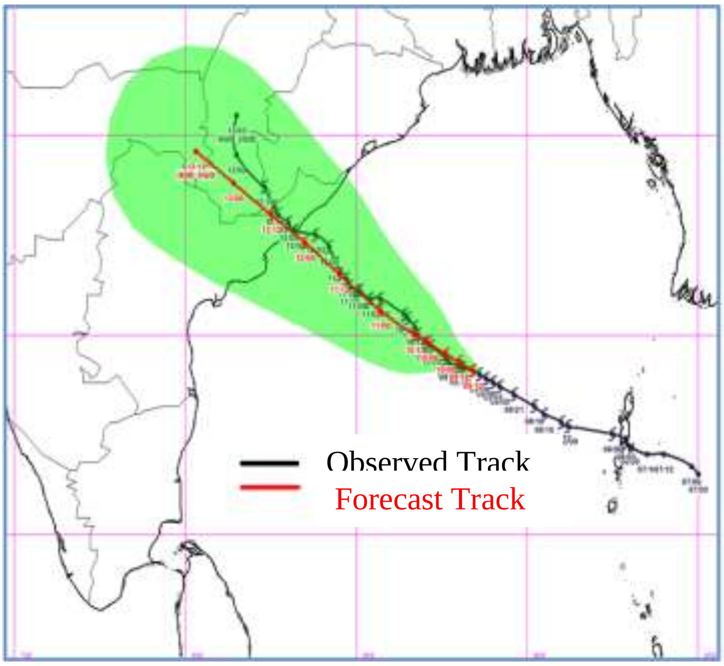


Fig.20. An example of forecast and actual track along with cone of uncertainty issued on 9th October 2014.

13.2. Operational track forecast error and skill

The operational average track forecast errors are shown in Table 16. It was less than 100 km for all forecast time scales upto 108 hrs (Table 16).

Table 16. Operational Track Forecast Error (km) of HUDHUD

Lead Period (hrs)	Track forecast error (Official)	Long period Average track forecast error (km) based on 2009-13
12	50.8 (21)	68.5
24	63.4 (19)	124.1
36	67.2 (17)	163.8
48	78.0 (15)	202.1
60	88.1 (12)	233.8
72	84.9 (11)	268.2
84	90.7 (9)	-
96	98.0 (7)	-
108	90.8 (5)	-
120	203.0 (3)	-

-:120 hr forecast has been introduced in 2013. Hence, no long period average is available for 84-120 hrs. ( ): Number of six hourly forecasts verified.

Table 17. Operational Track Forecast Skill (%)

Lead Period (hrs)	Skill (%) with reference to climatology and persistence forecast	Long period Average skill (%) based on 2009-13
12	43.8	31.2
24	63.8	35.9
36	74.9	43.9
48	79.6	52.6
60	82.2	58.1
72	86.8	61.8
84	88.7	-
96	90.0	-
108	92.3	-
120	92.5	-

-:120 hr forecast has been introduced in 2013. Hence, no long period average is available for 84-120 hrs.

It was also significantly less (103 km) for 120 hr forecast times. It was significantly less than the long period average errors based on 2009-13. The track forecast skill varied from 44% to 93 % for various time scales and was significantly higher than long period average (Table 17).

13.3. Operational Intensity forecast error and skill

The operational intensity forecast error in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 18. The AE varied from about 9 knots to 20 knots in different time scales. The error was significantly less than the long period average error based on 2009-2013. However, comparing the skill, the skill in intensity forecast compared to persistence forecast varied from 23% to 65% for different lead periods and has been significantly higher as compared to long period average skill (Table 19). Considering the RMSE, it varied from 11kmph to 22kmph for different forecast time scales and was significantly less than long period average RMSE. The skill varies from 31% to 67% and is significantly higher than the long period average skills.

Table -18. Operational Intensity forecast errors

Lead period (hrs)	Absolute Error (knots)	Root mean square (RMS) Error (knots	Long period Average (2009-2013):Absolute Error (knots)	Long period Average (2009-2013): RMS Error (knots)
12	8.8	12.5	10.4	14.0
24	8.9	11.3	15.7	20.5
36	9.2	12.3	20.5	25.2
48	10.7	14.7	22.5	27.6
60	13.3	16.4	23.5	26.4
72	15.3	18.0	26.7	30.8
84	15.7	19.1	-	-
96	19.7	22.0	-	-
108	18.8	21.1	-	-
120	16.9	17.4	-	-

120 hr forecast has been introduced in 2013. Hence, no long period average is available for 84-120 hrs.

Table - 19. Operational Intensity Forecast skill (%)

Lead period (hrs)	Skill (%) with reference to persistence forecast		Long period average Skill (%) based on 2009-2013	
	Absolute Error	Root mean square (RMS) error	Absolute Error	RMS Error
12	22.8	30.9	10.4	14.0
24	55.5	65.5	15.7	20.5
36	64.5	69.6	20.5	25.2
48	58.8	59.9	22.5	27.6
60	49.2	53.1	23.5	26.4
72	40.0	42.5	26.7	30.8
84	58.5	61.6	-	-
96	54.8	53.2	-	-
108	50.0	66.8	-	-
120	15.5	32.6	-	-

120 hr forecast has been introduced in 2013. Hence, no long period average is available for 84-120 hrs.

13.4. Adverse weather warning verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 20-22. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table - 20 .Verification of Heavy Rainfall warning

Date/ Time(IST)	Forecast Rainfall	Observed Rainfall
06.10.14	**Andaman and Nicobar Islands**: Isolated heavy to very heavy rainfall during the next 24 hours. Intensity would increase thereafter with heavy to very heavy rainfall at a few places and isolated extremely heavy falls (>=25 cm) during subsequent 48 hours.	**08 October 2014:** ANDAMAN & NICOBAR ISLANDS: Isolated heavy to very heavy rainfall **12 October 2014:** NORTH ANDHRA PRADESH: Heavy to very heavy rainfall at a few places ODISHA: Isolated heavy to very heavy rainfall **13 October 2014:** NORTH ANDHRA PRADESH: Heavy to very heavy rainfall at a few places with isolated extremely heavy rainfall. SOUTH ODISHA: Heavy to very heavy rainfall at a few places with isolated extremely heavy
07.10.14/ 0830	**Andaman and Nocobar Islands:** Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (>=25 cm) would occur over during subsequent 48 hours.	
08.10.14/ 0830	**Andaman and Nicobar Islands:** Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (≥25 cm) during next 24 hours. **North Andhra Pradesh and South Odisha:** Heavy to very heavy falls at a few places with isolated extremely heavy falls over south Odisha from 11th evening onwards. Heavy rain to very heavy rainfall would also commence at a few places over Visakhapatnam, Vizianagaram. Srikakulam districts of north coastal Andhra Pradesh and districts of north coastal Odisha during the same period.	
09.10.14/ 0830	**North Andhra Pradesh and South Odisha coasts:** Heavy (6.5 – 12.4 cm) to very heavy falls (12.5 – 24.4 cm) at a few places and isolated extremely heavy falls (≥ 24.5 cm) over East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts of North Coastal Andhra Pradesh and South Odisha from 11th evening onwards. Heavy to very heavy rainfall at isolated places over remaining districts of Andhra Pradesh and North Coastal Odisha during the same period.	
10.10.14/ 0830	**North Andhra Pradesh and South Odisha coasts:** Heavy (6.5 – 12.4 cm) to very heavy falls (12.5 – 24.4 cm) at a few places and isolated extremely heavy falls (≥ 24.5 cm) would occur over West and East Godavari, Visakhapatnam,	

<table>
<tr><td></td><td>Vizianagaram and Srikakulam districts of North Coastal Andhra Pradesh and Ganjam, Gajapati, Koraput, Rayagada, Nabarangpur, Malkangiri, Kalahandi, Phulbani districts of South Odisha commencing from 11th onwards. Heavy to very heavy rainfall at isolated places over Krishna, Guntur and Prakasham districts of Andhra Pradesh and North Coastal Odisha during the same period.</td><td rowspan="4">rainfall.
CHHATTISGARH: Isolated heavy to very heavy rainfall
JHARKHAND: Isolated heavy to very heavy rainfall.

14 October 2014:
NORTH ANDHRA PRADESH: Isolated heavy to very heavy rainfall.
SOUTH ODISHA: Isolated heavy to very heavy rainfall .
CHHATTISGARH: Heavy to very heavy rainfall at a few places over south Chhattisgarh and Isolated heavy to very heavy rainfall over north Chhattisgarh.
EAST MADHYA PRADESH: Heavy to very heavy rainfall at isolated places.

15 October 2014:
BIHAR: Heavy to</td></tr>
<tr><td>11.10.14/ 0830</td><td>Andhra Pradesh and Odisha coasts:
Heavy (6.5 – 12.4 cm) to very heavy falls (12.5 – 24.4 cm) at a few places and isolated extremely heavy falls (≥ 24.5 cm) over West & East Godavari, Visakhapatnam, Vizianagaram & Srikakulam districts of North Andhra Pradesh and Ganjam, Gajapati, Koraput, Rayagada, Nabarangpur, Malkangiri, Kalahandi, Phulbani districts of South Odisha during next 48 hrs. Heavy to very heavy rainfall at isolated places over Krishna, Guntur & Prakasham districts of Andhra Pradesh and North Coastal Odisha during the same period.</td></tr>
<tr><td>12.10.14/ 0830</td><td>Andhra Pradesh and Odisha coasts:
Heavy (6.5–12.4 cm) to very heavy falls (12.5–24.4 cm) at a few places and isolated extremely heavy falls (≥ 24.5 cm) over West & East Godavari, Visakhapatnam, Vizianagaram & Srikakulam districts of North Andhra Pradesh and Ganjam, Gajapati, Koraput, Rayagada, Nabarangpur, Malkangiri, Kalahandi, Phulbani districts of South Odisha during next 48 hrs. Heavy to very heavy rainfall at isolated places over Krishna, Guntur & Prakasham districts of Andhra Pradesh and North coastal Odisha during the same period.</td></tr>
<tr><td>13.10.14/ 0830</td><td>Isolated heavy falls (6.5–12.4 cm) over Vizianagaram and Srikakulam districts of North Andhra Pradesh and adjoining districts of South coastal Odisha during next 6 hours and decrease thereafter.
Isolated heavy (6.5–12.4 cm) to very heavy falls (12.5–24.4 cm) over Chhattisgarh & adjoining east Madhya Pradesh and interior Odisha during</td></tr>
</table>

	next 24 hrs and over East Uttar Pradesh, Jharkhand & Bihar during next 48 hrs.	very heavy rainfall at
14.10.14/ 0830	Heavy (6.5–12.4 cm) to very heavy falls (12.5–24.4 cm) at a few places over East Uttar Pradesh and Bihar; isolated heavy to very heavy over North Chhattisgarh & East Madhya Pradesh and isolated heavy over Jharkhand during next 24 hours. During subsequent 24 hours, heavy to very heavy falls at isolated places over East Uttar Pradesh, Bihar, Sub-Himalayan West Bengal and Sikkim and isolated heavy rainfall over Jharkhand and North Chhattisgarh.	isolated places. EAST UTTAR PRADESH: Heavy to very heavy rainfall at isolated places. SUB-HIMALAYAN WEST BENGAL & SIKKIM: Isolated heavy rainfall.

Table 21. Verification of Gale Wind Forecast

Date/ Time(IST)	Gale wind Forecast	Recorded wind
06.10.14	**Andaman and Nicobar Islands:** Squally wind speed reaching 45-55 kmph during next 24 hours. The wind speed would increase gradually reaching gale wind speed upto 70-80 kmph on 8th October 2014.	**08 October 2014:** Port Blair: 88 kmph
07.10.14/ 0830	**Andaman and Nicobar Islands:** Squally wind speed reaching 45-55 kmph during next 12 hours. The wind speed would increase gradually reaching gale wind speed of 70-80 kmph by 8th morning, October 2014.	**09 October 2014:** Port Blair: 60 kmph
08.10.14/ 0830	**North Andhra Pradesh and Odisha coasts:** Squally wind speed reaching 50-60 kmph gusting to 70 kmph would commence from 11th morning onwards. The wind speed would increase to 130-140 kmph gusting to 150 from 12th morning.	**10 October 2014:** Port Blair: 64 kmph
09.10.14/ 0830	**North Andhra Pradesh and South Odisha coasts:** Squally wind speed reaching 50-60 kmph gusting to 70 kmph would commence along and off North Andhra Pradesh and South Odisha coasts from 11th morning onwards. The wind speed would increase to 130-140 kmph gusting to 155 kmph from 12th morning along and off North Andhra coast and 80-90 kmph along and off South Odisha coast.	**11 October 2014:** Machilipatnam: 88 kmph Visakhapatnam: 74 kmph **12 October**

10.10.14/ 0830	**Andhra Pradesh and South Odisha coasts:** Squally wind speed reaching 50-60 kmph gusting to 70 kmph would commence along and off North Andhra Pradesh and South Odisha coasts from 11th morning onwards. The wind speed would gradually increase to 130-140 kmph gusting to 155 kmph from 12th morning along and off North Andhra coast (East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts) and 80-90 kmph along and off adjoining districts of South Andhra (West Godavari, Krishna districts) and South Odisha (Ganjam, Gajapati, Koraput and Malkangiri districts).	**2014:** Visakhapatnam: 180 kmph
10.10.14/ 2030	**Andhra Pradesh and South Odisha coasts:** Squally wind speed reaching 50-60 kmph gusting to 70 kmph would commence along & off North Andhra Pradesh and South Odisha coasts from 11th morning onwards. The wind speed would gradually increase to 140-150 kmph gusting to 165 kmph from 12th morning along & off North Andhra Pradesh (East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts) and 80-90 kmph along and off adjoining districts of South Andhra Pradesh (West Godavari, Krishna districts) and South Odisha (Ganjam, Gajapati, Koraput and Malkangiri districts).	
11.10.14/ 0830	**Andhra Pradesh and South Odisha coasts:** Squally wind speed reaching 50-60 kmph gusting to 70 kmph would prevail along & off North Andhra Pradesh and South Odisha coasts during next 12 hrs. The wind speed would gradually increase to 170-180 kmph gusting to 195 kmph around the time of landfall along & off North Andhra Pradesh (East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts) and 80-90 kmph along and off adjoining districts of South Andhra Pradesh (West Godavari, Krishna districts) and south Odisha (Ganjam, Gajapati, Koraput and Malkangiri districts).	
12.10.14/ 0830	**Andhra Pradesh and South Odisha coasts:** Gale wind speed upto to 170-180 kmph gusting to 195 kmph would prevail along & off North Andhra Pradesh (East Godavari, Visakhapatnam,	

	Vizianagaram and Srikakulam districts), 80-90 kmph along and off adjoining districts of Andhra Pradesh (West Godavari & Krishna districts) and south Odisha (Ganjam, Gajapati, Koraput and Malkangiri districts).	

Table 22. Verification of Storm Surge Forecast issued by IMD

Forecast Storm surge above astronomical tide and area to be affected	Actual Storm Surge
09.10.14/0830 IST Storm surge of about 1-2 meters above astronomical tide would inundate low lying areas of East Godavari, Visakhapatnam, Vizianagaram and Srikakulam districts of north coastal Andhra Pradesh at the time of landfall (12 Oct 2014/ Around noon) **10.10.14/0830 IST** Storm surge of about 1-2 meters above astronomical tide would inundate low lying areas of Visakhapatnam, Vizianagaram and Srikakulam districts of north coastal Andhra Pradesh at the time of landfall (12 Oct 2014/ Around noon)	Observed Storm Surge recorded by the tide gauge at Visakhapatnam was 1.4 m.

14. Conclusions

HUDHUD is the first cyclone that crossed Visakhapatnam coast in the month of Oct., after 1985 and it made landfall on the same day as VSCS Phailin did in 2013. At the time of landfall on 12th Oct, the estimated maximum sustained surface wind speed in association with the cyclone was about 100 Knots. The estimated central pressure was 950 hPa with a pressure drop of 54 hPa at the centre compared to surroundings. It caused very heavy to extremely heavy rainfall over North Andhra Pradesh and South Odisha and strong gale winds leading to large scale structural damage over North Andhra Pradesh and adjoining districts of South Odisha and storm surge over North Andhra Pradesh.coast. Maximum 24 hour cumulative rainfall of 38 cm ending at 0830 hrs IST of 13 October was reported from Gantyada (dist Vizianagaram) in Andhra Pradesh. Maximum of storm surge of 1.4 meters above the astronomical tide has been reported by the tide gauge at Visakhapatnam. The NWP and dynamical statistical models provided good guidance with respect to its genesis, track and intensity. Though there was divergence in model guidance with respect to landfall point and time in the initial stage, the consensus among the models emerged as the cyclone moved closer to the coast. IMD accurately predicted the genesis, intensity, track and point & time of landfall and also the adverse weather like heavy rainfall, gale wind and storm surge 4-5 days in advance. This success in early warning of cyclone has been possible due to many factors including upgradation of various components of early warning system of cyclones by IMD and Ministry of Earth Sciences and national & international collaborations in recent years.