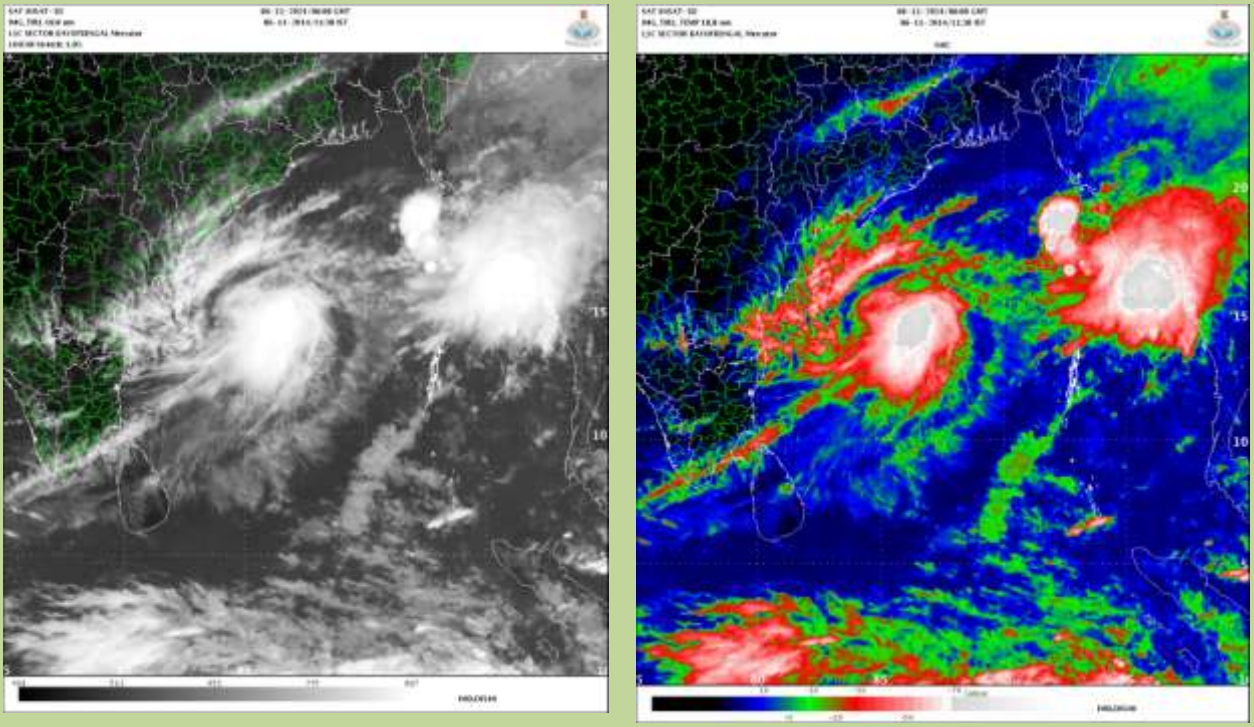
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
EARTH SYSTEM SCIENCE ORGANISATION
INDIA METEOROLOGICAL DEPARTMENT

Deep Depression over the Bay of Bengal (05-08 November 2014): A Report



Satellite imageries of DEEP DEPRESSION (05-08 NOVEMBER 2014)

Cyclone Warning Division

India Meteorological Department

New Delhi

November 2014

Deep Depression over the Bay of Bengal (05-08 November 2014)

1. Introduction

A *Deep Depression* formed over the central and adjoining southeast Bay of Bengal during the period 05-08 November 2014. It initially moved northwards on 5th November 2014, took a loop on 06th and turned westwards towards Andhra Pradesh coast on 7th morning. During its westward movement, it started weakening and became a well-marked low pressure area over the westcentral Bay of Bengal on 8th morning. However, it retained its intensity of well-marked low pressure area for some time, continued its movement towards Andhra Pradesh coast, crossed coast on 09th morning as a well-marked low pressure area and caused light to moderate rainfall activity at a few places over Andhra Pradesh on 09th and 10th November 2014.

The salient features of this system were

i. The system attained the maximum intensity of Deep Depression and weakened over the sea into a well-marked low pressure area.
ii. It had a looping track during the period between 06th morning to 07th morning as it lay sandwiched between two anticyclonic circulations to the west and east of the centre. Such kind of looping movement is not very common in the case of cyclones and depressions of North Indian Ocean. Last such looping of a cyclonic disturbance over Bay of Bengal occurred in a cyclone during 28 November-07 December, 1996.

The system was continuously monitored by the India Meteorological Department (IMD) right from its formative stages and forecasts on future movement and intensity were issued 72 hours in advance. A brief report on details of monitoring and prediction of genesis, movement and intensity of the system, its life history, associated weather etc., along with performance of numerical weather prediction models and operational forecast of IMD is presented and discussed in following sections.

2. Monitoring and prediction of Deep Depression (05-08 November 2014)

The *Deep Depression* (05-08 November, 2014) was monitored & predicted continuously since its inception by the IMD. IMD could predict well in advance the genesis, intensification, as well as weakening of the system before crossing the Andhra Pradesh coast. The system was monitored mainly with satellite observations, supported by meteorological buoys and ship observations. OMNI buoys deployed in the Bay of Bengal provided crucial observations for determining the location and intensity of the system.

Various national and international 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 system. 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. Brief life history

3.1. Genesis

Under the influence of active northeast monsoon conditions, a low pressure area (LOPAR) formed over the Bay of Bengal on 3rd November 2014. Moderate vertical wind

shear (VWS) of the order of 10-20 knots, warm sea surface temperature (SST) of 29-30°C, moderate ocean thermal energy of about 60-80 kJ/cm^2 and increasing low level relative vorticity and convergence around the region of the LOPAR favoured genesis of the low pressure system (LPS) from the existing LOPAR. With gradual increase in the organisation of convection on 4th, the associated low level circulation attained an intensity of T 1.5 on 05th/1430 IST with associated broken low and medium clouds with embedded intense to very intense convection between latitude 10.0°N to 17°N and longitude 82.5°E to 88.5°E. The low pressure area concentrated into a ***Depression*** (***D,*** MSW: 17-27 knots) over central & adjoining southeast Bay of Bengal and lay centred near latitude 13.0^0 N and longitude 87.5^0 E at 1430 IST of 5th November, 2014. A buoy located near latitude 14.0^{0}N and longitude 87.0^{0}E reported mean sea level pressure (MSLP) of 1001.5 hpa and surface wind of 010^0 /21 knots. The estimated central pressure (ECP) was 1000 hPa and MSW was 25 knots.

3.2. Intensification and movement

The upper tropospheric ridge at 200 hPa level was located along 15°N latitude on 5th morning. As the system centre was located to the south and close to western edge of the ridge, it was initially steered northwards on 5th. Under favourable environmental conditions of moderate VWS, warm SST, moderate ocean thermal energy, increasing low level vorticity and convergence and with strong poleward outflow in association with the anticyclonic circulation lying to the east-northeast of the system centre, it intensified into a ***Deep Depression*** and lay centred near latitude 14.0^0 N and longitude 87.5^0 E at 0830 IST on 6th. However, as the system moved northwards, it encountered increasing VWS (20-30 knots) and lower ocean thermal energy on 6th. Further, as the system centre was locked in the Col region between two anticyclonic circulations, one to the east and one to the west of the system, it executed a looping movement around the same region on 6th. This movement caused cooling of SSTs due to more and more upwelling in the same region. Thus, under conditions of high VWS, low ocean thermal energy and colder SST, it started weakening and became a ***Depression*** at 0830 IST of 7th and lay centred near latitude 14.2^0 N and longitude 87.5^0 E. On 7th, as the upper tropospheric ridge moved northwards and was located along 17°N, the system centre was located to the south of the ridge and was steered westwards by the anticyclonic circulation to the north of the system centre. During its westward movement, if further weakened into a well-marked low pressure area at 0830 IST of 08th. However, it continued its westward movement and crossed Andhra Pradesh coast on 09th morning as a well-marked low pressure area. The best track parameters of the system are presented in Table-1 and Fig.1.

4. Maximum Sustained Surface Wind speed and estimated central pressure:

The maximum sustained wind (MSW) in association with a low pressure system 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. 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. 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* $\sqrt{}$ pressure drop at the centre).

Table 1: Best track positions and other parameters of the Deep Depression over the Bay of Bengal (05-08 November 2014)

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
05-11-2014	*0900*	*13.0/87.5*	*1.5*	*1000*	*25*	*4*	*D*
	1200	*13.0/87.5*	*1.5*	*1000*	*25*	*4*	*D*
	1800	*13.5/87.5*	*1.5*	*1000*	*25*	*4*	*D*
06-11-2014	*0000*	*13.8/87.5*	*1.5*	*1000*	*25*	*4*	*D*
	0300	*14.0/87.5*	*2.0*	*998*	*30*	*5*	*DD*
	0600	*14.1/87.5*	*2.0*	*998*	*30*	*6*	*DD*
	1200	*14.1/88.0*	*2.0*	*998*	*30*	*6*	*DD*
	1800	*13.8/88.0*	*2.0*	*1000*	*30*	*6*	*DD*
07-11-2014	*0000*	*14.0/87.5*	*2.0*	*1001*	*30*	*5*	*DD*
	0300	*14.2/87.5*	*1.5*	*1001*	*30*	*5*	*DD*
	0600	*14.2/87.5*	*1.5*	*1003*	*25*	*4*	*D*
	1200	*14.2/87.5*	*1.5*	*1003*	*25*	*4*	*D*
	1800	*14.3/87.0*	*1.5*	*1004*	*25*	*4*	*D*
08-11-2014	*0000*	*14.3/86.5*	*1.5*	*1005*	*25*	*3*	*D*
	0300	*Weakened into a well marked low pressure area over westcentral Bay of Bengal*					

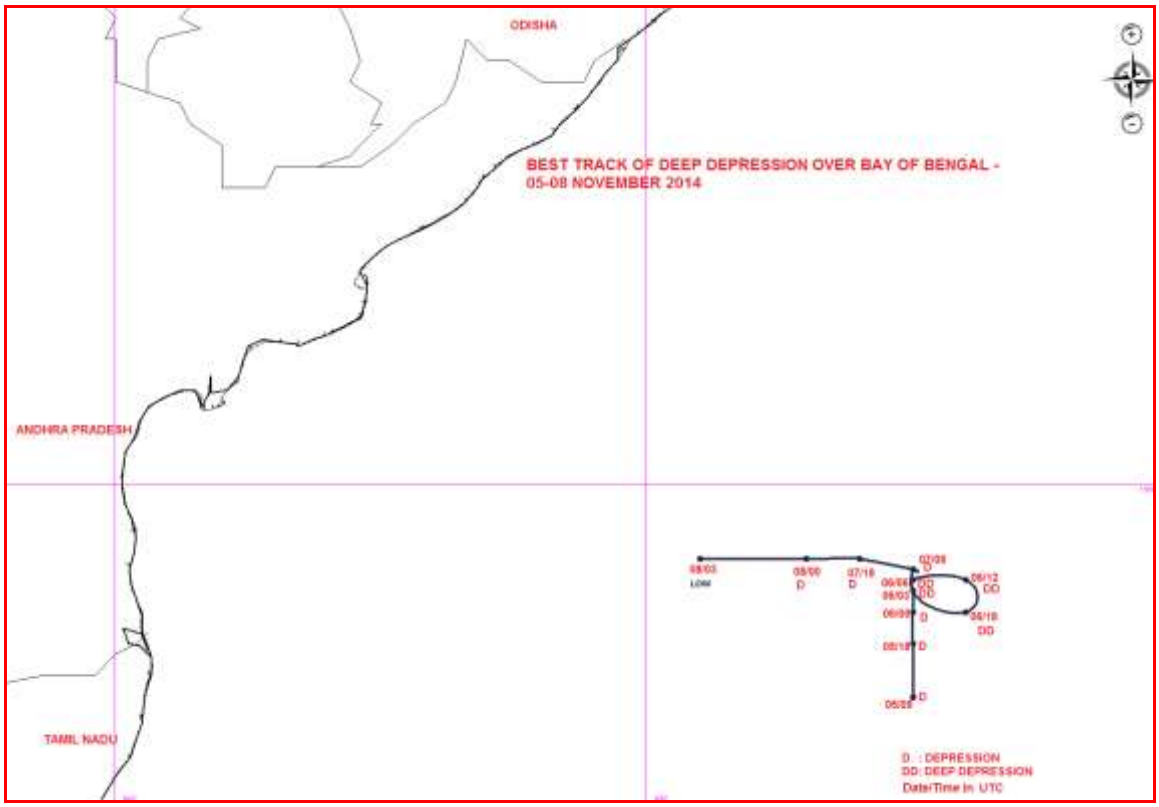


Fig. 1: The Best track of the Deep Depression over the Bay of Bengal during 05-08 November, 2014

The meteorological moored ocean buoys located near 14°N/87°E, 15°N/90°E, 17°N/87.3°E and 13.5°N/84°E provided some crucial wind and MSLP observations in determining the intensity of the system. The lowest Estimated Central Pressure (ECP) of the system was 998 hPa during 0830-1730 IST of 06th November, 2014 with a pressure drop of 6 hPa. The estimated MSW was 30 knots (55 kmph) at 0830 IST of 06th.

5. Characteristic features observed through Satellite and RADAR

5.1 Features observed through satellite

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 the Deep Depression (05-08 November 2014) representing the life cycle of the system are shown in Fig.2 - 4.

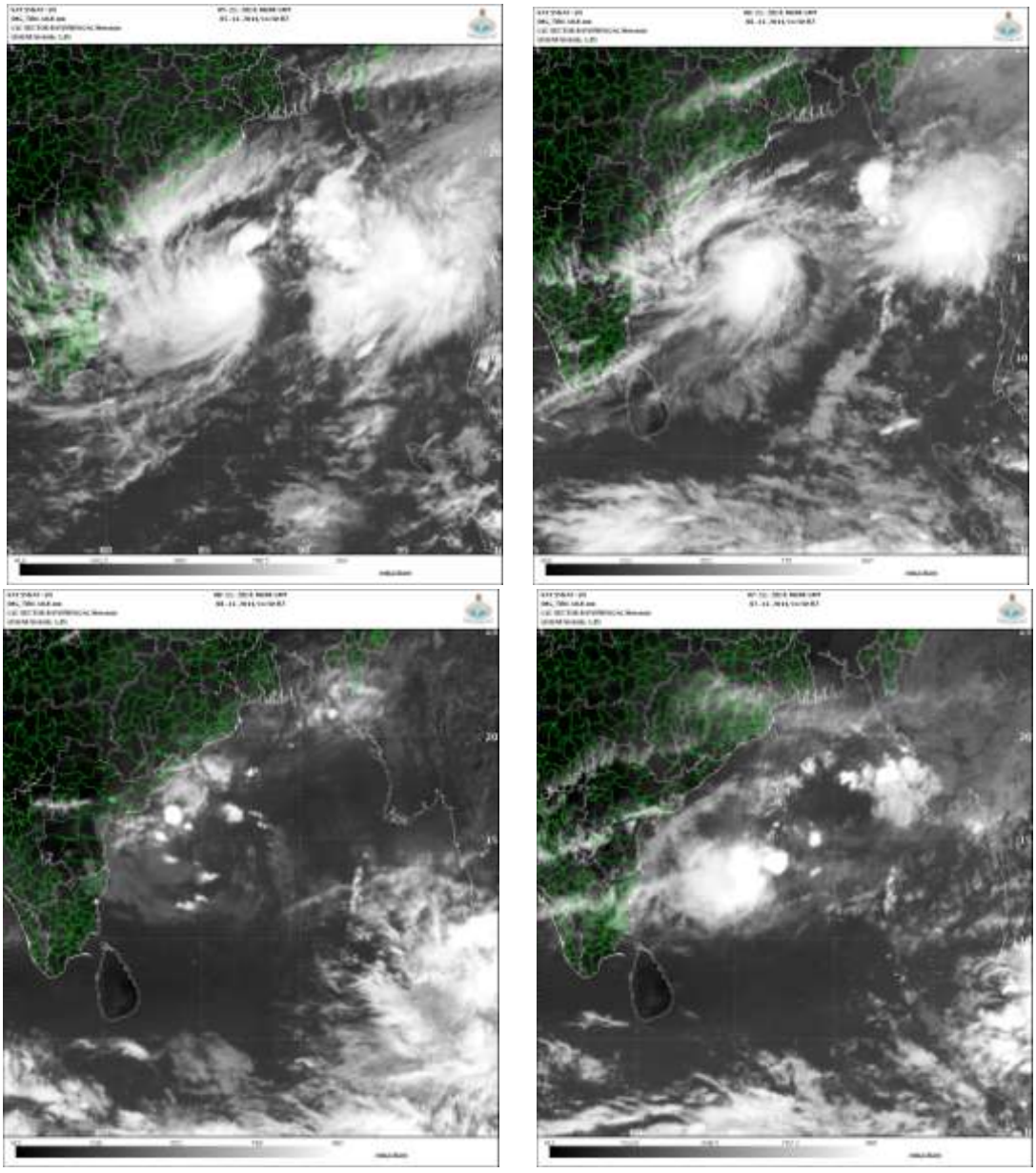


Fig. 2: Typical INSAT-3D IR imageries based on 0600 UTC in association with Deep Depression during 05-08 November 2014

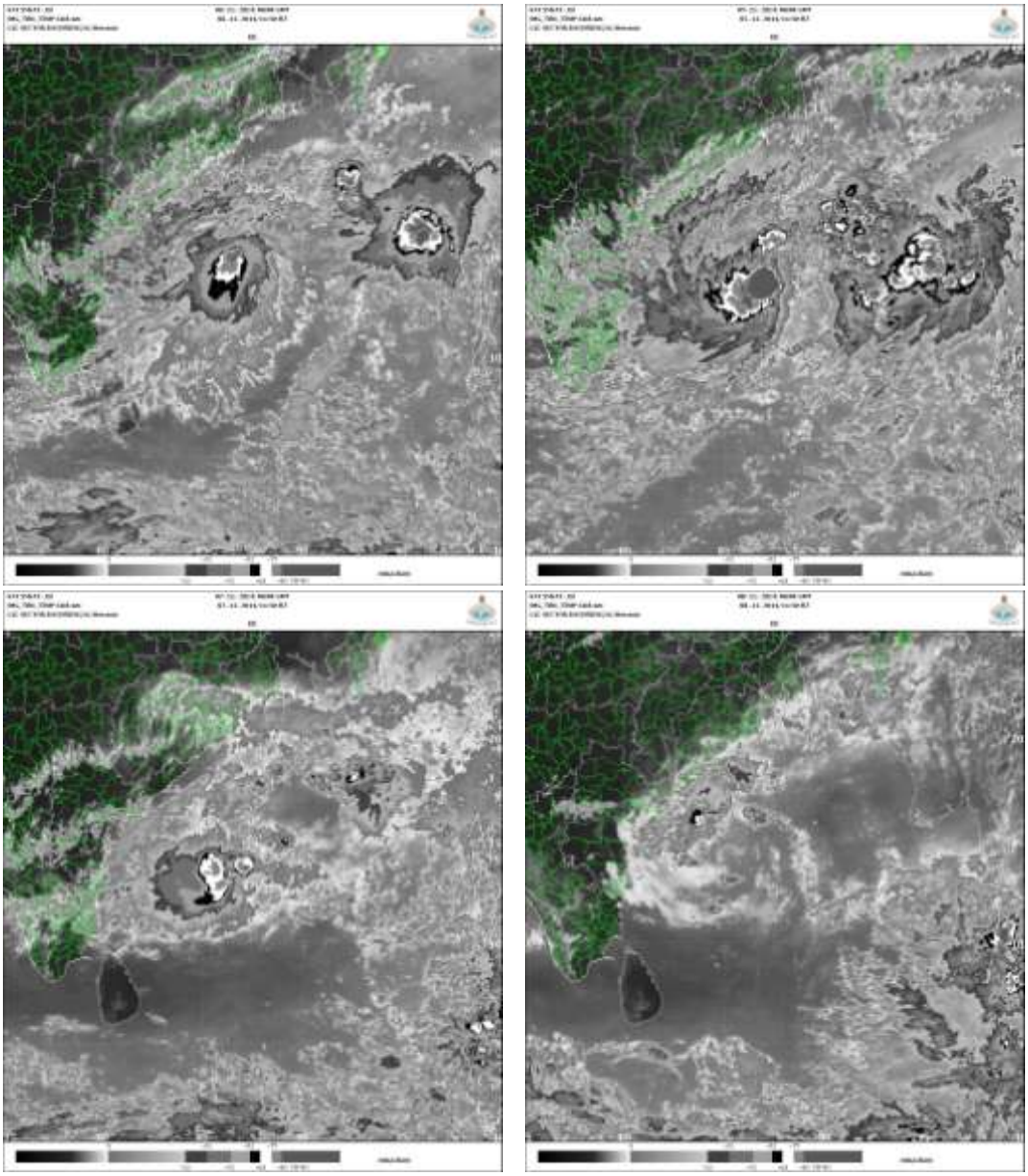


Fig. 3: INSAT-3D enhanced IR imageries based on 0600 UTC in association with Deep Depression during 05-08 November 2014

As per the satellite imagery of 05th/1430 IST, the vortex associated with the low level circulation attained an intensity of T.1.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over Bay of Bengal between latitude 10.0°N to 17.5°N and longitude 82.5°E to 88.5°E. Convection increased during the previous 24 hours with increase in organisation. At 1730 IST of 05th, the convection sheared to the west of the system centre. Associated broken low and medium clouds with embedded intense to very intense convection lay over Bay of Bengal between latitude 10.0°N to 17.5°N and longitude 82.5°E to 88.5°E.

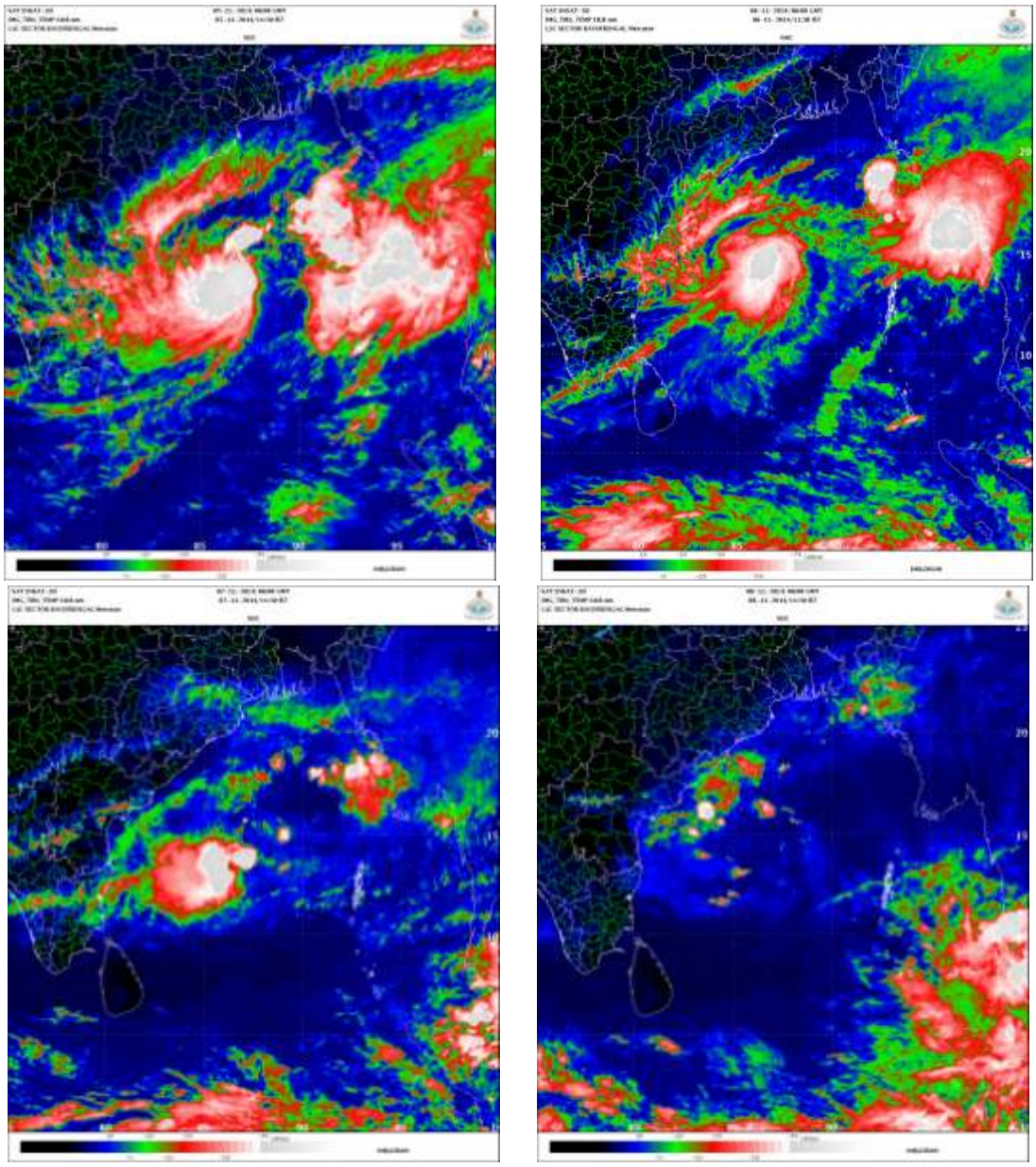


Fig. 4: INSAT-3D colored enhanced IR imageries based on 0600 UTC in association with Deep Depression during 05-08 November 2014

The lowest cloud top temparature (CTT) was -93°C. At 0830 IST of 6th, the system attained intensity of T.2.0 and convection showed curved band pattern. Associated with the weakening of the system, satellite imagery on 7th/0830 IST, indicated intensity of T.1.5 and pattern changed to shear pattern. Further at 1730 IST of 7th, satellite based intensity was T.1.0.

5.2 Features observed through RADAR

Due to weakening of the system over the westcentral Bay of Bengal the characteristic features like location and intensity could not be detected with RADAR. However, 24-hr accumulated precipitation as observed by the Doppler Weather Radar (DWR) Machilipatnam for day ending 0830 IST during the period 08-10th November 2014 is shown in Fig.5.

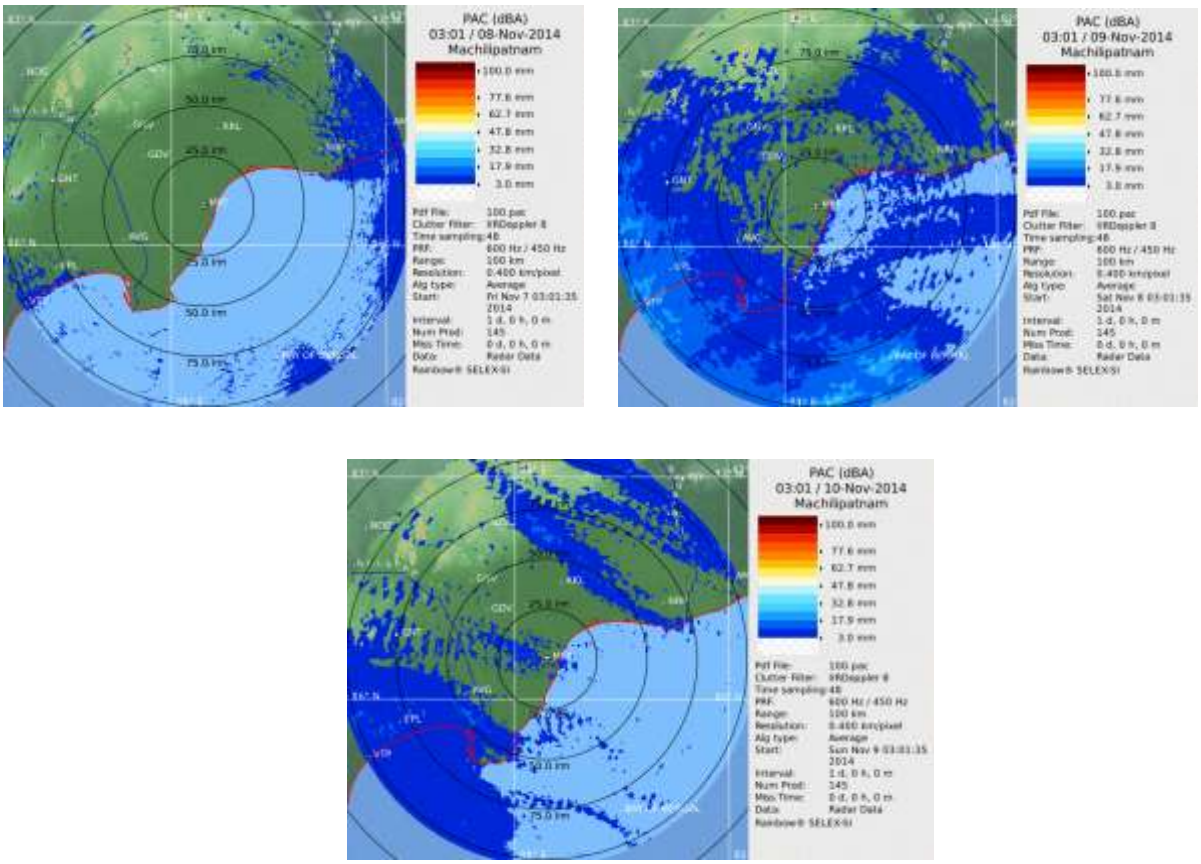


Fig.5 DWR MPT 24-hr accumulated precipitation product for 08-10th November 2014 ending 0830 IST.

6. Dynamical features

To analyse the dynamical features, the Mean Sea Level Pressure (MSLP), surface winds at 925, 850, 500 and 200 hPa levels and vertical wind shear between 850 and 200 hPa levels during the period 05-08 November 2014 are presented in Fig.6(a-d) based on NCMRWF-GFS analysis. As can be seen, the system extended from southwest to northeast in the lower and mid levels on 5th. There was moderate vertical wind shear (VWS) and strong outflow at the upper levels on 05th which helped in intensification of the system. On 6th, associated with the intensification of the Depression into a Deep Depression, the system organised and wind speed increased. However, equatorial easterlies in the upper levels strengthened on 6th leading to gradual increase in VWS near the system centre. The winds are stronger in the southeast sector of the system.

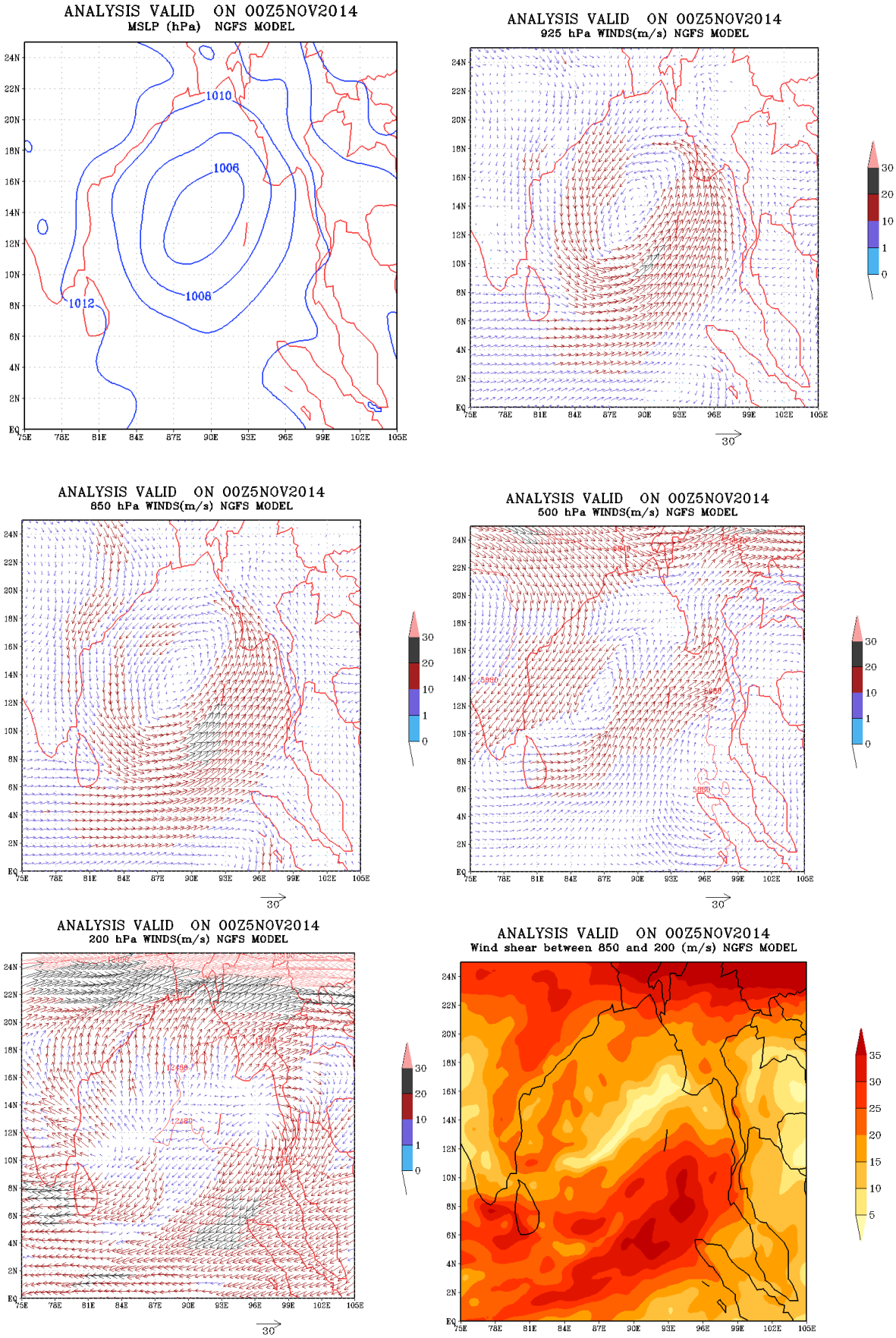


Fig.6a. NCMRWF-NGFS model analysis fields of MSLP, winds at 925, 850, 500 & 200 hPa levels and vertical wind shear (between 850 and 200 hPa) based on 05th November 2014 / 0000 UTC

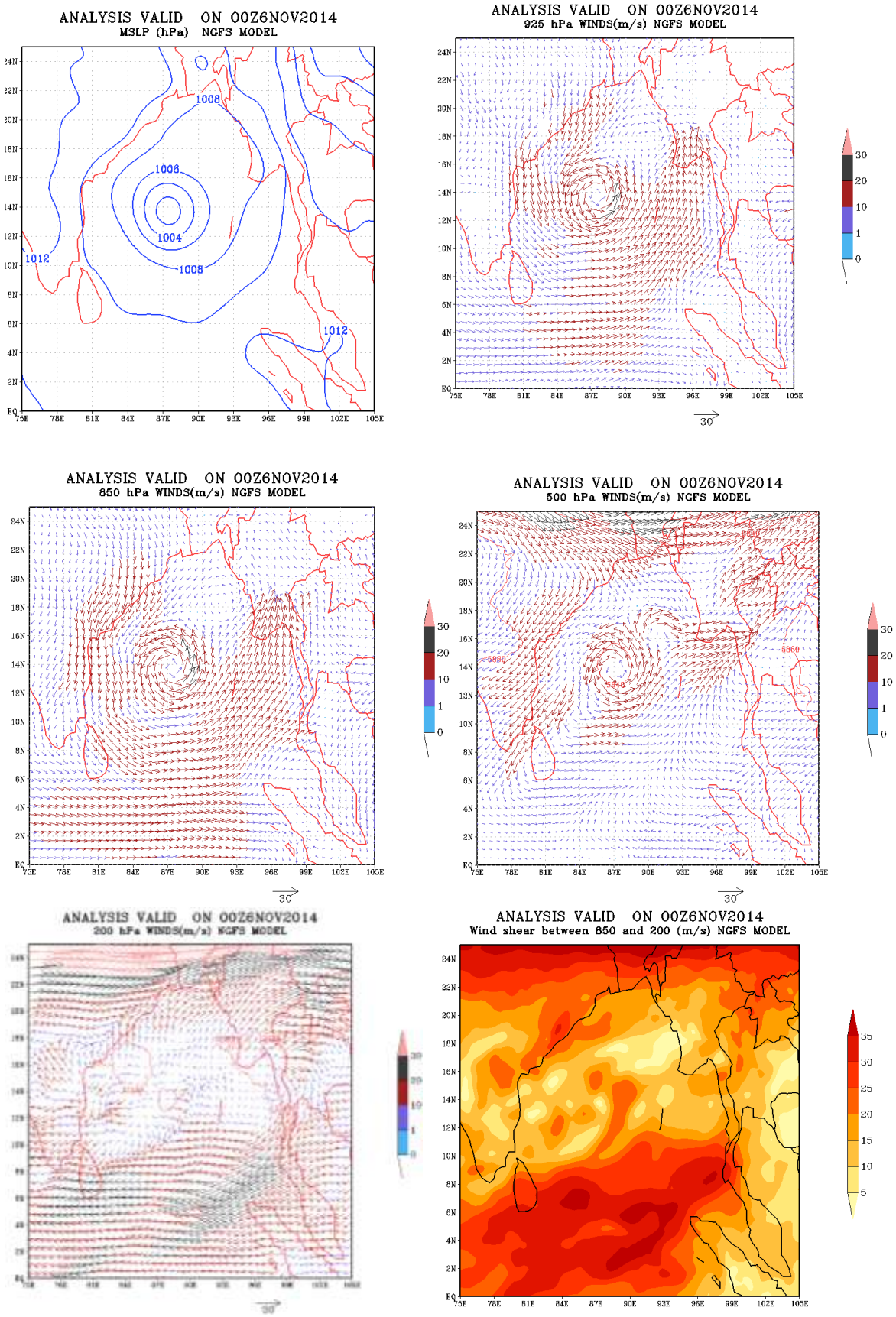
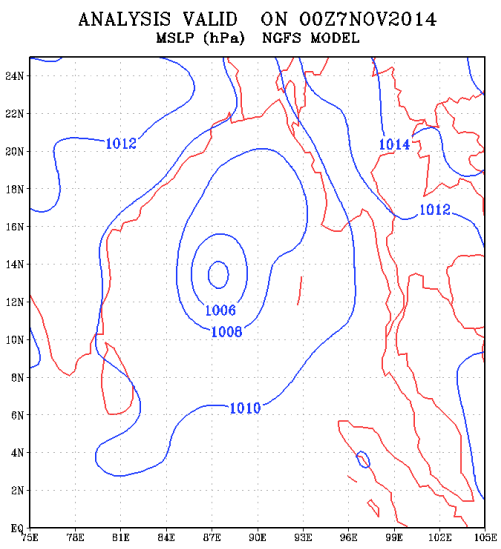
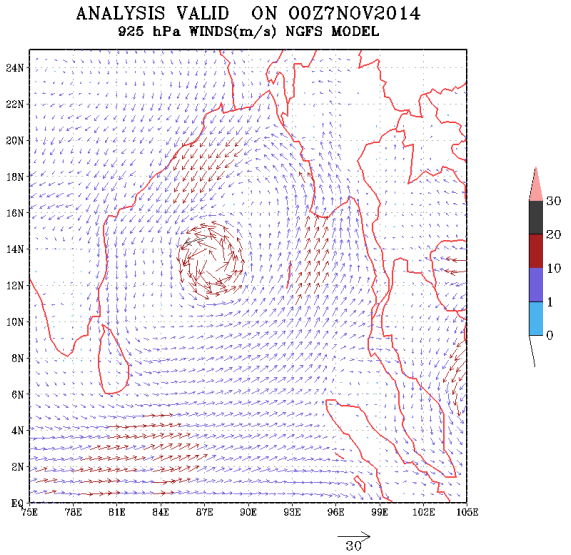
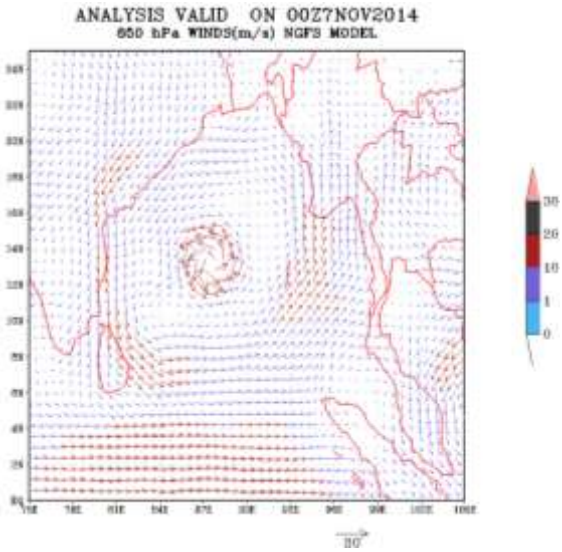
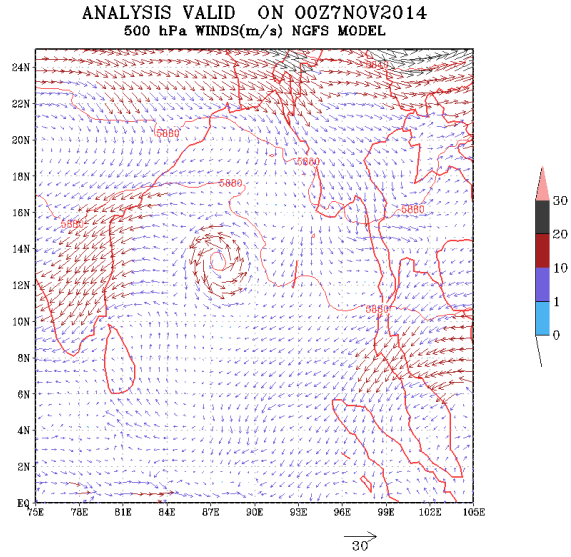


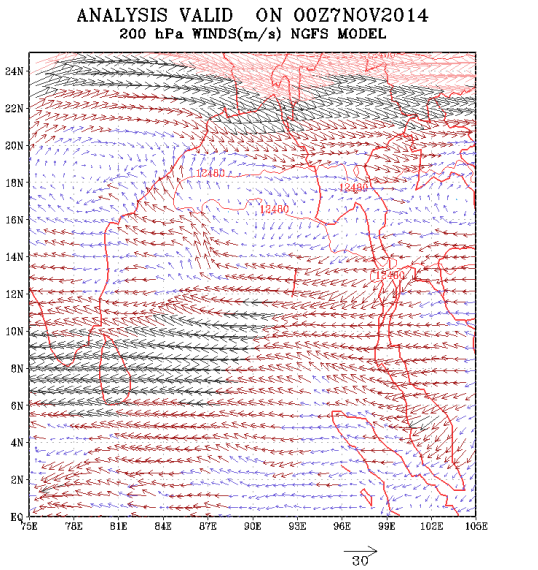
Fig.6b Same as Fig.6a, but based on 06th November 2014 / 0000 UTC











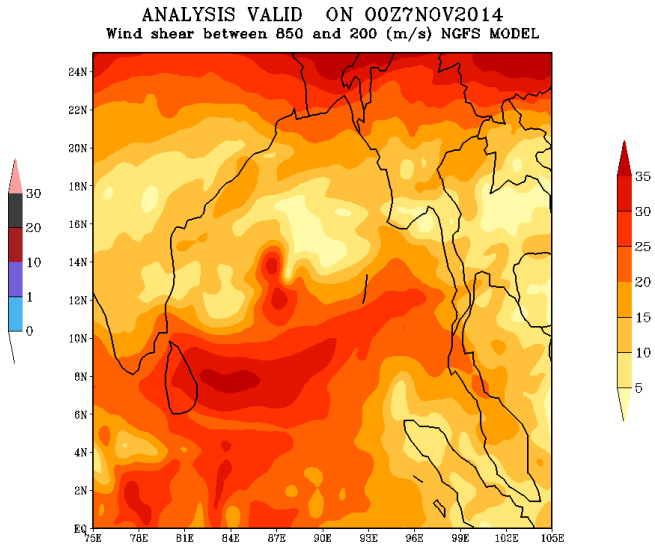


Fig.6c: Same as Fig.6a, but based on 07th November 2014 / 0000 UTC

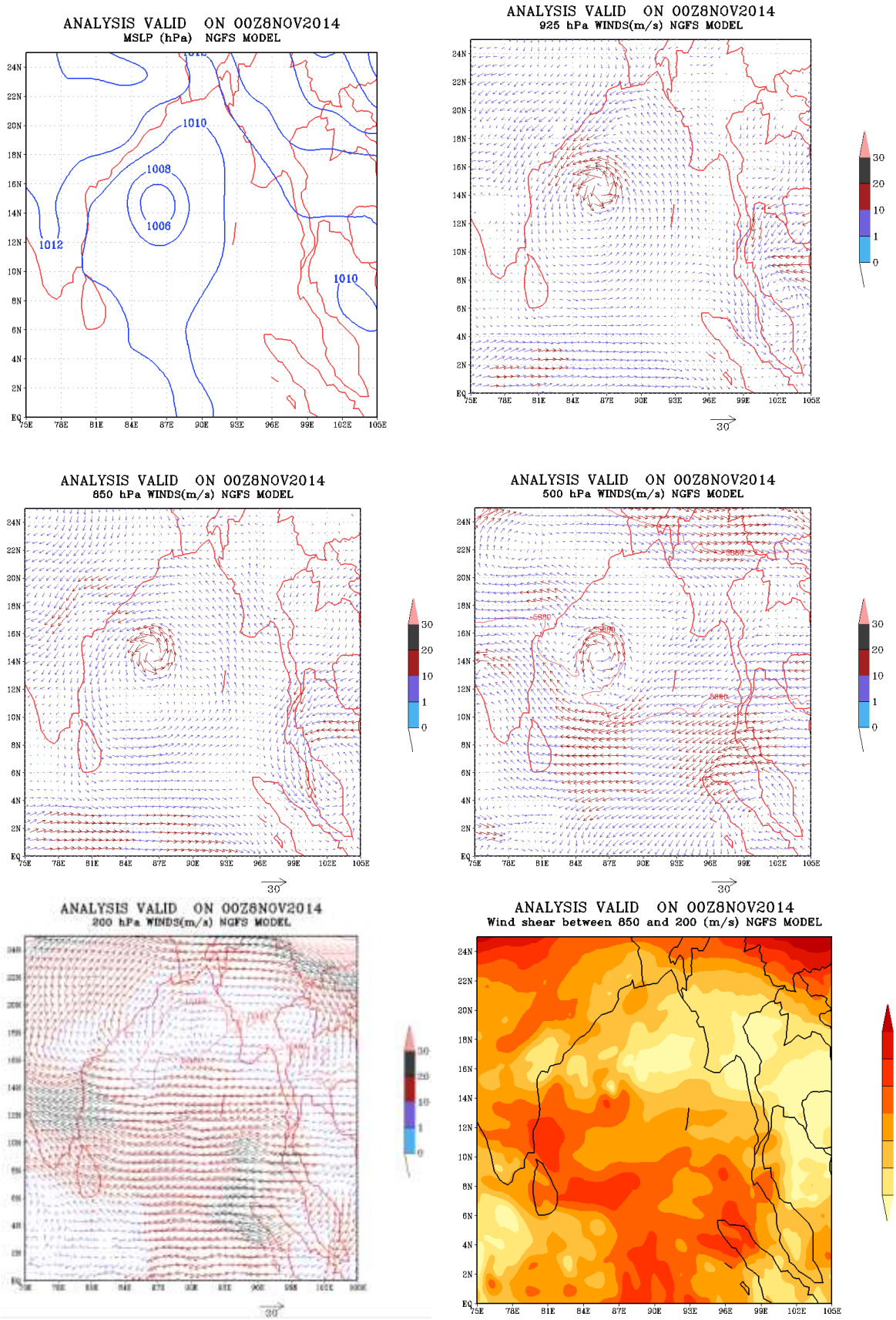


Fig.6d: Same as Fig.6a, but based on 08th November 2014 / 0000 UTC

7. Realised Weather:

7.1 Rainfall due to Deep Depression (05-08 November 2014)

Under the influence of the Deep Depression (05-08 November 2014), scattered light to moderate rainfall occurred over Andaman Islands during 04-06th and over Andhra Pradesh on 9th and 10th November. Chief rainfall amounts realised with the passage of the system are furnished below:

4 November 2014

ANDAMAN AND NICOBAR ISLANDS: Port Blair-4, Mayabandar–3, Nancowary-2, Hut Bay-2, Long Island–2, Car Nicobar-1

5 November 2014

ANDAMAN AND NICOBAR ISLANDS: Port Blair-4, Mayabandar–2, Hut Bay-2, Car Nicobar-2, Car Nicobar(IAF)-1

6 November 2014

ANDAMAN AND NICOBAR ISLANDS: Mayabandar–2, Port Blair-1

9 November 2014

ANDHRA PRADESH: Bapatla-2, Ongole-2, Kavali-2, Sriharikota-1.

10 November 2014

ANDHRA. PRADESH: Kakinada-3, Peddapuram(EastGodavari)-3, Yerragundapalem(Prakasam)-3, Makloor(Nizamabad)-3, Mahbubnagar-3, Aswaraopeta(Khammam)-3, Mulakalapalle(Khammam)-3, Makthal(Mahabubnagar)-3, Wanaparthy(Mahabubnagar)-3, NagarKurnool(Mahabubnagar)-2, Nizamabad-2, Maganoor(Mahabubnagar)-2, Bhadrachalam(Khammam)-2, Dharpalle(Nizamabad)-2, Suryapet(Nalgonda)-1, Nizamsagar(Nizamabad)-1, Kotgiri(Nizamabad)-1, Varni(Nizamabad)-1, Thimmajipetta(Mahabubnagar)-1, Yellareddy(Nizamabad)-1, Sangareddy(Medak)-1, Dichpalle(Nizamabad)-1, Nawabpet(Rangareddy)-1, Jakranpalle(Nizamabad)-1, Bikroor(Nizamabad)-1, Kamareddy(Nizamabad)-1, Miryalaguda(Nizamabad)-1, Bodhan(Nizamabad)-1, Aswapuram(Khammam)-1, Narayankhed(Medak)-1, Yeddapalle(Nizamabad)-1, Jadcherla(Mahabubnagar)-1.

Rainfall associated with the Deep Depression (05-08 November 2014) when it was out in the sea is determined from satellite-gauge merged rainfall dataset generated by IMD-NCMRWF for the North Indian Ocean region from 2013 onwards based on TRMM data. 24-hour accumulated rainfall associated with the system during the period 3-9 November 2014 as well as the 7-day average rainfall during the same period are furnished in **Fig. 7**.

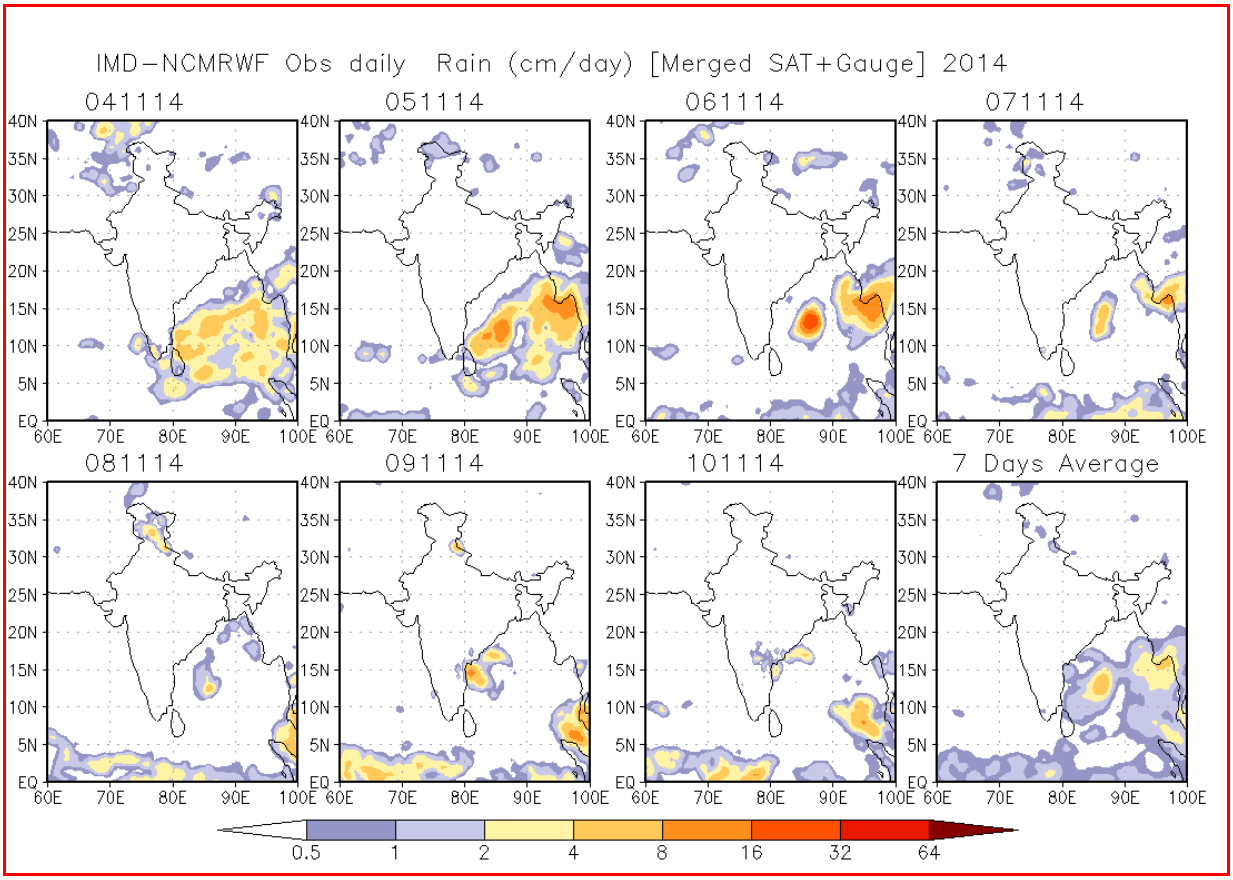


Fig.7 IMD-NCMRWF satellite-gauge merged daily rainfall (in cm) during the period 04-10 November 2014 and the 7-day average rainfall during the same period.

As can be seen, during the period 4th-5th November, when the system was in its formative phase, convection was widespread and disorganised. On 6th, convection organised around the centre. However, associated with the weakening of the system, rainfall activity reduced on 7th and light to moderate rainfall acitivity is seen in isolated / a few places over Andhra Pradesh on 9th and 10th (Description of spatial rainfall distribution: Isolated (one or two places): <25% of area gets rainfall; Scattered (A few places): 26-50% of area gets rainfall; Fairly Widespread (A many places): 51-75% of area gets rainfall; Widespread (Most places): 76-100% of area gets rainfall.
Description of rainfall intensity: Light: 2.5-7.5 mm; Moderate: 7.6-35.5 mm; Rather heavy: 35.6-64.4 mm; Heavy: 64.5-124.4 mm; Very Heavy: 124.5-244.4 mm).

7.2 Gale Wind

As the system weakened over the sea, no gale wind was reported. However, strong winds of 33 kmph was recorded by a coastal Automatic Weather Station (AWS) in Bapatla at 1230 IST of 9th. Kavali(AWS) and Darsi(AWS) recorded 22 kmph at 0930 IST and 1330 IST of 9th respectively.

7.3. Storm Surge

No storm surge has been reported due to weakening of the system over the sea.

7.4. Damage due to Deep Depression (05-08 November 2014)

No damage has been reported due to this system.

8. Performance of operational NWP models

8.1 IMD-NWP

8.1.1 Global Forecast System

The Global Forecast System (GFS), adopted from National Centre for Environmental Prediction (NCEP) was implemented at India Meteorological Department (IMD), New Delhi on IBM based High Power Computing Systems (HPCS) at T574L64 (~ 23 km in horizontal over the tropics) with Grid point Statistical Interpolation (GSI) scheme as the global data assimilation for the forecast up to 7 days. The model is run twice in a day (00 UTC and 12 UTC). The real-time outputs are made available to the national web site of IMD (http://www.imd.gov.in/section/nhac/dynamic/nwp/welcome.htm).

8.1.2 Regional Forecast System

IMD operationally runs three regional models WRFDA-WRFARW(v3.2), and HWRF for short-range prediction during cyclone condition.

8.1.3 Non-hydrostatic mesoscale modeling system WRFDA-WRF-ARW

The mesoscale forecast system Weather Research and Forecast WRFDA (version 3.2) with 3DVAR data assimilation is being operated daily twice to generate mesoscale analysis at 27 km and 9 km horizontal resolutions using IMD GFS-T574L64 analysis as first guess and forecasts as boundary condition. Using analysis and updated boundary conditions from the WRFDA, the WRF (ARW) is run for the forecast up to 3 days with double nested configuration with horizontal resolution of 27 km and 9 km and 38 Eta levels in the vertical. The model mother domain covers the area between lat. 25º S to 45º N long 40º E to 120º E and child covers whole India. The performance of the model is found to be reasonably skilful for cyclone genesis and track prediction. At ten other regional centres, very high resolution mesoscale models (WRF at 3 km resolution) are also operational with their respective regional setup/configurations. The latest version of NCEP HWRF is also implemented at IMD in 2012 for the Indian basins with the assimilation of local observations. The model has the provision for vortex re-location and moving nesting procedure.

8.1.4 Hurricane WRF Model (HWRF)

Recently under Indo-US joint collaborative program, IMD adapted Hurricane-WRF model for Tropical Cyclone track and intensity forecast for North Indian Ocean (NIO) region for its operational requirements. The basic version of the model HWRFV (3.2+) which was operational at EMC, NCEP, USA was ported on IMD IBM P-6/575 machine with nested domain of 27 km and 9 km horizontal resolution and 42 vertical levels with outer domain covering the area of 800x800 and inner domain 60x60 with centre of the system adjusted to the centre of the observed cyclonic storm. The outer domain covers most of the North Indian Ocean including the Arabian Sea and Bay of Bengal and the inner domain mainly covering the cyclonic vortex with moving along the movement of the system. The model has special features such as vortex initialization, coupled with Ocean model to take into account the changes in SST during the model integration, tracker and diagnostic software to provide the graphic and text information on track and intensity prediction for real-time operational requirement.

As part of model validation, case studies were undertaken to test the ability of the model for the Cyclonic storms formed during the year 2010 and model forecasts are produced upto 5 days during the 2011 cyclone season as an experimental forecast in real-time. In these runs only the atmospheric model (HWRF) was tested. The Ocean Model (POM-TC) and Ocean coupler requires the customization of Ocean Model for Indian Seas. In this regards, IMD is expecting to work in collaboration with INCOIS, Hyderabad which is running the Ocean Models (POM)/Hybrid co-ordinate ocean model (HYCOM) to support in porting the Ocean Model with Indian Ocean climatology and real time data of SST over Indian Seas. The model is run on real time twice a day (started from cyclone season 2012) based on 00 UTC and 12 UTC initial conditions to provide 6 hourly track and intensity forecasts valid up to 72 hours. The model uses IMD GFS-T574L64 analysis/forecast as first guess.

8.1.5 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.

8.1.5.1 Genesis Potential Parameter (GPP)

A cyclone genesis parameter, termed the genesis potential parameter (GPP), for the North Indian Sea is developed (Kotal et al, 2009). The parameter is defined as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability, and the inverse of vertical wind shear. The parameter is operationally used for distinction between non-developing and developing systems at their early development stages. The composite GPP value is found to be around three to five times greater for developing systems than for non-developing systems. The analysis of the parameter at early development stage of a cyclonic storm found to provide a useful predictive signal for intensification of the system.

The grid point analysis and forecast of the genesis parameter up to seven days is also generated on real time (available at http://www.imd.gov.in/section/nhac/dynamic/Analysis.htm). Higher value of the GPP over a region indicates higher potential of genesis over the region. Region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis. The analysis of the parameter and its effectiveness during cyclonic disturbances in 2012 affirm its usefulness as a predictive signal (4-5 days in advance) for cyclogenesis over the North Indian Ocean.

8.1.5.2 Multi-model ensemble (MME) technique

The multi model ensemble (MME) technique (Kotal and Roy Bhowmik, 2011) is based on a statistical linear regression approach. The predictors selected for the ensemble technique are forecasts latitude and longitude positions at 12-hour interval up to 72-hour of five operational NWP models. In the MME method, forecast latitude and longitude position of the member models are linearly regressed against the observed (track) latitude and longitude position for each forecast time at 12-hours intervals for the forecast up to 72-hour. The outputs at 12 hours forecast intervals of these models are first post-processed using GRIB decoder. The 12 hourly predicted cyclone tracks are then

determined from the respective mean sea level pressure fields using a cyclone tracking software. Multiple linear regression technique is used to generate weights (regression coefficients) for each model for each forecast hour (12hr, 24hr, 36 hr, 48hr, 60hr, 72hr) based on the past data. These coefficients are then used as weights for the ensemble forecasts. 12-hourly forecast latitude (LAT^f) and longitude (LON^f) positions are defined by multiple linear regression technique. In the updated version, MM5 model in the ensemble member is replaced by IMD WRF model and also included IMD GFS T574L64. 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), UKMO etc. A collective bias correction is applied in the MME by applying multiple linear regression based minimization principle for the member models GFS(IMD), GFS(NCEP), ECMWF, UKMO and JMA. ECMWF data are available at 24h intervals. Therefore, 12h, 36h, 60h, 84h, 108h forecast positions are computed based on linear interpolation. All these NWP products are routinely made available in real time on the IMD web site www.imd.gov.in.

8.1.5.3 Statistical Dynamical model for Cyclone Intensity Prediction (SCIP)

A statistical-dynamical model (SCIP) (Kotal et al, 2008) has been implemented for real time forecasting of 12 hourly intensity up to 72 hours. The model parameters are derived based on model analysis fields of past cyclones. The parameters selected as predictors are: Initial storm intensity, Intensity changes during past 12 hours, Storm motion speed, Initial storm latitude position, Vertical wind shear averaged along the storm track, Vorticity at 850 hPa, Divergence at 200 hPa and Sea Surface Temperature (SST). For the real-time forecasting, model parameters are derived based on the forecast fields of IMD-GFS model. The method is found to be provided useful guidance for the operational cyclone forecasting.

8.1.5.4 Rapid Intensification (RI) Index

A rapid intensification index (RII) is developed for tropical cyclones over the Bay of Bengal (Kotal and Roy Bhowmik, 2013). The RII uses large-scale characteristics of tropical cyclones to estimate the probability of rapid intensification (RI) over the subsequent 24-h. The RI is defined as an increase of intensity 30 kt (15.4 ms^{-1}) during 24-h. The RII technique is developed by combining threshold (index) values of the eight variables for which statistically significant differences are found between the RI and non-RI cases. The variables are: Storm latitude position, previous 12-h intensity change, initial storm intensity, vorticity at 850 hPa, divergence at 200 hPa, vertical wind shear, lower tropospheric relative humidity, and storm motion speed. The probability of RI is found to be increases from 0% to 100% when the total number of indices satisfied increases from zero to eight. The forecasts are made available in real time from 2013.

8.1.5.5 Decay of Intensity after the landfall

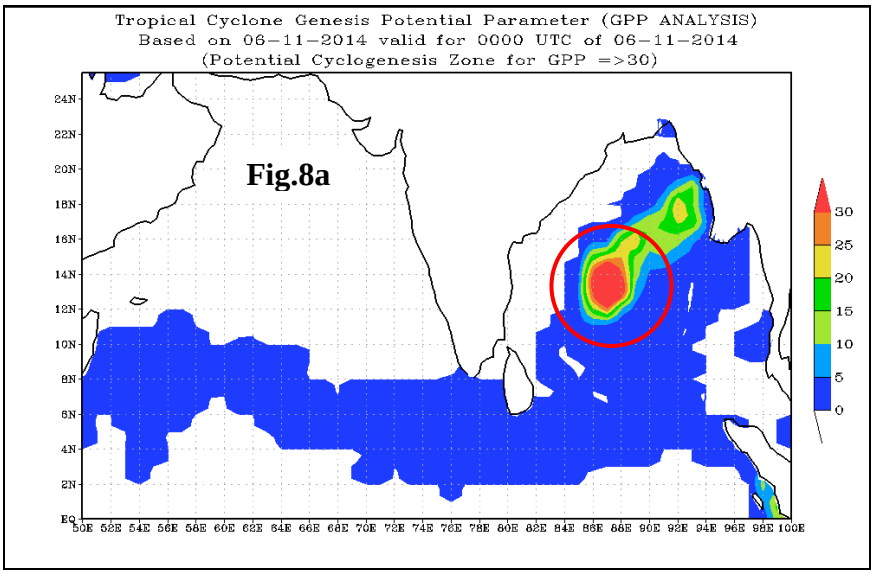
Tropical cyclones (TCs) are well known for their destructive potential and impact on human activities. The Super cyclone Orissa (1999) illustrated the need for the accurate prediction of inland effects of tropical cyclones. The super cyclone of Orissa maintained the intensity of cyclonic storm for about 30 hours after landfall. Because a dense population resides at or near the Indian coasts, the decay forecast has direct relevance to daily activities over a coastal zone (such as transportation, tourism, fishing, etc.) apart from disaster management. In view of this, the decay model (Roy Bhowmik et al. 2005) has been used for real time forecasting of decaying intensity (after landfall) of TCs.

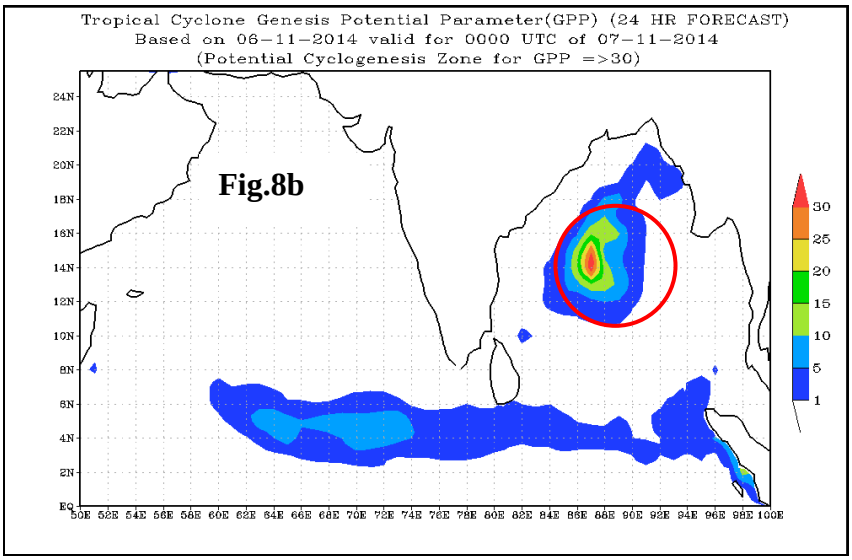
8.1.6 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for Deep Depression during (5-8) November 2014

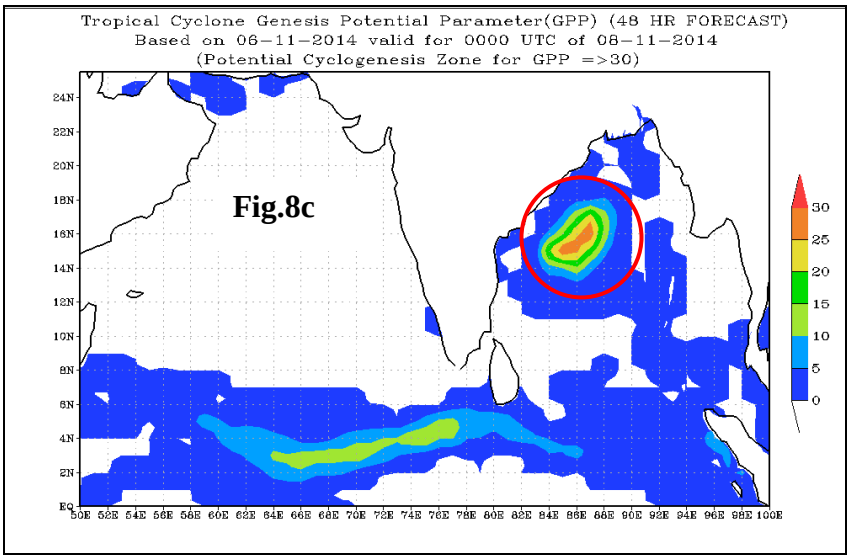
a. Grid point analysis and forecast of GPP

Objective: Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis.

Figure 8(a-d) below shows the predicted zone of formation of cyclogenesis.







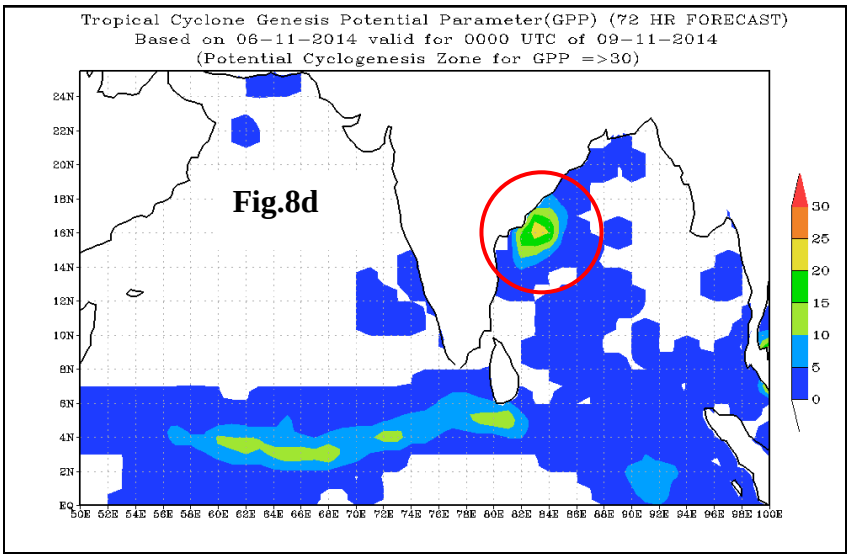


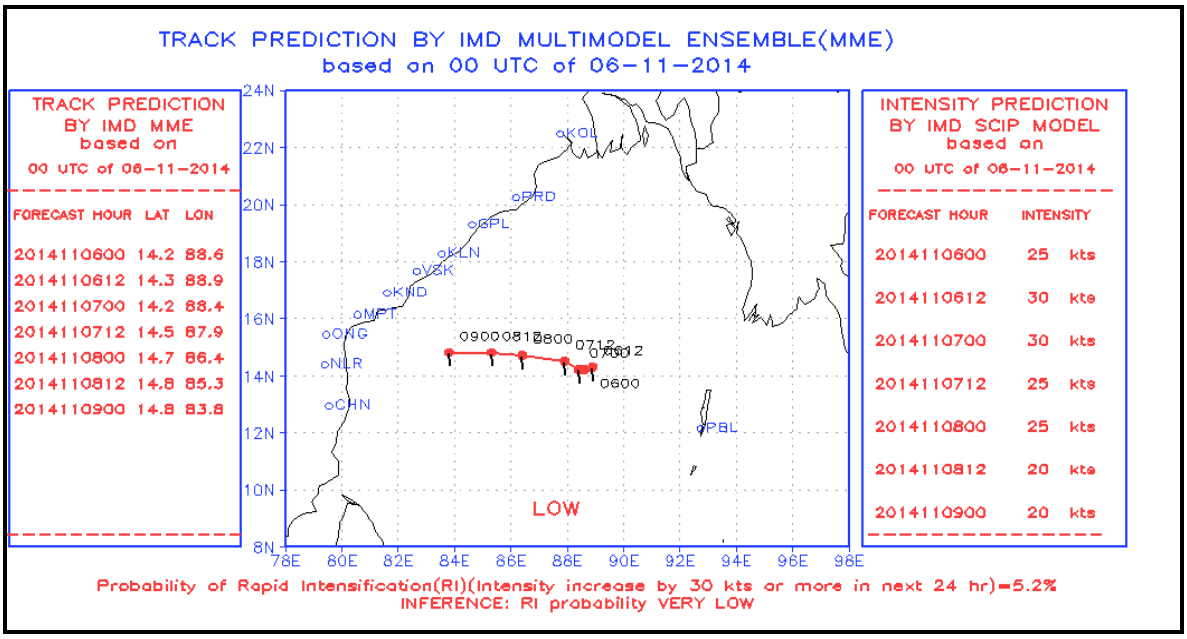
Figure 8(a-d): Predicted zone of cyclogenesis.

Inference: Grid point analysis and forecasts of GPP [Fig.1(a-d)] shows that it could able to predict the non-intensification and location of the system before 72 hours.

(Product available athttp://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

8.1.7 Consensus track prediction by MME and Intensity forecast by SCIP model

MME track forecast based on 0000 UTC of 6 November, 1200 UTC of 6 November 2014 and 0000 UTC of 7 November 2014 (Fig.9) suggested westward movement. Analysis of SCIP intensity forecast and various thermodynamical parameters of Genesis Potential Parameter (GPP) suggested decay of the system over the Sea. The average track and intensity forecast errors are presented in Tables 2 and 3.



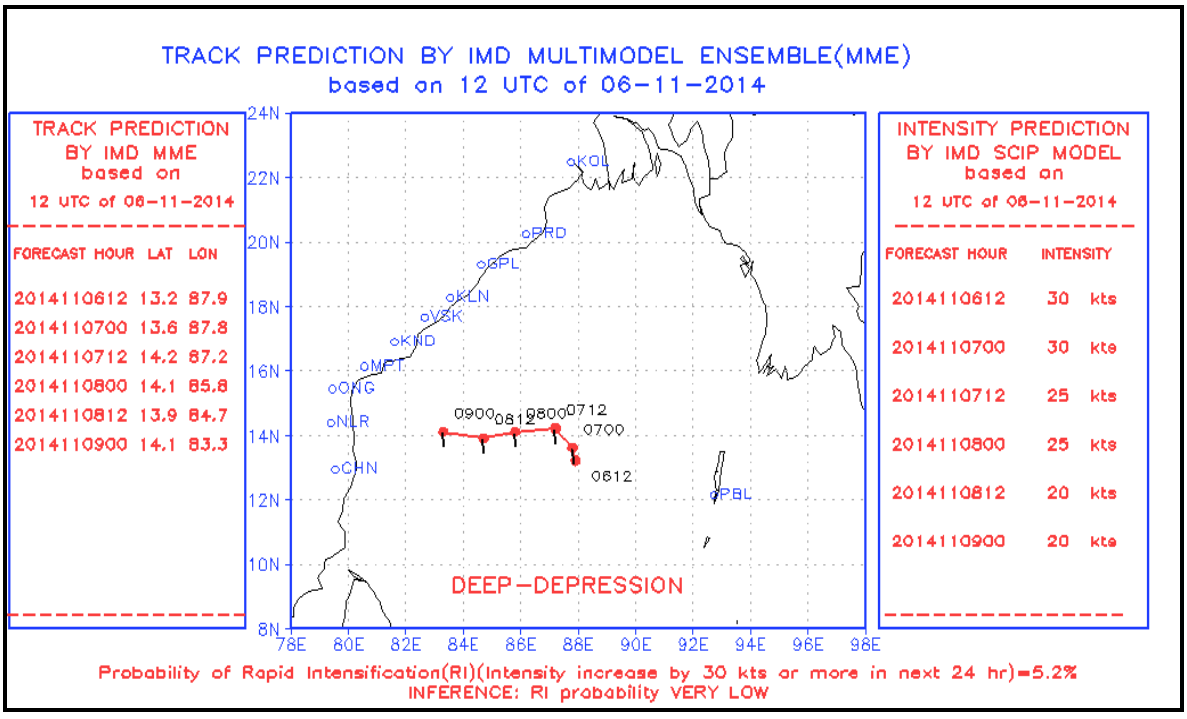


Fig. 9: Consensus track prediction by MME and Intensity forecast by SCIP model

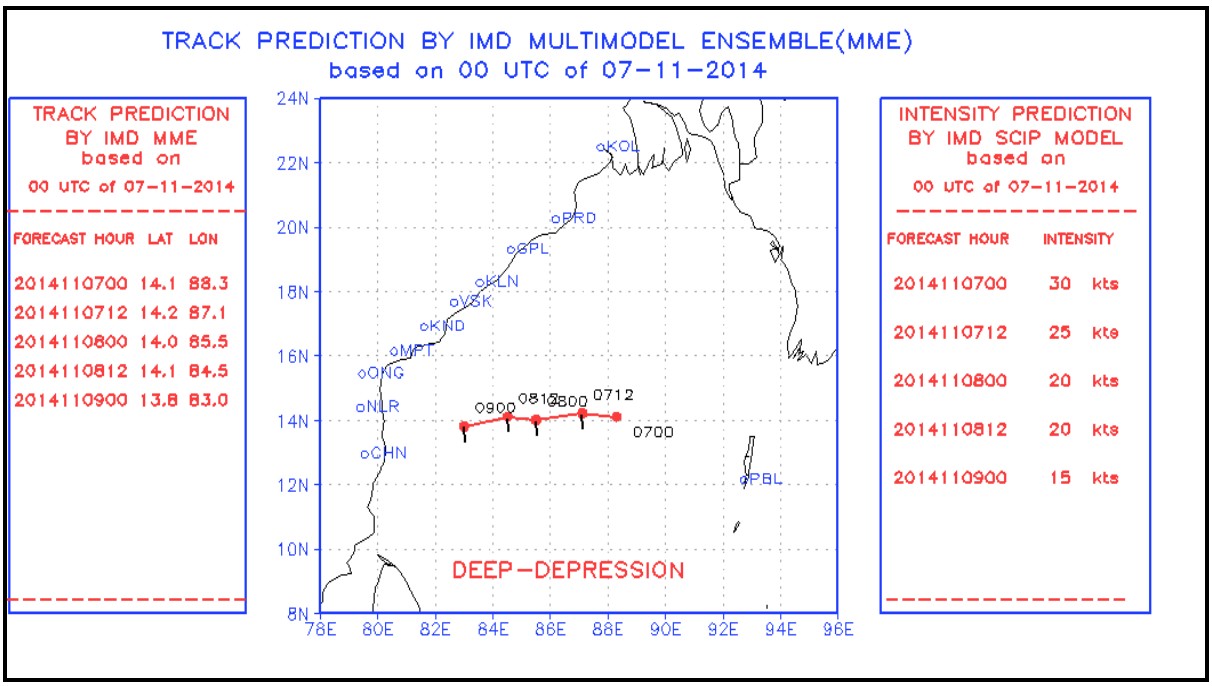


Fig. 9: (contd.)

Table 2. Average track forecast errors (Direct Position Error) in km (Number of forecasts verified is given in parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-GFS	55 (1)	77 (1)	217 (1)	271 (1)
JMA	209 (1)	325 (1)	207 (1)	77 (1)
NCEP-GFS	41 (3)	84 (3)	99 (2)	95 (1)
UKMO	102 (3)	111 (2)	93 (2)	161 (1)
ECMWF	109 (3)	128 (3)	99 (2)	104 (1)
IMD-MME	66 (3)	82 (3)	67 (2)	46 (1)

8.1.8 Intensity (kt) prediction by SCIP Model

Table 3. Average absolute errors (AAE) and Root Mean Square (RMSE) errors of SCIP model (Number of forecasts verified is given in parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr
AAE (kts)	0.0(3)	3.3(3)	0.0(2)	0.0(1)
RMSE (kts)	0.0	4.1	0.0	0.0

8.2 NCMRWF forecast verification

Verification of the NCMRWF model forecasts during the Deep Depression in the Bay of Bengal (6^{th} to 8^{th} November 2014) is furnished below. Verification of forecast tracks and landfall position are presented for NGFS (T574L64), NCMRWF Unified Model (NCUM) and NGEFS (T190L28; 20-member ensemble prediction system) and NGEFS_BC which is the bias corrected version of NGEFS. In addition to cyclone tracks NGEFS members are used to estimate cyclone strike probability based on the 20 members. Forecast tracks and verification is presented for all the models is presented. The forecasts based on the above mentioned models are provided to IMD in real time.

8.2.1 Forecast tracks based on NGFS, NCUM and NGEFS

Figure 10(a-c) shows the IMD's best track and forecast tracks from NGFS, NGEFS raw and bias corrected mean as well as NCUM based on 6^{th} to 8^{th} November 2014 initial conditions (IC) (NCUM is not available for 8^{th} Nov IC). Based on 6^{th} and 7^{th} IC (Figures 10(a) and (b)) it can be seen that NCUM is much farther away from the observed track as compared to NGFS and NGEFS. NGEFS both raw and bias corrected are closer to the observed track as compared to NGFS on all the three days.

8.2.2 Forecast track errors

Figures 11-13 show the along track, cross track and direct position errors for DD based on 6^{th} to 8^{th} Nov initial conditions from NGFS, NGEFS, NGEFS bias corrected and NCUM models. Forecast track errors are computed based on the IMD best track data from 00UTC of 6^{th} to 8^{th} November 2014. From Figure 11 which shows the along track error it is observed that the forecast tracks from all the models are moving faster than the observations (because of the positive values of the ATE). Also, till 30 hour forecast NGFS has the least ATE and NCUM has the maximum ATE. However from 36 to 48 hour forecast NCUM shows the least ATE followed by NGFS. From Figure 12 which shows the cross track error it is seen that for NCUM the CTE values are always positive, this implies that the forecast track is always to the right of the observed track. However, for NGFS and both the versions of NGEFS the CTE values are negative at all times implying that the forecast track is always to the left of the observed track. Also, NGEFS_BC shows the least CTE till 30 hour forecast. However, from 36 to 48 hour forecast NGFS shows the least CTE values. From Figure 13 it is observed that NGFS has the least DPE followed by NGEFS_BC till 36 hours and NCUM shows the highest DPE. From 36 to 48 hour forecast NCUM shows the least DPE.

8.2.3 Based on the above, performance of NCMRWF models in forecasting the Deep Depression (05-08 November 2014) is summarised as follows:

For the DD 05-08 November 2014, the forecast tracks were available from NGFS, NCUM and NGEFS. Additionally the forecast tracks from NGEFS_BC (bias corrected) are also evaluated. Salient points on the performance of these models in predicting the tracks for the system are:

1. From the ATE values it is seen that NGFS has the least along track error out of all the models. NGEFS raw on the other hand shows the highest ATE values.
2. NCUM predicted track always lie to the right of the observed track (positive CTE). The forecast tracks obtained from NGFS and NGEFS all are to the left of the observations as seen from the negative CTE values at all lead times.
3. NCUM has the highest direct position error till 36 hour forecast and NGFS has the least DPE for almost all forecast lead times.
4. Bias corrected NGEFS shows better performance than its raw version as indicated by lower errors at all lead times.

Table 4. Average Track Forecast Errors in km

	00hr	24hr	48hr
NGFS	**74.3**	**73.6**	**249.2**
NGEFS	**43.6**	**125.1**	**360.1**
NGEFS_BC	**46.5**	**89.2**	**271.9**
NCUM	**53.1**	**238.1**	**237.7**
No of Cases	*3*	*2*	*1*

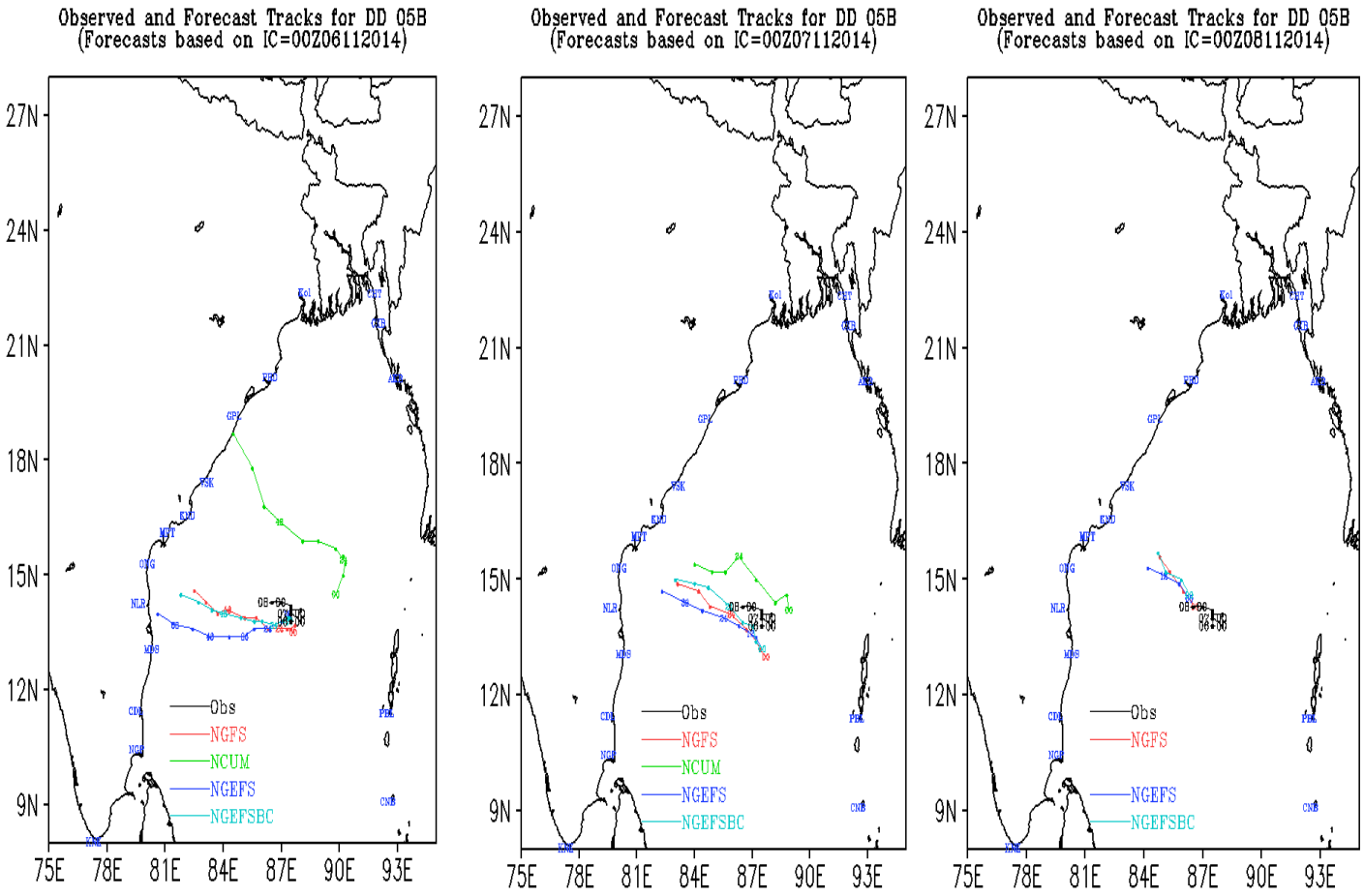


Fig.10 Forecast tracks of NGFS, NGEFS raw and bias corrected mean as well as NCUM based on 6th to 8th November 2014 initial conditions (NCUM is not available for 8th Nov IC) alongwith the IMD's best track

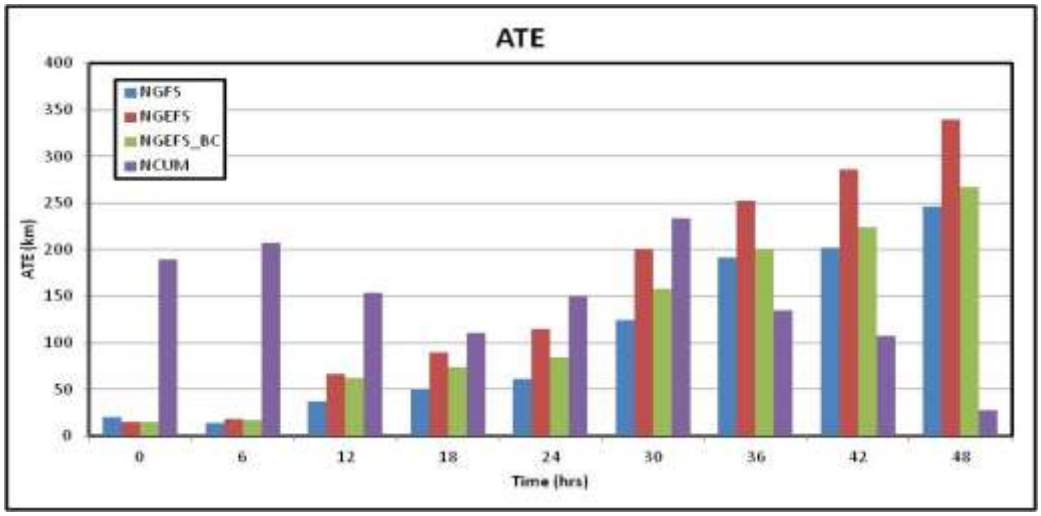


Fig.11 Along track errors (ATE) for NGFS, NGEFS, NGEFS_BC and NCUM models based on 6-8th November 2014 initial conditions

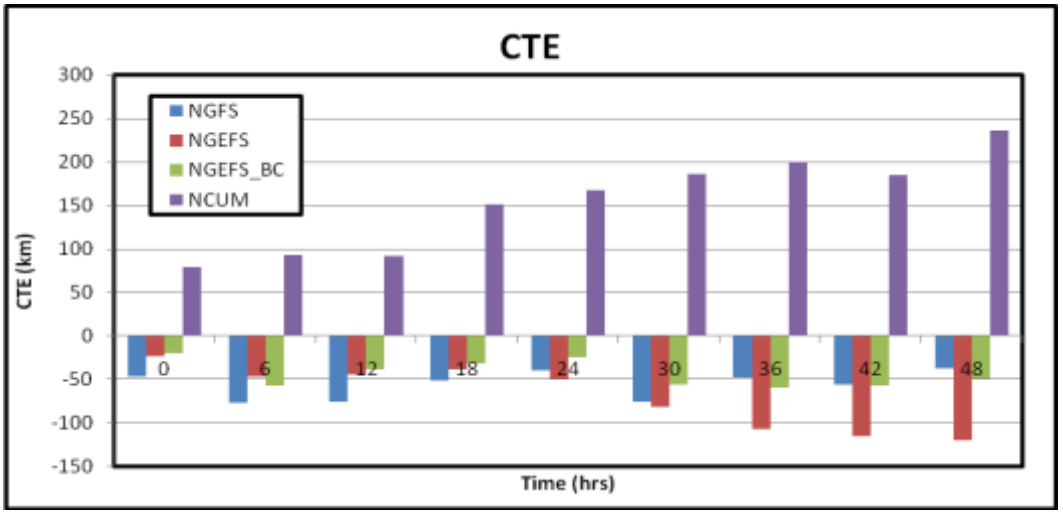


Fig.12 Along track errors (CTE) for NGFS, NGEFS, NGEFS_BC and NCUM models based on 6-8th November 2014 initial conditions

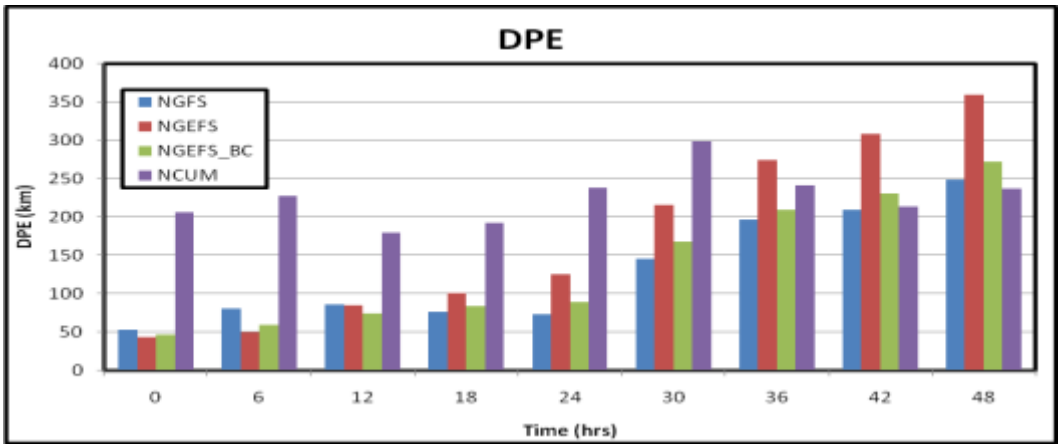


Fig.13 Direct position errors (DPE) for NGFS, NGEFS, NGEFS_BC and NCUM models based on 6-8th November 2014 initial conditions

9. Bulletins issued by IMD

Bulletins issued by Cyclone Warning Division, New Delhi

IMD continuously monitored, predicted and issued bulletins containing track & intensity forecast at +06, +12, +18, +24, +36, +48, +60 and +72, 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 and ≥34 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 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. Tropical cyclone vitals were prepared every six hourly from deep depression stage onwards and sent to NWP modeling groups in India for bogusing purpose.

Bulletins issued by Cyclone Warning services of IMD in association with Deep depression (05-08 November 2014) are given in Tables 5-8.

Table 5. Bulletins issued by Cyclone Warning Division, New Delhi

Bulletins issued by Cyclone Warning Division, New Delhi in association with Deep Depression over Bay of Bengal during the period 05-08 November 2014			
S.No.	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	15	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, Tamilnadu, Met. Office Visakhapatnam, BhuBaneshwar 3. Email's to a. Modelling Groups- IIT-Delhi, IIT-Bhubaneswar, NCMRWF, INCOIS. b. Chief Secretary-Govt. of Andhra Pradesh, Puducherry, Andaman & Nicobar Islands, West Bengal, Odisha,
2	RSMC Bulletin	12	1. IMD's website 2. All WMO/ESCAP member countries through GTS and E-mail. 3. Indian Navy, IAF, by E-mail
3	Personal Briefings At National level		Cabinet Secretary Chief Secy. Andhra Pradesh Special Relief Commissioner / Commissioner for Disaster Management, Andhra Pradesh,

			Odisha. MHA, NDMA for Disaster Management, Central Water Commission etc. Press, Electronic Media & Public.
4	Personal Briefings At State level		Chief Commissioners, Chief Secretary, State Relief Commissioner, Chief Disaster Management , District Collectors of Andhra Pradesh, Odisha
5	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	05	1. IMD's website 2. Meteorological Watch Office for International Civil Aviation
6	ADRR Bulletin to Hong Kong website	05	(Through ftp) to ADRR HongKong
7	TC vitals For creation of synthetic vortex in NWP Models	05	(Through ftp) To: modelling group-NCMRWF, IIT, INCOIS, IMD NWP (Through E-mail).To: NCMRWF, IIT, INCOIS, IMD NWP
8	Quadrant Wind radii forecast	05	E-mail to modelling group- NCMRWF, IIT, INCOIS, IMD NWP.
9	SMS to Senior Govt. Officials	02	1. Disaster Management Officers, at National level. 2. Chief Secretary, Relief Commissioner / Revenue Secretary/ Commissioner of Disaster Management, Andhra Pradesh and Odisha.

Table 6. Bulletins issued by Area Cyclone Warning Centre, Chennai

S.No	Type of Bulletin	Number
1.	Port Warnings	06
2.	Fishermen Warnings	16
3.	Coastal Weather Bulletin	08
4.	Special Weather Bulletin issued to State Government officials (Commissioner of Revenue Administration (CRA), PWD, Chief Secretary)	10
5.	Sea Area Bulletin	08
6.	Bulletins to Indian Navy	08
7.	CWDS Bulletins	04
8.	All India Radio / Doordarshan Bulletins	08
9.	Gale / Strong Wind Warnings	08
10.	Personal briefings at state level (to Electronic media, press, CRA, Chief secretaries, other Government Officials and Mayor)	Daily briefing

Table 7. Bulletins issued by Cyclone Warning Centre Visakhapatnam:

	Type of Bulletin	**Number**
1.	Port Warnings	5
2.	Fishermen Warnings	20
3.	Coastal Weather Bulletin	18

Table 8. Bulletins issued by Meteorological Centre Bhubaneswar:

S.No	**Type of Bulletin**	**Number**
11.	Port Warnings	05
12.	Fishermen Warnings	08
13.	Cyclone informatory messages	08
14.	All India Radio Bulletins	08
15.	Press Bulletin	08
16.	Heavy Rainfall Warning	Nil

9. Operational Forecast Performance

The salient features of the bulletins issued by IMD are furnished in Table 9.

Table 9. Salient features of the bulletins issued by IMD

Date and Time	Current Status	Forecast issued
05.11.2014 (1430 IST)	Depression over central & adjoining southeast Bay of Bengal	It would move northwestwards initially and intensify into a deep depression during next 24 hrs.
06.11.2014 (0830 IST)	Deep Depression over central Bay of Bengal	It would move northwestwards and intensify further into a Cyclonic Storm during next 24 hrs. It would then move west-northwestwards towards Andhra Pradesh coast. It would weaken gradually into a depression while reaching near the coast on 8th Nov. 2014, night.
07.11.2014 (0830 IST)	Deep Depression over central Bay of Bengal	It would move westwards towards Andhra Pradesh coast. It would weaken into a Depression during next 6 hours and into a well marked low pressure area subsequently while reaching near the coast on 9th Nov. 2014, morning.
07.11.2014 (1130 IST)	Depression over central Bay of Bengal	It would move westwards towards Andhra Pradesh coast and weaken into a well marked low pressure area during next 48 hours.

9.1 Operational landfall forecast error

The system was expected to start weakening over sea and cross Andhra Pradesh on 8th night / 9th morning. The system weakened over the sea and reached Andhra Pradesh coast as a well-marked low pressure area.

9.2. Operational track and intensity forecast error and skill

The operational average track forecast errors and skill are shown in Table 10. The 12hr forecast error (skill) is greater (less) than the long period average error (skill) which is due to the errors in the initial position when the system executed a looping movement. Operational intensity forecast errors, forecast errors based on persistence and forecast skill based on persistence forecast are furnished in Tables 11(a-c). The 12hr intensity forecast error is greater than the persistence forecast error and hence the 12hr intensity forecast skill is negative.

Table 10. Operational average track forecast errors and skill

Lead Period (hrs)	**Track forecast error (km) (Official)**	**Long period Average error (km) (2009-13)**	**Forecast skill (%)**	**Long period Average skill (%) (2009-13)**
12	109.3 (4)	68.5	19.9	31.2
24	123.8 (4)	124.1	48.3	35.9
36	121.2 (2)	163.8	72.6	43.9

( ) : Number of six hourly forecasts verified. Due to short life period, forecast could not be verified beyond 36 hrs. The long period average error and skill are applicable to cyclone cases only.

Table 11a. Operational Intensity forecast errors

Lead period (hrs)	Absolute Error (knots)	Root mean square (RMS) Error (knots)	Long period Average (2009-2013):	
			Absolute Error (knots)	RMS Error (knots)
12	8.3 (4)	8.7 (4)	10.4	14.0
24	9.4 (4)	10.2 (4)	15.7	20.5
36	8.7 (2)	8.9 (2)	20.5	25.2

( ) : Number of six hourly forecasts verified. Due to short life period, forecast could not be verified beyond 36 hrs

Table 11b. Intensity forecast errors based on persistence

Lead period (hrs)	**Absolute Error (knots)**	**RMS Error (knots)**	**Long period Average (2009-2013):Absolute Error (knots)**	**Long period Average (2009-2013): RMS Error (knots)**
12	5(6)	5(6)	10.4	14.0
24	10(4)	11.2(4)	15.7	20.5
36	20(2)	20(2)	20.5	25.2

( ) : Number of six hourly forecasts verified. Due to short life period, forecast could not be verified beyond 36 hrs

Table 11c. Operational Intensity Forecast skill (%)

Lead period (hrs)	Skill (%) with reference to persistence forecast		Long period average Skill (%) based on 2009-2013	
	Absolute Error	RMS error	Absolute Error	RMS Error
12	-66	-74	10.4	14.0
24	6	9	15.7	20.5
36	57	56	20.5	25.2

Due to short life period, forecast could not be verified beyond 36 hrs

9.3 Adverse weather forecast verification

Associated with the coastal crossing and passage of the system as a low pressure area over Andhra Pradesh light to moderate rainfall of the order of 1-3 cm/day occurred over a few / many places of Andhra Pradesh on 09th and 10th November 2014. Maximum wind speed of 33 kmph was recorded by the Automatic Weather Station at Bapatla on 09th/1230 IST. The adverse weather warning verification is presented in Tables 12-14.

Table 12. Gale wind forecast verification for Deep Depression (05-08 Nov, 2014)

Date/ Time (IST)	**Gale wind Forecast**	**Recorded wind**
05.11.14/ 1430	**Andaman and Nicobar Islands:** Squally wind speed reaching 45-55 kmph gusting to 65 kmph will prevail in and around Andaman Islands during next 48 hours.	**09 November 2014:** Bapatla: 33 kmph Kavali, Darsi: 22 kmph **10 November 2014:** Tandur: 22 kmph Darsi: 20 kmph
06.11.14/ 0530	**Andaman and Nicobar Islands:** Squally wind speed reaching 40-50 kmph gusting to 60 kmph will prevail in and around Andaman Islands during next 24 hours.	
06.11.14/ 0830	**Andaman and Nicobar Islands; North Andhra Pradesh and Odisha coasts:** Squally wind speed reaching 35-45 kmph gusting to 55 kmph would prevail in and around Andaman Islands during next 24 hours and along and off north Andhra Pradesh and south Odisha coast on 8th and 9th Nov 2014.	
06.11.14/ 1130	**Andaman and Nicobar Islands; Andhra Pradesh:** Squally wind speed reaching 35-45 kmph gusting to 55 kmph would prevail in and around Andaman Islands during next 24 hours and along and off Andhra Pradesh coast on 8th and 9th Nov 2014.	
07.11.14/ 0830	**Andhra Pradesh and North Tamil Nadu:** Squally wind speed reaching 30-40 kmph gusting to 50 kmph would prevail along and off Andhra Pradesh and north Tamilnadu coast on 8th and 9th Nov. 2014.	
08.11.14/ 0830	**Andhra Pradesh:** Squally wind speed reaching 30-40 kmph gusting to 50 kmph would prevail along and off Andhra Pradesh coast during next 24 hours.	

Table 13. Rainfall forecast verification for Deep Depression (05-08 November 2014)

Date/ Time(IST)	Forecast Rainfall	Observed Rainfall (cm)
05.11.2014 / 1430	Rainfall at most places with isolated heavy to very heavy falls over Andaman & Nicobar Islands during the next 48 hours.	05 November 2014: Andaman & Nocobar Islands: Moderate rainfall over many places. 06 November 2014: Andaman & Nocobar Islands: Moderate rainfall over a few places. 09 November 2014: Andhra Pradesh: Light to moderate rainfall over a few places. 10 November 2014: Andhra Pradesh: Light to moderate rainfall over many places.
06.11.2014 / 0530	Rainfall at many places with isolated heavy to very heavy falls over Andaman during the next 24 hours. Moderate rainfall at many places over districts of north Andhra Pradesh and coastal Odisha on 8th & 9th November, 2014.	
06.11.2014 / 0830	Moderate rainfall at many places over districts of north Andhra Pradesh and coastal Odisha on 8th & 9th November, 2014.	
07.11.2014 / 0830	Light to moderate rainfall at a few places on 8th and at many places on 9th November, 2014 over Andhra Pradesh and adjoining north coastal Tamil Nadu.	
08.11.2014 / 0530	Light to moderate rainfall at a few places on 8th and at many places on 9th November, 2014 over Andhra Pradesh.	
08.11.2014 / 0830	Light to moderate rainfall at a few places during next 24 hours and at many places during the subsequent 24 hours over Andhra Pradesh.	

Description of spatial rainfall distribution: Isolated (one or two places): <25% of area gets rainfall; Scattered (A few places): 26-50% of area gets rainfall; Fairly Widespread (A many places): 51-75% of area gets rainfall; Widespread (Most places): 76-100% of area gets rainfall.
Description of rainfall intensity: Light: 2.5-7.5 mm; Moderate: 7.6-35.5 mm; Rather heavy: 35.6-64.4 mm; Heavy: 64.5-124.4 mm; Very Heavy: 124.5-244.4 mm;

Table 14. Verification of storm surge prediction for Deep Depression (05-08 Nov, 2014)

Forecast Storm surge above astronomical tide and area to be affected	Actual Storm Surge
No storm surge was forecast	No storm surge reported

10. Conclusions

The Deep Depression over the Bay of Bengal (05-08 November, 2014) made a looping track and weakened over the sea itself. During the genesis of the system, it was predicted that it would intensify only upto a stage of a marginal cyclonic storm. Subsequently, it was forecast that the system would weaken after attaining the intensity of a deep depression. However, the looping track of the system could not be predicted accurately. Prediction of such tracks need further study.