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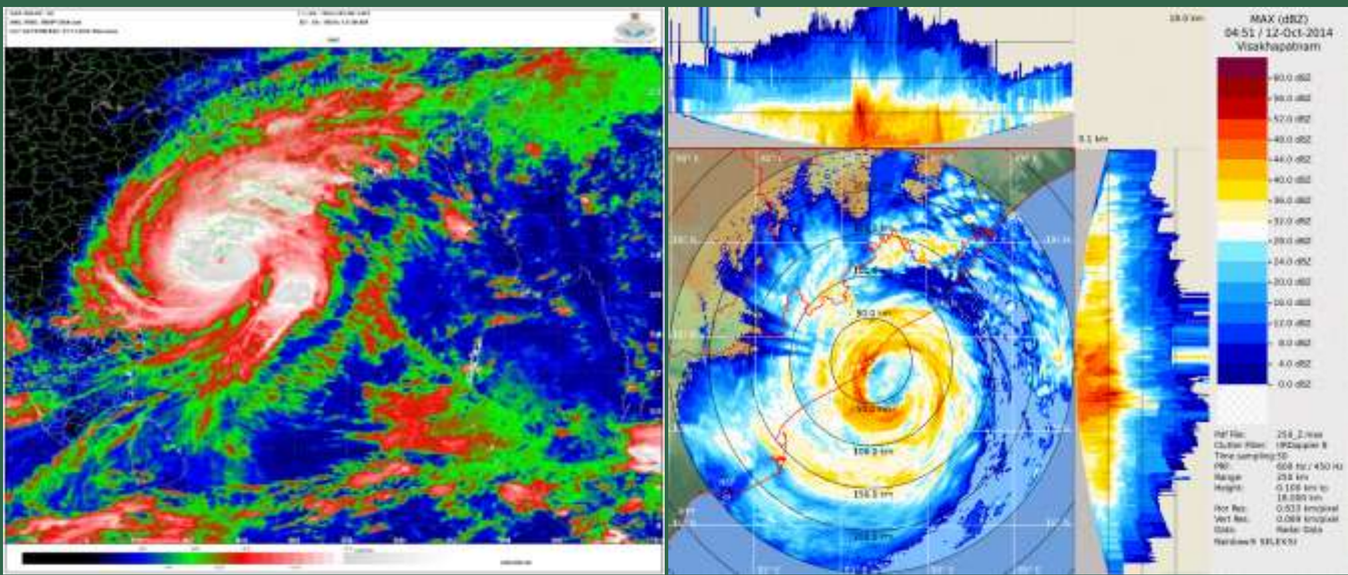
Ministry of Earth Sciences
India Meteorological Department

No. ESSO/IMD/RSMC-Tropical Cyclones Report No. 01 (2015)/6

REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2014



SATELLITE AND DWR IMAGERIES OF VERY SEVERE CYCLONIC STORM, “HUDHUD"

RSMC-TROPICAL CYCLONES, NEW DELHI

JANUARY 2015

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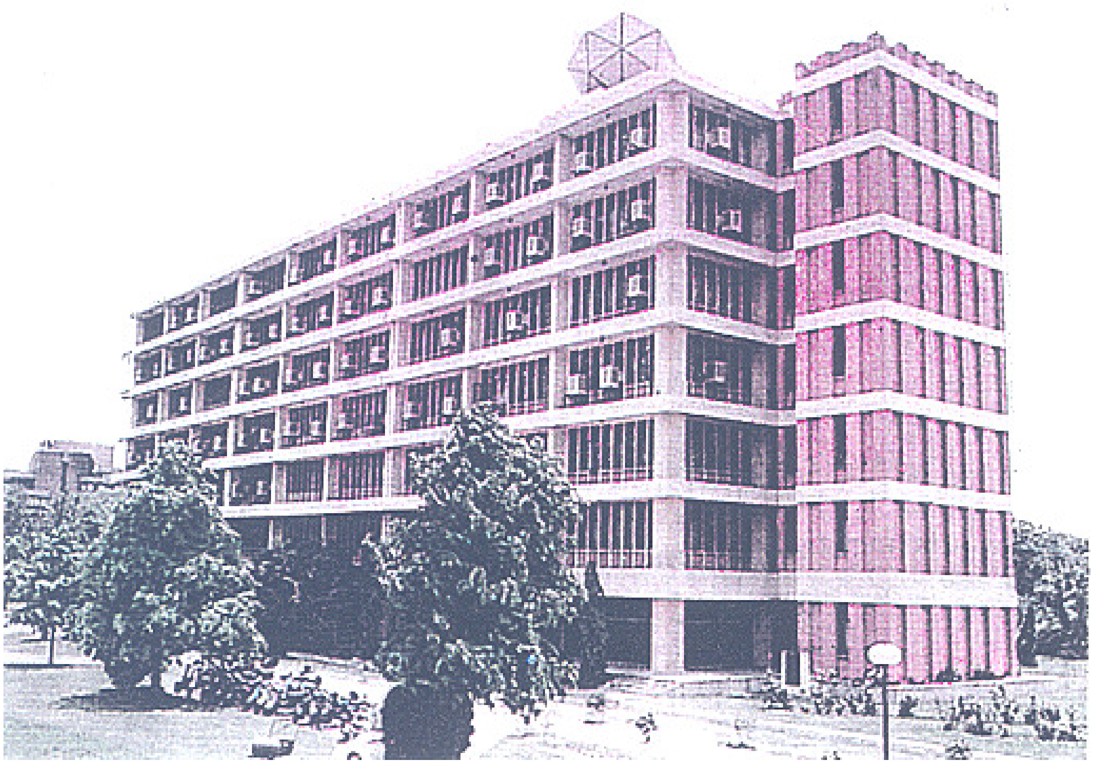
INDIA METEOROLOGICAL DEPARTMENT



RSMC- TROPICAL CYCLONES, NEW DELHI

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13.	Abstract	The activities of Regional Specialised Meteorological Centre (RSMC) – Tropical Cyclone New Delhi are briefly presented alongwith the current state of art for monitoring and prediction of cyclonic disturbances over the north Indian Ocean. This report further describes the characteristics of cyclonic disturbances formed over the north Indian Ocean during 2014. The special emphasis has been given on the features associated with genesis, intensification, movement, landfall and associated adverse weather like heavy rain, strong wind and storm surge. The performance of the forecasts issued by RSMC, New Delhi with respect to tropical cyclones are verified and discussed. Also the performance of various dynamical and statistical models for cyclone forecasting has been evaluated and discussed.

CONTENTS

INTRODUCTION

Regional Specialized Meteorological Centre (RSMC) - Tropical Cyclones, New Delhi, which is co-located with Cyclone Warning Division has the responsibility of issuing Tropical Weather Outlook and Tropical Cyclone Advisories for the benefit of the countries in the World Meteorological Organization (WMO)/ Economic and Social Co-operation for Asia and the Pacific (ESCAP) Panel region bordering the Bay of Bengal and the Arabian Sea, namely, Bangladesh, Maldives, Myanmar, Pakistan, Sultanate of Oman, Sri Lanka and Thailand. It has also the responsibilities as a Tropical Cyclone Advisory Centre (TCAC) to provide Tropical Cyclone Advisories to the designated International Airports as per requirement of International Civil Aviation Organization (ICAO).

The broad functions of RSMC- Tropical Cyclones, New Delhi are as follows:

- Round the clock watch on weather situations over the entire north Indian Ocean.
- Analysis and processing of global meteorological data for diagnostic and prediction purposes.
- Detection, tracking and prediction of cyclonic disturbances in the Bay of Bengal and the Arabian Sea.
- Running of numerical weather prediction models for tropical cyclone track and storm surge predictions.
- Interaction with National Disaster Management Authority and National Disaster Management, Ministry of Home Affairs, Govt. of India to provide timely information and warnings for emergency support services. RSMC-New Delhi also coordinates with National Institute of Disaster Management (NIDM) for sharing the information related to cyclone warning.
- Implementation of the Regional Cyclone Operational Plan of WMO/ESCAP Panel.
- Issue of Tropical Weather Outlook and Tropical Cyclone Advisories to the Panel countries in general.
- Issue of Tropical Cyclone advisories to International airports in the neighbouring countries for International aviation.
- Collection, processing and archival of all data pertaining to cyclonic disturbances viz. wind, storm surge, pressure, rainfall, damage report, satellite and Radar derived information etc. and their exchange with Panel member countries.
- Preparation of comprehensive annual reports on cyclonic disturbances formed over North Indian Ocean every year.
- Preparation of annual review report on various activities including meteorological, hydrological and disaster preparedness and prevention activities of panel member countries.
- Research on storm surge, track and intensity prediction techniques.

CHAPTER- I

ACTIVITIES OF REGIONAL SPECIALIZED METEOROLOGICAL CENTER – TROPICAL CYCLONES, NEW DELHI

1.1 Area of Responsibility

The area of responsibility of RSMC- New Delhi covers Sea areas of north Indian Ocean north of equator between 45^0 E and 100^0 E and includes the member countries of WMO/ESCAP Panel on Tropical Cyclones viz, Bangladesh, India, Maldives, Myanmar, Pakistan, Sri Lanka, Sultanate of Oman and Thailand as shown in Fig. 1.1.

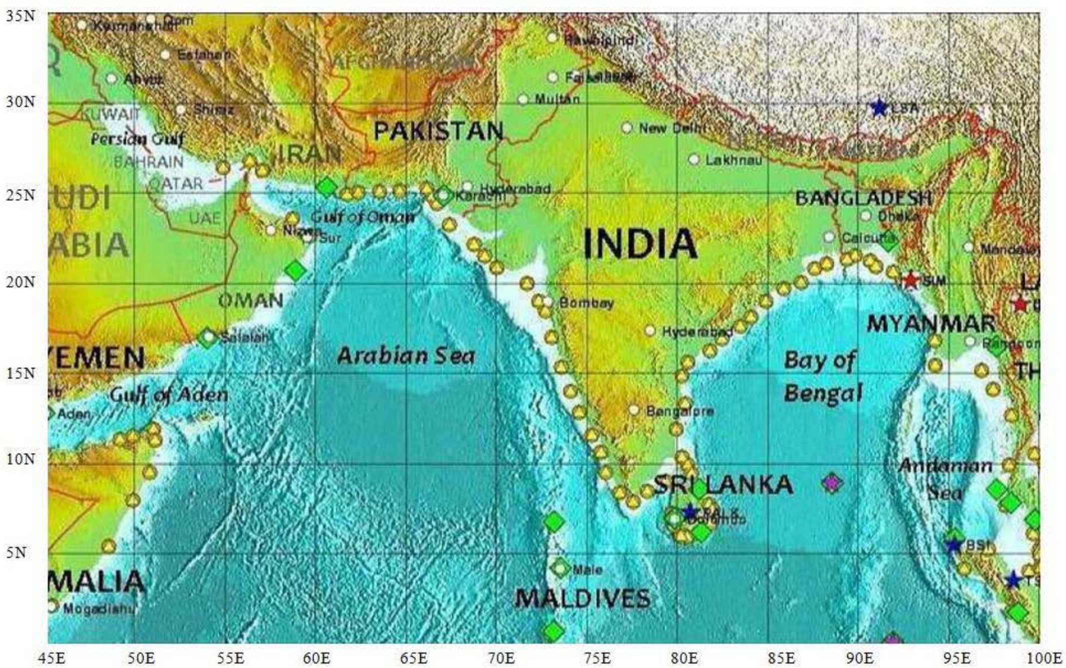


Fig. 1.1 Area of responsibility of RSMC- Tropical Cyclone, New Delhi

1.2 Naming of tropical cyclones over north Indian Ocean:

The WMO/ESCAP Panel on Tropical Cyclones at its twenty-seventh Session held in 2000 in Muscat, Sultanate of Oman agreed in principle to assign names to the tropical cyclones in the Bay of Bengal and Arabian Sea. After long deliberations among the member countries, the naming of the tropical cyclones over north Indian Ocean commenced from September 2004, by RSMC New Delhi. The first name was ‘ONIL’ which developed over the Arabian Sea (30 September to 03 October, 2004). According to approved principle, a list of 64 names in eight columns has been prepared. The name has been contributed by Panel members. The RSMC tropical cyclones New Delhi gives a tropical cyclone an identification name from this name list. The Panel member’s name is listed alphabetically country wise in each column. The names are used sequentially column wise. The first name starts from the first row of column one and continues sequentially to the last row in column eight. The names are not rotated every few years unlike that over Atlantic and Eastern Pacific lists. Out of 64 approved names, 38 names have been utilized till the end of year 2014.

1.3 Observational System

A brief description of different types of observational network of India Meteorological Department (IMD) and observations collected from networks are given below.

1.3.1 Surface Observatories

IMD has a good network of surface observatories satisfying the requirement of World Meteorological Organization. There are 559 surface observatories in IMD. The data from these stations are used on real time basis for operational forecasting. Recently a number of moored ocean buoys including Meteorological Buoy (MB), Shallow Water (SW), Deep Sea (DS) and Ocean Thermal (OT) buoys have been deployed over the Indian Sea, under the National Data Buoy Programme (NDBP) of the Ministry of Earth Sciences, Government of India.. The surface observatory network of IMD is shown in fig 1.2

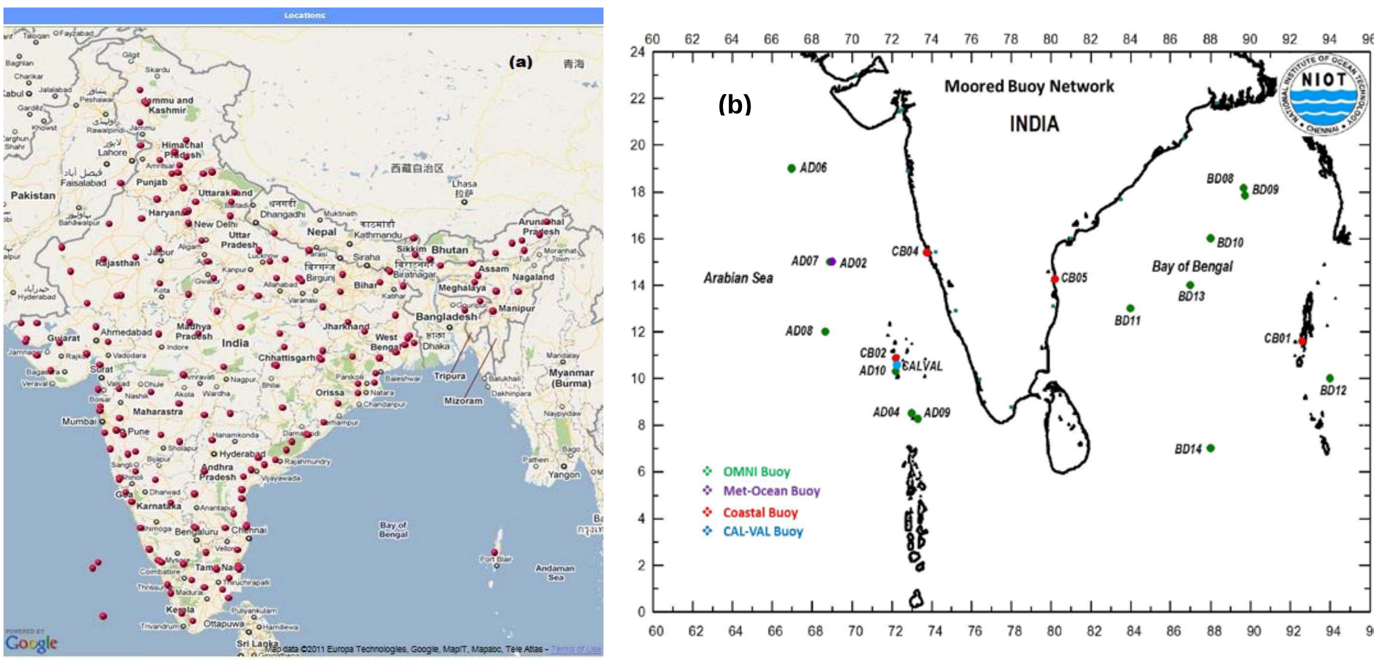


Fig.1.2. (a) The surface Observatory Network of IMD (b) Buoy network of NIOT

In accordance with the recommendations of the committee, under Modernization Project Phase-I, a network of 550 AWS have been installed across the country. In order to have a uniform distribution of network stations, efforts have been taken to install one AWS in each district of India. In the year 2006-2007, a network of 125 AWS was established by IMD across the country. These AWS were primarily installed along the coastline to strengthen the surface observational network for monitoring low pressure systems including cyclonic disturbances. A fairly dense network of AWS as shown in Figure 1.3 is now available for operational utilization. In addition to AWS, a network of 1350 Automatic Rain Gauge (ARG) Stations is also being established across the country under the Modernization Program Phase-I with about 1240 stations already installed in different states.

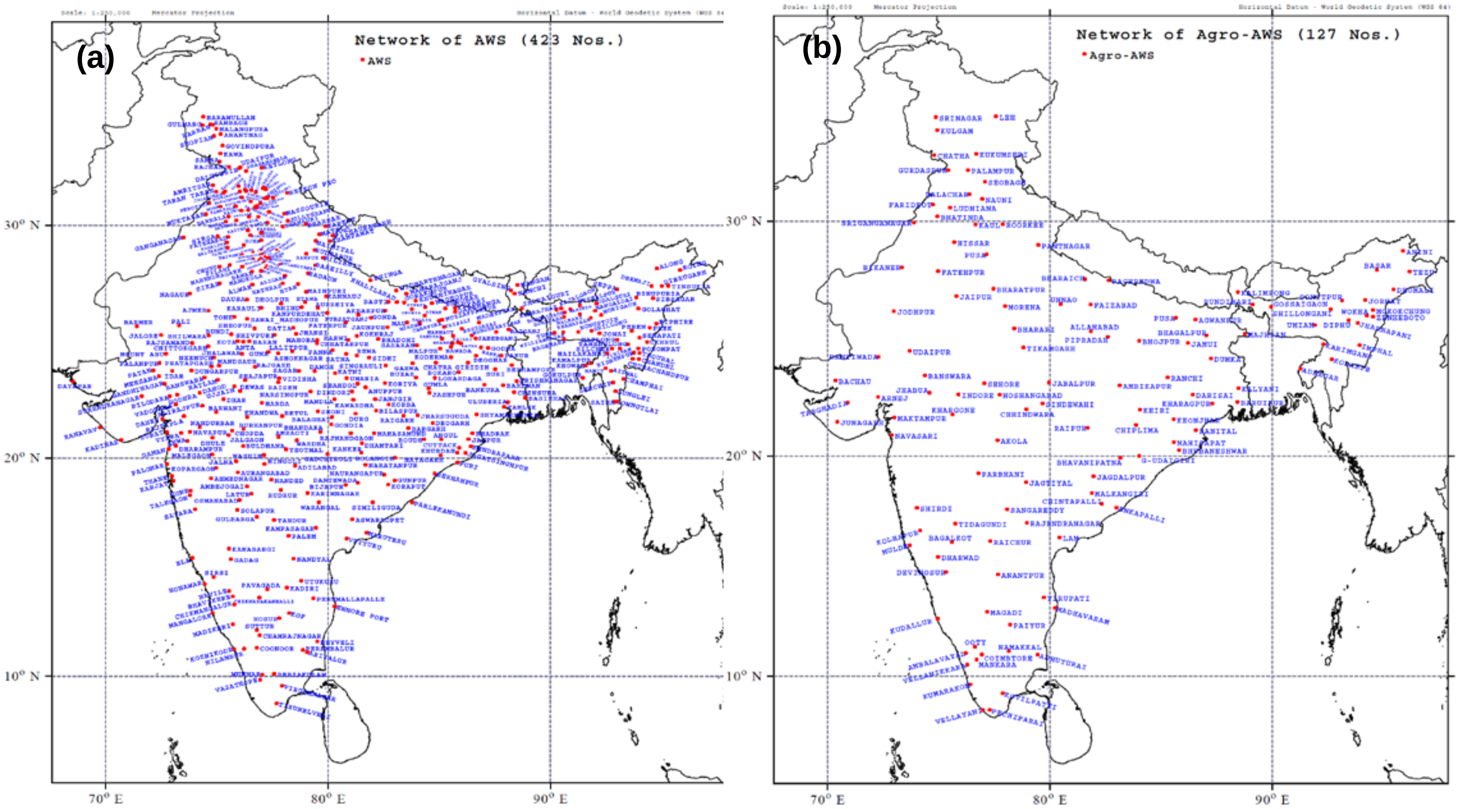


Fig. 1.3 (a) Network of 423 AWS and (b) 127 Agro-AWS established during 2008-2012.

1.3.2. Upper Air Observatories

There are at present 62 Pilot Balloon Observatories, 37 Radiosonde/ Radio wind observatories and 02 Radiosonde Observatory. Among the 37 Radiosonde/Radiowind observatories, 17 stations are GPS based stations, 8 with Sameer instruments, 7 with IMS-1500 instruments and 5 with RSGE instruments. The pilot balloon observation network and RS/RW network of IMD is shown in fig 1.4

To monitor the daily ascent status and the stock of various consumables the observatory performance monitoring system has been started on the intra imd portal metnet.imd.gov.in/ual

The upper air meteorological data collected all over the country are used on real time basis for operational forecasting.

A Wind Profiler/Radio Acoustics Sounding System has been installed at Pashan, Pune in collaboration with M/S SAMEER, Mumbai and IITM, Pune. The instrument is capable of recording upper air temperature up to 3 km and upper wind up to 9 km above Sea level.

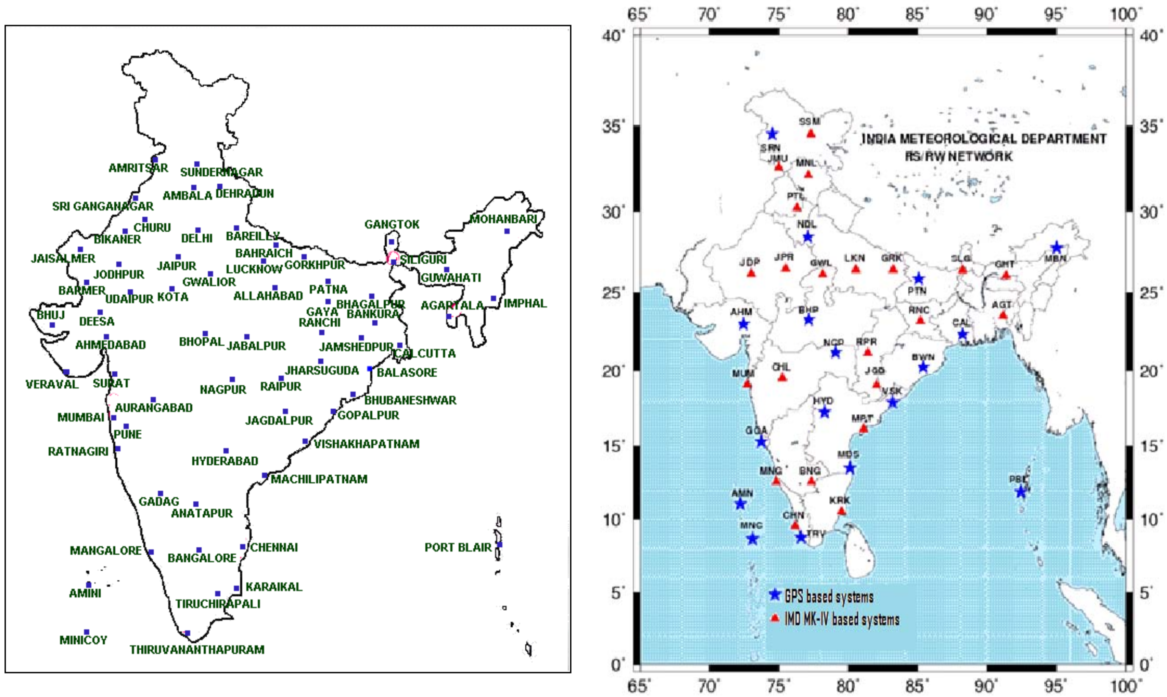


Fig.1.4 (a) Network of Pilot Ballon Observatories and (b) Network of Radiosonde/ Radio wind observatories

1.3.3. Radars

1.3.3.1. Current status

Weather radar network of India is managed by India Meteorological Department, and consists of twenty three radars presently spreading across the country. There are sixteen sites with Doppler Weather Radars, including fourteen sites operating in S-band and two sites with C-band Polarimetric Doppler weather radars. Nine more sites have analogue non Doppler Weather Radars. Two indigenously manufactured S-band Doppler weather radars, which have been installed at Mumbai and Bhuj are undergoing tests before being put to operational use.

S-band Doppler Weather Radars are installed at Agartala, Bhopal, Chennai, Hyderabad, Kolkata, Lucknow, Machilipatnam, Mohanbari, Nagpur, New Delhi, Patna, Patiala, Sriharikota and Visakhapatnam. C-band Polarimetric Doppler weather radars are installed at Jaipur and New Delhi. The Supply Order for one X-Band transportable radar for Srinagar has been placed and the installation of the same is expected within next two months.

Two Nos. of DWRs are being installed at Gopalpur and Kochi under ISRO and IMD Memorandum of understanding

Analogue types of S-band radars are installed at Jaisalmer, Karaikal and Kochi. X-band weather radars are installed at Ahmedabad, Bhubaneswar, Guwahati, Kolkata, Mangalore, Ranchi and are being phased out.

Conventional radar provides information only on reflectivity whereas Doppler weather radars provide information on reflectivity, velocity and spectral width.

Radars of IMD are being used for detection of dust storms, thunder storms and tracking of cyclonic storms. They also detect rainfall and hail. Various meteorological, hydrological and aviation products derived from Doppler weather radar data using software algorithms are extremely useful to the forecasters for estimating the storm's center, intensity, location and for forecasting its future path for safe navigation of aircrafts and ships. The existing digital Doppler weather radars have also been networked to super computers for numerical weather prediction models for now casting. Composite images are being generated centrally. Data is also converted to scientific formats such as NetCDF, HDF5, and Opera BUFR for assimilation Numerical Weather Prediction (NWP) models.

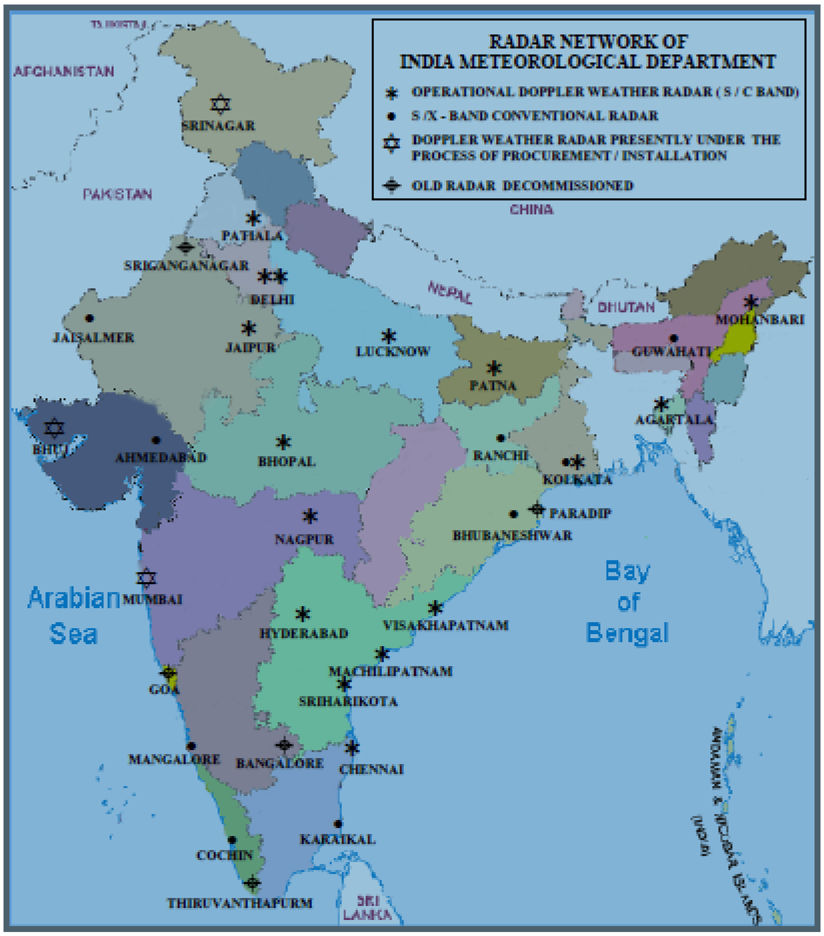


Fig. 1.4(b) Network of Radar

1.3.3.2 Future Plan:

The Radar division is involved in implementation of the work of modernization of Radar Network by replacing old conventional Radars with state of art Doppler Weather Radar. IMD has a plan to induct more than 55 DWRs in its network in the phased manner to bring entire Country and coasts under Doppler Network Radar coverage. For improved efficient management, there are also plans, to establish a Weather Radar Operation Center, which would be responsible for weather radar related activities of the department. It will manage radar network, archival, dissemination of data, development of algorithms, network planning and related R&D.

1.3.4 Satellite Monitoring

1.3.4.1 Current status

At present IMD is receiving and processing meteorological data from three Indian satellites namely Kalpana-1, INSAT-3A & INSAT-3D. Kalpana-1 was launched on 12th September, 2002 and is located at 74.0°E. INSAT-3A was launched on 10 April, 2003 and is located at 93.5°E. INSAT-3D has been launched on 26 July 2013. Kalpana-1 and INSAT-3A both have payload of Very High Resolution Radiometer (VHRR) for imaging the earth in three channels viz. Visible (0.55-0.75 µm), Infra-Red (10.5-12.5µm) and Water vapour (5.7-7.1µm) having resolution of 2X2 km in visible and 8X8 km in Water vapour (WV) and Infra-red (IR) channels. In addition, the INSAT-3A has a three channel Charge Coupled Device (CCD) payload for imaging the earth in Visible (0.62- 0.69um), Near IR (0.77-0.86µm) and Short Wave IR (1.55-1.77µm) bands of Spectrum.

The Resolution of CCD payload in all the three short wave (SW) channels is 1KmX 1 Km. INSAT-3D has an advanced imager with six imagery channels {(Visible, Short wave Infra-Red (SWIR), Medium Infra-Red (MIR), Thermal Infra-Red-1(TIR-1), TIR-2, & WV} and a nineteen channel sounder (18 IR &1 Visible) for derivation of atmospheric temperature and moisture profiles. It provides 1 km. resolution imagery in visible band, 4 km resolution in IR band and 8 km in WV channel.

At Present about 48 nos. of satellite images are taken daily from Kalpana-1, approximately 20 images are taken from INSAT-3A. Imaging from CCD is done 5 times during daytime only. Half hourly satellite imageries are also obtained from all the six imager channels and hourly images from the sounder channels of INSAT-3D satellite. All the received data from the satellite are processed and archived in National Satellite Data Center (NSDC), New Delhi. INSAT-3D Meteorological Data Processing System (IMDPS) is processing meteorological data from INSAT VHRR and CCD data and supports all operational activities of the Satellite Meteorology Division on round the clock basis. Cloud Imagery Data are processed and transmitted to forecasting offices of the IMD as well as to the other users in India and foreign countries.

The following products derived from the satellite are useful for monitoring of tropical cyclones

1. Outgoing Long wave Radiation (OLR) at 0.250X0.250 resolution
2. Quantitative Precipitation Estimation (QPE) at 10 /10 resolution
3. Sea Surface Temperature (SST) at 10 /10 resolution
4. Cloud Motion Vector (CMV)
5. Water Vapour Wind (WVW)
6. Upper Tropospheric Humidity (UTH)
7. Temperature, Humidity profile
8. Value added parameters from sounder products
    a. Geo-potential Height
    b. Layer Precipitable Water
    c. Total Precipitable Water
    d. Lifted Index
    e. Dry Microburst Index
    f. Maximum Vertical Theta-E Differential
    g. Wind Index

At present Dvorak technique is used but manually applied. Recently efforts have been made for automation of this technique. Automated Dvorak technique is running in experimental mode at

Synoptic Application Unit, Satellite Meteorology Division. Satellite Application Unit is also using Microwave imageries operationally from NOAA, Metop's DMSP satellites for locating the tropical systems. Satellite Application Unit issues three hourly bulletins in general and hourly and half hourly bulletins in case of tropical cyclones and other severe weather events. The unit is modifying these bulletins from time to time.

With the Web Archival System developed at IMD, KALPANA-1/INSAT-3A/INSAT- 3D products & imageries are archived. The automatic script is being used to keep and update the images/products on the website for 6 months. These are available to all users.

On 23rd Sept 09, polar orbiting satellite OCEANSAT–II was launched by Indian Space Research Organisation (ISRO) which carried a ku band pencil beam scatterometer to provide ocean surface winds at 10 m height for early detection of tropical cyclones. Winds from this satellite were used regularly for locating the Center and intensity of the tropical systems in the formative stage. The OSCAT suffered an anomaly early in February 2014, which could not be recovered and ceased operations on April 2, 2014.

Space Application Center (SAC), ISRO, Ahmedabad developed a technique to predict the formation of tropical cyclones over north Indian Ocean before 24-96 hrs based on OCEANSAT-II Scatterometer wind. Satellite Division of IMD acquired the software and validated the technique. However as Oceansat-II has become defunct and no more data is available from the satellite, the technique is not being used for predicting cyclogenesis.

1.3.4.2 Future Plan

It has been planned to procure software for better monitoring & warning of severe weather events.There is a plan for automization of Advanced Dvorak Technique and objective tracking of thunderstorms.

1.4. Analysis and Prediction

1.4. Analysis and Prediction system

Various strategies have been adopted in recent years for improvement of analysis and prediction of cyclone. The tropical cyclone analysis, prediction and decision-making process is made by blending scientifically based conceptual models, dynamical & statistical models, meteorological datasets, technology and expertise. Conventional observational network, automatic weather stations (AWS), buoy & ship observations, cyclone detection radars and satellites are used for this purpose. A new weather analysis and forecasting system in a digital environment is used to plot and analyse different weather parameters, satellite, Radar and Numerical Weather Prediction (NWP) model products. An integrated fully automated forecasting environment facility is thus set up for this purpose.

The manual synoptic weather forecasting has been replaced by hybrid systems in which synoptic method could be overlaid on NWP models supported by modern graphical and GIS applications to produce

- high quality analyses

- Ensemble of forecasts from NWP models at different scales - global, regional and mesoscale
- Prediction of intensity and track of tropical cyclone

A schematic representation of the monitoring and analysis, forecast and warning procedure is given in Fig.1.5.

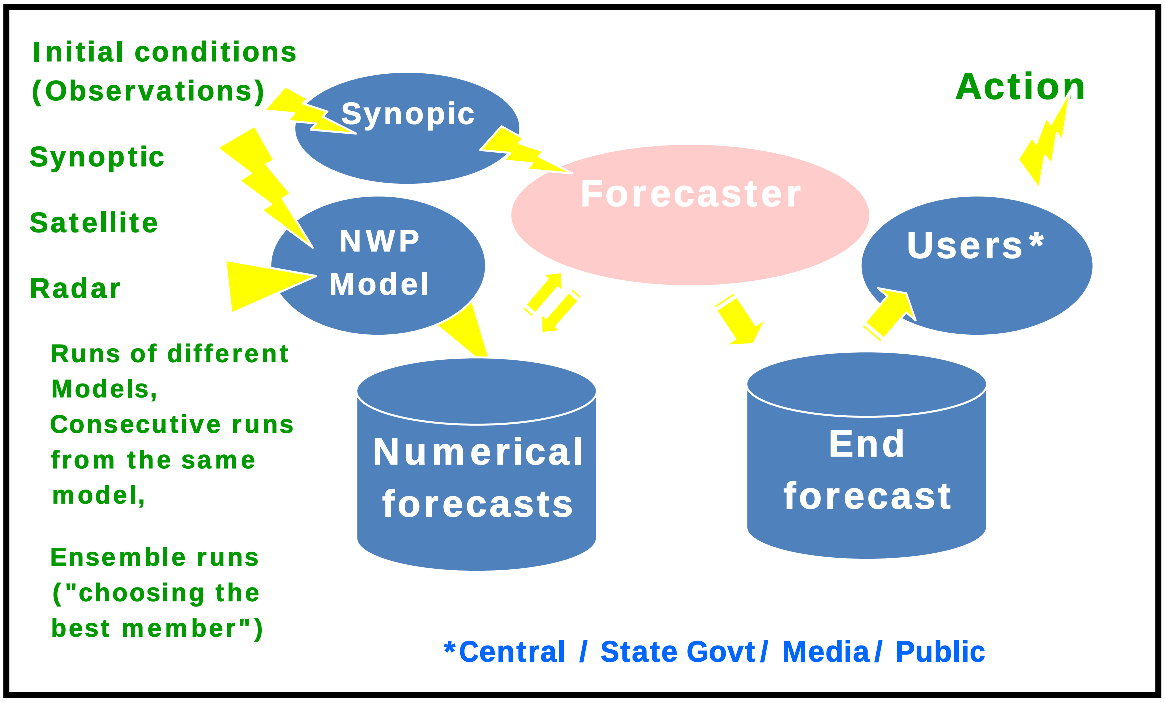


Fig.1.5. Strategy adopted for cyclone analysis and forecasting

The **Tropical Cyclone Module** installed in this forecasting system has the following facilities.

- Analysis of all synoptic, satellite and NWP model products for genesis, intensity and track monitoring and prediction
- Preparation of past and forecast tracks up to 120 hrs
- Depiction of uncertainty in track forecast
- Preparation of quadrant wind radii forecast up to 120 hrs.

All the available data and products form various national and international sources are systematically considered for analysis and prediction of cyclones. Various data and products utilized for this purpose are as follows.

- ❖ Data and analysis Products through digitized system as mentioned above.
- ❖ Radar data and products from IMD's radar network and neighbouring countries
- ❖ Satellite imageries and products from IMD and international Centers
- ❖ Dynamical and statistical Model products from various national and international Centers.
- ❖ Data, analysis and forecast products from various national and international Centers through internet.

Cloud imageries from Geostationary Meteorological Satellites INSAT-3A, METSAT (KALPANA-1) and INSAT-3D are the main sources of information for the analysis of tropical cyclones over the data-sparse region of north Indian Ocean. Data from scatteometry based satellites and Ocean buoys also provide vital information. Ship observations are also used critically during the cyclonic disturbance period. When the system comes closer to the coastline, the system location and intensity are determined based on hourly observations from Radar as well as from coastal observatories. The AWS stations along coast are also very useful as they provide hourly observations on real time basis. The WVW and CMV in addition to the conventional wind vectors observed by Radio Wind (RW) instruments are very useful for monitoring and prediction of cyclonic disturbance, especially over the Sea region. The direction and speed of the movement of a tropical cyclone are determined primarily from the three hourly displacement vectors of the Center of the. The consensus forecast that gather all or part of the numerical forecast and used synoptic and statistical guidance are utilised for issue of official forecast.

1.5. NWP Models in operational use during the year 2014

1.5.1. Global Forecast System

The Global Forecast System (GFS), adopted from National Center 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 (based on 00 UTC and 12 UTC initial conditions). The real-time outputs are made available to the national web site of IMD (http://www.rsmcnewdelhi.imd.gov.in/section/nhac/dynamic/nwp/welcome.htm).

IMD also makes use of NWP products prepared by some other operational NWP Centers like, ECMWF (European Center for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency), UKMO etc.

1.5.2. Regional Forecast System

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

1.5.2.1. 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. 25ºS to 45ºN long 40ºE to 120ºE 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 Centers, very high resolution mesoscale models (WRF at 3 km resolution) are also operational with their respective regional setup/configurations.

1.5.2.2. 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 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 Center of the system adjusted to the Center of the observed cyclonic storm. The outer domain covers most of the North Indian and the inner domain mainly covering the cyclonic vortex which moves 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. It has been further upgraded to 3km horizontal resolution in 2015.

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 up to 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 working 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 120 hours. The model uses IMD GFS-T574L64 analysis/forecast as first guess.

1.5.3. Dynamical Statistical models

The Dynamical Statistical models include (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.

1.5.3.1 Genesis Potential Parameter (GPP)

A cyclone genesis parameter, termed the genesis potential parameter (GPP), for the North Indian Ocean 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 with threshold of T3.0 at GPP value of 8.0 or more. The composite GPP value is found to be around three tofive times greater for developing systems than for non -developing systems. The analysis of the parameter at early development stage of T1.5 is 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.rsmcnewdelhi.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 affirm its usefulness as a predictive signal (4-5 days in advance) for cyclogenesis over the North Indian Ocean.

1.5.3.2. 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 120-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 120-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,84hr, 96hr, 108hr and 120 hrs) 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. 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.rsmcnewdelhi.imd.gov.in.***

1.5.3.3. 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 provide useful guidance for the operational cyclone forecasting.

1.5.3.4. 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 increase 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.

1.5.3.5. 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.

1.5.4. Tropical Cyclone Ensemble Forecast based on Global Models Ensemble (TIGGE) Data

As part of WMO Program to provide a guidance of tropical cyclone (TC) forecasts in near real-time for the WMO/ESCAP panel Member Countries based on the TIGGE Cyclone XML (CXML) data, IMD implemented JMA supported software for real-time TC forecast over North Indian Ocean (NIO) during 2011.

The Ensemble and deterministic forecast products from ECMWF (50+1 Members), NCEP (20+1 Members), UKMO (23+1 Members) and MSC (20+1 Members) are available near real-time for NIO region for named TCs. These Products includes: Deterministic and Ensemble TC track forecasts, Strike Probability Maps, Strike probability of cities within the range of 120 kms 4 days in advance. The JMA provided software to prepare Web page to provide guidance of tropical cyclone forecasts in near real-time for the WMO/ESCAP panel Members. The forecast products are made available in real time.

1.6. Bulletins and Products Generated By RSMC, New Delhi

RSMC, New Delhi prepares and disseminates the following bulletins.

1.6.1. Tropical Weather Outlook

Tropical Weather Outlook is issued daily at 0600 UTC based on 0300 UTC observations in normal weather for use of the member countries of WMO/ESCAP Panel. This contains description of synoptic systems over NIO along with information on significant cloud systems as seen in satellite imageries and ridge line at 200 hPa level over Indian region. It also provides probabilistic genesis forecast (formation of depression) over Bay of Bengal and Arabian sea separately for day 1 (up to 24 hrs), day 2 (24 – 48 hrs) and day 3 (48 – 72 hrs). The forecast is issued in probabilistic terms like Nil, Low, Fair, Moderate and High probability corresponding to expected probability of occurrence of 00, 01 – 25, 26 – 50, 51 – 75 and 75 – 100 %. This forecast has been introduced on 1st June 2014.

1.6.2. Special Tropical Weather Outlook

The Special Tropical Weather Outlooks are issued at 0600 & 1500 UTC based on 0300 & 1200 UTC observations respectively when a tropical depression form over NIO. The special tropical outlook indicates discussion on various diagnostic and prognostic parameters. The 120 hours track and intensity forecasts are issued from the stage of deep depression. The track and intensity forecast are issued for +06, +12, +18, +24, +36, +48, +60, … 120 hours or till the system is likely to weaken into a low pressure area. These bulletins contain the current position and intensity, past movement, central pressure of the cyclone, description of satellite imageries, cloud imageries, expected direction and speed of movement, expected track and intensity of the system up to 120 hour. It also includes the description of sea condition. The time of issue of this bulletin is HH+03 hours. The cone of uncertainty in the track forecast is also included in the graphical presentation of the bulletin.(Fig.1.5). Tropical weather outlooks are transmitted to panel member countries through global telecommunication system (GTS) and are also made available on real time basis through internet at IMD's website:**www.rsmcnewdelhi.imd.gov.in**. RSMC, New Delhi can also be contacted through e-mail (**cwdhq2008@gmail.com**) for any real time information on cyclonic disturbances over NIO.

1.6.3. Tropical Cyclone Advisories

Tropical cyclone advisory bulletin is issued when a deep depression intensifies into a tropical cyclone (wind speed= 34 knots or more). It replaces the 'special tropical weather outlook' bulletin. Tropical cyclone advisories are issued at 3 hourly intervals based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC observations. The time of issue is HH+03 hrs. These bulletins contain the current position and intensity, past movement, central pressure of the cyclone, description of satellite imageries, cloud imageries, expected direction and speed of movement, expected track and intensity of the system up to 120 hours like that in special tropical weather outlook. The expected point and time of landfall, forecast winds, squally weather and state of the Sea in and around the system are also mentioned. Storm surge guidance is provided in the bulletin as and when required. Tropical cyclone advisories are transmitted to panel member Countries through GTS and are also made available on real time basis through internet at IMD's website: **www.rsmcnewdelhi.imd.gov.in** . RSMC, New Delhi can also be contacted through e-mail (**cwdhq2008@gmail.com**) for any real time information on cyclonic disturbances over NIO.

1.6.4. Storm Surge Guidance

RSMC New Delhi is providing storm surge guidance to the panel member countries since 2009 based on IIT Delhi Storm Surge model. Recently INCOIS Hyderabad has developed a Storm Surge and Coastal Inundation model which is running experimentally since 2013. In future it will be used as an input for providing storm surge guidance to member countries.

1.6.5. Global Maritime Distress and Safety System (GMDSS)

Under Global Maritime Distress and Safety System (GMDSS) Scheme, India has been designated as one of the 16 services in the world for issuing Sea area bulletins for broadcast through GMDSS for MET AREA VIII (N), which covers a large portion of NIO. As a routine, two GMDSS bulletins are issued at 0900 and 1800 UTC. During cyclonic situations, additional bulletins (up to 4) are issued for GMDSS broadcast. In addition, coastal weather and warning bulletins are also issued for broadcast through NAVTEX transmitting stations.

1.6.6. Tropical Cyclone Advisories for Aviation

Tropical Cyclone Advisories for aviation are issued for international aviation as soon as any disturbance over the NIO attains or likely to attain the intensity of cyclonic storm (maximum sustained surface wind speed≥ 34 knots) within next six hours. These bulletins are issued at six hourly intervals based on 00, 06, 12, 18 UTC synoptic charts and the time of issue is HH+03 hrs. These bulletins contain present location of cyclone in lat./long., maximum sustained surface wind (in knots), direction of past movement and estimated central pressure, forecast position in Lat./Long. and forecast winds in knots valid at HH+6, HH+12, HH+18 and HH+24 hrs in coded form. The tropical cyclone advisories are transmitted on real time basis through GTS & AFTN channels to designated International Airports of the region prescribed by ICAO and ftp to ADRR, Hong Kong (WMO's Aviation Disaster Risk Reduction) in coded form.. It is also being sent in graphics in **.png** format through GTS.

1.6.7. Bulletin for India coast

These bulletins are issued from the stage of depression onwards. During the stage of depression/deep depression; it is issued based on 00, 03, 06, 12, and 18 UTC observations. When the system intensifies into a cyclonic storm over NIO, these bulletins are issued at 00, 03, 06, 09, 12, 15, 18 and 21 UTC (every three hourly interval) based on previous observations. This bulletin contains present status of the system i.e. location, intensity; past movement and forecast intensity & movement for next 120 hours or till the systems weaken into a low pressure area, likely landfall point & time and likely adverse weather including heavy rain, gale wind & storm surge. Expected damage and action suggested are also included in the bulletins. This bulletin is completely meant for national users and these are disseminated through various modes of communication including All India Radio, Door Darshan (National TV), Telephone/Fax, SMS Print and electronic media. It is also posted on cyclone page of IMD website.

1.6.8. Wind forecast for different quadrants

The forecast of radius of maximum sustained wind in four quadrants of a cyclone commenced with effect from cyclone, GIRI during October 2010. In this forecast, the radius of 28, 34, 50 and 64 knot winds are given for various forecast periods like +06, +12, +18, +24, +36, +48, +60, … 120 hrs. A typical graphical presentation of this forecast is shown in Fig.1.6. This quadrant wind forecast is issued as bulletin from the deep depression stage onwards to various users through global telecommunication system.

1.6.9. TC Vital

The TC Vital is issued by RSMC New Delhi to various NWP Centers in coded form for their use in creating the synthetic vortex in NWP models and running storm surge and coastal inundation model. It is issued 4 times a day based on 00, 06, 12 and 18 UTC. This bulletin contains the information on location (Latitude/Longitude), intensity (MSW and estimated central pressure), movement (Speed/Direction), size, radius of maximum wind and wind radii of 34kts wind in 4 geographical quadrants namely NE,NW,SE and SW quadrants etc. This system has been introduced in 2012.

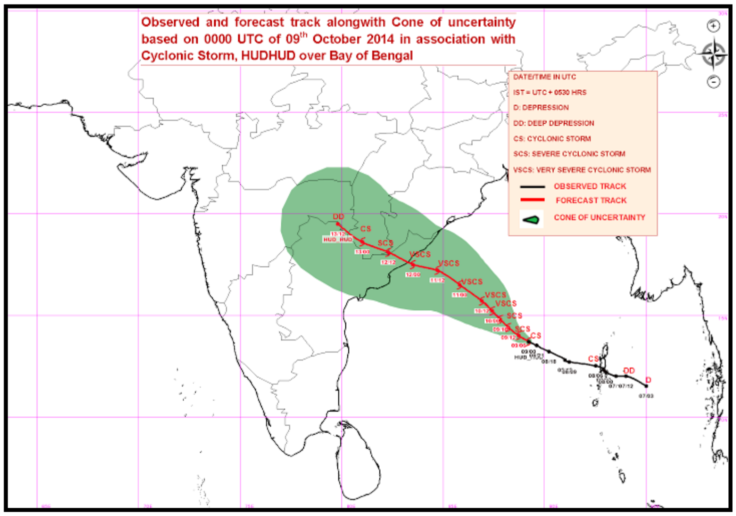


Fig.1.6. A typical example of observed and forecast track of Cyclonic Storm HUDHUD which later on became a VSCS.

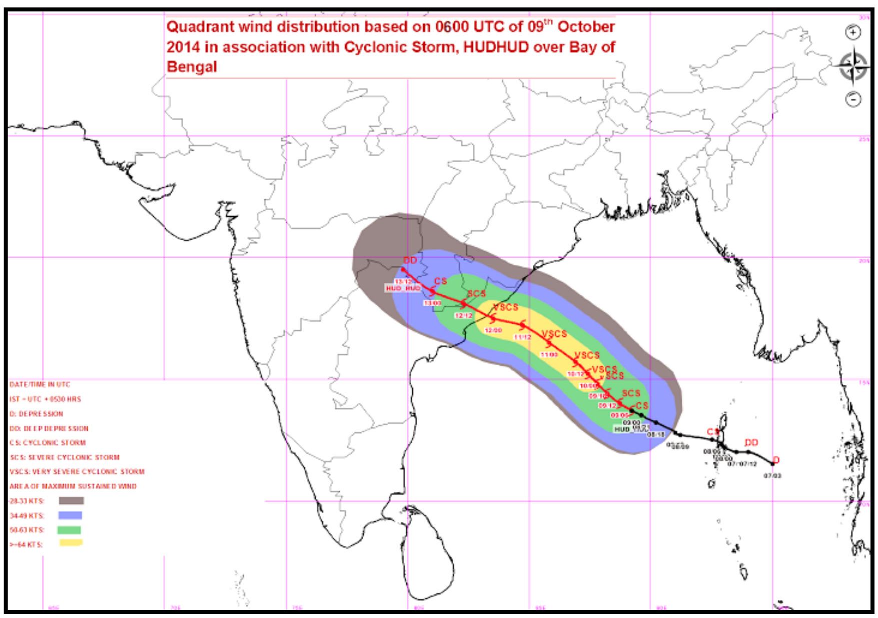


Fig.1.7. A typical graphical presentation of cyclone wind forecast during VSCS HUDHUD

1.6.10. Cone of uncertainty forecast

The Cone of uncertainty (COU) represents the probable position of a CD/ TC's circulation Center, and is made by drawing a set of circles centered at each forecast point—06, 12, 18, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hours for a five-day forecast. The radius of each circle is equal to the average official track forecast errors of 10, 20, 30, 45 60, 80, 100, 120, 135, 150, 160, 170 and 180 nautical miles for 06, 12, 18, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hr forecasts respectively. The radii of circle to construct cone of uncertainty have been changed based on the average error of 2009-2013. The new radii have been introduced with effect from cyclone, Hudhud in October, 2014.

1.7. Cyclone Warning Dissemination System

Cyclone warnings are disseminated to various users through telephone, fax, email SMS, Global Telecom System (GTS), All India Radio, Television and other print & electronic media. These warnings/advisories are also put in the website **(www.rsmcnewdelhi.imd.gov.in)** of IMD. Another means to transmit warning is IVRS (Interactive Voice Response system). The requests for weather information and forecasts from general public are automatically answered by this system. For this purpose, the person has to dial a toll free number “18001801717” from anywhere in the country. This system has been installed at 26 Meteorological Centers (MC) / Regional Meteorological Centers (RMC). High Speed Data Terminals (HSDT) are installed at almost all MCs and RMCs. HSDTs are capable of sending short warning message as SMS and the whole warning message as email. Local weather warnings are put in IMD website for common people. Global Maritime Distress and Safety System (GMDSS) message is also put in IMD website as well as transmitted through GTS.

In addition to the above network, for quick dissemination of warning against impending disaster from approaching cyclones, IMD has installed specially designed receivers within the vulnerable coastal areas for transmission of warnings to the concerned officials and people using broadcast capacity of INSAT satellite. This is a direct broadcast service of cyclone warning in the regional languages meant for the areas affected or likely to be affected by the cyclone. Since the existing 252 Cyclone Warning Dissemination System (CWDS) stations and 101 digital CWDS have become obsolete and many of these systems have stopped working and were beyond repair, IMD and ISRO jointly decided to replace all these CWDS systems by new 500 numbers of Direct Telecom Hub (DTH) based Disaster Warning Dissemination Systems (DWDS) for issuing warning to cyclone prone areas. Till date 178 numbers of DTH based DWDS systems has been installed in Tamil Nadu, Pondicherry and Andhra Pradesh. The IMD’s Area Cyclone Warning Centers (ACWCs) at Chennai, Mumbai & Kolkata and Cyclone Warning Center (CWCs) at Bhubaneswar, Visakhapatnam & Ahmedabad are responsible for originating and disseminating the cyclone warnings through this system.

The DTH based DWDS system can disseminate the warning messages in real time to multiple receiving locations spread over large coastal areas. This service is unique in the world and will help the public in general and the administration, in particular, during the cyclone.

1.8. Forecast Demonstration Project (FDP) on Landfalling Tropical Cyclones over the Bay of Bengal

A Forecast Demonstration Project (FDP) on landfalling tropical cyclones over the Bay of Bengal was taken up in 2008. It helps us in minimizing the error in prediction of tropical cyclone track and intensity forecasts.

The project is operated during 15 October to 30 November every year. During 15 Oct- 30 Nov. 2014, several national institutions participated for joint observational, communicational & NWP activities, like during 2008-2013. However there was improved observational campaign with the observation from Buoys, Scatterometry based satellite I and microwave satellites. There was intense observation period for 5 days during the field phase 2014 in association with the systems over Bay of Bengal and Arabian Sea. The daily reports prepared during this period are helpful to find out the characteristics of genesis, intensification and movement of the systems as well as environmental features over the NIO.

CHAPTER-II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2014.

During the year 2014, 8 cyclonic disturbances developed over north Indian Ocean including one Very Severe Cyclonic Storm (VSCS) and one Cyclonic Storm (CS) over Arabian Sea, one land depression (D) and 5 cyclonic disturbances over Bay of Bengal. Out of 5 disturbances over Bay of Bengal, one intensified into Very Severe Cyclonic Storm, two into Deep Depression (DD) and two into Depression. Considering season-wise distribution, out of eight disturbances, one developed during winter, one in pre-monsoon, three during monsoon and three during post-monsoon season. Salient features of cyclonic disturbances during 2014 are given below.

i. There was one cyclone over the Bay of Bengal and two over the Arabian Sea against the long period average of 5 per year over the entire north Indian Ocean including about four over Bay of Bengal and one over Arabian Sea. Thus the cyclonic activity was subdued in the Bay of Bengal during the year 2014. However, the frequency of very severe cyclonic storms was near normal (two)
ii. Though there were three cyclones, only one cyclone (Hudhud) crossed coast and other two (Nanauk and Nilofar) dissipated over the Sea.
iii. The tracks of all the storms were recurving in nature. While Hudhud recurved northwards after landfall, Nilofar recurved northeastwards after attaining maximum intensity and only the remnant of the Cyclone Nanauk recurved northeastwards.
iv. Velocity Flux, Accumulated cyclone energy and Power Distribution Index of the period 2014 are 2970, 206850 and 16004250against long period average based on the data of 1990-2013 and 2117, 130867 and 9673246 respectively.
v. The total duration of cyclonic disturbances during 2014 was 30.4 days against the long period average of 29.4 days base on data of 1990-2013.

Brief descriptions of the disturbances with intensity cyclonic storm and above are given in the following sections.

(a) Cyclonic Storm, ‘NANAUK’ over the Arabian Sea(10-14 June 2014)

A Cyclonic Storm (CS) **‘NANAUK’** originated from a low pressure area over east central Arabian Sea which developed on 9th June, 2014. It concentrated into a depression over the same region in the afternoon of 10th June, 2014. Moving north-northwestwards, it intensified into a CS **‘NANAUK’** in the early morning of 11th June 2014. It weakened into a deep depression in the afternoon of 13th June, 2014 over westcentral Arabian Sea and into a depression in the evening of 1.3 June, 2014 and further into a well marked low pressure area over the same region in the morning of 14th June, 2014. The salient features of CS, Nanuak are given below.

i. It developed in association with the southwest monsoon surge over Arabian Sea during the onset phase
ii. It caused temporary hiatus in progress of monsoon over south India

i. It weakened over the northwest Arabian Sea on 14th June and its remnant moved northeastwards leading to revival and progress of monsoon along the west coast of India

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

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 CS in the morning of 8th Oct. and crossed Andaman Islands, close to Long Island between 0300 and 04000 UTC 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 185 kmph over the West Central Bay of Bengal off Andhra Pradesh coast. It crossed north Andhra Pradesh coast over Visakhapatnam (VSK) between 0630 and 0730 UTC 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 VSCS are as follows.

ii. 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.
iii. At the time of landfall on 12th Oct, the estimated maximum sustained surface wind speed in association with the cyclone was about 100 Knots.
iv. The estimated central pressure was 950 hPa with a pressure drop of 54 hPa at the centre compared to surroundings.
v. 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 Pradeshcoast.
vi. Maximum 24 hour cumulative rainfall of 38 cm ending at 0300 UTC of 13October was reported from Gantyada (dist Vizianagaram) in Andhra Pradesh. Maximum storm surge of 1.4 meters above the astronomical tide has been reported by the tide gauge at Visakhapatnam.
vii. 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 5 days in advance.

(C) Very Severe Cyclonic Storm (VSCS) NILOFAR over the ArabianSea(25-31 October 2014)

The very severe cyclonic storm, Nilofar developed from a low pressure area which lay over southeast Arabian Sea in the morning of 21st October. It moved northwestwards and concentrated into a Depression in the early morning of 25th over westcentral and adjoining southwest Arabian Sea. It intensified into a CS over the same region in the morning of 26th. It then moved nearly northwards and further intensified into a SCS over westcentral Arabian Sea in the early morning of 27th and into a VSCS around noon of the same day. It continued to move nearly northwards and reached its maximum intensity around midnight of 28th with wind speed of 205 kmph. It then moved north-northeastwards and started to weaken rapidly under the influence of high vertical wind shear, entrainment of dry and cold air from the north and relatively lower ocean thermal energy. It weakened into a SCSduring early hours of 30th October and into a CS in the afternoon of 30th October. It weakened into a Deep Depression in the early hours and into a Depression in the early morning of 31st October. It weakened into a well marked low pressure area over northeast Arabian Sea off north Gujarat coast in the forenoon of 31st Oct.

The salient features of this system are as follows.

i. The track of the system was unique, as it initially moved northwestward on the day of formation and then re-curved northeastwards. It further moved nearly northwards very slowly up to 29th evening and then east-northeastwards.
ii. The estimated maximum sustained surface wind speed in association with the cyclone was about 110 kt (205 kmph).
iii. The estimated central pressure was 950 hPa with a pressure drop of 56 hPa at the centre compared to surroundings.
iv. It exhibited rapid intensification as well as rapid weakening. The maximum sustained wind increased from about 100 kmph in the early morning of 27th to about 205 kmph in the early evening of 28th (in 36 hours). It weakened rapidly from VSCS (wind speed of about 205 kmph) in the morning of 29th into SCS (wind speed of about 110 kmph) in the morning of 30th and further into a low pressure area (wind speed < 30 kmph) on 31st morning.
v. Though the re-curvature of the track could be predicted by NWP models 3 to 4 days in advance, there was large variation in the position and time of the landfall as well as re-curvature.
vi. Though genesis, track and intensification/weakening were predicted by IMD with reasonable accuracy five days in advance, prediction of rapid weakening and hence dissipation over the Sea were more challenging.

Details of the cyclonic disturbances formed over the north Indian Ocean and adjoining land areas are given in Table 2.1-2.4. The tracks of these disturbances are shown in Fig. 2.1

Table 2.1: Cyclonic disturbances formed over north Indian Ocean and adjoining land areas during 2014

1.	Depression over the Bay of Bengal	04-07 January, 2014
2.	Depression over the Bay of Bengal	21-23 May, 2014
3.	Cyclonic Storm 'NANAUK' over the Arabian Sea	10-14 June, 2014
4.	Land Depression over northeastern parts of Odisha and adjoining areas of Gangetic West Bengal	21-23 July, 2014
5.	Deep Depression over the Bay of Bengal	03-07 August, 2014
6.	Very Severe Cyclonic Storm, 'Hudhud' over the Bay of Bengal	07-14 October, 2014
7.	Very Severe Cyclonic Storm, 'Nilofar' over the Arabian Sea	25-31 October, 2014
8.	Deep Depression over the Bay of Bengal	05-08 November, 2014

Table 2.2: Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2012

Cyclonic Storm / Depression	**Date, Time & Place of genesis (Lat.^{0}N/ Long.^{0}E)**	**Date, Time (UTC) place (Lat.^{0}N/Long.^{0}E) of landfall**	**Estimated lowest central pressure, Time &Date (UTC) & lat^{o}N / long^{o}E**	**Estimated Maximum wind speed (kt), Date & Time**	**Max. T.No. Attained**
Depression (D) over the Bay of Bengal (04-07 January, 2014)	4th January 2014, 0300 UTC over southwest Bay of Bengal (8.5/83.5)	Crossed Sri Lanka coast 9.2/.80.8 between 0500 and 0600 UTC of 06th January 2014.	1004 hPa at 1200 UTC 05th January 2014 near 9.3/81.5	25 knots at 1200 UTC of 05th January 2014.	T-1.5
Depression (D) over the Bay of Bengal (21-23 May 2014)	21st May2014, 0300UTC over eastcentral Bay of Bengal (15.5/90.5)	Weakened into a well-marked low pressure area over central Bay of Bengal at 0300 UTC on 23rd May, 2014.	1000 hPa at 0000 UTC of 22nd May, 2014 near 16.5/92.0	25 knots at 0300 UTC of 21st May, 2014	T-1.5

Cyclonic Storm (CS) 'NANAUK' over the Arabian Sea (10-14 June, 2014)	10th June, 2014, 0900 UTC over the east central Arabian Sea(15.5/68.5)	Weakened into a well-marked low pressure area over northwest and adjoining westcentral Arabian Sea at 0300 UTC 14th June, 2014	986 hPa0000 UTC of 12th June, 2014 near 17.8/65.3	45 knots at 0000UTC on 12th June 2014	T3.0
Land Depression (D) over northeastern parts of Odisha and adjoining areas of Gangetic West Bengal (21-23 July 2014)	21 July, 0300 UTC over northeastern parts of Odisha and adjoining areas of Gangetic West Bengal (22/ 87.0)	Weakened in to a well-marked low pressure area over west Madhya Pradesh at 0900 UTC on 23rd July 2014.	986 hPa at 1200 UTC of 21st July, 2014 at near latitude 22.5/85.0	25 knots at 0300 UTC of 21st July, 2014	-
Deep Depression (DD) over Bay of Bengal (3- 7 Aug, 2014)	3rd Aug, 2014, 1200 UTC over northwest Bay of Bengal 21.5/88.5	Weakened into a well marked low pressure area over northwest Madhya Pradesh and neighbourhood at 0300 UTC on 7th morning	988 hPa at 1200 UTC 04th Aug, 2014 near 22.2/86.0	30 knots at 0000 UTC on 4th Aug, 2014	-
Very Severe Cyclonic Storm (VSCS) HUDHUD over the Bay of Bengal(07-14 October, 2014)	07th Oct, 2014, 0300 UTC over the North Andaman Sea near11.5/95.0	The System crossed Andhra Pradesh coast over Visakhapatnam (near 17.7/83.3 between 0630-0730 UTC On 12th Oct,2014	950 hPa at 0000UTC on 12th Oct, 2014near 17.2/84.2	100 knots at 1800 UTC of 11thOctober, 2014 near 16.4/84.7	T5.0
Very Severe Cyclonic Storm (VSCS) NILOFAR over the Arabian Sea (25-31 October, 2014)	25th October, 2014, 0000 UTC over westcentral and southwest Arabian Sea near. 12.5/ 61.5	Weakened into a well marked low pressure area over northeast Arabian Sea off north Gujarat coast at 0300 UTC on 31st October, 2014	950 hPa at 1800 UTC of 28th October, 2014near 17.6/61.8	110 knots at 1800 UTC of 28th October, 2014near. 17.6/61.8	T5.5

Deep Depression (DD) over the Bay of Bengal(05-08 November, 2014)	5th November, 2014, 0900 UTC over central & adjoining southeast Bay of Bengal near 13.0 / 87.5	Weakened into a well marked low pressure area over westcentral Bay of Bengal at 0300 UTC on 8th Nov., 2014	998 hPa at 0300 UTC on 06th Nov., 2014 near latitude 14.0/87.5	30 knotsat 0300 UTC on 06th Nov., 2014 near l14.0/87.5	T2.0

Table 2.3: Statistical data relating to cyclonic disturbances over the North Indian Ocean during the year 2014

A) Monthly frequencies of cyclonic disturbances(C I .≥1.5).

S. No.	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	D	↔				↔							
2	DD								↔			↔	
3	CS						↔						
4	SCS												
5	VSCS										↔ ↔		
6	SuCS												
7	LAND DEP							↔					

↔Peak intensity of the system

B) Duration of cyclonic disturbances during 2014 at different stages of intensity

S.No.	Type	Duration (Days)
1	D	14.5
2	DD	4.5
3	CS	4.9
4	SCS	2.3
5	VSCS	4.7
6	SuCS	0
	Total Life Time (Days)	30.9

C.) Frequency of distribution of cyclonic disturbances with different intensities based on satellite assessment

CI No. ≥	≥ 1.5	≥2.0	≥2.5	≥3.0	≥3.5	≥4.0	≥4.5	≥5.0	≥5.5	≥6.0
No. of Disturbances	7	5	3	3	2	2	2	2	1	

D.) Basin-wise distribution of cyclonic disturbances

Basin	Number of cyclonic disturbances
Bay of Bengal	**5**
Arabian Sea	**2**
Land	**1**

Table 2.4.Cyclonic disturbances formed over the north Indian Ocean and land areas of India during 1997-2014

Year	Basin	D	DD	CS	SCS	VSCS	SuCS	Total
1997	BOB	1	4	1	1	1	0	8
	ARB	1	0	0	0	0	0	1
	Land	0	0	0	0	0	0	0
	Total							**9**
1998	BOB	0	3	0	1	2	0	6
	ARB	0	1	1	1	1	0	4
	Land	1	0	0	0	0	0	1
	Total							**11**
1999	BOB	2	2	1	0	1	1	7
	ARB	0	0	0	0	1	0	1
	Land	1	0	0	0	0	0	1
	Total							**9**
2000	BOB	1	1	2	--	2	0	6
	ARB	0	0	0	0	0	0	0
	Land	1	0	0	0	0	0	1
	Total							**7**
2001	BOB	2	0	1	0	0	0	3
	ARB	0	0	2	0	1	0	3
	Land	0	0	0	0	0	0	0
	Total							**6**
2002	BOB	1	1	2	1	0	0	5
	ARB	0	0	0	0	0	0	1
	Land	0	0	0	0	0	0	0
	Total							**6**
2003	BOB	2	2	0	1	1	0	6
	ARB	0	0	0	1	0	0	1
	Land	0	0	0	0	0	0	0
	Total							**7**
2004	BOB	2	0	0	0	1	0	3
	ARB	0	2	0	3	0	0	5
	LAND	2	0	0	0	0	0	2
	Total							**10**
2005	BOB	2	3	4	0	0	0	9

	ARB	2	0	0	0	0	0	2
	LAND	1	0	0	0	0	0	1
	Total							**12**
2006	BOB	5	2	1	0	1	0	9
	ARB	0	1	0	1	0	0	2
	LAND	1	0	0	0	0	0	1
	Total							**12**
2007	BOB	3	4	1	0	1	0	9
	ARB	0	1	1	0	0	1	3
	Land	0	0	0	0	0	0	0
	Total							**12**
2008	BOB	1	2	3	0	1	0	7
	ARB	1	1	0	0	0	0	2
	LAND	1	0	0	0	0	0	1
	Total							**10**
2009	BOB	0	2	2	1	0	0	5
	ARB	2	0	1	0	0	0	3
	LAND	0	0	0	0	0	0	0
	Total							**8**
2010	BOB	2	1	0	2	1	0	6
	ARB	0	0-	1	0	1	0	2
	LAND	0	0	0	0	0	0	0
	Total							**8**
2011	BOB	2	2	0	0	1	0	5
	ARB	1	2	1		0	0	4
	LAND	1	0	0	0	0	0	1
	Total							**10**
2012	BOB	0	2	1	0	0	0	3
	ARB	0	1	1	0	0	0	2
	LAND	0	0	0	0	0	0	0
	Total							**5**
2013	BOB	3	0	1	1	3	0	8
	ARB	0	1	0	0	0	0	1
	LAND	1	0	0	0	0	0	1
	Total							**10**
2014	BOB	2	2	0	0	1	0	5
	ARB	0	0	1	0	1	0	2
	LAND	1	0	0	0	0	0	1
	Total							**8**

D: Depression **DD:** Deep Depression, CS**:** Cyclonic Storm, **SCS:** Severe Cyclonic Storm, **VSCS:** Very Severe Cyclonic Storm, **SuCS:** super Cyclonic Storm
BOB: Bay of Bengal, **ARB:** Arabian Sea

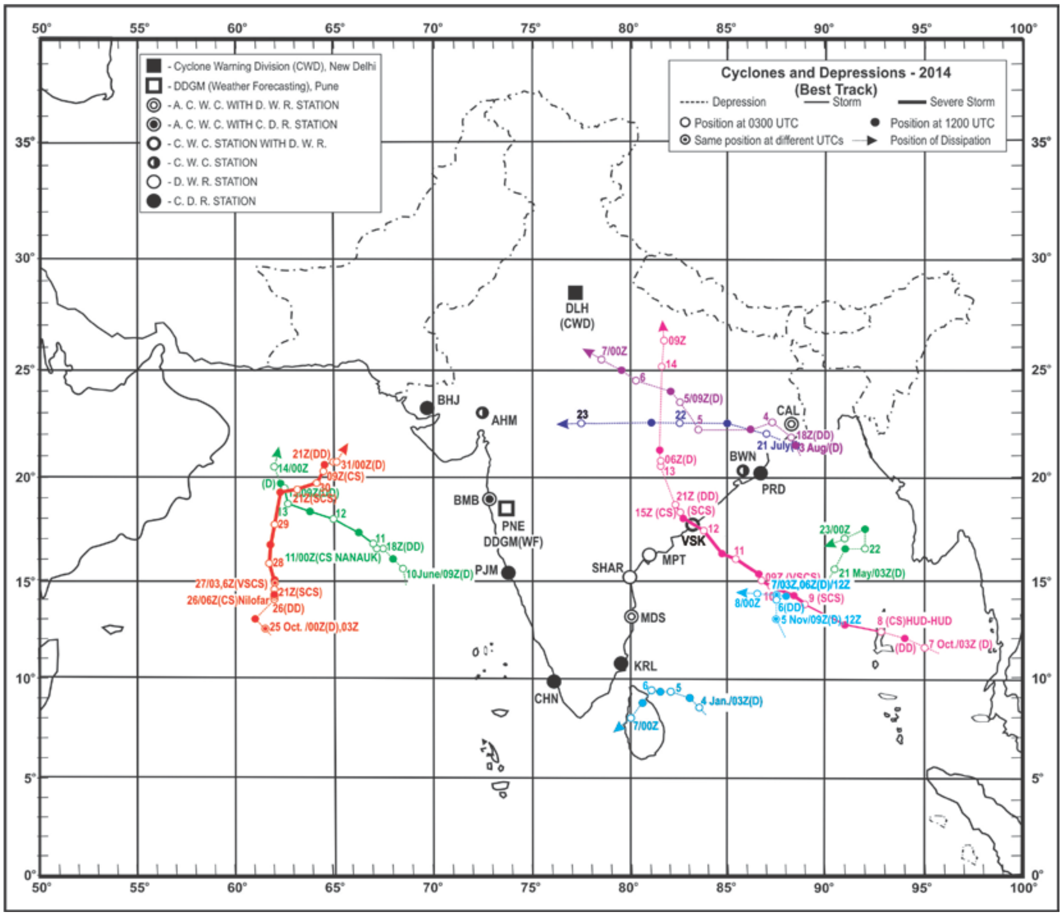


Fig. 2.1 Tracks of the cyclonic disturbances over the north Indian Ocean and adjoining land regions during the year, 2014

2.1. Depression over Bay of Bengal (4 – 7th January, 2014)

2.1. 1. Introduction

A depression formed over the southwest Bay of Bengal on 4th January 2014. It moved west-north-westwards initially and then westwards and crossed Sri Lanka coast near lat. 9.2^{0}N long. 80.8^{0}E between 0500 UTC and 0600 UTC of 06th January 2014. It then moved southwestwards across Sri Lanka and weakened gradually into a well-marked low pressure area over Sri Lanka and adjoining Gulf of Mannar at 0300 UTC of 07th January 2014. The salient features of this depression are given below.

i. It was the first cyclonic disturbance in the month of January after 2005. The cyclonic storm (HIBARU) formed during 13th - 17th January 2005 over the Bay of Bengal. It however weakened into a well-marked low pressure area over the Bay of Bengal and adjoining Equatorial Indian Ocean while moving westwards.
ii. This is the only cyclonic disturbance formed over southwest Bay of Bengal in January which crossed Sri Lanka coast as per the records of IMD (1891 onwards).
iii. The low vertical wind shear around the depression centre throughout its life period helped it to maintain the intensity of depression till landfall.

2.1. 2. Monitoring and prediction

The depression was mainly monitored by satellite. The half hourly INSAT/ Kalpana imageries and products, Oceansat-II surface winds along with the products from newly launched INSAT-3D satellite and other internationally available satellite products were also used for monitoring of this depression. Various numerical weather prediction (NWP) models and statistical-dynamical models including IMD's global and meso-scale models were utilized to predict the genesis, track and intensity of the depression. Tropical Cyclone Module in the digitized forecasting system of IMD was utilized for analysis and comparison of various observational and NWP model products and decision making process.

2.1. 3. Genesis

Under the influence of an active inter-tropical convergence zone, a low pressure area formed over southeast and adjoining southwest Bay of Bengal at 0300UTC of 2nd January. It moved northwestwards and became a well-marked low at 0300 UTC of 3rd January.It concentrated into a depression at 0300 UTC of 4th January, 2014 and lay centred over southwest Bay of Bengal near latitude 8.5^{0}N and longitude 83.5^{0}E, about 470 km southeast of Nagapatinam and 250 km east of Trincomalee(Sri Lanka). The OceanSat wind data indicated cyclonic circulations with wind speed of 25-30 knots around the system centre. The winds were stronger in the northern semicircle of the system. The low level convergence along with low level relative vorticity and upper level divergence increased from 3rd to 4th January favouring cyclogenesis. The sea surface temperature was 26^o-28^{o}C and ocean thermal energy was 60-80 kJ/cm^2 around system centre. The vertical wind shear was moderate (10 – 20 kts) which was favourable for cyclogenesis. Satellite imageries indicated intense to very intense convection with lowest cloud top temperature of about -75^{o}C.

The best track parameters are shown in Table 2.1.1. The track of the system is shown in Fig.2.1. The typical satellite imageries of depression are shown in Fig.2.1.1 respectively. The IMD GFS model analysis of wind at 10m, 850 hPa, 500 hPa and 200 hPa levels are shown in Fig.2.1.2 based on 0000 UTC of 4 – 7th January 2014.

Table 2.1.1 Best track positions and other parameters of the Depression over the Bay of Bengal during 04-07 January, 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
04/01/2014	0300	08.5/83.5	1.5	1006	25	3	D
	0600	09.0/83.0	1.5	1006	25	3	D
	1200	09.0/83.0	1.5	1006	25	3	D
	1800	9.2/82.5	1.5	1006	25	3	D

05/01/2014	0000	9.3/82.0	1.5	1006	25	3	D
	0300	9.3/82.0	1.5	1006	25	3	D
	0600	9.3/81.8	1.5	1006	25	3	D
	1200	9.3/81.5	1.5	1004	25	4	D
	1800	9.3/81.3	1.5	1004	25	4	D
06/01/2014	0000	9.3/81.3	1.5	1004	25	4	D
	0300	9.4/81.0	1.5	1006	25	4	D
	0600	9.0/80.7	Crossed Sri-Lanka coast near Lat. 9.2° N Long. 80.8° E between 0500 and 0600 UTC of 6th January 2014				
	1200	8.8/80.6	-	1006	25	3	D
07/01/2014	0000	8.0/80.0	-	1006	25	3	D
	0300	Weakened into a well-marked low pressure area over Sri Lanka and adjoining Gulf of Mannar.					

2.1.4. Intensification and movement

The favourable condition of lower level relative vorticity, lower level convergence, upper level divergence, warmer SST (26-28^{0}C) and associated convection persisted during 4th to 6th January 2014. However as the system came closer to Sri Lanka coast, it experienced relatively colder sea and ocean thermal energy of less than 50 KJ/cm^2. Further, the system interacted with land surface from 6th January onwards as it lay close to the coast. The convection was sheared to the west of system centre. As a result the depression did not intensify further and gradually weakened after crossing the coast. The southwestward movement of the system over Sri Lanka was also not favourable for maintaining the intensity of the system. The Madden Julian Oscillation (MJO) index lay in phase 6
with amplitude less than 1 during the life period of the depression. The phase 6 is not favourable for intensification of the system over Bay of Bengal. The depression lay to the south of upper tropospheric ridge which ran along lat 11^{0}N on 4th January 2014. It led to west-northwestwards movement of the depression initially. However from 5th onwards, the upper tropospheric ridge shifted northwards and lay along 13^0 N on 6th January. It led to more westward component of the movement of depression. With the gradual weakening of the system over Sri Lanka, it was steered southwestwards under the influence of the easterly waves and northeast monsoon circulation.

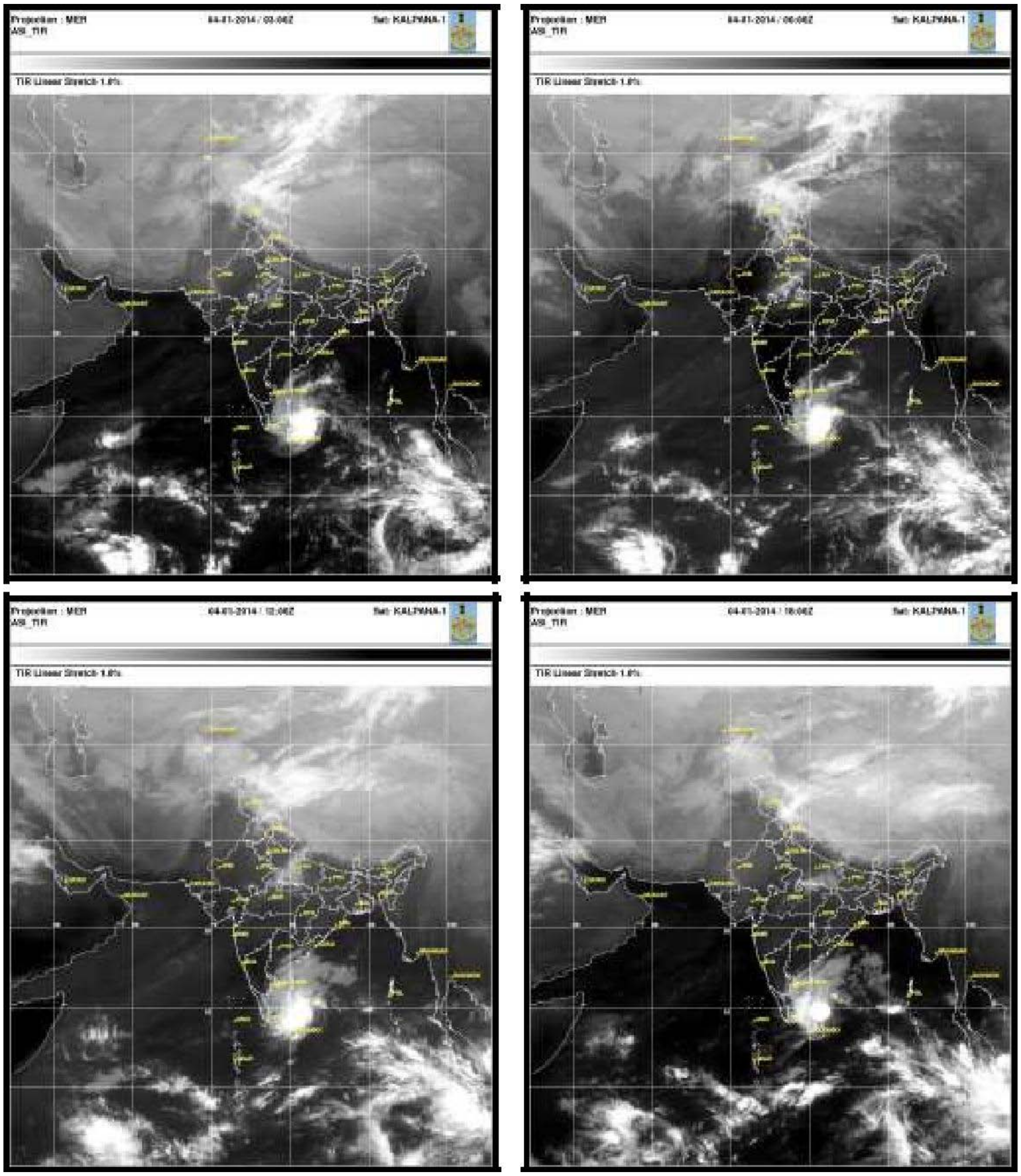


Fig. 2.1.1(a). Kalpana-1 satellite imageries of depression over the Bay of Bengal at 03, 06,12 & 18 UTC of 4th January

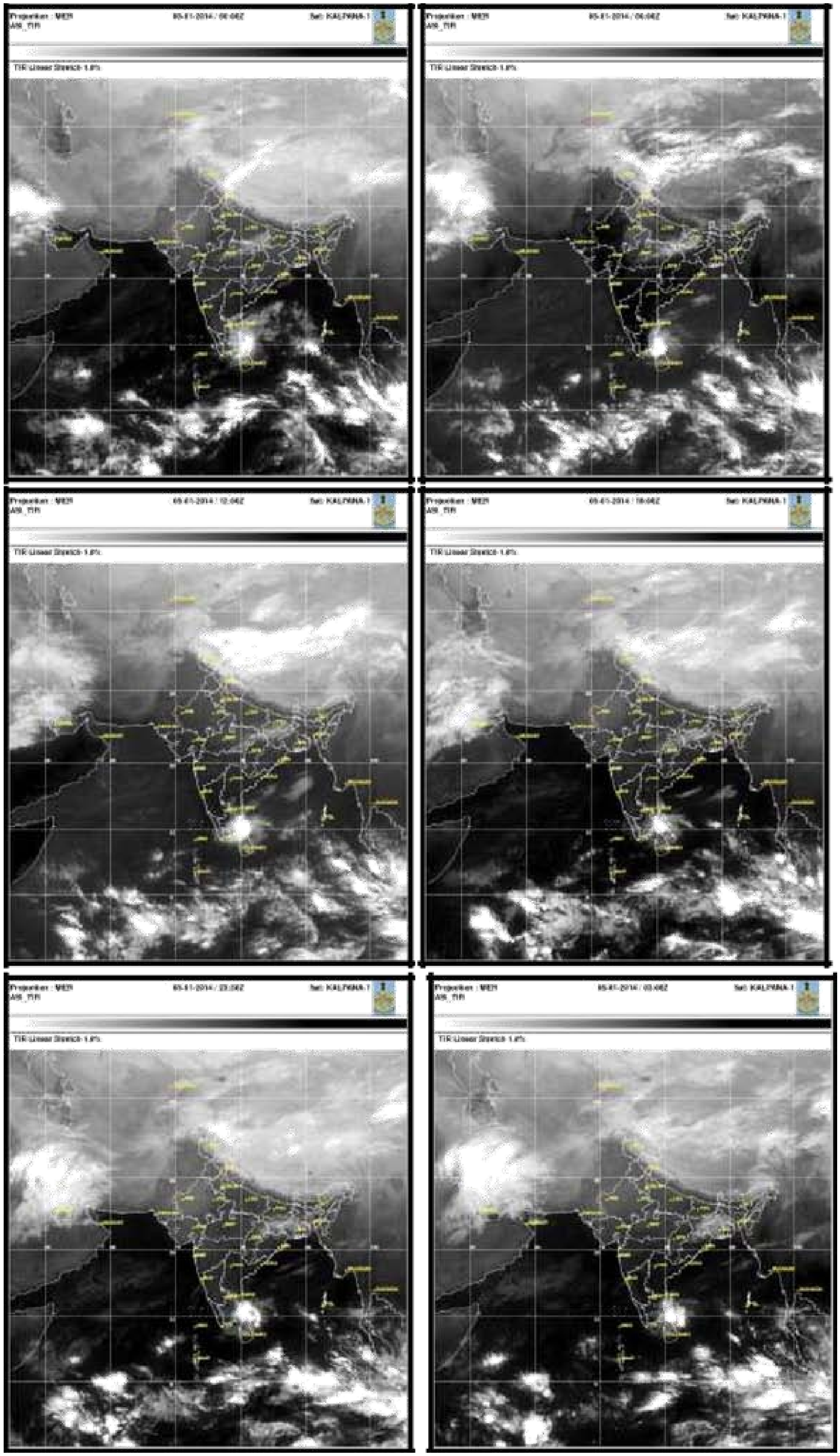


Fig. 2.1.1(b) Kalpana-1 satellite imageries of depression over the Bay of Bengal at 00, 06,12& 18 UTC of 05th, 00 & 03UTC of 6th January 2014.

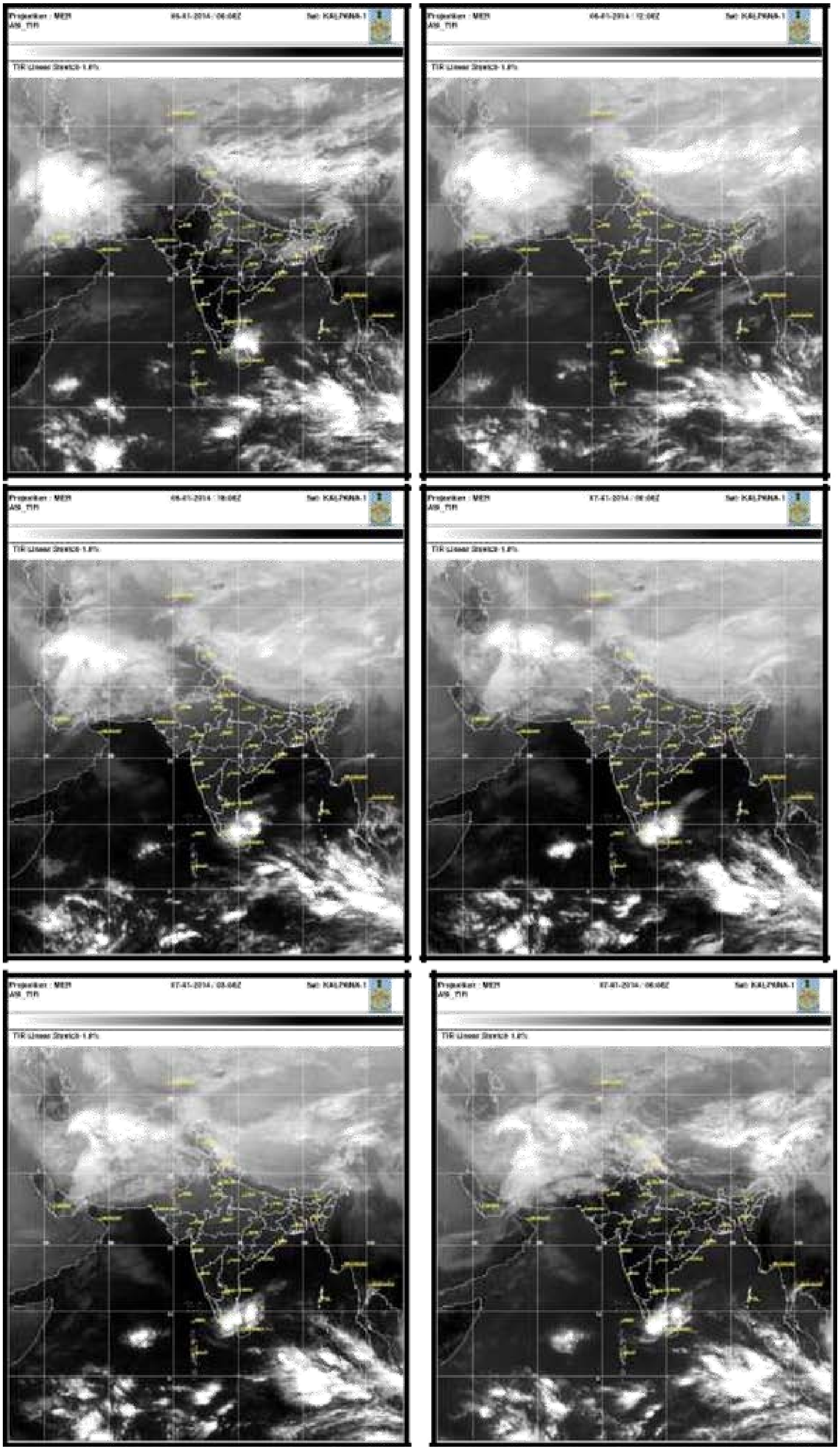


Fig. 2.1.1(c). Kalpana-1 satellite imageries of depression over the Bay of Bengal at 06,12 &18 of 6th and 00,03 & 06 UTC of 7th January 2014

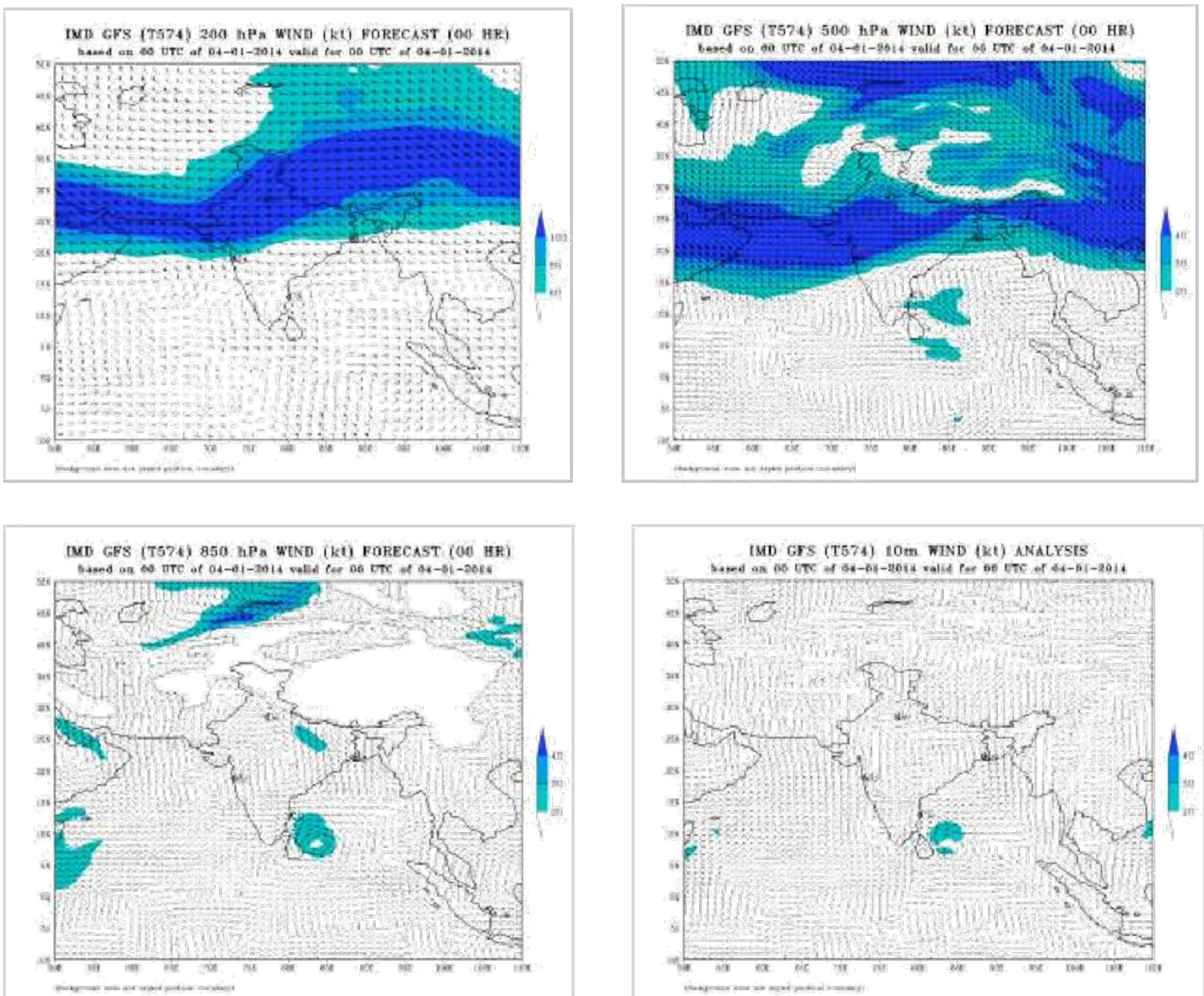


Fig. 2.1.2 IMD GFS winds at 850, 500 & 200 hPa levels and 10meter wind based on 00 UTC of 04th January, 2014.

2.1.6. Realized Weather: India:

Chief amounts of 24 hrs. Rainfall (1 cm or more) ending at 0300 UTC of 08th January, 2014 are given below:

Rameswaram-5, Manimutharu-4, Vedaranyam-4, Kanyakumari-3, Tondi-3, Vedaranyam-3, Pamban-2, Nagercoil-2, Nanguneri-2, Sivaganga-2, Ottapadiram-2, R.S.Mangalam-2, Papanasam-2, Radhapuram-2, Tirupuvanam-2, Ambasamudram-2, Srivaikuntam-2, Palayamkottai-2, Cheranmahadevi-2, Tiruvadanai-1, Ramanathapuram-1, Paramakudi-1, Muthupet-1, Manamadurai-1, Thiruthuraipoondi-1, Arantangi-1, Colachel-1, Tuticorin-1, Tiruchendur-1, Madurai(AP) -1, Pamban-1, Ramanathapuram-1

Sri Lanka:

As estimated by satellite imagery and products, the sustained maximum wind of 25 knots prevailed along and off Sri Lanka coast, when the depression crossed this coast.

Chief amounts of 24 hrs. Rainfall (1 cm or more) ending at 0300 UTC during January 2014 are given below:

4th Jan 2014:
Jaffna-close to the Northern coast: 3;

5th Jan 2014:
Jaffna 3, Trincomalee- 10; Mannar 5; Anuradhapura1

6th Jan 2014:
Vavuniya21; Puttalam8; Anuradhapura and Trincomalee- 5 each; Jaffna2; Mannar 1.

7th Jan 2014:
Jaffna3; Mannar- 2; Anuradhapura, Puttalam, Trincomalee and Vavuniya1 each.

8th Jan 2014:
No station reported 1 cm or more rainfall.

The realised rainfall as per the gridded rainfall data of IMD/NCMRWF based satellite estimation over sea area and point rainfall over land region during 2-8 January, 2014 are shown in Fig.2.1.3. It indicates that the maximum rainfall occurred over the left forward sector of the depression. The rainfall intensity was maximum (8-16 cm) during 3-5th January, 2014.

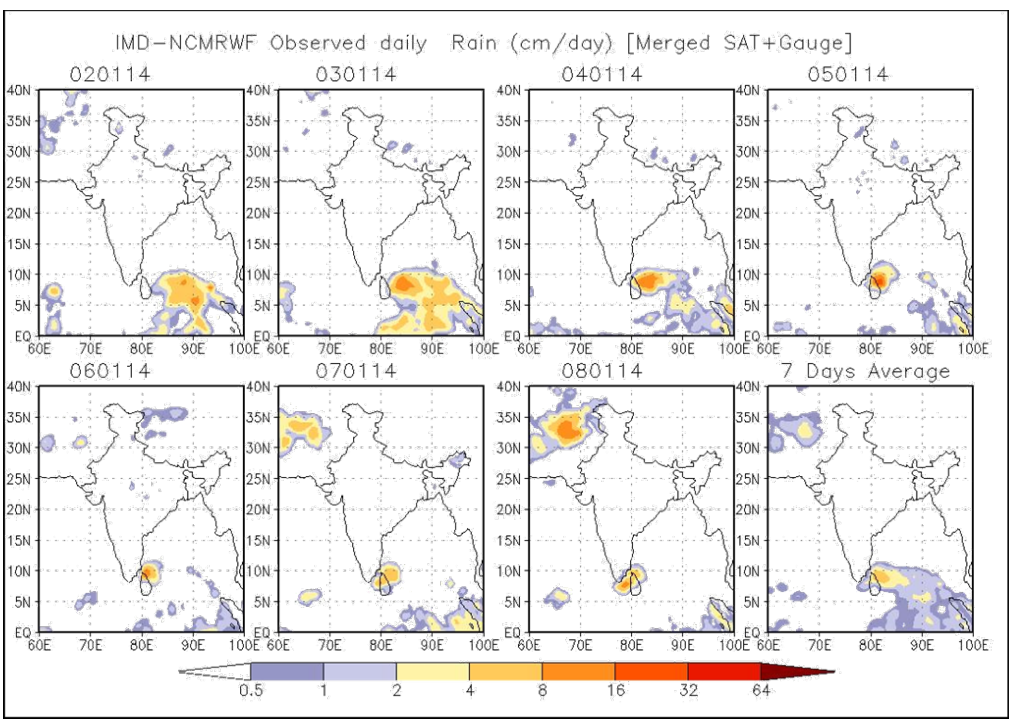


Fig. 2.1.3 Daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during 2-8 January 2014.

2.2 Depression over Bay of Bengal (21–23May,2014)

2.2.1. Introduction

A depression formed over eastcentral Bay of Bengal on 21st May2014. It moved north-northeastwards initially and then southwestwards and weakened into a well-marked low pressure area over central Bay of Bengal in the morning of 23rd May 2014.The salient features of this depression is given below.

Though the depression weakened over the sea, its remnant low pressure area moved across Odisha causing heavy rainfall over Odisha and adjoining areas.

The monitoring and prediction procedure along with the brief life cycle of the depression and associated adverse weather, warnings issued by IMD and its verification are described below.

2.2.2 Monitoring and prediction

The depression was mainly monitored by satellite. The half hourly INSAT3D/ Kalpana imageries, and products, ASCAT surface winds and other internationally available satellite products were used for monitoring of this depression. Various numerical weather prediction (NWP) models and dynamical-statistical models including IMD's global and meso-scale models and models run at NCMRWF were utilized to predict the genes is track and intensity of the depression. Tropical Cyclone Module in the digitized forecasting system of IMD was utilized for analysis and comparison of various observational and NWP models products and decision making process.

2.2.3 Genesis

Under the influence of an active on soon surge ,an upper air cyclonic circulation formed over north Andaman Sea and neighbourhood extending up to 4.5 km above mean sea level (amsl) on 17th May. It persisted over the same area and extended up to 5.8km (amsl) on 18th. Under its influence, a low pressure area formed over southeast and adjoining eastcentral Bay of Bengal at 0300 UTC of 19th May 2014. It moved northwestwards and became a wellmarked low at 0300 UTC of 20th May 2014. It concentrated in to a depression at 0300 UTC of 21st May 2014 over east central Bay and lay centred near latitude 15.5^{0}N and longitude 90.5^{0}E, about 490 km north-northeast of Port Blair. The ASCAT winds data indicated cyclonic circulations with wind speed of 20-25 knots around the system centre. The winds were stronger in the southern semicircle of the system in association with monsoon surge. The low level convergence along with low level relative vorticity and upper level divergence increased from 20th to 21st May2014 favouring cyclogenesis. The sea surface temperature was 30-32^{0}C and ocean thermal energy was 60-80kJ/cm^2 around the system centre. The vertical wind shear was moderate to high (15 –30 knots). Satellite imageries indicated intense to very intense convection with lowest cloud top temperature of about -75^{0}C.The system had shear pattern as per the Dvorak's intensity classification and the T number was 1.5.

The best track parameters are shown in Table 2.2.1. The track of the system is shown in Fig.2.1. The typical satellite imageries of depression are shown in Fig.2.2.1. The IMD GFS model analysis charts based on 0000 UTC of 21-27 May 2014 are shown in Fig.2.2.2.

2.2.4 Intensification and movement

The favourable conditions of lower level relative vorticity, lower level convergence, upper level divergence, warmer SST (26-28^{0}C) and associated convection persisted during 21st to 23rd May 2014. The system was mainly steered by the mid-tropospheric flow. As the system lay close to the ridge in the middle level it could not follow any persistent direction of movement. As a result, it initially moved northeastwards and then recurred southwestwards as shown in fig2. How ever due to increase in vertical winds hear which became high since 22nd evening, the depression weakened into a well-marked low pressure area on 23rd May 2014. The well-marked low pressure area moved west-northwestwards and lay over west central and adjoining northwest Bay of Bengal off south Odisha and north Andhra Pradesh coasts on 25th,over south coastal Odisha and neighbourhood on 26th and over Odisha and neighbourhood on 27th. There after it weakened in to a low pressure area over east Bihar and neighbourhood on 28th and over Sub-Himalayan West Bengal and adjoining Bangladesh on 29th. It became less marked on 30th.

Table 2.2.1:Best track positions and other parameters of the Depression over the Bay of Bengal during 04-07 May 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
21/05/2014	0300	15.5/90.5	1.5	1004	25	3	D
	0600	16.0/90.5	1.5	1004	25	3	D
	1200	16.5/91.0	1.5	1002	25	4	D
	1800	16.5/91.0	1.5	1002	25	3	D
22/05/2014	0000	16.5/92.0	1.5	1000	25	3	D
	0300	16.5/92.0	1.5	1000	25	3	D
	0600	17.0/92.5	1.5	1000	25	3	D
	1200	17.5/92.0	1.5	1000	25	4	D
	1800	17.5/92.0	1.5	1000	25	4	D
23/05/2014	0000	17.0/91.0	1.5	1000	25	4	D
	0300	Weakened into a well-marked low pressure area over Bay of Bengal					

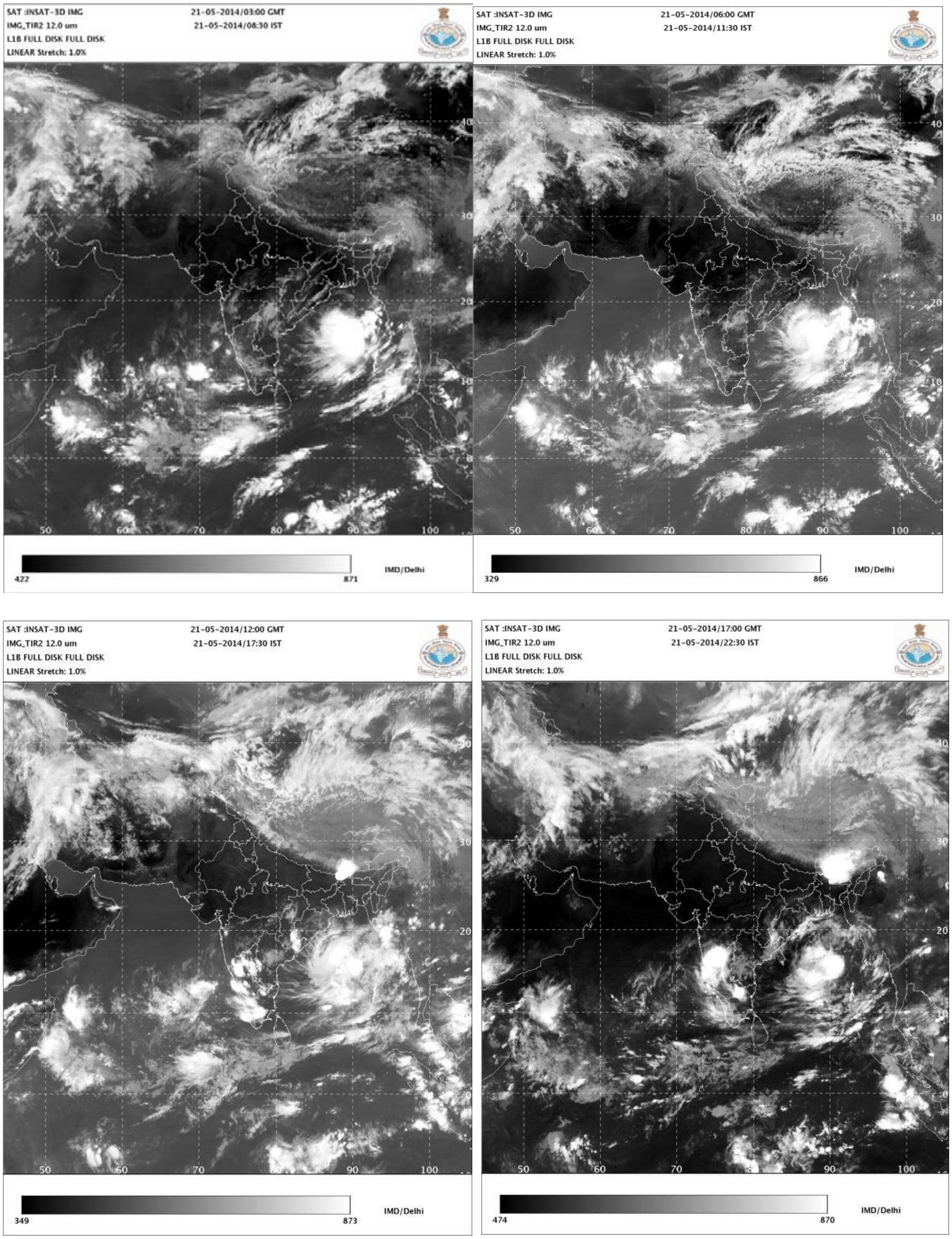


Fig.2.2.1(a)INSAT-3D satellite imageries of depression over the Bay of Bengal at 0300,0600, 1200& 1800UTC of 21st May 2014.

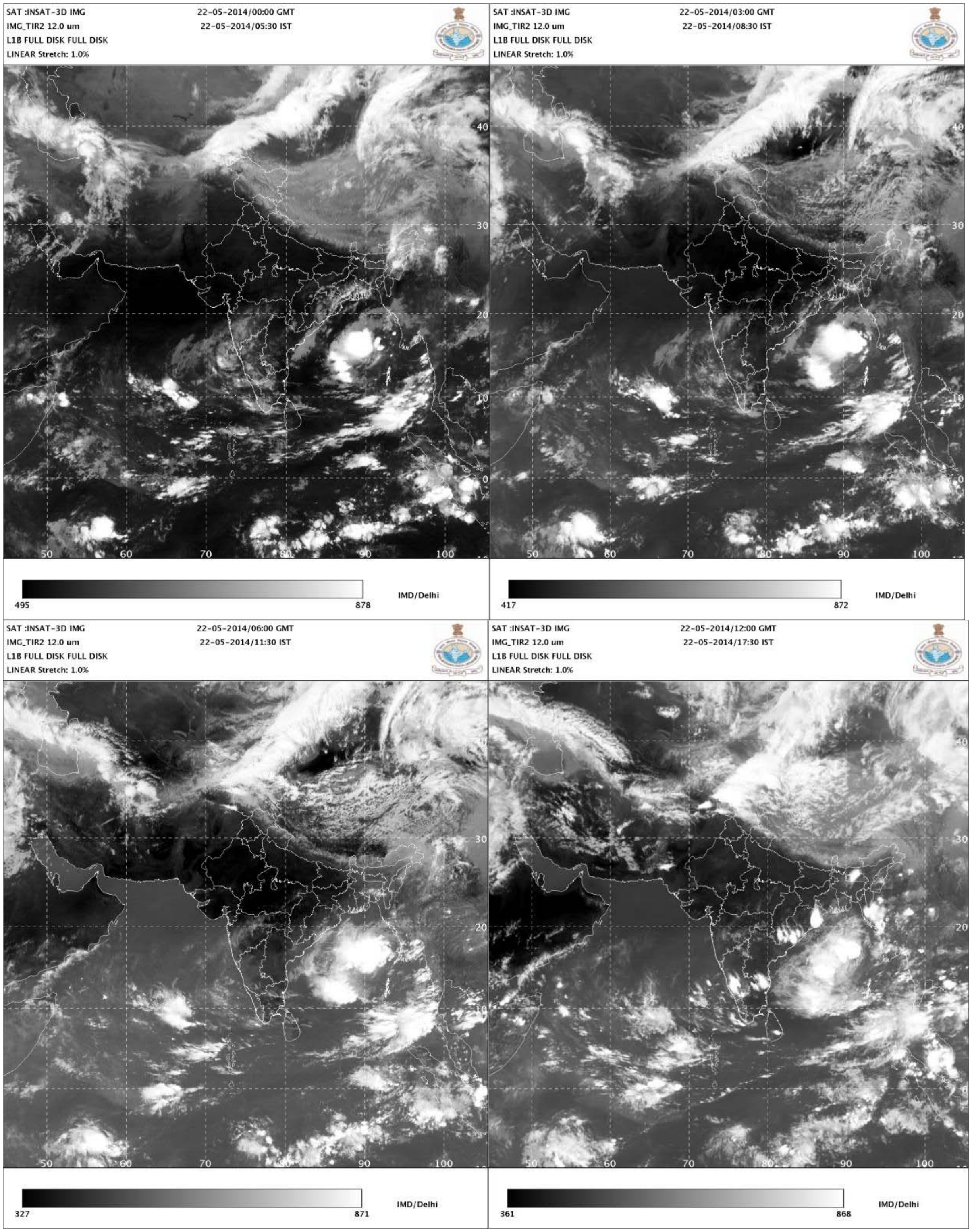


Fig. 2.2.1(b) INSAT-3D satellite imageries of depression over the Bay of Bengal at 0000,0300, 0600 & 1200UTC of 22nd May 2014

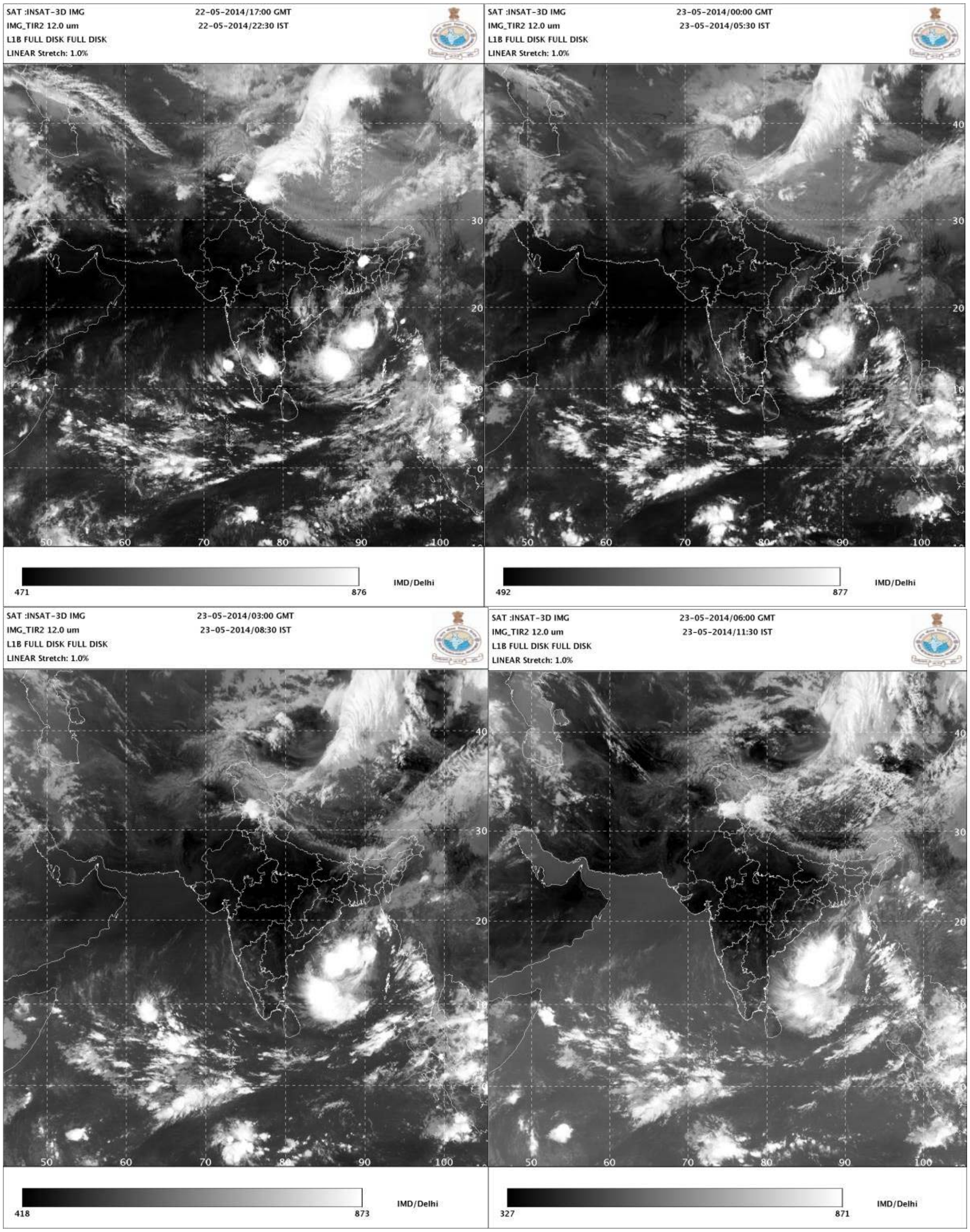


Fig. 2.2.1(c).INSAT-3D satellite imageries of depression over the Bay of Bengal at 1800 UTC of 22nd May 0000, 0300 & 0600 UTC of 23rd May 2014.

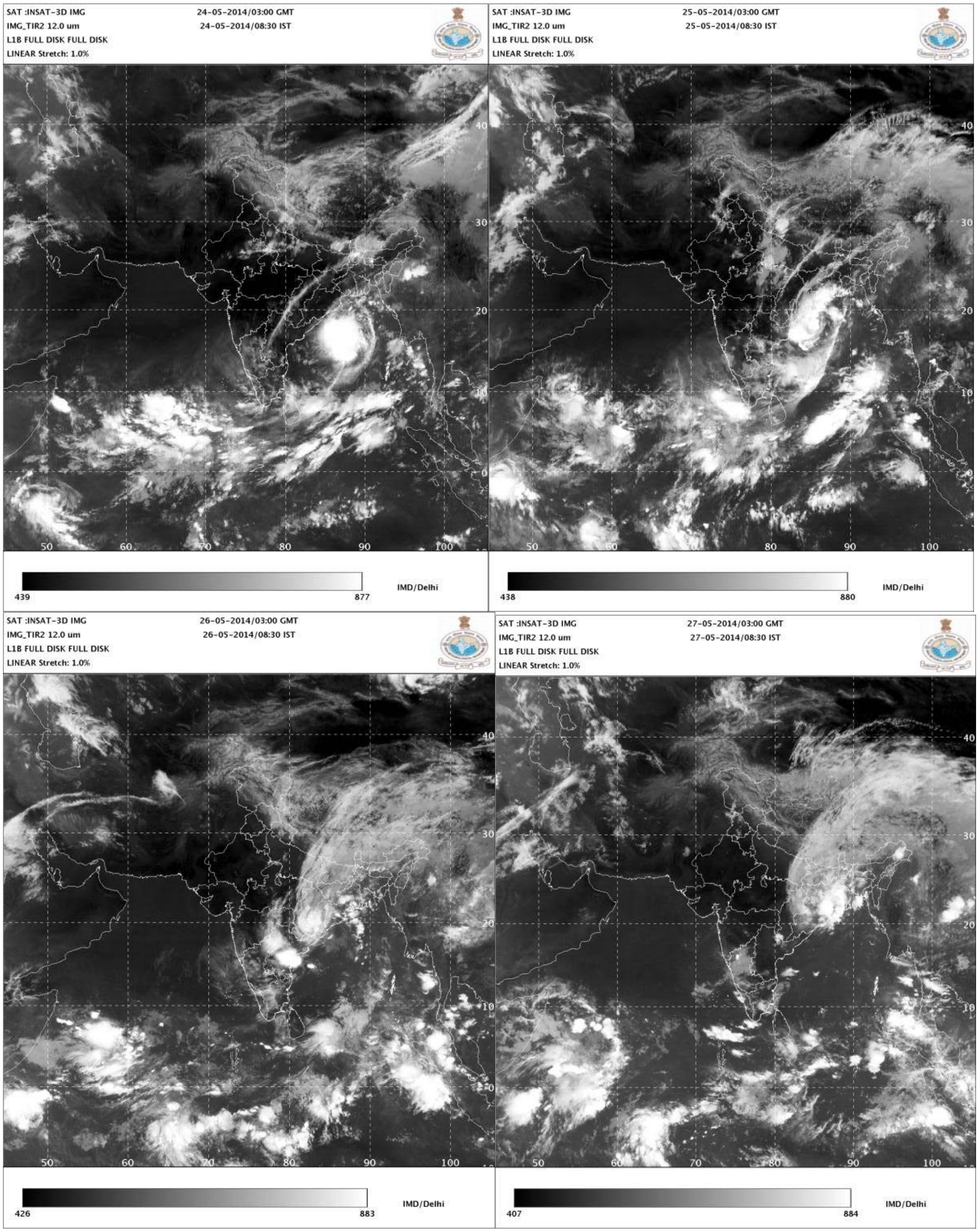


Fig. 2.2.1(d)INSAT-3D satellite imageries of depression and its remnants over the Bay of Bengal at 0300 UTC of 24th–27thMay2014.

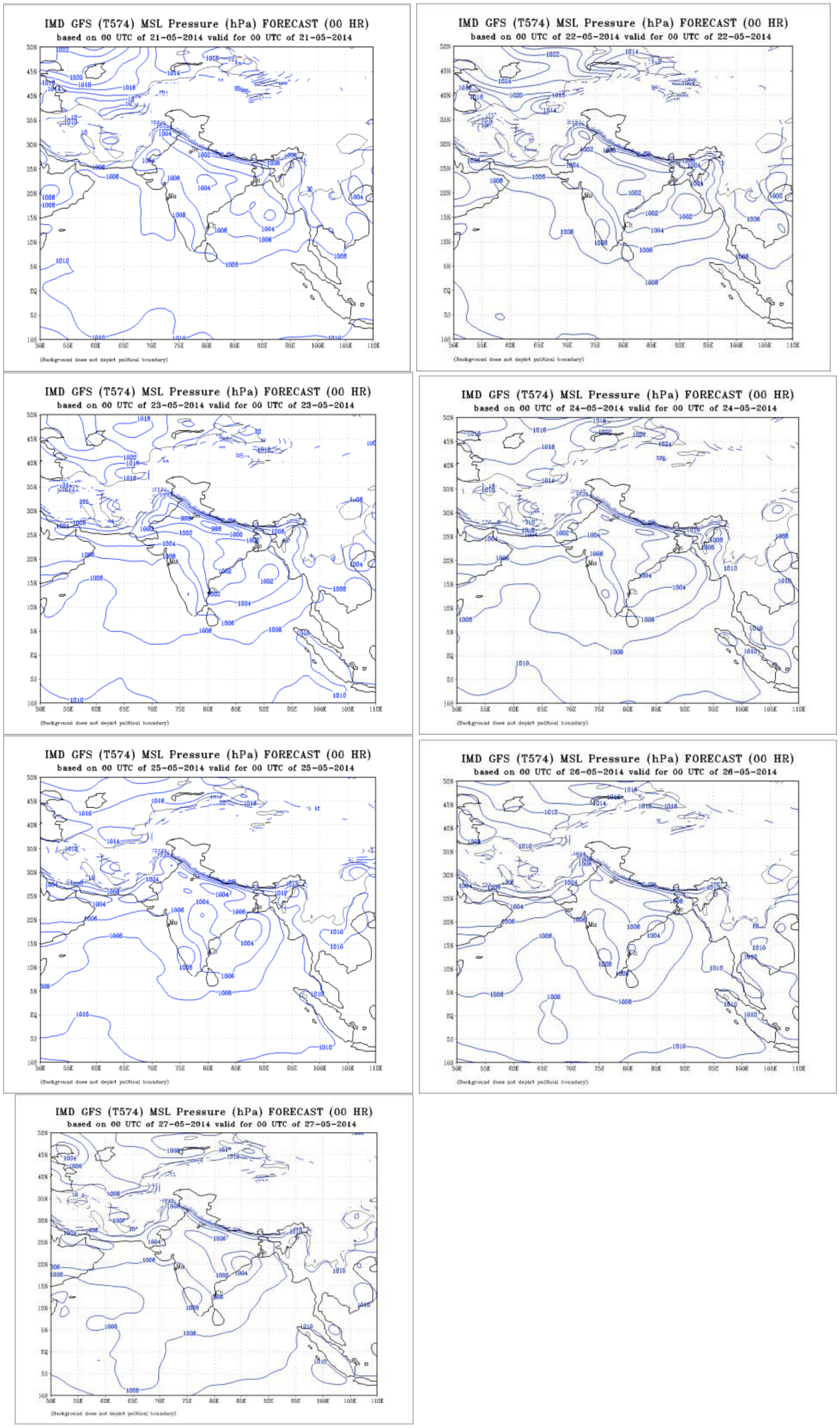


Fig. 2.2.2(a).IMD-GFS MSLP charts based on 0000z on 21st– 27th May 2014

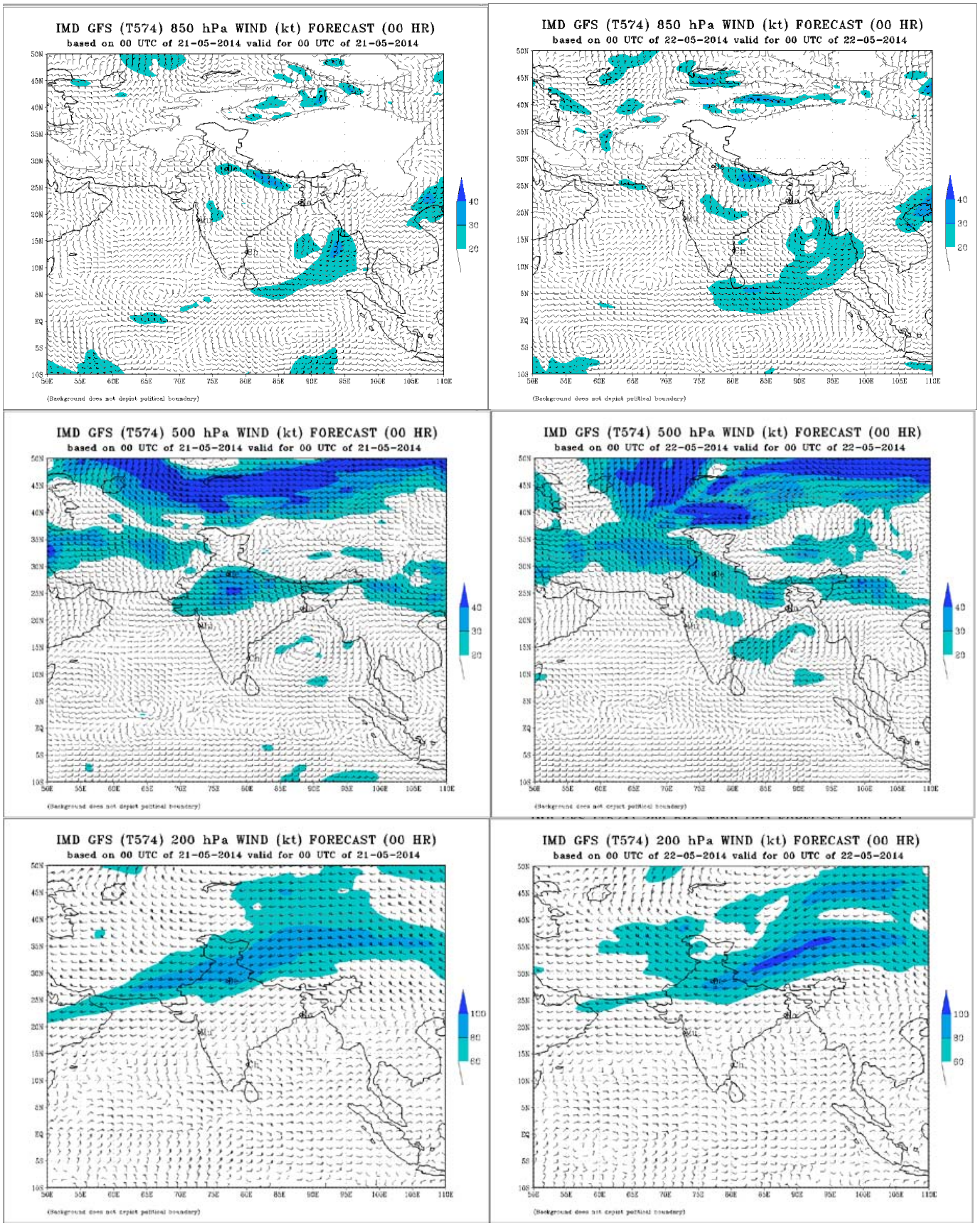


Fig. 2.2.2(b).IMD-GFS analysed charts based on 0000z on 850, 500 and 200 hPa on 21st– 22nd May 2014

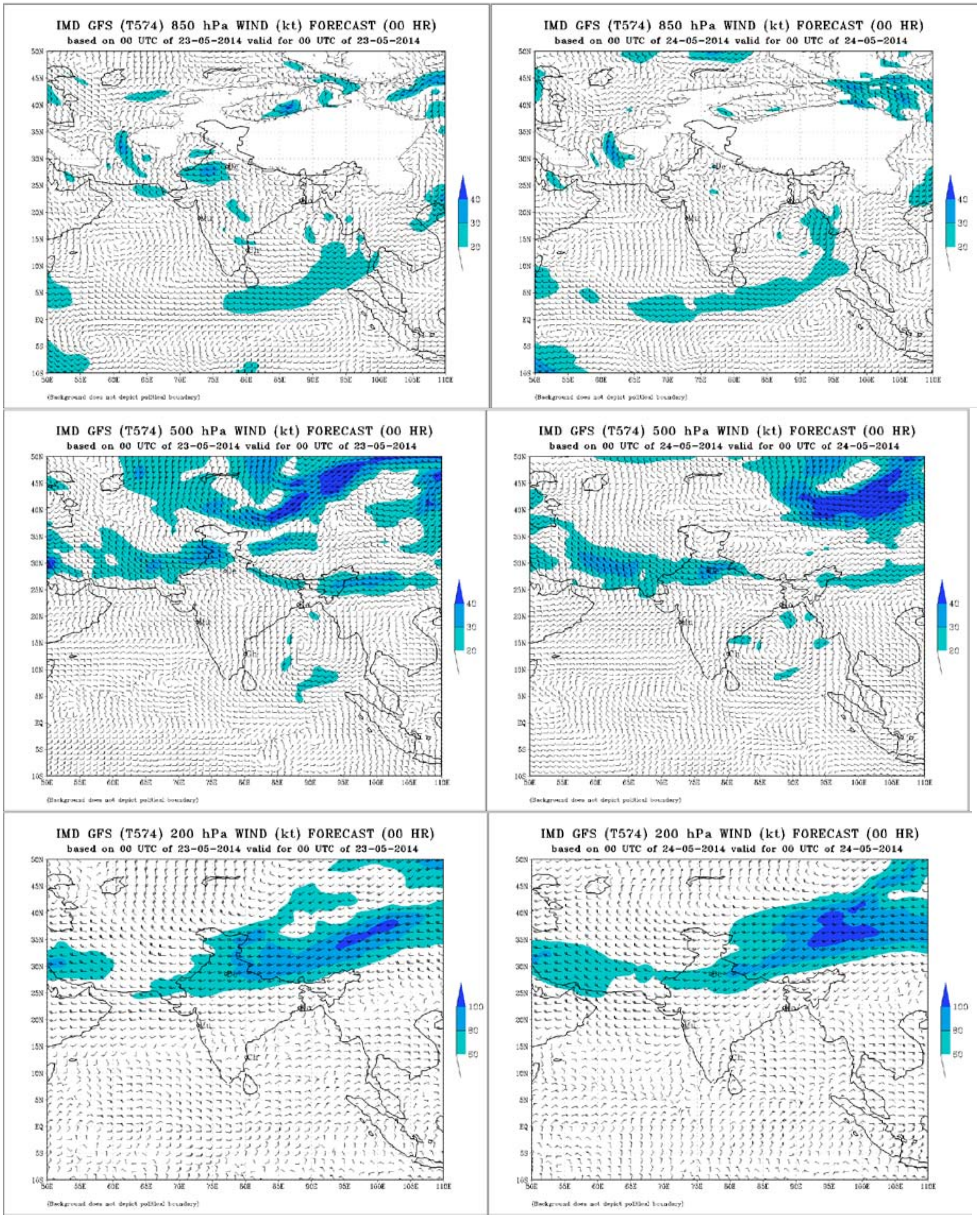


Fig. 2.2.2(c) IMD-GFS analysed charts based on 0000z on 850,500 and 200 hPa on 23rd–24th May 2014

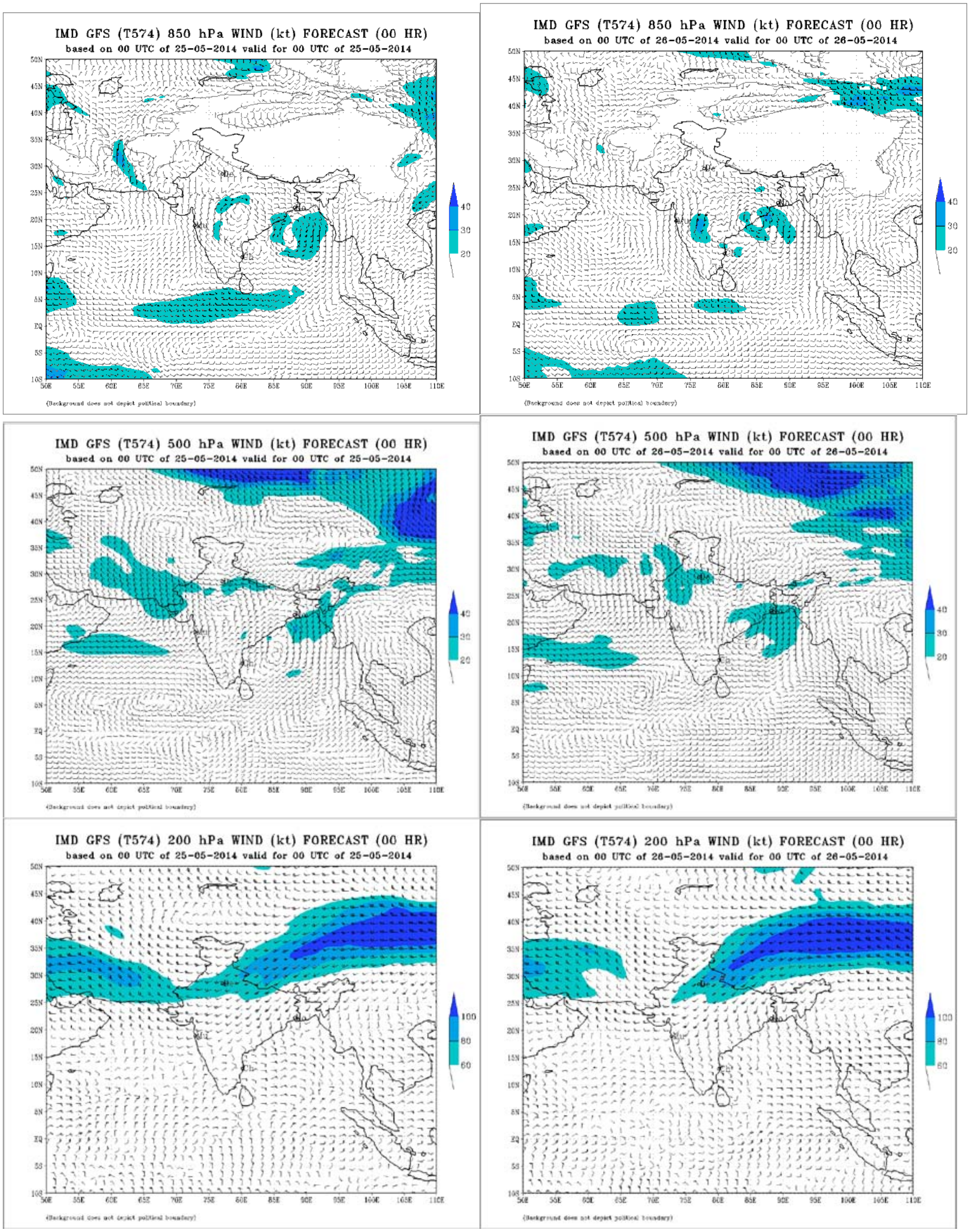


Fig. 2.2.2(d).IMD-GFS analysed charts based on 0000z on 850, 500 and 200 hPa on 25th– 26th May 2014

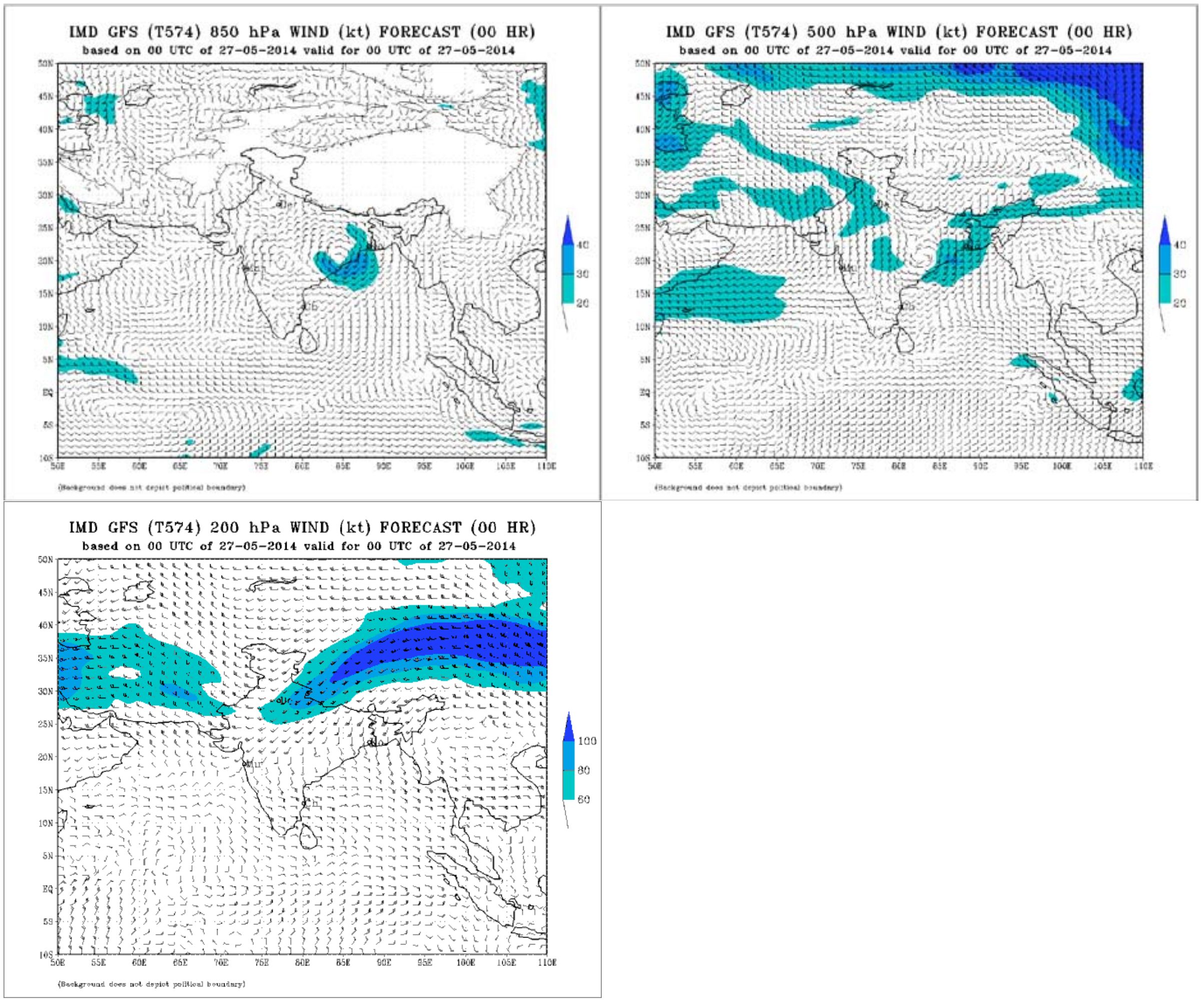


Fig. 2.2.2(e).IMD-GFS analysed charts based on 0000z on 850, 500 and 200hPa on 27th May 2014

2.2.5. Realized Weather:

Chief amounts of 24hrs.Rainfall (7cmormore) ending at 0300 UTC from 22- 27 May 2014 are given below:

26 May2014

COASTALANDHRA PRADESH: Kalingapatnam-23, Tekkali-20,Pathapatnam-19, Palakonda-15,Veeragattam-11,Sompeta-11, Parvatipuram-10,Komarada-9,Palasa-9, Itchapuram, Bobbiliand ,Cheepurupalli7 each

TELANGANA: Miryalguda-8,

ODISHA: Balasore and Gunupur21 each, NH5 Gobindpur and Paralakhemundi-20 each, Kashinagar and Pattamundai19 each, Nuagada ARG-17,Soro, Mahendragarh and TihidiARG-16 each, Dhamnagar ARG, Bhubaneswar Aero, R.Udaigiri and Cuttack-14 each, TirtolARG, Basudevpur AWS and NialiARG-13 each,MahangaARG,Khandapara,Bonth,Nilgiri-12,Kotraguda and Athgarh-12 each, Bissem-Cuttack, Muniguda ARG, Betanati ARG, Jagatsinghpur AWS, Raghunathpur ARG, Salepur ARG, Nischintakoili ARG and BhadrakAWS-11 each, Bari ARG andTikabali-10 each, Binjharpur ARG, Rayagada, Akhuapada, Banki ARG, Chandikhol ARG, Purushottampur, Balikuda ARG, Sorada, Derabis ARG and Gudari-9 each, Chandbali, Kendrapara, Bhograi, Mohana Dhenkanal, Tigiria ARG, Tangi, Jenapur and Kashipur-8 each, Banarpal ARG, Jaipur, Balipatna ARG, Madhabarida, Anandpur, Thakurmunda, Gopalpur, Hindol, Jajpur, Bolagarh ARG, Balimundali, Danagadi ARG, Puri, Daringibadi and Marsaghai ARG-7 each

SUB–HIMALAYAN WESTBENGAL &SIKKIM: Bagrakote-9
GANGETIC WESTBENGAL: Contai-15, Digha-14

27 May2014

ODISHA: Kesinga ARGand Titlagarh-28 each, Bhawanipatna-26, Khariar-25, Komna-23,Junagarh-22,Patnagarh-19,Chandanpur,Paikmal-17 each,Padampur-16,Narla ARG, Balasore and Pattamundai-15 each,Ambabhona,Lanjigarh-14 each,Bolangir,NH5Gobindpur, TarvaARG, JharbandhARG-13 each, Kantamal-11, Betanati ARG,Banki ARG, Kotraguda-10 each, DharmagarhARG, Jajpur,Muniguda ARG, Nilgiri,Tigiria ARG-9 each, Samakhunta AWS, Korei ARG,Tikabali, Bangiriposi, Rajkanika, Akhuapada, Remuna ARG, Rajghat-8 each, Madanpur Rampur, Udala, Gaisilet ARG, Bonth, Kaptipada ARG, Thakurmunda, Boden ARG, Dhamnagar ARG, Nawapara, Joshipur, Sinapali ARG, Tihidi ARG, Jaipur-7each,

JHARKHAND: Rajmahal-25,Dumri-11, Tenughat, Godda-10 each,Hiranpur-8, Ghatsila, Bokaro, Mohanpur-7 each

SUB–HIMALAYANWEST BENGAL&SIKKIM: Ratua ARG-10,

GANGETIC WESTBENGAL: Durgachack-8,

The merged at a of rainfall based on station observed was satellite estimates for the period of 21-27th May 2014 are shown below in Fig.2.2.3.

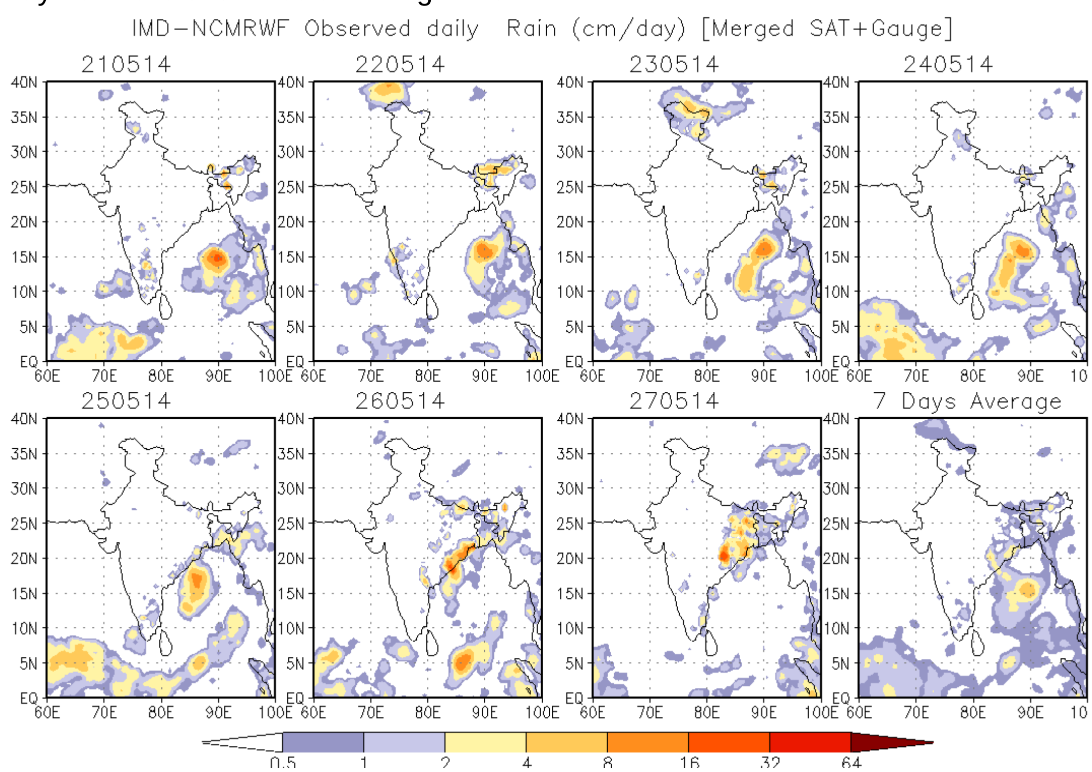


Fig. 2.2.3.Rainfall in merged data set map in association with depression over the Bay of Bengal during 21st–27th May 2014

2.2.6. Damages.

No damage has been reported due to this depression.

2.3 Cyclonic Storm, 'NANAUK' over the Arabian Sea(10-14 June 2014)

2.3.1 Introduction

A Cyclonic Storm (CS) **'NANAUK'** originated from a low pressure area over east central Arabian Sea which developed on 9th June, 2014. It concentrated into a depression over the same region in the afternoon of 10th June, 2014. Moving north-northwestwards, it intensified into a cyclonic storm (CS), **'NANAUK'** in the early morning of 11th June 2014. It weakened into a deep depression in the afternoon of 13th June, 2014 over westcentral Arabian Sea and into a depression in the evening of 1.3 June, 2014 and further into a well marked low pressure area over the same region in the morning of 14th June, 2014. The salient features of this cyclone are given below.

i. It developed in association with the southwest monsoon surge over Arabian Sea during the onset phase
ii. It caused temporary hiatus in progress of monsoon over south India
iii. It weakened over the northwest Arabian Sea on 14th June and its remnant moved northeastwards leading to revival and progress of monsoon along the west coast of India

2.3.2 Monitoring and Prediction:

The cyclonic storm **'NANAUK'** was monitored & predicted continuously since its inception by the India Meteorological Department. The forecast of its genesis, track, and intensity, as well as associated adverse weather were predicted exceedingly well with sufficient lead time which helped the disaster managers to maximize the management of cyclone. The system was monitored mainly with satellite observations, supported by meteorological buoys and coastal and Island observations. Data from conventional observatories and Automatic Weather Stations (AWSs) were also used. The half hourly INSAT/ Kalpana imageries, available microwave imageries and scatteometry products were used for monitoring of the system. Various national and international NWP models and dynamical-statistical models including IMD's global and meso-scale models, dynamical statistical models for genesis and intensity and models run at NCMRWF were utilized to predict the genesis, track and intensity. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance and decision making process and warning product generation.

2.3.3 Genesis

Under the influence of the active southwest monsoon surge over the Arabian Sea during its onset phase, a low level cyclonic circulation formed on 9th June morning. It concentrated into a vortex (T=1.0 as per Dvorak's analysis) in the evening of 09th June, which corresponded to a low pressure area over the east central Arabian Sea. It became a well marked low pressure area over the same region in the morning of 10th June. It concentrated into a depression over the same region in the afternoon of 10th June. According to satellite imagery and Dvorak's technique, the intensity was T1.5. The lowest cloud top temperature was about -75^{0}C. The maximum sustained wind speed was about 25 knots. However, the wind speed was higher in the southern sector in association with the southwest monsoon surge.

Considering the environmental conditions, the sea surface temperature (SST) was 30-32^{0}C. The tropical cyclone heat potential was about 60-80 kJ/cm^2. The vertical wind shear of horizontal wind was about 20-30 knots between upper and lower tropospheric level. There was increase in low level vorticity, lower level convergence and upper level divergence from 9th to 10th June favouring genesis of the depression. The Madden Julian Oscillation index lay in phase 3 (east equatorial |Indian Ocean) with amplitude less than 1. The past studies indicate that phase 3 is favourable for cyclogenesis. However, the amplitude was not favourable for further intensification.

The best track parameters are shown in Table 2.3.1 and the best track is shown in Fig.2.1.

2.3.4 Intensification and movement

As the favourable environmental parameters like vorticity and divergence/convergence continued to prevail on 10th and 11th, even though the vertical wind shear and MJO index were not favourable, the depression moved west-northwestwards and intensified into a deep depression around midnight of 10th June, 2014 and further into a cyclonic storm (CS), **'NANAUK'** in the early morning of 11th June 2014. It continued to move west–northwestward for some more time till early morning of 13th June. It then moved northwestwards for some time and finally northwards to westcentral and adjoining northwest Arabian Sea till afternoon of 13th June, where it weakened into a deep depression and further weakened into a depression in the evening of 13th due to increase in vertical wind shear, entrainment of dry air and relatively colder SST. It then moved northwards to northwest and adjoining westcentral Arabian Sea. It weakened into a well marked low pressure area over the same region in the morning of 14th June, 2014.

According to satellite imageries, the initial curved band pattern changed to central dense overcast (CDO) pattern as the system intensified into a cyclonic storm. The maximum intensity was T 3.0 corresponding to 45 knots. The lowest estimated central pressure was about 986 hPa. The CDO pattern changed to the shear pattern due to increase in vertical wind shear during the weakening of the system on 13th. The cloud mass was sheared to the southwest of the centre of low level circulation. There was rapid weakening as the cyclonic storm weakened in to depression (40 kts to 25 kts) during six hrs (from 0600 UTC to 1200 UTC of 13th June). It was mainly due to high vertical wind shear which was about 30-40 knots. To highlight the satellite features, the typical satellite imageries are shown in Fig.2.3.1. The IMD GFS analyses based on 0000 UTC of 10th to 14th June are shown in Fig.2.3.2 to highlight the dynamical features.

Table 2.3.1. Best track positions and other parameters of the Cyclonic Storm 'NANAUK' over the Arabian Sea during 10-14 June, 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
10/06/2014	0900	15.5/68.5	1.5	998	25	3	D
	1200	16.0/68.0	1.5	996	25	3	D
	1800	16.5/67.5	2.0	994	30	5	DD
11/06/2014	0000	16.5/67.2	2.5	992	35	8	CS
	0300	16.7/67.0	2.5	992	35	8	CS
	0600	16.9/66.7	3.0	990	45	10	CS
	0900	17.0/66.5	3.0	990	45	10	CS
	1200	17.3/66.2	3.0	988	45	10	CS
	1500	17.5/66.0	3.0	988	45	10	CS
	1800	17.5/65.8	3.0	988	45	10	CS
	2100	17.5/65.7	3.0	988	45	10	CS
12/06/2014	0000	17.8/65.3	3.0	986	45	10	CS
	0300	18.0/65.0	3.0	986	45	10	CS
	0600	18.1/64.7	3.0	986	45	10	CS
	0900	18.3/64.3	3.0	988	45	10	CS
	1200	18.3/63.9	3.0	988	45	10	CS
	1500	18.3/63.6	3.0	988	45	10	CS
	1800	18.3/63.4	3.0	988	45	10	CS
	2100	18.4/63.3	3.0	988	45	10	CS
13/06/2014	0000	18.4/62.9	3.0	988	45	10	CS
	0300	18.7/62.7	3.0	990	45	10	CS
	0600	19.0/62.6	2.5	992	40	8	CS
	0900	19.5/62.5	2.0	994	30	5	DD
	1200	19.8/62.4	1.5	996	25	3	D
	1800	20.0/62.0	1.5	996	25	3	D
14/06/2014	0000	20.5/62.0	1.5	996	25	3	D
	0300	Weakened into a well-marked low pressure area over northwest and adjoining westcentral Arabian Sea.					

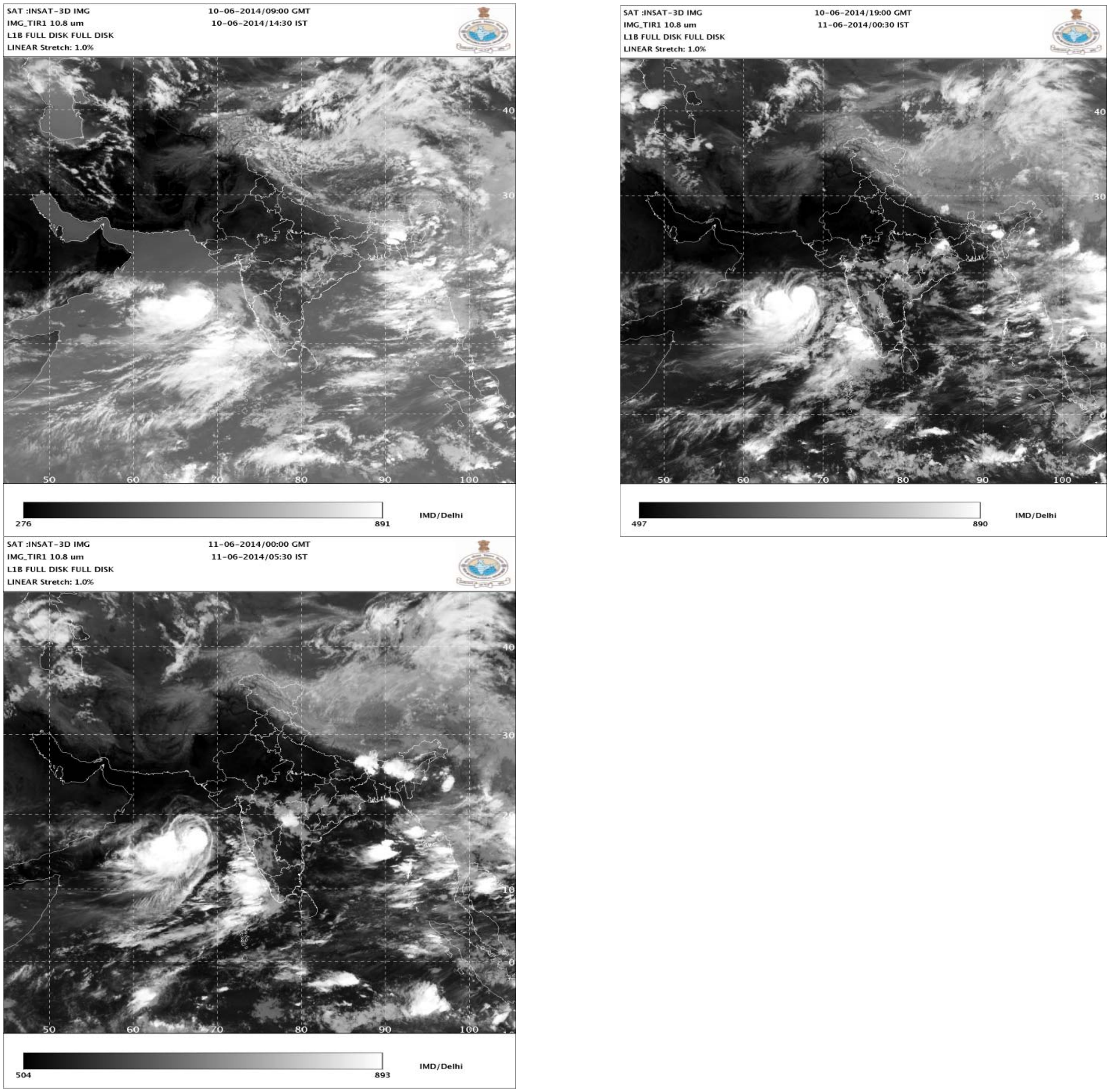


Fig. 2.3.1 Typical INSAT 3D imageries of cyclonic storm 'NANAUK' at 0900,1900 UTC of 10th June and 0000 UTC of 11th June.

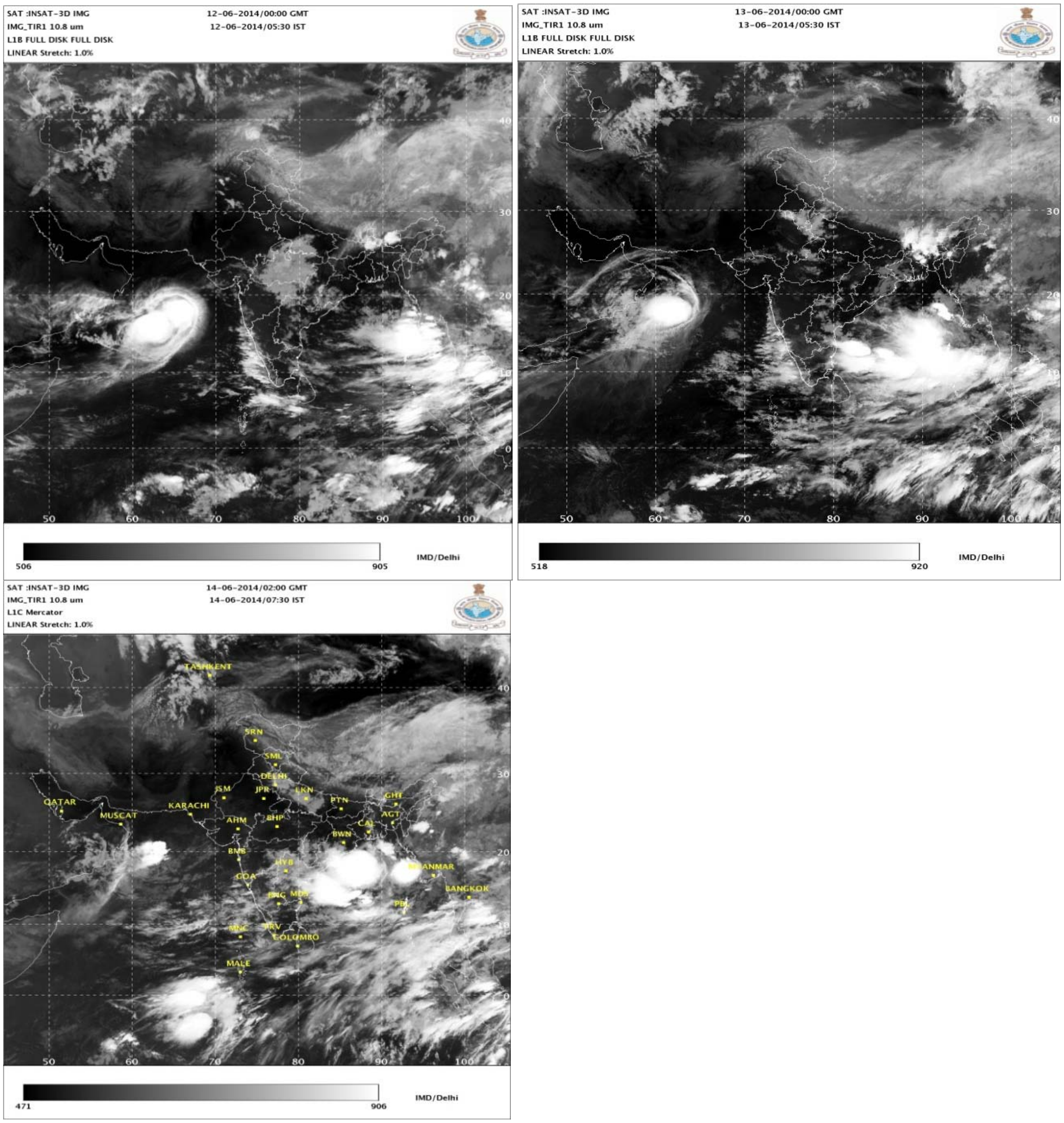


Fig. 2.3.1(Contd) Typical INSAT 3D imageries of cyclonic storm 'NANAUK' at 0000 UTC of 12 & 13thJune and 0200 UTC of 14th June.

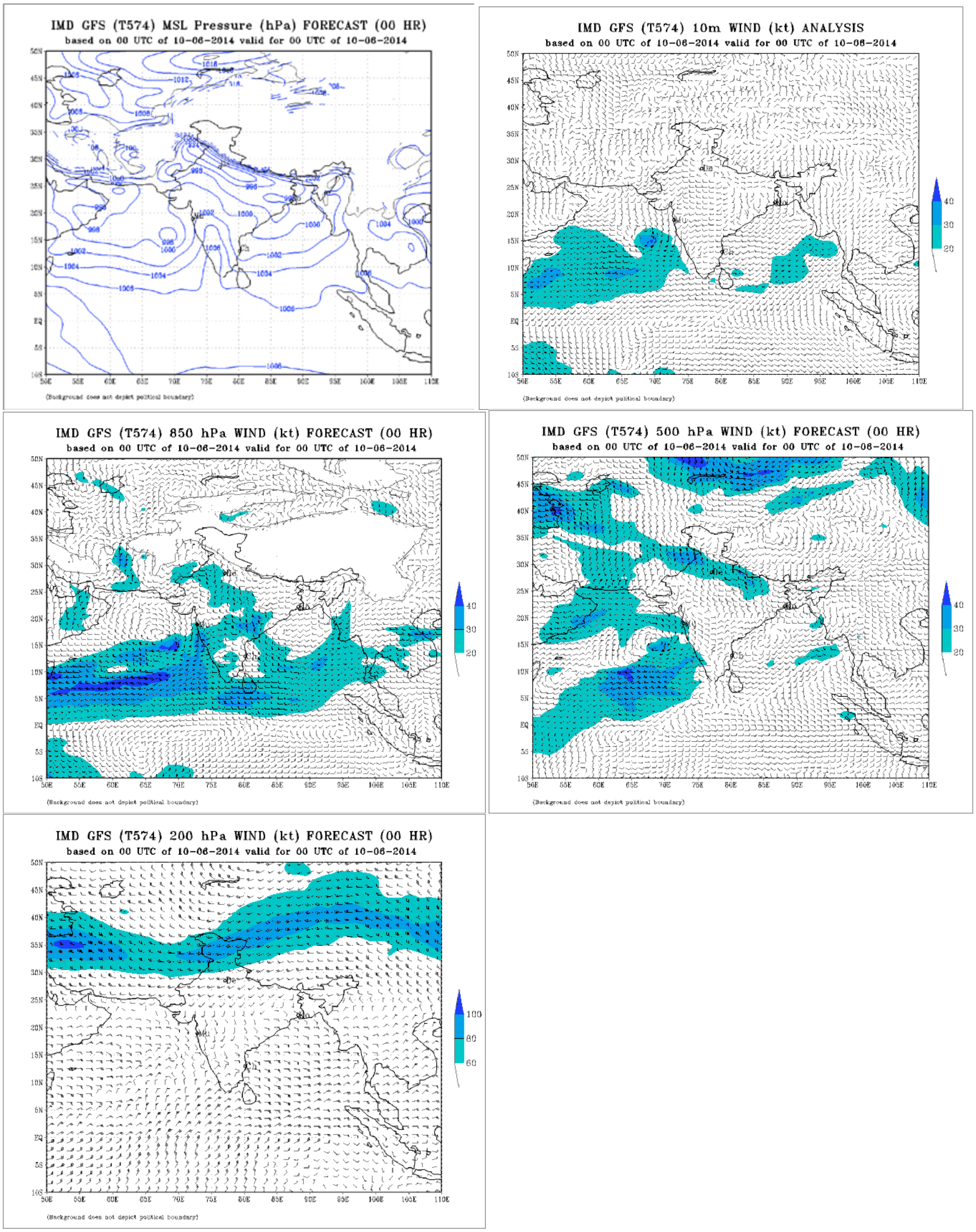


Fig. 2.3.2 (a) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10meter wind based on 10th June 2014

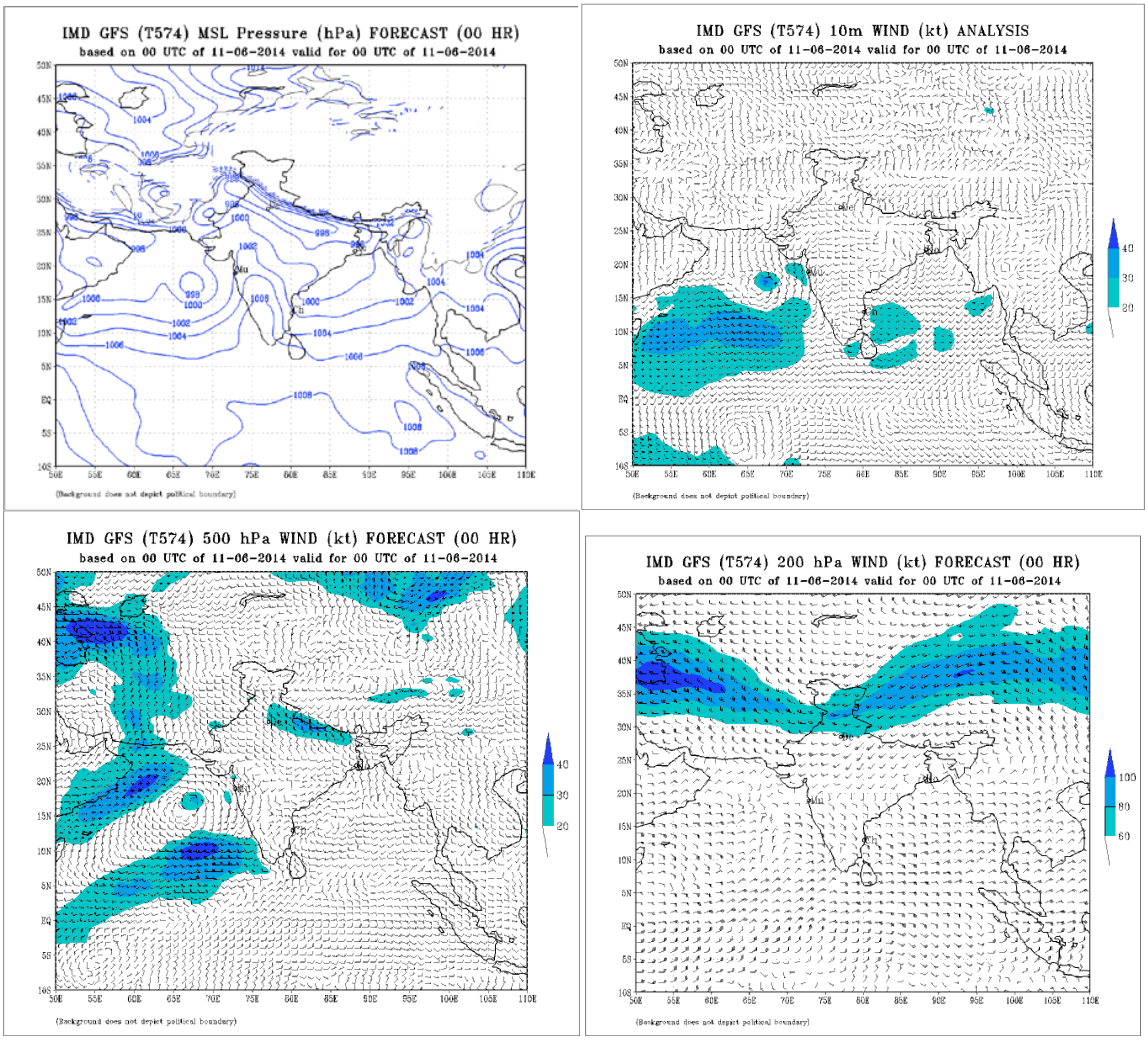


Fig. 2.3.2(b) IMD GFS MSLP and winds at 500 & 200 hPa levels analysis and 10meter wind based on 11th June 2014

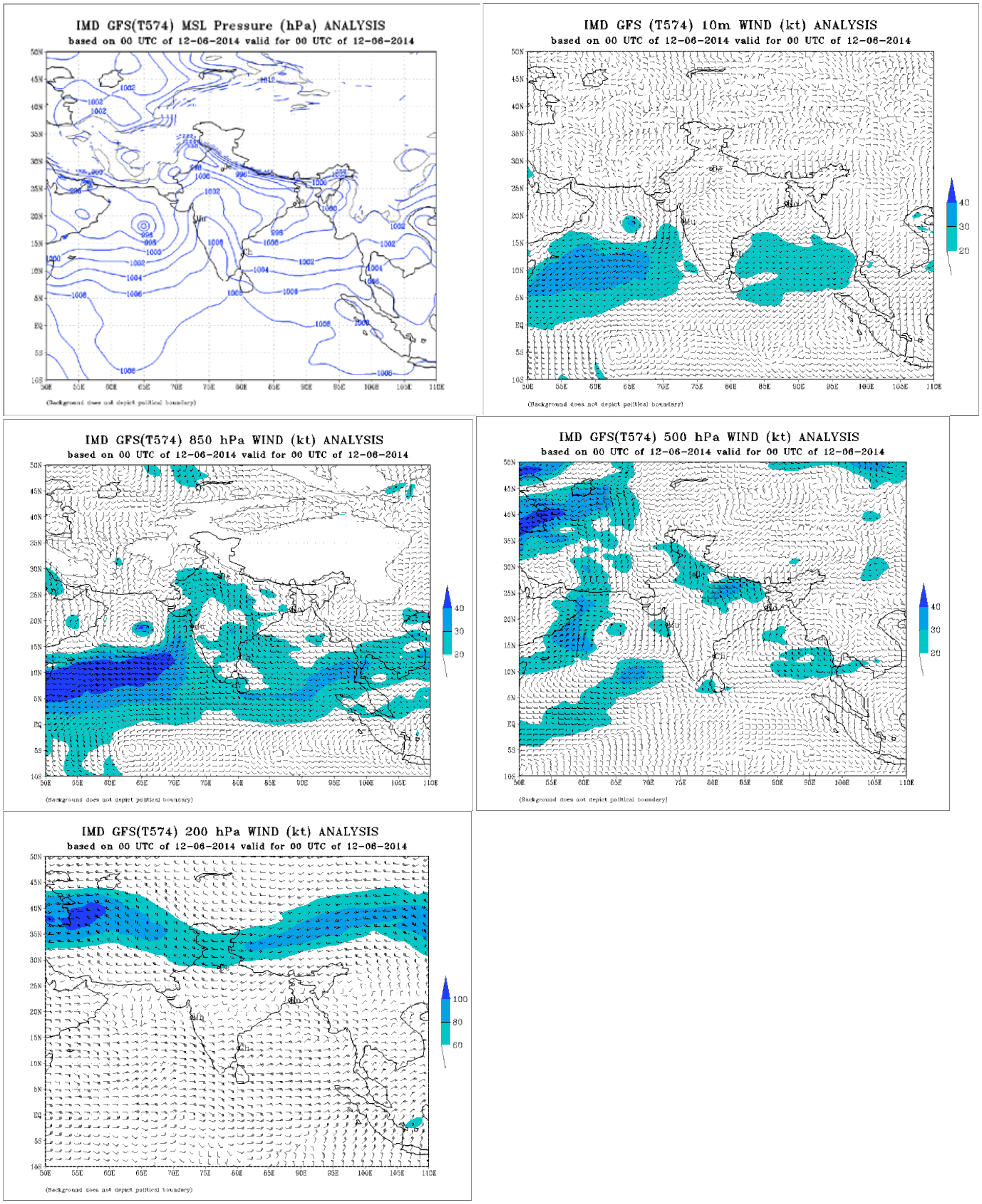


Fig. 2.3.2(c) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10meter wind based on 12th June 2014

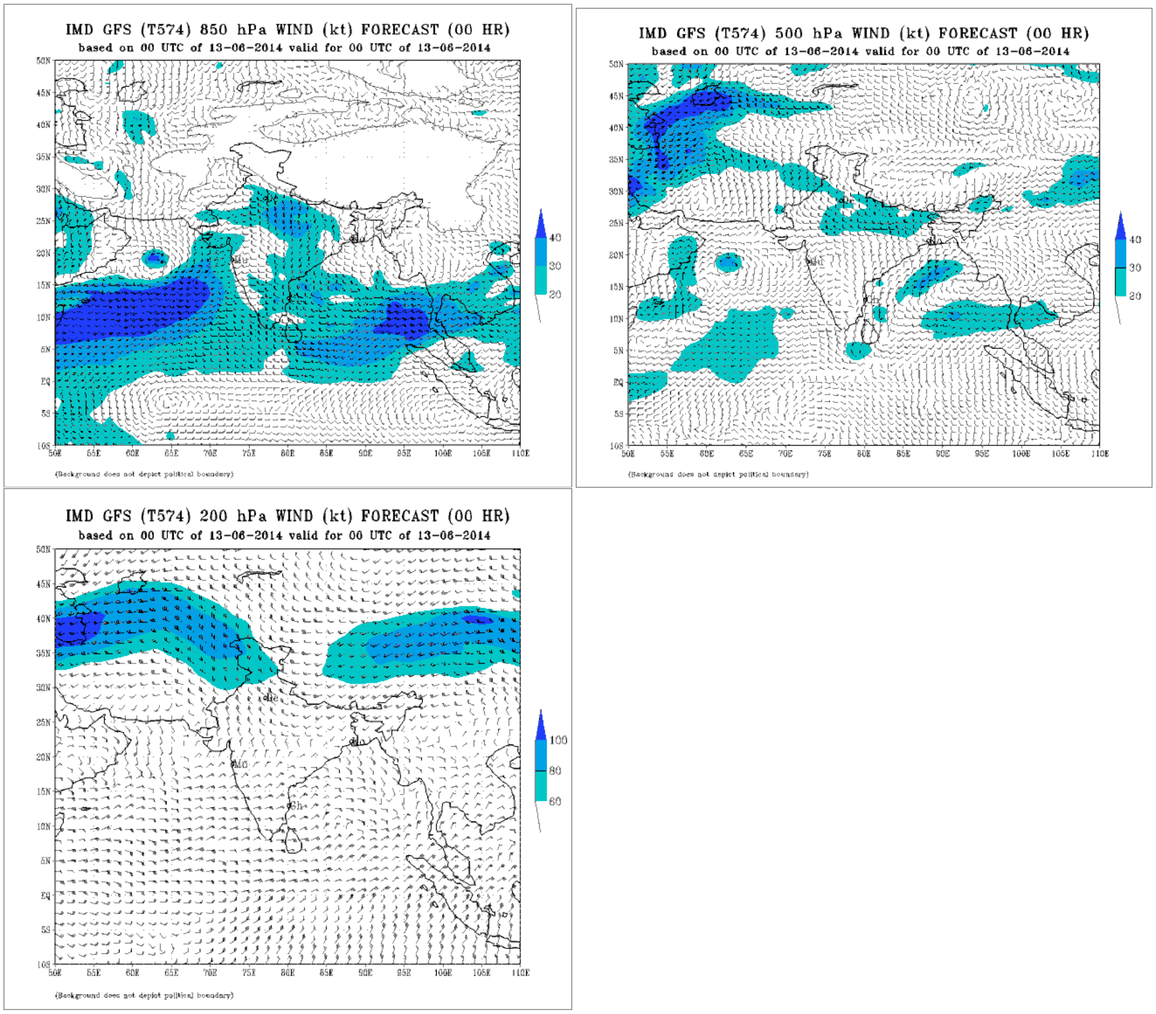


Fig. 2.3.2(d) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10meter wind based on 13th June 2014

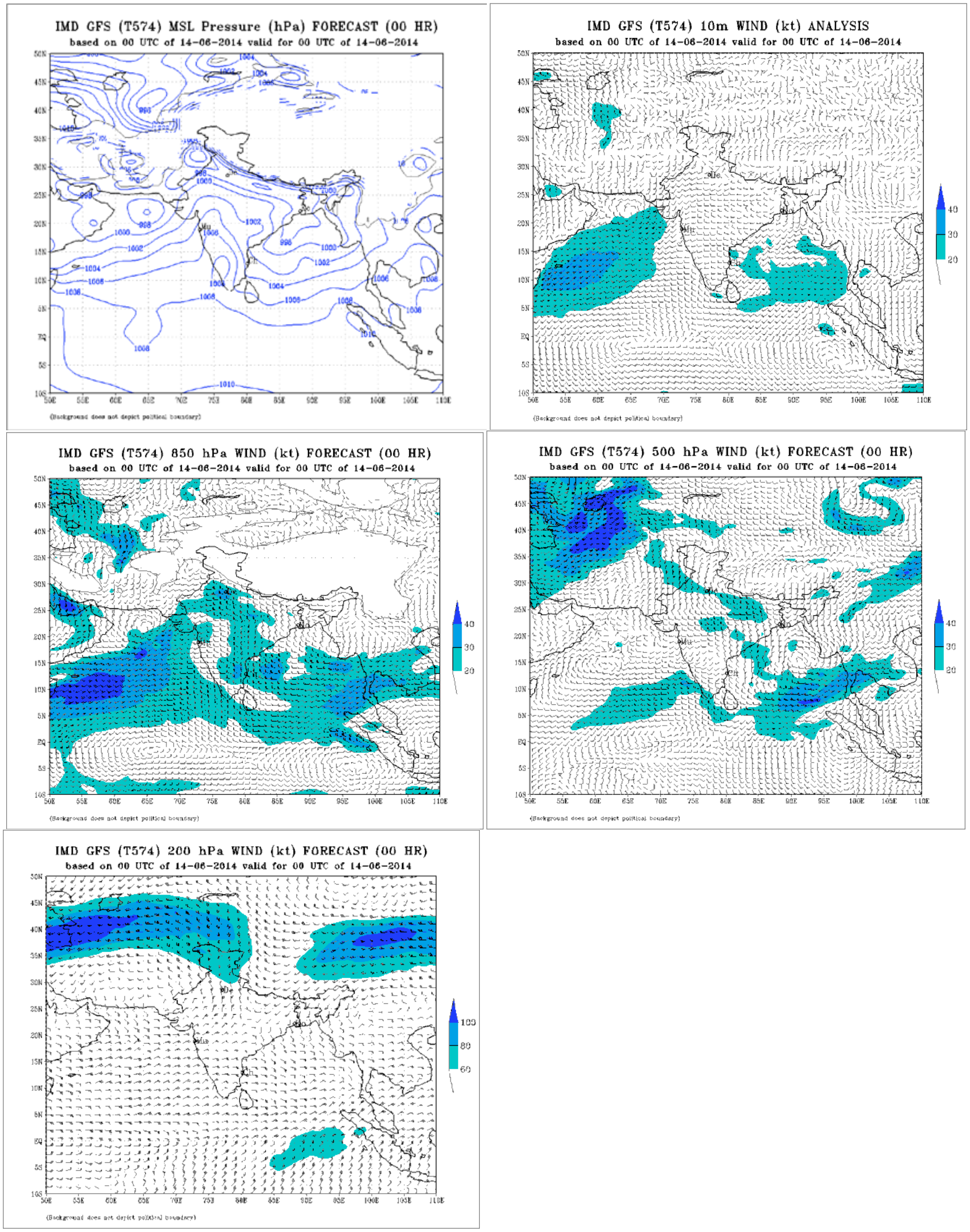


Fig. 2.3.2(e) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10meter wind based on 14th June 2014

2.3.5. Realized Weather:

2.3.5.1. Rainfall: Chief amounts of 24 hrs. Rainfall (7 cm or more) ending at 0300 UTC from 10th to 14th June 2014 are given below:

10 JUNE,

LAKSHADWEEP: Agathi-8

11 JUNE

COASTAL KARNATAKA: Gokarna-8,

12 JUNE

COASTAL KARNATAKA: Bajpe Obsy-10, Bantwal, Mudubidre-9 each, Manki, Siddapura, Kollur-8 each, Kundapura, Mani-7 each,

KERALA: Ponnani-11, Taliparamba-10, Cheruthazham, Enamakkal, Hosdurg-9 each, Vadakara-8, Kannur, Mancompu, Tellichery-7 each.

13 JUNE

COASTAL KARNATAKA: Shirali-11, Bhatkal, Manki-9 each, Karkala, Udupi, Karwar-8 each, Honavar, Mangalore Panambur Obsy, Mani, Bantwal, Bajpe Obsy, Gorsoppa-7 each,

KERALA: Cheruthazham-10, Kudulu, Kunnamkulam, Kodungallur-9 each, Vadakara-8, Enamakkal, Kozhikode, Kannur-7 each,

The rainfall distribution based on satellite estimate and station recorded data during 10-16 June 2014 are shown in Fig.2.3.3

2.3.5.2 Wind

Strong wind of about 35-45 kmph prevailed along and off Konkan, Goa and south Gujarat coast during 11-13th June 2014

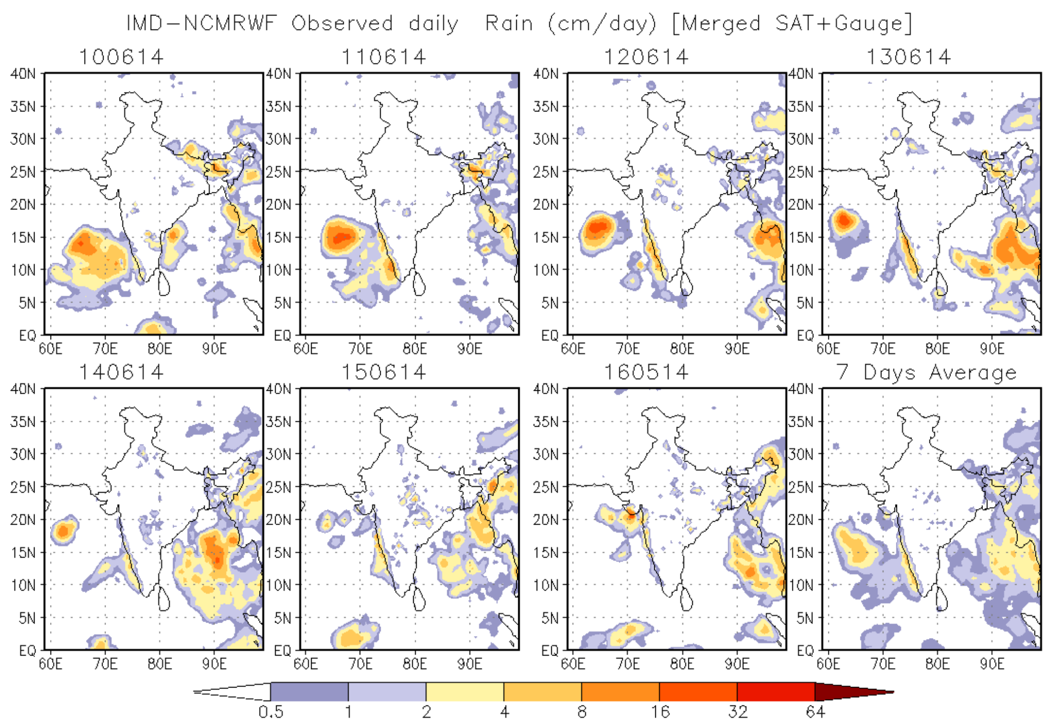


Fig. 2.3.3. Rainfall distribution based on satellite estimate and station recorded data during 10-16 June 2014

2.3.6. Damage:

As the cyclone dissipated over the sea, it did not cause any significant damage. However, as the cyclone developed during the full moon day and there was strong wind along west coast of India in association with cyclone and monsoon surge, the tidal wave inundated low lying areas in Konkan, including Mumbai. But no damage has been reported due to this system.

2.4 Land Depression over northeastern parts of Odisha and adjoining areas of Gangetic West Bengal during 21st - 23rd July 2014

2.4.1 Introduction

A land depression formed and lay centred over northeastern parts of Odisha and adjoining areas of Gangetic West Bengal on 21st July 2014 morning. It moved westnorthwestwards and weakened into a well marked low pressure area over west Madhya Pradesh and neighbourhood on 23rd July. The salient features of the system are as follows:

i. It caused heavy to very heavy rainfall at a few places with isolated extremely heavy falls over central part of the country including Odisha, Chhattisgarh, Madhya Pradesh and Vidarbha.
ii. Deficiency in monsoon rainfall during the month of June and the 1st week of July due to sluggish advance of monsoon was largely compensated due to formation of this system.

2.4.2. Monitoring and Prediction:

The depression was monitored with satellite network, ocean buoys, coastal, observations and Doppler Weather Radar (DWR), Kolkata & Nagpur.The half hourly INSAT/ Kalpana imageries and every 10 minutes DWR imageries and products were used for monitoring of depression. The intensity of the depression was mainly monitored through synoptic observations from surface stations. Various numerical weather prediction (NWP) models including IMD's global and meso-scale models were utilized to predict the track and intensity of the depression.

2.4.3. Genesis:

During the 3rd week of July, southwest monsoon was active as the monsoon trough lay to the south of its normal position and extended southeastwards up to eastcentral Bay of Bengal. An upper air cyclonic circulation between 1.5 & 5.8km amsl lay over northeast Bay of Bengal and neighbourhood on 19th. Under its influence, a low pressure area formed over north Bay of Bengal and adjoining areas of Gangetic West Bengal and Odisha and associated cyclonic circulation extended up to 7.6km amsl on 20th. It concentrated into a depression and lay centred over northeastern parts of Odisha and adjoining areas of Gangetic West Bengal, near Lat. 22.0°N / Long. 87.0°E, about 50 km east of Baripada at 0300 UTC of 21st.

Considering the environmental features, the low-level relative vorticity gradually increased and was about 100×10^{-5} sec^{-1} in the morning of 21st July. The vorticity was maximum at the southwest sector of the system. Lower-level convergence and upper-level divergence also increased and were about 20×10^{-5} sec^{-1} and 20×10^{-5} sec^{-1} respectively. The vertical wind shear was low and it was about 5-10knots. Hence all the environmental features supported the genesis of the system.

2.4. 4. Intensification and movement:

The above mentioned favorable environmental features continued to prevail on 21st and 22nd. However, the system moved west-northwestwards along the monsoon trough, under the influence of middle to upper level steering. The mid-tropospheric ridge ran along latitude 32^0N. As a result, the steering winds in upper troposphere were east to east-southeasterly leading to westward/ west-northwestward movement of the system The system moved west northwestwards and lay centred over south Jharkhand and neighbourhood near Lat. 22.5°N/Long.85.0°E, about 100km west southwest of Jamshedpur at 1200UTC 21st. It further moved westwards and lay centred over north Chhattisgarh and neighbourhood near Lat.22.5°N / Long.82.5°E, about 50km southeast of Pendra at 0300UTC of 22nd. It moved westwards and lay centered over east Madhya Pradesh and neighbourhood near Lat.22.5°N / Long.81.0°E about 100km southeast of Jabalpur at 1200UTC of 22nd. It further moved westwards and lay centred over west Madhya Pradesh and neighbourhood near Lat. 22.5°N / Long. 77.5°E about 50 km southeast of Bhopal at 0300UTC of 23rd and weakened into a well marked low pressure area over the same region by the afternoon of 23rd and persisted there in the same evening. It lay as a low pressure area over northwest Madhya Pradesh and neighbourhood on 24th, over southwest Rajasthan and neighbourhood in the evening and merged with the monsoon trough on 25th. However, the associated cyclonic circulation extending up to lower tropospheric levels persisted over southwest Rajasthan and neighbourhood on 25th, over northeast Rajasthan and neighbourhood on 26th & 27th; over Punjab and adjoining north Rajasthan on 28th and over Punjab and neighbourhood on 29th & 30th and became less marked on 31st July.

The best track of the depression is shown in fig.2.4.1. The best track parameters are given in Table.2.4.2.

Table. 2.4.2: Best track positions and other parameters of land depression over northeastern parts of Odisha and adjoining areas of Gangetic West Bengal during 21st - 23rd July 2014.

Date	Time (UTC)	Location of the centre lat.^{0}N/ long.^{0} E	CI No.	ECP in hPa	Estimated Sustained Maximum Wind in KT	Estimated pressure drop at the centre in hPa	Grade
21.07.2014	0300	22.0/87.0	-	988	25	4	D
21.07.2014	0600	22.2/86.4	-	988	20	4	D
21.07.2014	1200	22.5/85.0	-	988	20	4	D
21.07.2014	1800	22.5/84.0	-	990	20	4	D
22.07.2014	0000	22.5/83.0	-	990	20	4	D

22.07.2014	0300	22.5/82.5	-	990	20	4	D
22.07.2014	0600	22.5/82.0	-	990	20	4	D
22.07.2014	1200	22.5/81.0	-	990	20	4	D
22.07.2014	1800	22.5/79.6	-	992	20	3	D
23.07.2014	0000	22.5/78.2	-	992	20	3	D
23.07.2014	0300	22.5/77.5	-	992	20	3	D
23.07.2014	0600	22.5/77.0	-	992	20	3	D
23.07.2014	1200	Weakened into a well-marked low over west Madhya Pradesh and neighbourhood.					

Typical satellite imageries of the depression are shown in fig.2.4.1 and radar imageries in fig.2.4.2 satellite imageries indicate shearing of convective clouds to the west of low level circulation centre under the influence of the high vertical wind shear. Reflectivity images from Doppler weather Radar (DWR) Kolkata also indicated convective clouds lying to the southwest of centre of depression**.**

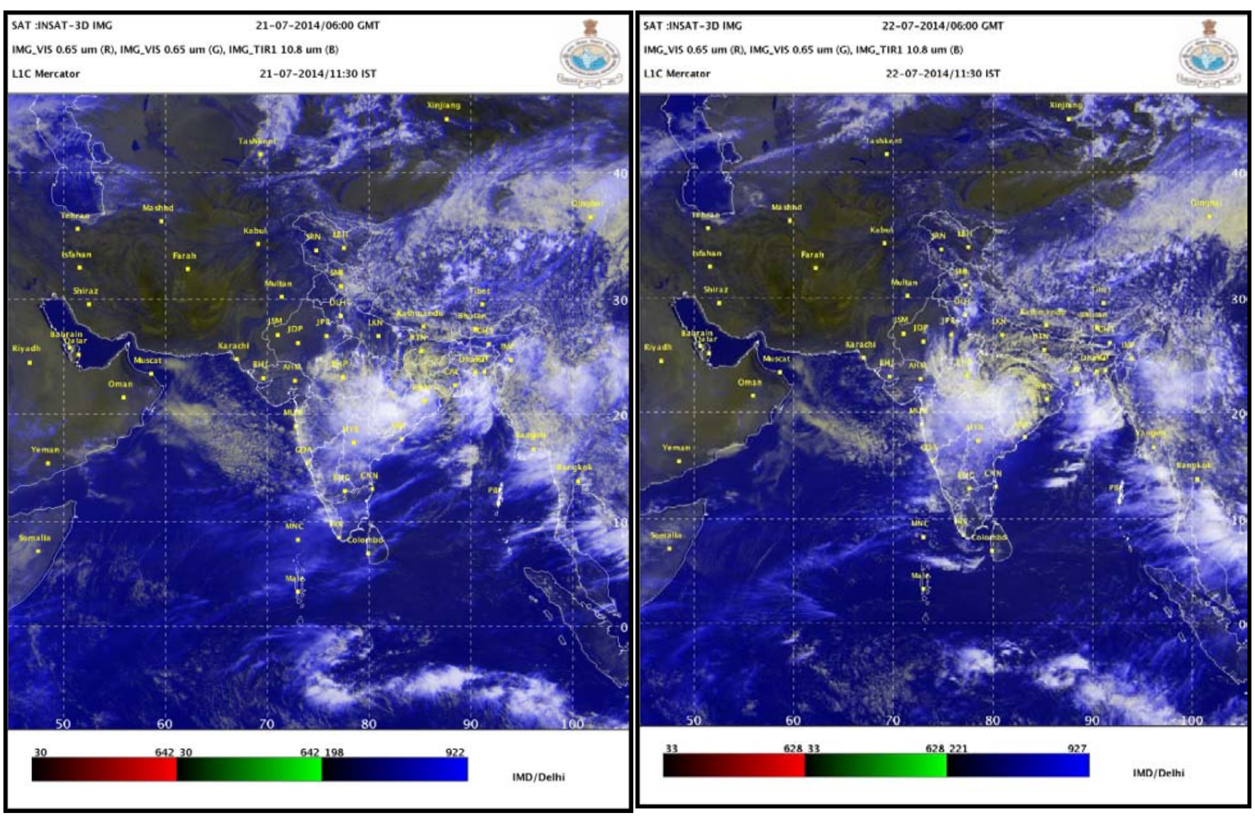


Fig. 2.4.1 Typical INSAT-3D Satellite images of depression at 0600 UTC of 21 and 22nd July, 2014

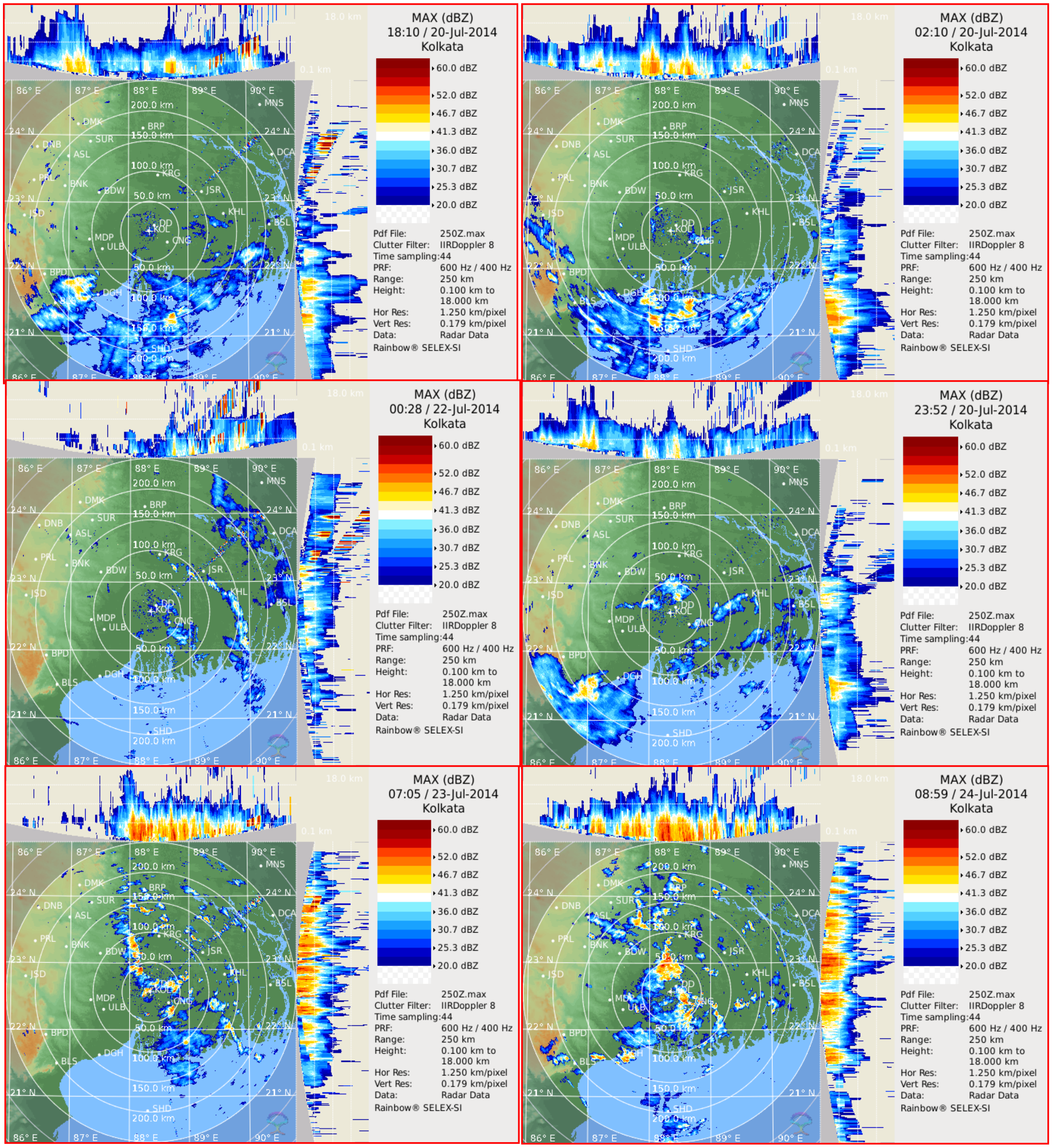


Fig. 2.4.2 Reflectivity images (Max Z) of DWR Kolkata from 20th July-24th July,2014

2.4. 5. Realised weather:

Chief amounts of rainfall (7 cm and above) during the last 24 hours ending at 0300 UTC of 21-23rd July 2014 are given below:

21st July 2014:

Gangetic West Bengal: Contai-13, Sagar Island (AWS)-8

Odisha: Anandpur, Nawapara- 27 each, Jhorigam (ARG), Balasore- 26 each, Soro-25, Champua &. Pallahara-24 each, Jaipatna-22, Komna-21, Khaprakhol(ARG)-21, Ranital(AWS) & Chandahandi (ARG)-20 each, Ghatagaon & Swam Patna-19 each, Karanjia-17, Rajghat,NH5 Gobindpur & Barkote-16 each, Jhumpura, Umarkote, Keonjhargarh, Telkoi, Dabugan (ARG), Jharbandh (ARG), Joshipur, Bhograi & Nilgiri-15 each, Remuna (ARG), Paikmal, Bari (ARG) & Kaptipada (ARG)-14 each, Jaleswar, Bonth, Jajpur & Basudevpur (AWS)-13 each, Raighar (ARG), Patnagarh, Kosagumda, Turekela & Jujumura (ARG)-12 each Harichandanpur (ARG), Lahunipara, Panposh, Danagadi (ARG), Bhadrak (AWS) & Nawana-11 each, Dhamnagar (ARG) & Belgaon-10 each, Binjharpur (ARG), Daitari, Khariar, Kuchinda, Tentulikhunti(ARG), Belpada(ARG), Tarva (ARG), Gurundia (ARG), Rajkanika, Joda (ARG), Kashipur, Nawarangpur, Kendrapara, Baripada & Chandbali-9 each, Akhuapada, Derabis (ARG), Ranpur, Rairangpur, Kantamal, Chandanpur, Reamal, Dhenkanal, Junagarh, Bolangir, Bamra (ARG) & Raghunathpur (ARG)-8 each, Rajgangpur-, Rengali, Nischintakoili (ARG), Tirtol (ARG), Betanati (ARG), Kotraguda, Madanpur, Rampur, Pattamundai, Ambadola, Thakurmunda, Naktideul, Paradeep (CWR), Lanjigarh, Muniguda (ARG), Jamankira, Birmaharajpur (ARG), Mandira Dam, Deogarh, Batagaon, Kesinga (ARG) and Saintala (ARG)-7 each.

22nd July 2014:

Odisha:Bijepur-27, Sohela-25, Paikmal-23, Khaprakhol (ARG)-21, Khariar,Ambabhona, Phiringia (ARG)&Komna-19 each, Padampur-18, Nawapara-15, Junagarh, Raighar (ARG), Jharbandh (ARG) &Bargarh-13 each, Patnagarh,Banaigarh (AWS),Tensa, Keiri (AWS) &Lahunipara-12 each, Sinapali (ARG), Chandahandi (ARG) & Telkoi-11each, Jharsuguda, Batli (ARG), Bargaon, Turekela &Jhorigam (ARG)-10 each, Deogaon, Gaisilet (ARG), Pallahara(9), Belpada (ARG), Binika, Narla (ARG),Bhawanipatna &Hemgiri-9 each, Deogarh, Jaipatna, Kesinga (ARG), Barkote, Dunguripalli, Atabira (ARG), Lakhanpur (ARG), Reamal-8 each, Bamra (ARG), Belaguntha (ARG), Titlagarh, Balisankara (ARG) and Salebhatta (ARG)-7 each.
Jharkhand: Kurdege-7.
West Uttar Pradesh: Jhansi-7.
East Rajasthan: Nadoti-7.
East Madhya Pradesh: Malanjkhand-16, Pushpajgarh and Jaithari-13 each.Narsinghpur(AWS)-11, Jabalpur New (AWS).andSeoni (AWS)-7.
Vidarbha:Deori&Korchi-18 each, Salekasa &Amgaon-17 each, Sadakarjuni & Gondia-14 each, Goregaon-13, Sakoli-11, Tirora, Kurkheda &Lakhani-10 each, Arjuni Morgaon-9, Mohadi, Dhanora, Lakhandur, Bhandara & Pauni-8 each and Desaiganj-7.

Chhattisgarh:Saraipali-34, Mahasamund-23, Bemetara-21, Arang-19, Simga-18, Bhopalpatnam, Bhanupratappur, Mana Raipur AP &Dhamtari-17, Baloda Bazar,Raipur &Gariabund-16 each, Durg, Raigarh, Ambagarh Chowki, Bijapur &Kanker-15 each, Dongargarh, Dantewara&Balod-13 each , Sarangarh &Rajnandgaon-12 each, Pali &Kawardha-11 each, Pallari/Palari &Dondilohara-10 each, Kondagaon, Mungeli, Champa, Bilaspur, Janjgir &Pendra Road-9 each, Rajim-8, Sakti, Katghora, Narayanpur and Dongargaon-7 each.
Madhya Maharashtra:Mahabaleshwar-21, Igatpuri-10, Gaganbawada & Paud Mulshi-7 each.

23rd July 2014:
Odisha: Nil.
East Rajasthan:Shahabad-12, Chabra & Aklera-7 each.
West Madhya Pradesh: Khaknar-41, Khandwa (AWS)-30, Nepanagar-24, Bhainsdehi-21, Betul (AWS)-20, Atner-19, Multai &Burhanpur-15 each, Chicholi-14, Pandhana-13, Kolaras-12, Bhikangaon-11, Narsingarh &Bhanpura-10, Barwaha, Sonkatch &Khilchipur-9 each, Sarangpur, Shegaon, Khargone (AWS), Kurwai, Khategaon &Udaipura-8 each, Bhopal (AWS) (ARG), Budhni, Shivpuri (AWS), Rajgarh &Harsud (ARG)-7 each.
East Madhya Pradesh: Katangi-14, Balaghat (AWS)-13, Sausar-12, Gadarwara, Chindwara (AWS) &Keolari-11 each, Amarwara-9, Seoni (AWS)-8,Waraseoni and Lakhnadon-7 each.
Chhattisgarh: Ambagarh Chowki-10, Gandai & Dongargarh-8 each, Dondilohara, Bemetara, Gariabund, Dongargaon and Rajnandgaon-7 each.
Vidarbha:Chikhalda-28, Wardha, Ashti & Arvi-20 each, Kharangha & Lakhani-18 each, Tiwsa, Deori, Tirora & Jalgaon Jamod-17 each, Chandur Bazar, Akot, Dharni, Narkheda & Salekasa-16 each, Gondia, Amgaon, Sangrampur, Kurkheda & Goregaon-15 each, Tumsar, Kamptee, Dhamangaon Rlwy, Nagpur Aerodrome, Chandur Rlwy, Yeotmal & Warud-14 each, Umrer, Pauni, Katol, Telhara, Desaiganj, Deoli, Anjangaon, Akola, Morsi, Kuhi, Perseoni, Bhandara, Samudrapur & Saoner-13, Nandgaonkazi, Arjuni Morgaon, Sadakarjuni, Mauda, Hingna & Mohadi-12, Bramhapuri, Ramtek, Hinganghat, Daryapur, Sakoli, Chimur, Lakhandur, Ner, Paratwada, Nagbhir, Bhiwapur & Darwha-11, Kalmeshwar & Manora-10, Mangrulpir, Karanjalad, Amraoti, Balapur, Barshitakli, Murtajapur & Washim (AWS)-9 each, Armori, Khamgaon, Malegaon, Selu, Batkuli, Ralegaon & Nandura-8 each , Patur and Kalamb-7 each.

24th July 2014:
Madhya Maharashtra: Mahabaleshwar Imd Obsy-20, Shirpur-16, Gaganbawada & Chopda-14 each, Shahuwadi,Yaval-10 each, Amalner,Patan, Surgana, Sindkheda, Radhanagari, Chalisgaon, Jalgaon Imd Pt-9 each, Raver, Chandgad,Shirala, Bhor, Navapur, Shahada-8 each, Gargoti / Bhudargad ,Peint,Akkalkuwa, Paud Mulshi, Kalvan, Taloda, Ajra, Satna Baglan & Bhadgaon-7 each.
East Rajasthan: Dungarpur Tehsil SR-11, Devel SR-10, Khushalgarh-9, Kherwara & Danpur-8, Bhungra SR & Kanva SR-7 each.
Gujarat Region: Kamrej-20, Mahudha-17, Vyara-16, Sankheda & Vansda-15,Kathalal , Dangs (Ahwa) & V.Vidyanagar SR-14, Godhra, Chhota Udepur,Nadiad, Sojitra, Wanakbori, Halol, & Padra-13 each, Umreth, Borsad, Kapadvanj, Mahemdavad, Balasinor, Anand, Mandvi , Mangrol, Umerpada & Bharuch-12 each, Tarapur, Chikhli, Ghoghamba, Surat City, Songadh Dascroi & Olpad-11 each, Kheda, Shahera,Tilakwada,Petlad, Dabhoi, Jetpur Pavi, Dholka, Bodeli, Gandevi &

Matar-10 each, Savli, Dahod, Sinor, Bavla, Valod, Kaprada, Abad City, Kalol, Mahuva, Vadodara,Uchchhal, Ukai, Sagbara & Dhansura-9 each, Mc Ahmedabad ARG , Jambughoda, Bardoli, Karjan, Khambhat, Dharampur, Jalalpor & Modasa-8 each, Anklav, Devgadh Baria, Ankleshwer, Navsari, Malpur, Viramgam, Thasra, Rajpipala, Dhanpur,Nandod, Nizer & Valsad-7 each.

West Madhya Pradesh: Sendhwa(Med)-16, Badnagar-15Depalpur-14Bhikangaon & Shegaon-13 each, Nepanagar, Dhar AWS & Mhow-12 each, Bhabhra, Thikri, Khaknar, Khargone AWS, Indore AWS & Khandwa AWS-11 each, Jabot, Badnawar & Sardarpur-10 each, Gandhwani, Maheshwar & Barwaha-9 each, Kasarwad & Pandhana-8 each, Khirkiya ARG, Alirajpur AWS, Gautampura, Thandla, Burhanpur, Badwani AWS, Manawar, Jhabua AWS, Ratlam AWS & Nalchha-7 each.

Vidarbha: Amraoti-13,Jalgaon Jamod & Dharni-8 each

(AWS: Automatic Weather Station; ARG : Automatic Rain Gauge; AP: Airport)

2.4. 6. Damages:

Odisha.

- Human casuality- 12,
- Live stock loss-38
- Crop are affected 29479 ha,
- Number of house damage= 1351.

2.5 Deep Depression over Bay of Bengal during 3rd - 7th Aug 2014

2.5.1 Introduction

A Depression formed over north Bay of Bengal off West Bengal coast during evening of 3rd. It moved west-northwestwards and intensified into a Deep Depression over neighbourhood around midnight of 3rd. Further moving west-northwestwards, it weakened into a Depression and lay centered over north Chhattisgarh and adjoining east Madhya Pradesh near east of Umaria in the afternoon of 5th. Continuing the westnorthwestward movement, it weakened into a well marked low pressure area over northwest Madhya Pradesh and neighbourhood on 7thmorning. The salient features of the system are as follows:

i. The monsoon condition over central India was activated with the deep depression which contributed to bountiful rains and compensated the deficit in monsoon rainfall.
ii. The deep depression resulted in torrential rains and flood over many rivers and rivulets of Odisha.

2.5.2 Genesis

A cyclonic circulation between 5.8 & 9.5 km amsl lay over northwest Bay of Bengal and neighbourhood on 1stAug. Under its influence, a low pressure area formed over north Bay of Bengal and neighbourhood on 2nd morning. It lay as a well marked low pressure area over the same region on 3rd morning. It concentrated into a Depression and lay centered over northwest Bay of Bengal and adjoining coastal areas of West Bengal near Lat. 21.5°N and Long. 88.5°E, about 80 km southeast of Diamond Harbor at 1200UTC of 3rd.

Considering the environmental features, the low-level relative vorticity gradually increased and was about $100X10^{-5}$ sec^{-1} in the morning of 3rd August. Lower-level convergence and upper-level divergence also increased and were about 20 $X10^{-5}$ sec^{-1} and 40 $X10^{-5}$ sec^{-1} respectively. The vertical wind shear was moderate and it was about 10-20 knots. Hence, the environmental features supported the genesis of the system.

2.5.3. Intensification and movement:

The above mentioned favorable environmental features continued to prevail on 4th and 5th and there was increased relative vorticity. As a result, it intensified into a depression on 3rd August near Lat. 21.9°N and Long. 88.3°E, about 80 km southeast of Kolkata at 1800 UTC of 3rd. However, the system moved west-northwestwards along the monsoon trough under the influence of middle to upper level steering. The mid-tropospheric ridge ran along latitude 30^0N. As a result, the steering winds in upper troposphere were east to east-southeastly leading to westward/ west-northwestward movement of the system. Further moving west northwestwards it lay centered over Jharkhand and adjoining Gangetic West Bengal near Lat. 22.2°N and Long. 86.1°E, about 50 kms south of Jamshedpur at 1200 UTC of 4th and over north Chhattisgarh, adjoining Jharkhand and east Madhya Pradesh near Lat. 22.2°N and Long. 83.5°E, about 100 kms east-southeast of Ambikapur at 0300 UTC of 5th. Further moving west northwestwards, it weakened into a Depression and lay centered over north Chhattisgarh and adjoining east Madhya Pradesh near Lat. 23.5°N and Long. 82.5°E, about 150 kms east of Umaria at 0900 UTC of 5th and over northeast Madhya Pradesh and neighborhood, close to Sidhi near Lat. 24.0°N and Long. 82.0°E at 1200 UTC of 5th. It further moved west northwestwards and lay centered over central parts of north Madhya Pradesh and neighborhood about 50 kms southeast of Khajuraho, near Lat. 24.5°N and Long. 80.2°E at 0300 UTC of 6th. It lay centered over the same region close to Nowgong near Lat. 25.0°N and Long. 79.5°E at 1200 UTC of 6th.Moving slightly west-northwestwards it lay centred over northwest Madhya Pradesh and neighbourhood, near lat. 25.5°N and Long. 78.5°E, about 50 km. southeast of Gwalior at 0000 UTC of 7th. Continuing the west northwestward movement, it weakened into a well marked low pressure area over northwest Madhya Pradesh and neighbourhood on 7th morning. It lay as a low pressure area over northwest Madhya Pradesh and adjoining east Rajasthan in the same evening. It merged with the monsoon trough on 8th. However, the associated cyclonic circulation extending up to mid tropospheric levels lay over northeast Rajasthan and neighbourhood on 8th & 9th, northwest Madhya Pradesh and adjoining southwest Uttar Pradesh on 10th, southwest Uttar Pradesh and neighbourhood on 11thand became less marked on 12th.

The best track parameters of the deep depression are given in the Table.2.5.1 and the best track is shown in the fig.2.1.

Table. 2.5.1 Best track positions and other parameters of Deep Depression over the Bay of Bengal during 3-7 Aug 2014

Date	Time (UTC)	Location of the centre lat.^{0}N/ long.^{0} E	CI No.	ECP in hPa	Estimated Sustained Maximum Wind in KT	Estimated pressure drop at the centre in hPa	Grade
03.08.2014	1200	21.5/88.5	1.5	990	25	4	D
03.08.2014	1800	21.9/88.3	2.0	990	30	6	DD
04.08.2014	0000	22.3/87.6	-	990	30	6	DD
04.08.2014	0300	22.5/87.2	-	990	30	6	DD
04.08.2014	0600	22.5/86.5	-	990	30	6	DD
04.08.2014	1200	22.2/86.1	-	990	30	6	DD
04.08.2014	1800	22.2/85.1	-	990	30	6	DD
05.08.2014	0000	22.2/84.1	-	990	30	6	DD
05.08.2014	0300	22.2/83.5	-	994	30	6	DD
05.08.2014	0600	22.9/83.0	-	992	30	5	DD
05.08.2014	0900	23.5/82.5	-	992	25	4	D
05.08.2014	1200	24.0/82.0	-	992	25	4	D
05.08.2014	1800	24.2/81.3	-	992	25	4	D
06.08.2014	0000	24.4/80.6	-	992	25	4	D
06.08.2014	0300	24.5/80.2	-	996	25	4	D
06.08.2014	0600	24.6/80.0	-	994	25	4	D
06.08.2014	1200	25.0/79.5	-	994	25	4	D
06.08.2014	1800	25.3/79.0	-	994	25	4	D
07.08.2014	0000	25.5/78.5	-	994	25	3	D
07.08.2014	0300	Weakened into a well-marked low pressure area over northwest Madhya Pradesh and neighbourhood					

Typical satellite imageries of the depression are shown in fig.2.5.2 indicating active monsoon conditions over Indian region in association with the deep depression and major convection lying to the west of depression centre under the influence of easterly wind shear.

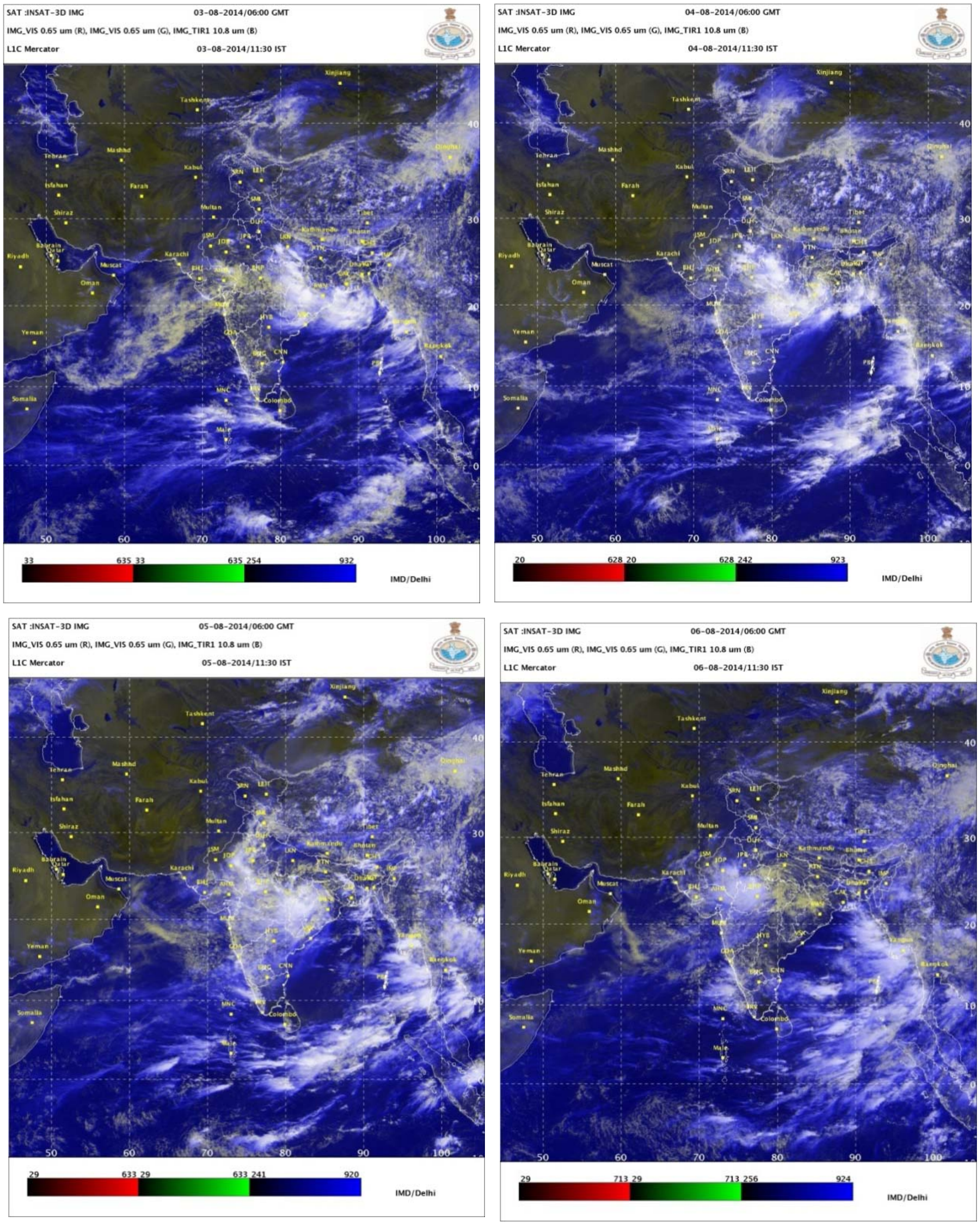


Fig. 2.5.1 Typical Kalpana-1 Satellite imageries of depression at 0600 UTC of 03rd-04th August, 2014.

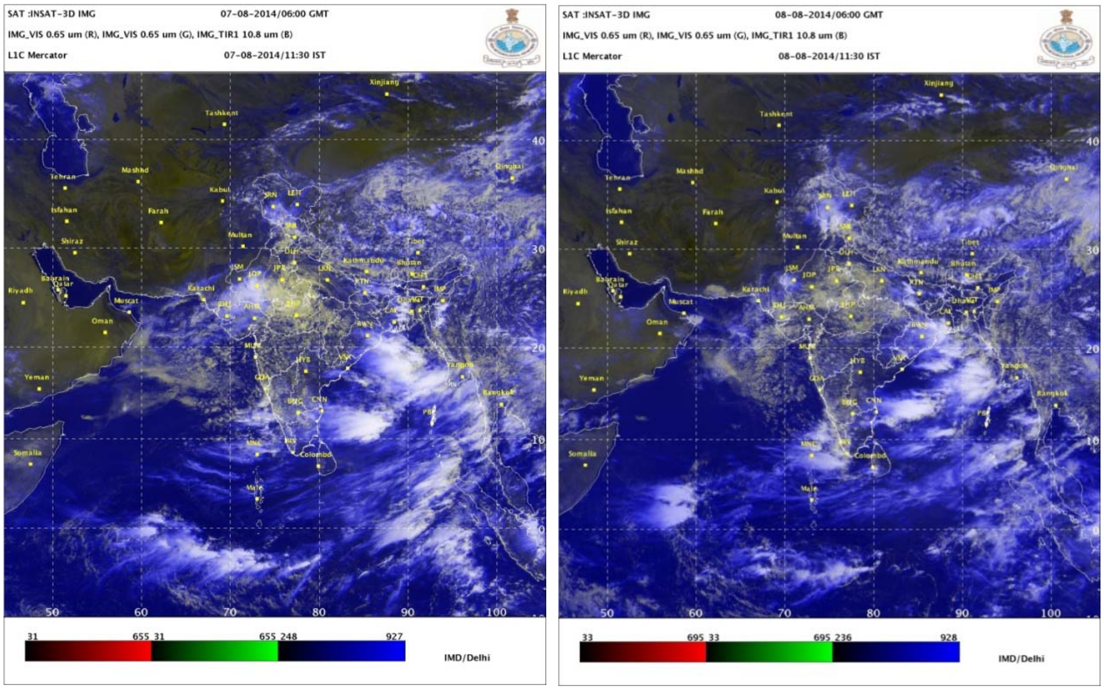


Fig. 2.5.2.Typical Kalpana-1 Satellite imageries of depression at 0600 UTC of 05th-08th August, 2014.

2.5.4. Realised weather:

Chief amounts of rainfall (7 cm and above) during the last 24 hours ending at 0300UTC from 4th -8th August 2014 are as given below:

Date.04.08.2014:

Gangetic West Bengal:Digha-31, Contai-20 and Sagar Island (AWS)-14.
Odisha: Sambalpur-34, Jujumura (ARG)-29, NH5 Gobindpur, Balasore-23 each, Bhograi-21, Lakhanpur (ARG)-20, Nilgiri, Burla (ARG)-18 each, Jaipur, Basudevpur (AWS), Athmalik, Bonth-17 each, Rajkishorenagar, Barmul-16 each, Rairakhol, Hirakud and Tikarpara-15 each, Danagadi (ARG), Jaleswar & Pallahara-14 each, Bhadrak (AWS), Kankadahad (ARG) & Altuma (CWC)-13 each, Korei (ARG), Anandpur and Banki (ARG)-12 each, Akhuapada , Telkoi ,Rajghat, Kotagarh, Nimpara, Tensa, Kamakhyanagar-11 each, Tihidi (ARG), Kashipur, Narsinghpur, Dhamnagar (ARG), Sukinda& Jaipatna-10 each, Junagarh, Jajpur, Deogaon, Daitari, Umarkote, Jhorigam (ARG), Khairamal, Jenapur, Gania (ARG), Kendrapara, Pattamundai&Batagaon-9 each, Nischintakoili (ARG), Boudhgarh , Derabis (ARG), Mundali, Narla (ARG), Mohana and Nuagada (ARG)-8 each, Jhumpura, Binjharpur (ARG), Garadapur (ARG), Kantamal, Keonjhargarh, Hindol, Bari (ARG), Kolabira (ARG), Swam Patna, Khandapara, Cuttack, Chandbali, Rajkanika, Niali (ARG), Dhenkanal, Rengali) and Raighar (ARG)-7 each.
Chhattisgarh:Balod-11, Katghora, Ambikapur-9 each, Gharghoda, Dhamtari, Dondilohar, Surajpur&Korba-8each, Manendragarh, Raigarh ,Dongargaon&Saraipali-7 each.

Dt. 05.08.2014:

Gangetic West Bengal: Jagatballavpur (ARG) 7

Odisha:Pallahara-40, Kuchinda-32,Barkote-29, Naktideul-28, Sambalpur & Burla (ARG) 27 each, Deogarh,Jujumura (ARG) & Jamankira-26 each,Hirakud, Deogaon & Batagaon- 25 each, Keiri (AWS) &Ambabhona-24 each,Atabira (ARG)-22, Bargarh, Athmalik, Banaigarh (AWS)- 21 each, Lahunipara, Bargaon and Bijepur-20 each, Reamal-19,Swam Patna-18, Karanjia, Rengali, Telkoi and Sundargarh-16 each,Laikera, Rairakhol,Thakurmunda, Keonjhargarh & Jhumpura-15 each, Banki (ARG), Sohela, Khariar, Rajkishorenagar & Chandahandi (ARG)-14 each, Ghatagaon, Sinapali (ARG), Bamra (ARG), Batli (ARG) & Joshipur-13 each, Kaniha (ARG), Rajgangpur, Kaptipada (ARG),Hemgiri,Joda (ARG) & Chandanpur-12 each, Nawana,Jharsuguda and Junagarh-11 each, Boudhgarh,Champua,Barmul & Kankadahad (ARG)-10 each, Barpalli (ARG), Jhorigam (ARG), Balisankara (ARG), Boden (ARG), Chendipada, Jaipur, Khandapara, Mandira Dam, Narsinghpur, Bangiriposi & Binika-9 each, Kotagarh,Parjang (ARG), Komna,Harichandanpur (ARG), Lanjigarh, Udala, Birmaharajpur (ARG), Remuna (ARG),Bhawanipatna, Phulbani, Ambadola & Daitari-8 each, Harabhanga, Ullunda (ARG), Padampur, Tigiria (ARG), Kantamal,Nischintakoili (ARG), Raighar (ARG), Betanati (ARG), Panposh, Altuma (CWC),Balimundali, Dunguripalli, Daspalla, Daringibadi, Titlagarh, Nh5 Gobindpur and Dharmagarh (ARG)-7 each.

Jharkhand: Raidih-8 and Kurdege-7.

Chhattisgarh: Saraipali-16, Dhamtari-15, Deobhog & Bhanupratappur 13 each, Manendragarh-12, Ambagarh Chowki-11, Bilaspur & Sarangarh 10 each, Kanker-8,Janakpur, Katghora & Pali-7 each.

East Madhya Pradesh: Sidhi (AWS)-18, Tikamgarh (AWS)-16, Kotma-12, Jaithari &.Gadarwara-10 each, Anuppur (AWS) &.Amarkantak-8 each, Dindori (AWS) &.
Pushpajgarh-7 each.

Vidarbha: Korchi-17, Deori &.Sadakarjuni-12 each, Amgaon-11, Goregaon & Gondia-9 each, Kurkheda-8 and Salekasa-7.
West Madhya Pradesh: Guna (AWS)-10, Chanderi-9, Sheopur (AWS)-8, Pachmarhi &Udaipura-7 each.

Madhya Maharashtra: Mahabaleshwar-31, Igatpuri-13, Vadgaon Maval-12, Paud Mulshi-10, Gaganbawada & Velhe-9 each and Bhor-7.

East Rajasthan: Jhalawar-15, Bonli & Lalsot-13 each, Baran & Mangrol-11 each, Jamwaramgarh, Anta & Jhalarapatan-10 each, Kishanganj, Asnawar & Shergarh-8 each, Khanpur, Kishngarhwas, Chabra,Baseri, Indergarh, Ramganjmandi and Sawai Madhopur-7 each.

06.08.2014:

West Madhya Pradesh: Lateri and Khilchipur-15 each, Bhanpura, Kurwai&Chanderi-13 each, Narsingarh, Rajgarh, Guna-AWS-11 each, Pichhore-10, Biaora, Sironj, Chachoda and Ganjbasoda-9 each, Salwani/Silvani, Ashoknagar-AWS and Alipur (Jaura)-8 each, Begumganj, Mungaoli, Dabra, Morena-AWS and Garoth-7 each.

East Madhya Pradesh:Katni-AWS-21,Khurai-19, Umaria-AWS&Damoh-AWS-17 each, Patan-16,Kotma and Bichhia-15 each, Sohagpur-AWS, Khajuraho Aero&Sagar-AWS-13 each, Tikamgarh-AWS-12, Deori, Buxwaha,Tendukheda&Nainpur-11, Amarkantak-10, Rehli&Narsinghpur-AWS-9 each, Pushpajgarh, Hatta, Jaithari,Chahtarpur-AWS and Gotegaon-8, Kaneli, Ajaigarh, Rajnagar and Dindori-AWS-7.

Chhattisgarh: Manendragarh-18, Katghora-17, Mungeli-14,Janakpur-9, Pali-8, Baikunthpur , Pendra Road&Kawardha-7 each.

VIDARBHA:Mehkar-19, Sindkhed Raja-19, Chikhli-13, Lonar&Korchi-9 Each, Buldanaand Deolgaon Raja-7 each.

East Rajasthan:Baseri SR-21,Hindaun-15, Nainwa-14, Asnawar SR-13, Gangapur &. Chothkabarwara SR-12 each, Atru SR, Bakani SR, Shahabad, Deoli & Pisagan SR-11 each, Aklera, Lalsot & Bamanwas SR-10 each, Sapau SR, Dholpur Tehsil SR, Manohar Thana, Hindoli-9 each Kesarpura SR, Khanpur, Jhalawar, & Chipabarod SR-8 each, Indergarh SR, Niwai Mangliawas SR, Pachpahar SR, Bayana,Tonk Tehsil SR, Bonli,Kishanganj,Jhalarapatan SR, Karauli,Mandana SR, Nagrarfort SR and Chambal/R.B.Dam-7 each.

Madhya Maharashtra: Mahabaleshwar- Imd Obsy-11and Gaganbawada-10.

West Uttar Pradesh: Mahroni-13,Garotha-8 and Lalitpur-7.

Date.07.08.2014:

West Madhya Pradesh: Manasa -18, Jawad-17, Bhanpura-15, Neemuch (AWS)-15, Kolaras-13, Mungaoli-13, Garoth & Kurwai-12, Agar & Guna (AWS)-11 each, Sarangpur-10, Mandsaur (AWS) , Khilchipur, Suvasara & Chanderi-8 and Ashoknagar (AWS)-7.

East Rajasthan:Bhinay-27, Shahabad & Hurda -26 each, Bijoliya -23, Sangod, Geola, Sarwar, Deoli-22 each, Badesar -21,Anta -20,Jahazpur & Hindoli-19 each, Bhainsroadgarh-18, Banera, Baran,Mandal,Gangrar &.Nimbahera-17 each ,Bhilwara Tehsil,Sawaimadhopur Tesil, Atru, Chambal/ R.B.Dam, Chittorgarh,Mangrol,Nainwa, Patan, Sahada, Pachpahar -15 each ,Indergarh, Shahpura, Kotri,Ramganjmandi,Kishanganj-14 each, Bundi, Kapasan, Rashmi,Chhotisadri, Vijaynagar, Asind,Ladpura,Talera -13 each, Mandalgarh, Malpura,Khanpur, Begu, Sawar, Kota Aero-12 each, Tonk Vanasthali, Nagrarfort,Pisagan ,Mandana, Railmagra,Piplu-11 each, Bhopalsagar,Tonk Tehsil,Masuda , Bari Sadri,Todaraisingh,Arai,Kekri -10 each, Pratapgarh, Uniara/Aligarh,Vallabhnagar, Nayanagar/Beawar, Deogarh,Jhalawar,Sawai Madhopur,Degod,Asnawar , Gangdhar,Jhalarapatan -9 each,Dungla ,Amet,Raipur,Chabra, Dug, Kumbhalgarh, Mavli-8 each, Bhim, Rajsamand, Chothkabarwara, Manohar Thana, Niwai, Tatgarh, Chipabarod , Bakani, Jawaja and Pirawa-7

West Rajasthan:Jayal-15, Merta City-9, Marwar Junction&Desuri-9, Raipur-9 each, Degana&Rohat-8 each, Jaitran, Pali&Sojat-7 each.

Gujarat Region:Mahudha-7.

Date.:08.08.2014:
West Rajasthan: Jaitran-10, Desuri & Pali 9 each, Bhopalgarh-8, Marwar Junction & Sojat-7 each.
East Rajasthan: Nayanagar/Beawar, Amet-9 each, Deogarh-7.
Gujarat Region: Matar & Nadiad-7 each.
(AWS: Automatic Weather Station; ARG : Automatic Rain Gauge; AP: Airport)

2.4.5. Damage:

Odisha:

- Human causality due to flood = 32
- Human causality due to lightning = 15
- Live stock loss=149 (due to flood and heavy rainfall.)
- Number of houses damaged = 45953 (massive damage occurred to public infrastructure such as embankments, roads, culverts etc.)
- Crop area affected 367691.7 hac.

(Source: Govt. of Odisha).

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

2.6.1 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 0300 and 0400 UTC of 8th Oct. It continued to move west-northwestwards, 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 crossed north Andhra Pradesh coast over Visakhapatnam (VSK) between 0630 and 0730UTC of 12th Oct. with the wind speed of 100 knots.

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 0300 UTC of 13October 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.
vii. 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.

2.6.2 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 22 UTC 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 Machhilipatnam 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.

2.6.3 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 products from NCEP USA and IIT based on 00 and 12 UTC observations were used

(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 0000 UTC 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 was reduced by about 20-30 % 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 were sent by IMD to Disaster Managers at National level and up to District Collector level
- A new dedicated website for cyclone (www.rsmcnewdelhi.imd.gov.in) has been developed and was fully operational during VSCS HUDHUD.
- Internet Lease Line Bandwidth was upgraded from 60mbps to 100mbps during VSCS ‘HUDHUD’ leading to failure-free accessibility of IMD website.

2.6.4 Brief life history

2.6.4.1 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^{0}N to 16.0^{0}N and east of long 90.0^{0}E to Tenasserim coast at 0300 UTC 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^{0}C. The convective cloud clusters came closer and merged with each other during past 24 hrs ending at 0300 UTC 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 0300 UTC of 7th with its centre near latitude 11.5^{0}N and longitude 95.0^{0}E, 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^{0}N and 93.9^{0}E 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.2.1.

2.6.4.2 Intensification and movement

On 7th Oct. morning, the upper tropospheric ridge at 200 hPa level ran along 19^{0}N 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 0300 UTC of 7th Oct.. The sea surface temperature based on satellite and available buoys and ships observation was about 30-32^{0}C 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 1200 UTC of 7th Oct. over North Andaman Sea near 12.0^{0}N and 94.0^{0}E about 130 km east-southeast of Long Island. It further intensified into a cyclonic storm HUDHUD at 0300 UTC of 8th Oct. and crossed Andaman Islands close to Long Island (near latitude 12.4^{0}N and longitude 92.9^{0}E) between 0300-0400UTC of 8th Oct. with maximum sustained wind speed of 70-80 kmph gusting to 90 kmph. Port Blair reported 88 kmph at 0300 UTC of 8th Oct. It then continued to move west-northwestwards and intensified into a severe cyclonic storm (SCS) and lay centered at 0300 UTC of 9th Oct. over eastcentral Bay of

Bengal (BoB) near 13.8^{0}N and 89.0^{0}E 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 0900 UTC 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 0900 UTC of 10th Oct. over westcentral BoB near 15.0^{0}N and 86.8^{0}E, 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. There after 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^{0}N and longitude 83.3^{0}E) with a maximum sustained wind speed of 100 kt gusting to 110 kt between 0630-0730UTC of 12th Oct.. After the landfall, the system continued to move northwestward for some time and weakened into a SCS at 1200 UTC of 12th Oct. over North Andhra Pradesh close to South Odisha near latitude 18.0^{0}N and longitude 82.7^{0}E. It then moved north-northwestward and weakened into a CS at 2100 UTC of 12th in the border of South Chhattisgarh and South Odisha near latitude 18.7^{0}N and longitude 82.3^{0}E. It then recurved northwards and weakened into a deep depression at 0000 UTC of 13th Oct. over South Chhattisgarh and further into a depression at 1200 UTC of 13th Oct. over central part of Chhattisgarh and neighbourhood. It continued to move northward up to 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 1200 UTC of 14th Oct. over East Uttar Pradesh and neighbourhood (Fig.2.1). The best track parameters of VSCS ‘HUDHUD’ are shown in Table 2.6.1.

Table 2.6.1: Best track positions and other parameters of the Very Severe Cyclonic Storm, ‘HUDHUD’ over the Bay of Bengal during 07-14 October, 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
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 islands near Long island (near Lat. 12.4° N and Long. 92.9° E) 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	6.1/85.0	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° N and Long. 83.3° 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	**DD**
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	**D**

	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					

The place and time of landfall was determined through monitoring of hourly observations from the coastal stations as shown in Fig. 2.6.1. 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 0630-0730UTC of 12th Oct. Similar was the case considering the landfall near Long Island on 8th Oct. between 0300-0400UTC of 8th Oct. 2014 as Long Island reported lowest mean sea level pressure and veering of wind.

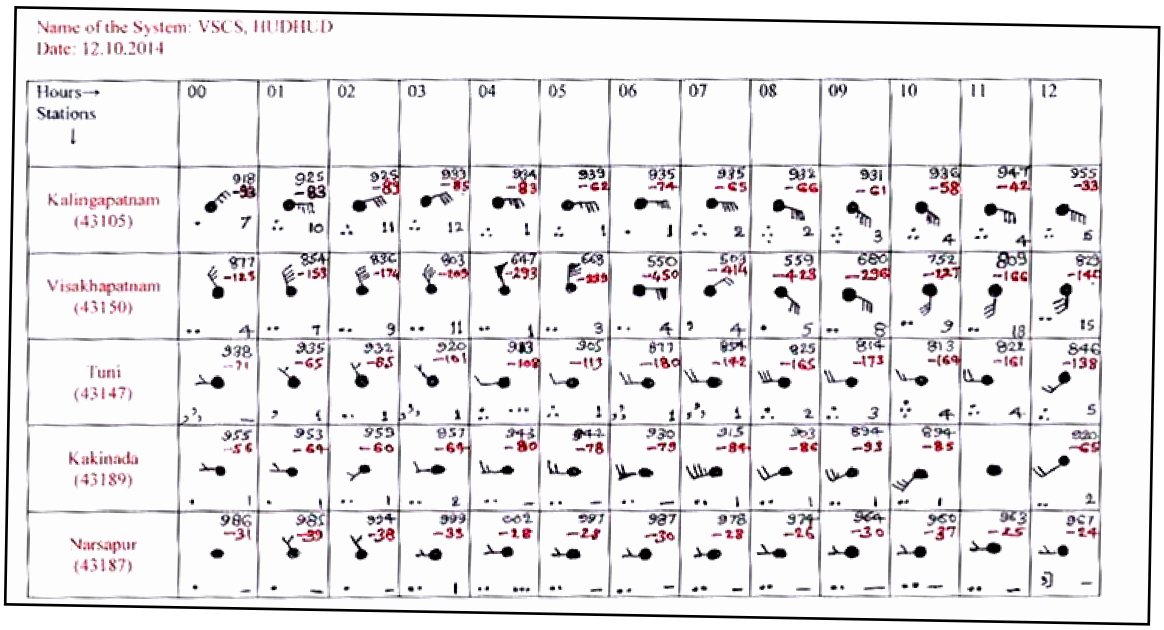


Fig. 2.6.1: Hourly observations from coastal stations on 12th October 2014.

2.6.5 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.

2.6.5.1 Estimated central pressure of VSCS, HUDHUD

The hourly MSLP as recorded by Visakhapatnam is shown in Fig.2.6.2a 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.

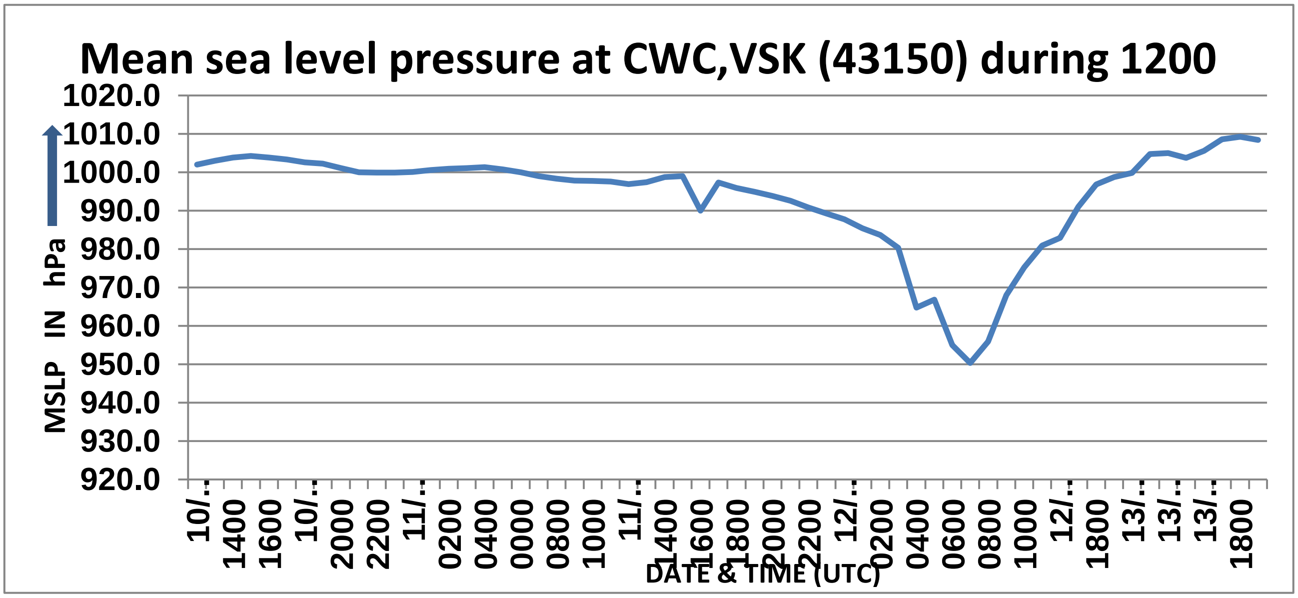


Fig. 2.6.2a: Hourly MSLP recorded at Visakhapatnam during 10-12th Oct. 2014

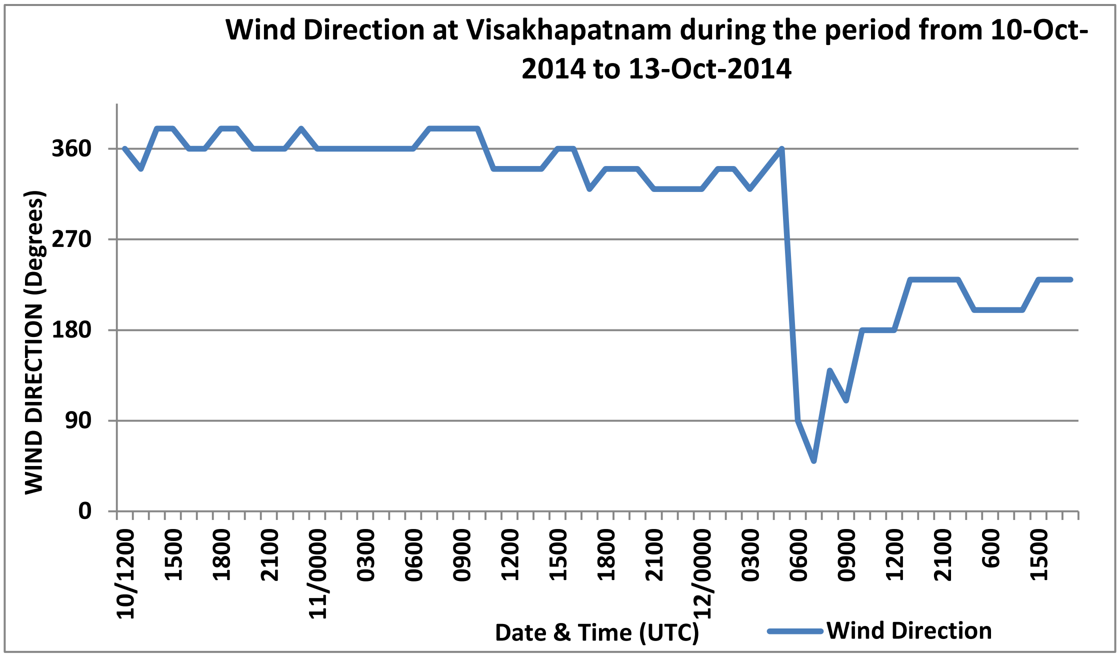


Fig. 2.6.2(b)Hourly wind direction reported by Visakhapatnam Observatory during the period from 1200 UTC of 10th October 2014 to 2100 UTC of 13th October 2014.

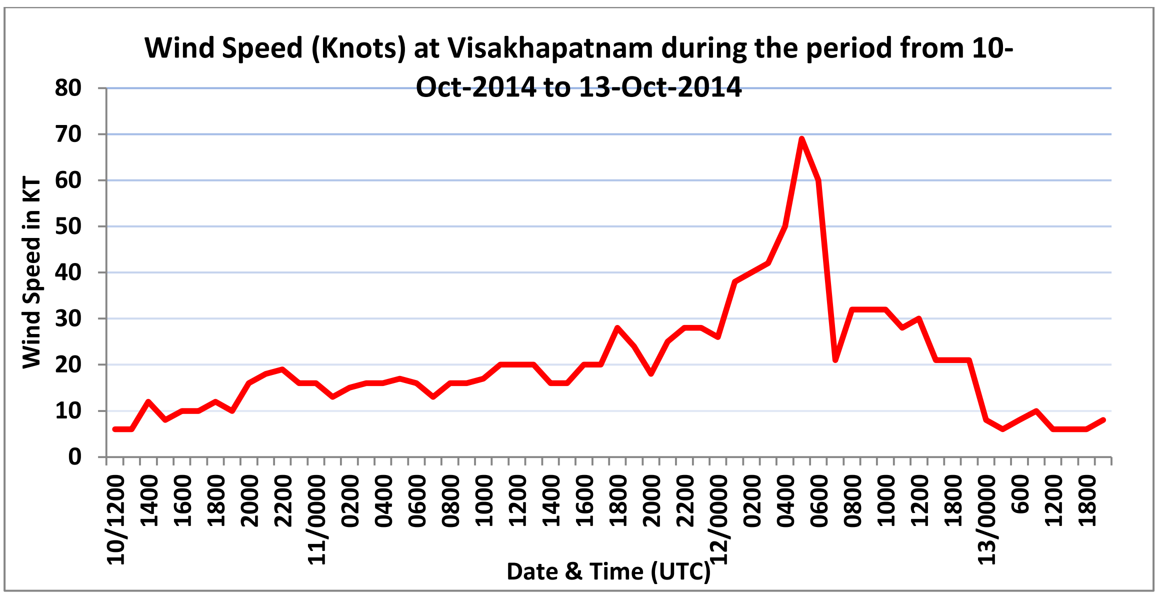


Fig. 2.6.2(c) : Hourly wind speed reported by Visakhapatnam Observatory during the period from 1200 UTC of 10th October 2014 to 2100 UTC of 13th October 2014.

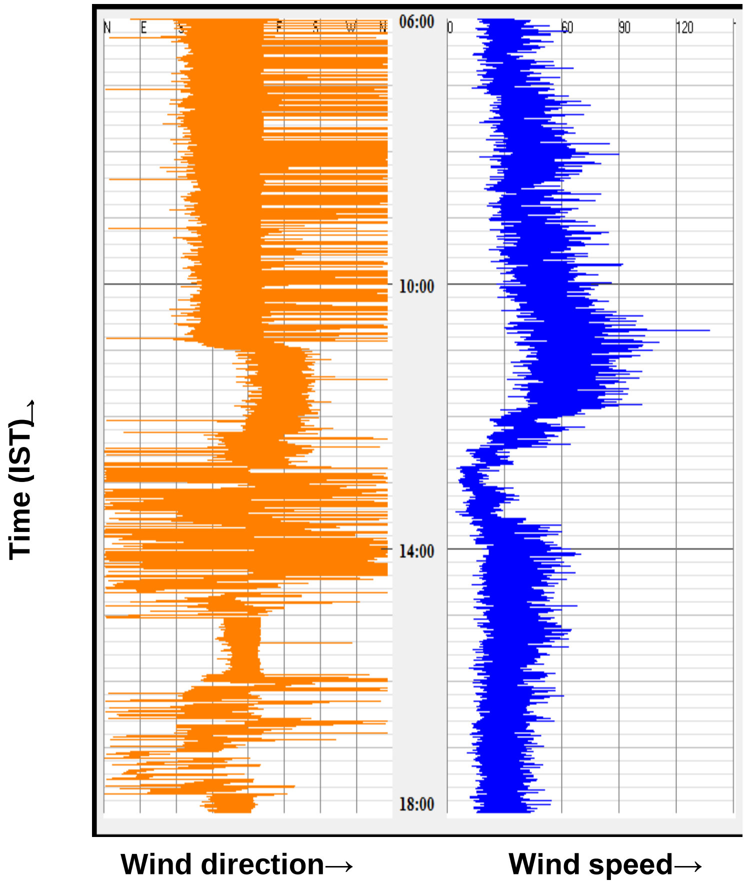


Fig. 2.6.2d Wind speed and direction recorded by HWSR, Visakhapatnam on 12 October 2014

2.6.5.2 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 0531UTC and the 3-minute average MSW which is the standard practice of the IMD was about 69 knots (128kmph) at 0533UTC of 12th October, 2014 (Fig. 2.6.3b).

2.6.5.3 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.

2.6.5.4 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).

2.6.5.5 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)

2.6.5.6. 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 185kmph (100 knot). The gust which is a sudden rise in wind speed in association with a cyclone can reach up to 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 0512UTC of 12th October, 2014.

2.6.6 Characteristic observed by buoy

OMNI buoys deployed in the Bay of Bengal have captured the signals of cyclone passage and the time series observations clearly exhibit the importance of the proximity of the location to the cyclone track. The buoy BD12 &BD13 is closer to the track and met and surface observations show its severity. The buoy BD11 and BD14 are far away from the cyclone track and hence the response is less even though it is located at the left side of the track. The buoy BD08, BD09 and BD10 are also away from the cyclone track and it is located at the right side of the track. Table 2.6.2shows the distance between cyclone track and OMNI buoy location.

Table 2.6.2 Distance of buoys from track of cyclone Hudhud

Sl.No	Buoy ID/Position	Distance between cyclone track and Buoy position	Remarks
1	BD12	66 nm	Captured on 7thand 8th Oct 2014
2	CB01	44 nm	Captured on 7thand 8th Oct 2014
3	BD13	47 nm	Captured on 9th and 10th Oct 2014
4	BD10	117 nm	Captured on 10th Oct 2014
5	BD09	235 nm	Variation observed
6	BD08	249 nm	Variation observed
7	BD11	160nm	To be observed

Fig.2.6.3indicates the Atmospheric Pressure recorded at the three OMNI buoy locations in the Bay of Bengal with a maximum drop observed at BD13 recorded a minimum pressure of 994.6 hPa on October 10, 2014.

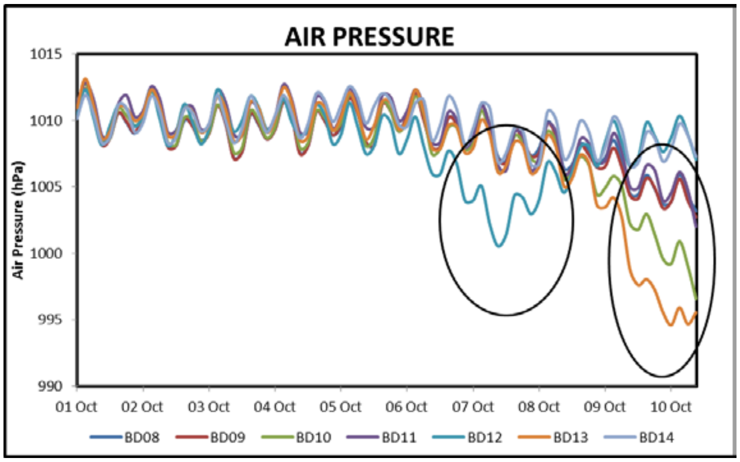


Fig. 2.6.3 Time series of MSLP as recorded by the buoys during 1-10 October

Fig. 2.6.4 indicates the wind speed recorded at three OMNI buoys and one coastal buoy in the Bay of Bengal, with BD13 which is on the track of the cyclone recorded a maximum wind speed of 20.5 m/s on October 10, 2014.

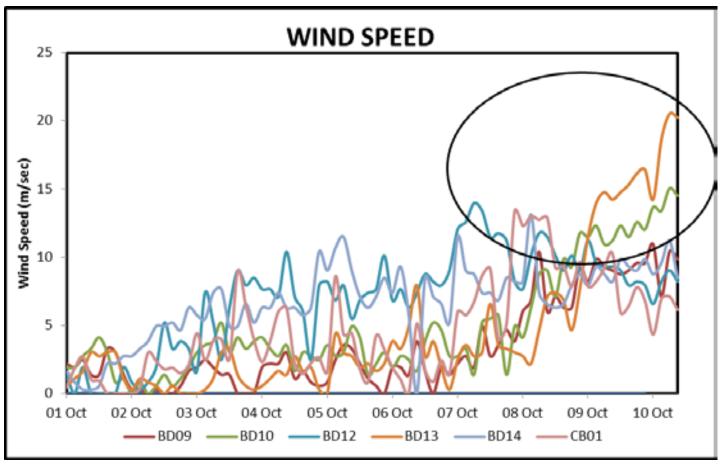


Fig. 2.6.4Wind speed recorded by the buoys during 1-10 October

Fig. 2.6.5 indicates that BD08 recorded a maximum significant wave height of 3.75 m on 10th October, 2014

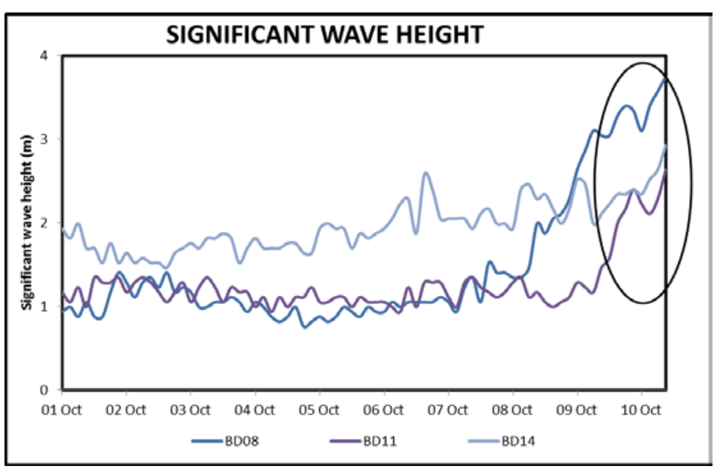


Fig. 2.6.5wave height recorded by the buoys during 1-10 October

Fig. 2.6.6The decrease in the surface temperature by 1.1 °C

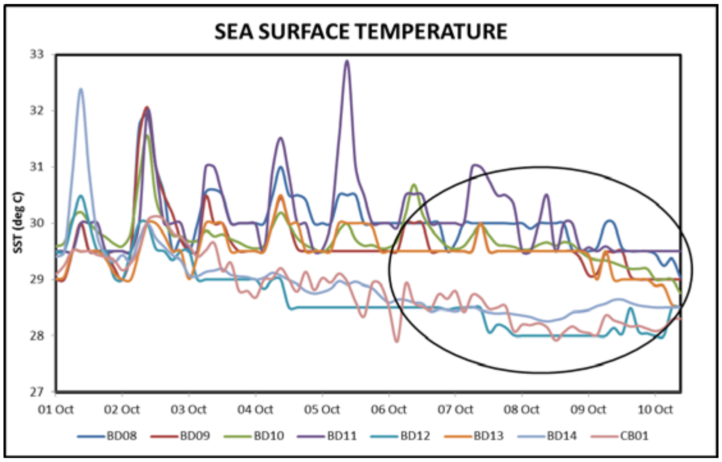


Fig. 2.6.6Sea Surface Temperature recorded by the buoys during 1-10 October

Fig. 2.6.7indicate the increase in surface current speed was recorded maximum at BD13 location with a speed of 100.09 cm/s on 10th October, 2014.

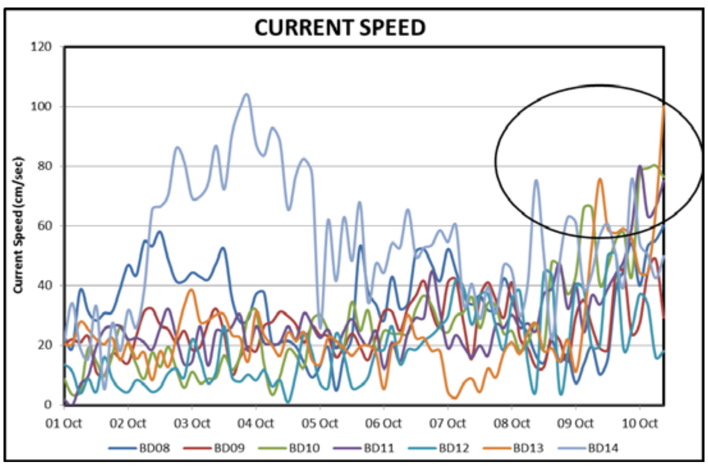


Fig. 2.6.7Surface Ocean current recorded by the buoys during 1-10 October

2.6.7 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. 2.6.8-2.6.10.

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 0300 UTC 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 1130 UTC 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 1200 UTC 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 0300 UTC 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 1800 UTC of 8th Oct. It further intensified to T3.5 at 0300 UTC 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 0600 UTC 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 0300 UTC of 11th and further to T5.0 at 0600 UTC of 11th near 16.1°N/85.2°E. The eye was clearly visible at 0000 UTC 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.

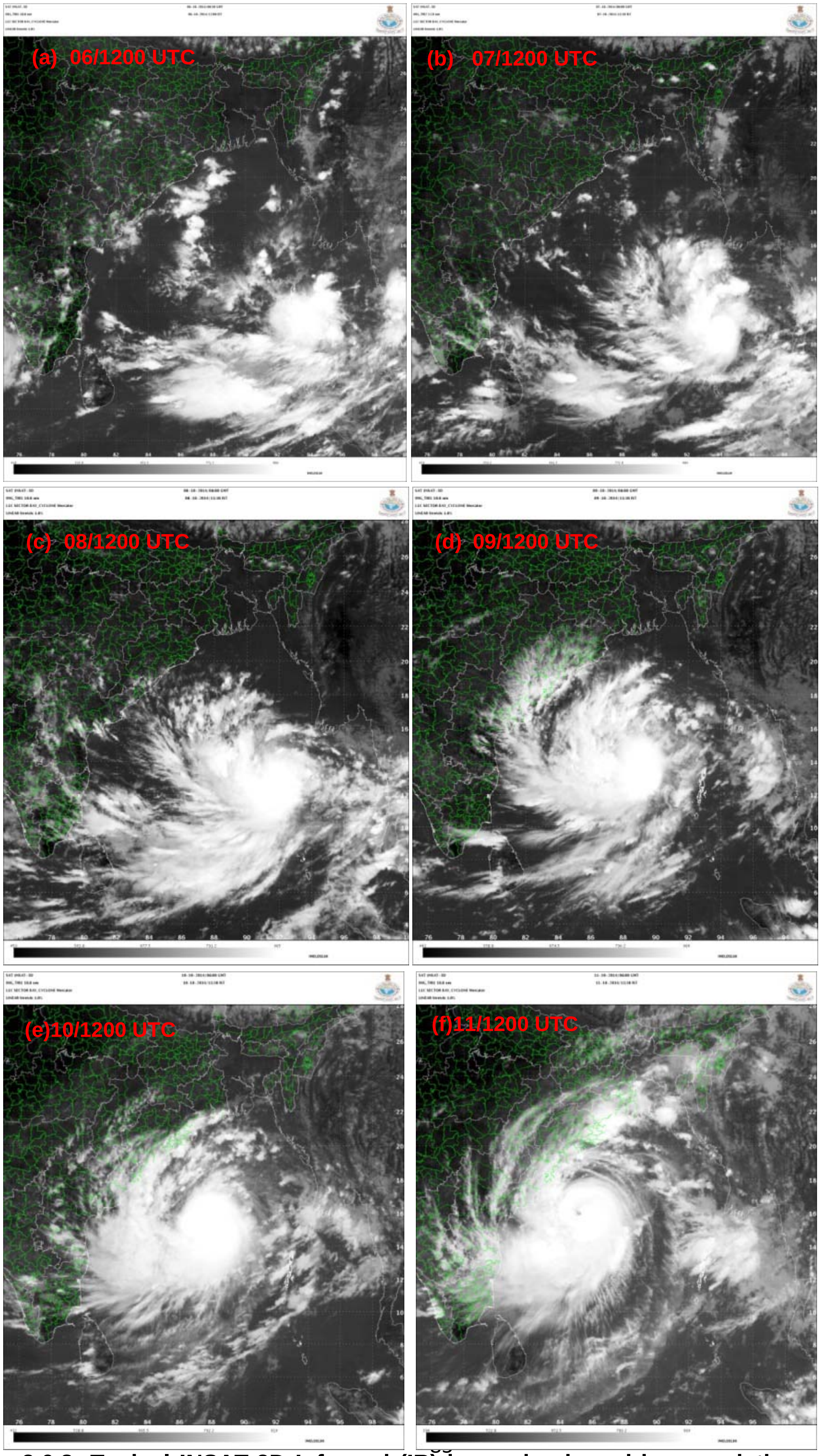


Fig. 2.6.8: Typical INSAT-3D Infra-red (IR) imageries based in association with VSCS HUDHUD during 06-14 October 2014

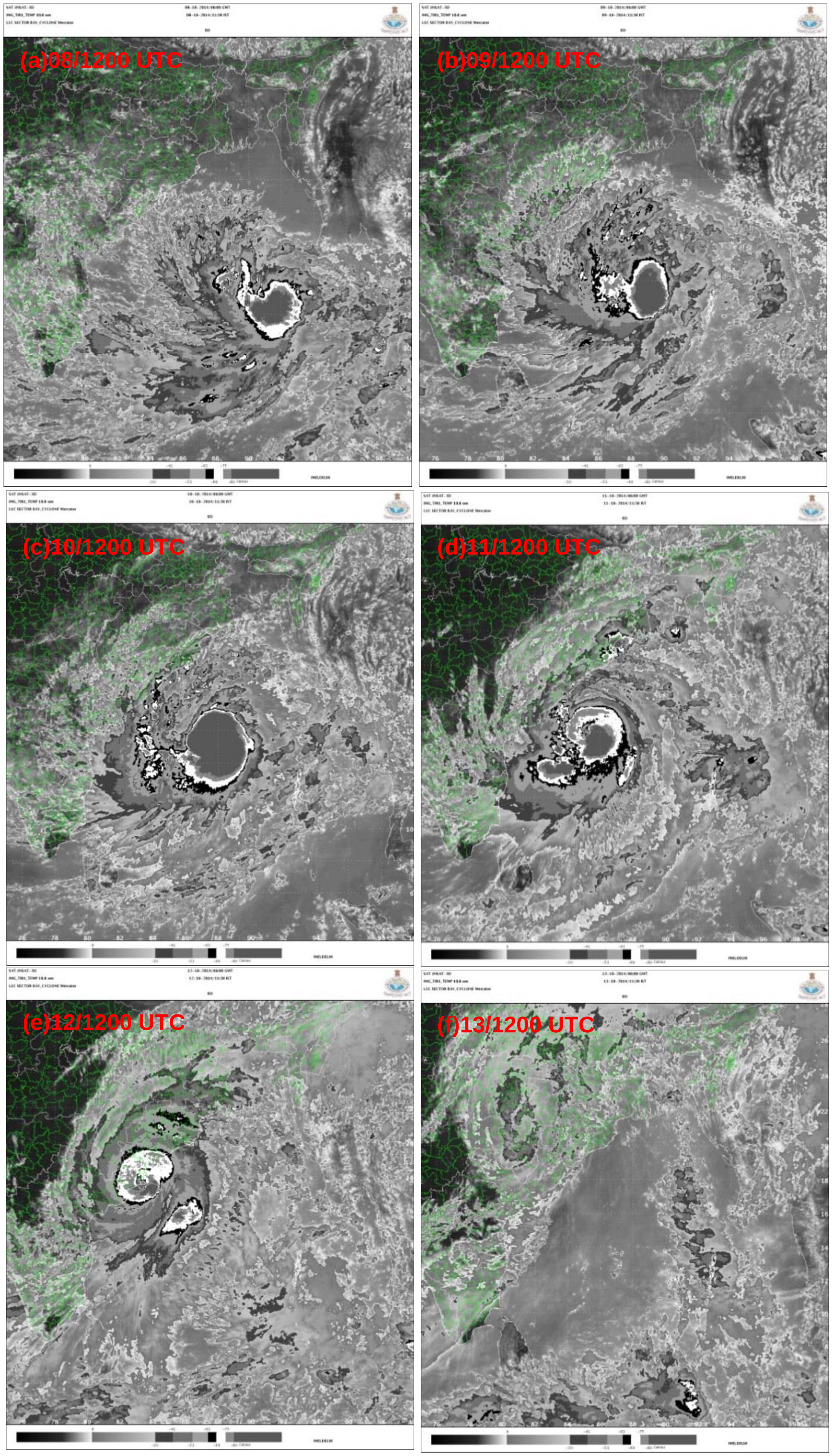


Fig. 2.6.9 INSAT-3D enhanced IR imageries in association with VSCS HUDHUD during 08-13 October 2014

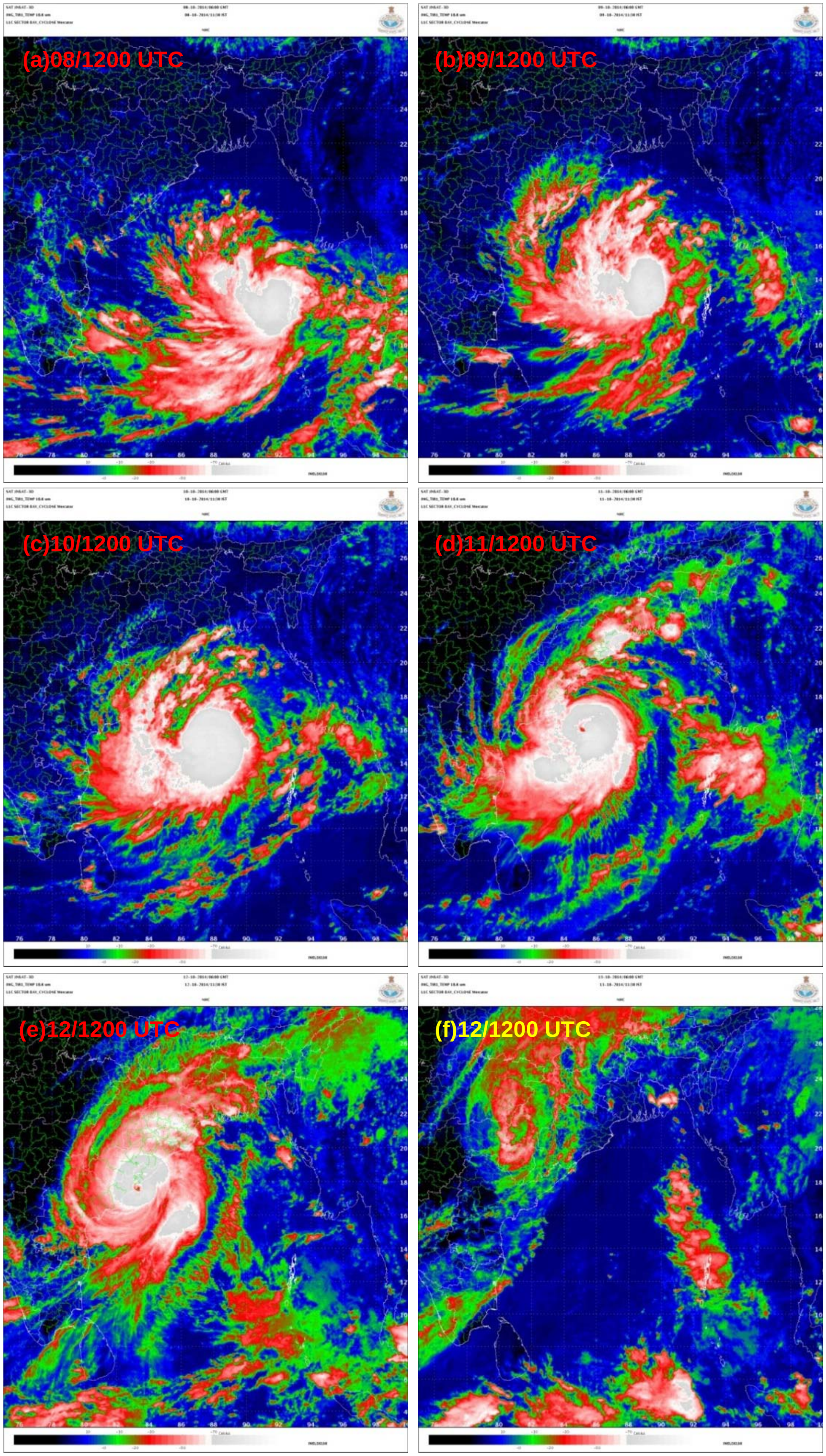


Fig. 2.6.10 INSAT-3D colored enhanced IR imageries based on 0600 UTC in association with VSCS HUDHUD during 08-13 October 2014

2.6.8 Features observed through Radar

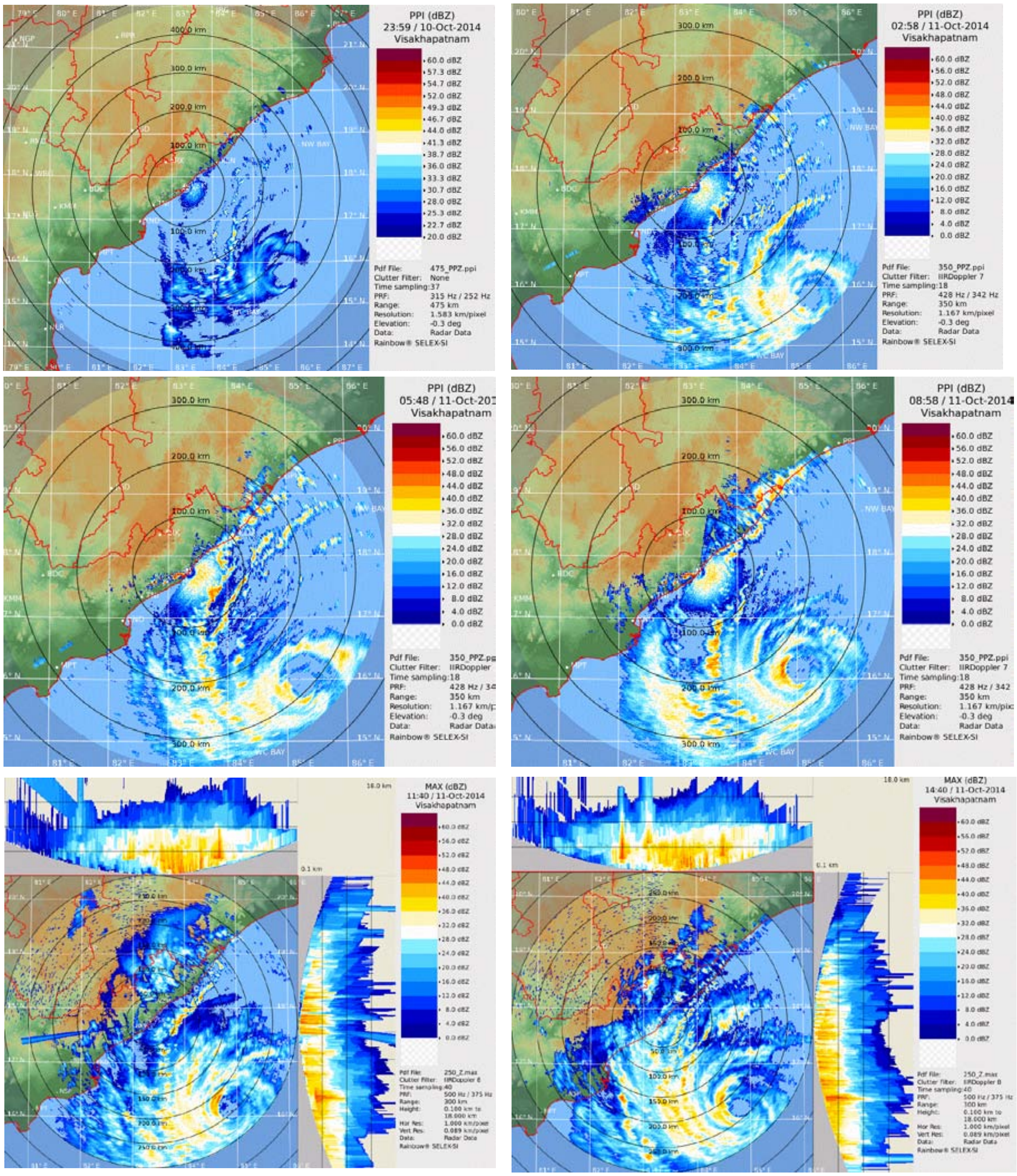
VSCS HUDHUD was monitored by DWR Visakhapatnam continuously and observations were taken every 10 min. and bulletins were issued hourly till 0450UTC of 12th. After that telecommunication was disrupted and the issue of bulletins was stopped. However, the observations from DWR Machillipatnam were used to monitor the cyclone till 12th evening. The initial cloud echoes were observed at 2200 UTC 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 0300UTC of 12th (Table 2.6.2). When reduced to surface level, it is about 90 kts. The half eye of the cyclone was visible till 0130 UTC 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 1030-1230 UTC of 11th. By 1100UTC of 11th, it was again a closed eye and the same continued till 0000 UTC of 12th. It became a weak eye during 0000-0200 UTC and became elliptical at 0200 UTC of 12th. The eye became ill defined from 0300 UTC onwards. The eye diameter increased initially reaching the maximum of 52 km at 0200 UTC of 11th Oct. Thereafter, it decreased up to 0500UTCand then increased again till 1100 UTC 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 2.6.2. A few DWR imageries are shown in Fig.2.6.11to 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 0430 UTC 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-2.6.3. 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 and height (km) above msl	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	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 km	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	43.0	Closed eye
10	11.10.14 0700	16.0	85.20	281.9	133.6	42.2 at 2.9 km	42.0	Open eye
11	11.10.14 0800	16.13	85.12	260.4	133.0	42.5 at 2.4 km	45.0	Open eye
12	11.10.14 0900	16.12	85.01	252.9	135.0	46.0 at 2.6 km	41.3	Open eye
13	11.10.14 1000	16.15	84.92	243.7	136.5	46.0 at 4.6 km	42.1	Open eye
14	11.10.14 1100	16.17	84.86	238.2	137.2	46.0 at 4.3 km	48.7	Closed eye
15	11.10.14 1200	16.15	84.83	237.6	138.1	43.0 at 4.1 km	31.0	Closed eye
16	11.10.14 1300	16.19	84.79	232.0	138.1	46.0 at 3.9 km	40.4	Closed eye
17	11.10.14 1400	16.198	84.77	230.7	138.9	46.0 at 3.8 km	36.1	Closed eye
18	11.10.14 1500	16.23	84.80	229.7	137.3	46.0 at 3.5km	38.1	Closed eye
19	11.10.14 1600	16.32	84.8	221.0	135.9	46.0 at 3.9 km	46.0	Closed eye
20	11.10.14 1700	16.43	84.81	212.6	133.9	49.0 at 3.6 km	41.8	Closed eye
21	11.10.14 1800	16.57	84.75	198.8	131.1	48.6 at 2.8 km	40.6	Closed eye
22	11.10.14 1900	16.71	84.66	180.8	129.4	51.8 at 3.0 km	40.1	Closed eye
23	11.10.14 2000	16.77	84.57	170.0	129.8	48.2 at 3.1 km	38.7	Closed eye
24	11.10.14 2100	16.86	84.47	155.1	129.5	49.8 at 1.9 km	40.8	Closed eye
25	11.10.14 2200	16.99	84.41	140.3	126.6	49.5 at 1.7 km	37.2	Closed eye
26	11.10.14 2300	17.17	84.29	118.7	122.3	49.0 at 1.2 km	44.2	Closed eye
27	12.10.14 0000	17.26	84.17	103.1	121.1	54.0 at 1.0 km	66.0	Closed eye

28	12.10.14 0100	17.17	84.05	98.3	130.9	57.0 at 0.8 km	30.1	Weak eye
29	12.10.14 0130	17.34	83.93	77.0	126.6	58.6 at 0.6 km	27.5/18.5	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



2.6.11 : Visakhapatnam RADAR imageries based on 0000 UTC to 1500 UTC of 11th October 2014

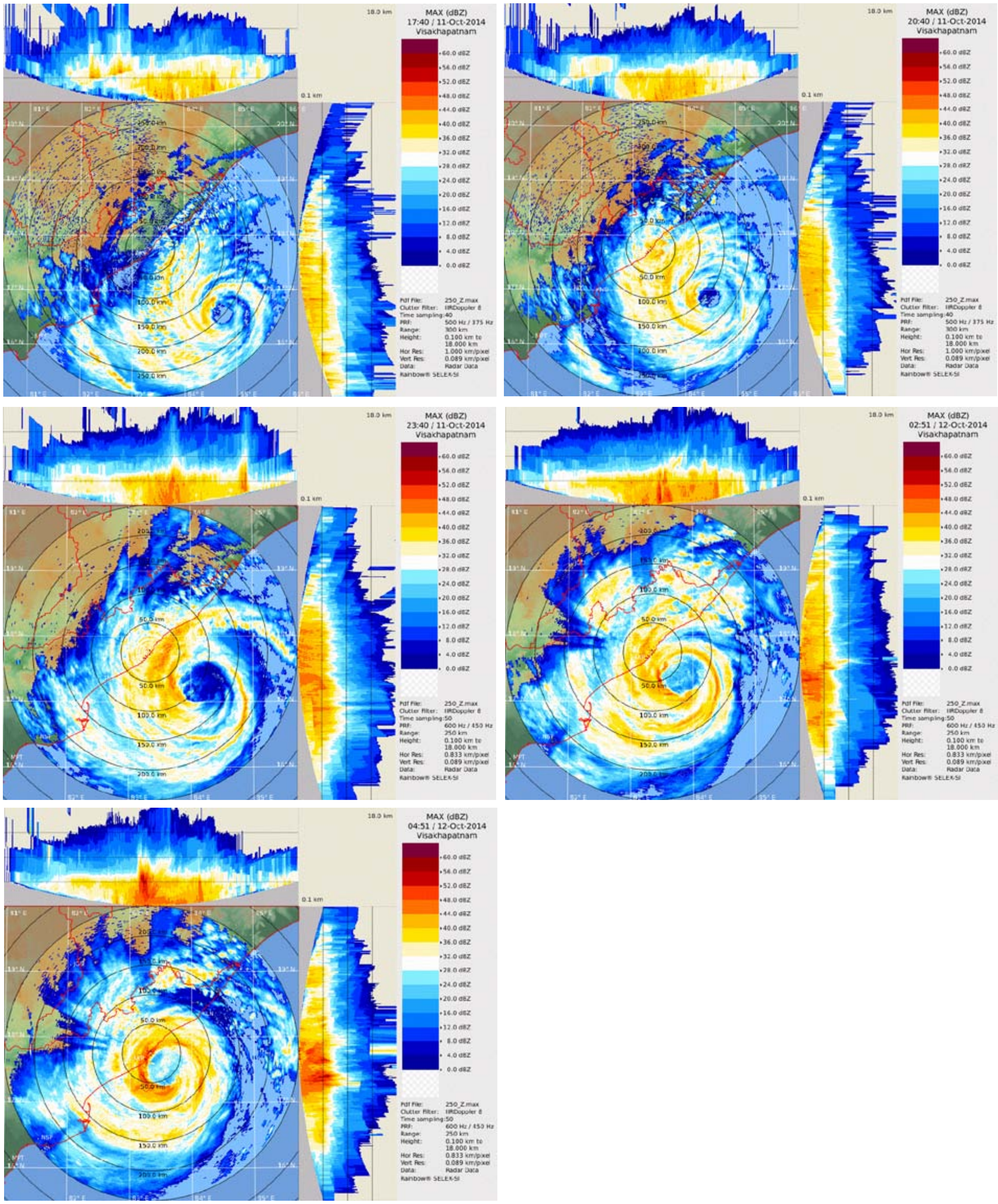


Fig. 2.6.11 (contd.): Visakhapatnam RADAR imageries based on 1800 UTC of 11th October 2014 to 0500 UTC of 12th October 2014

2.6.9 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. 2.6.12. based on IMD-GFS analysis.

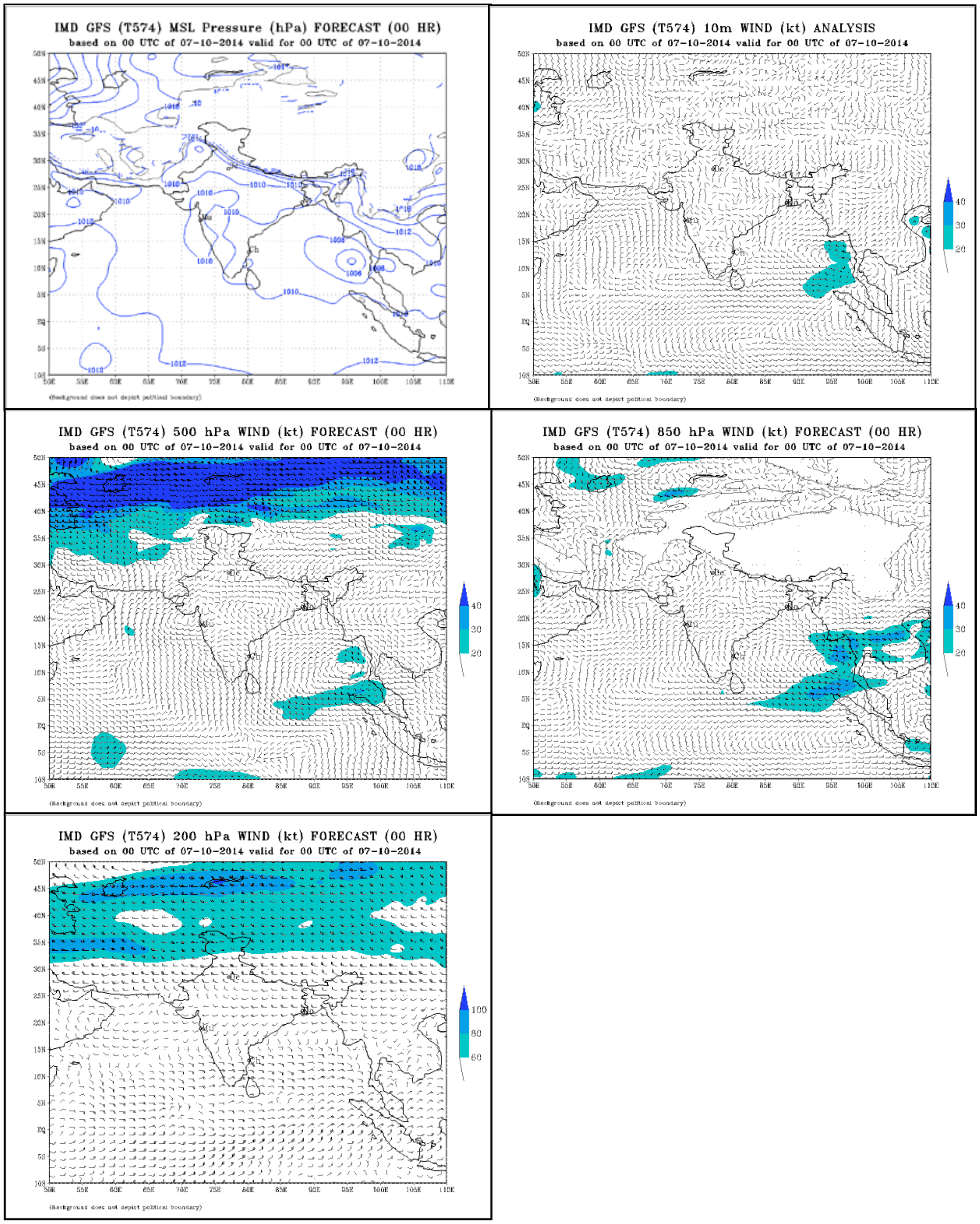


Fig 2.6.12 IMD-GFS Analysed charts on 7th MSLP Analysis, 10 m winds, 850 hPa winds, 500 hPa winds& 200 hPa winds

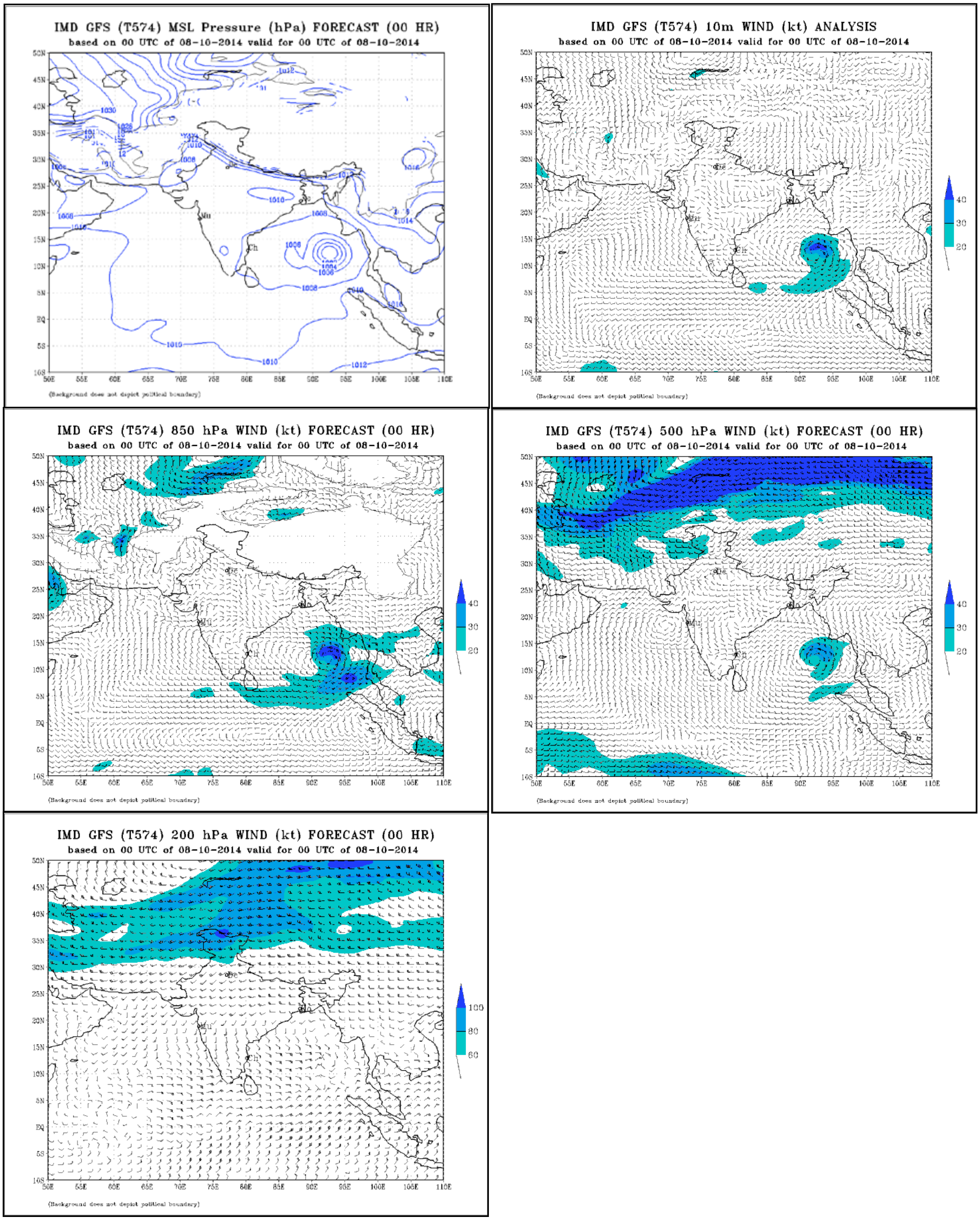


Fig. 2.6.12 (contd.) IMD-GFS Analysed charts on 8th MSLP Analysis, 10 m winds, 850 hPa winds, 500 hPa winds & 200 hPa winds

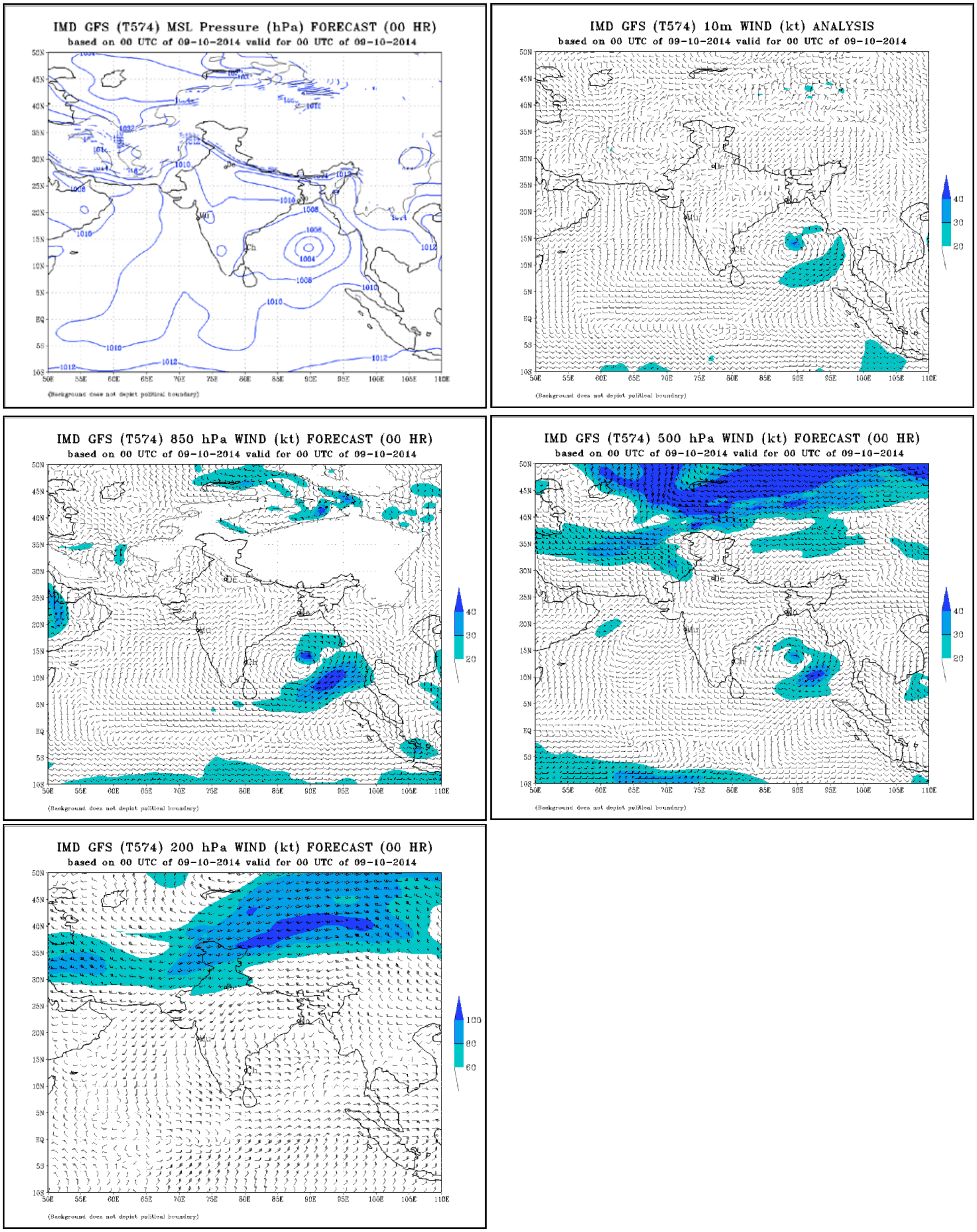


Fig. 2.6.12(contd.): IMD-GFS Analysed charts on 9th MSLP Analysis, 10 m winds, 850 hPa winds, 500 hPa winds & 200 hPa winds

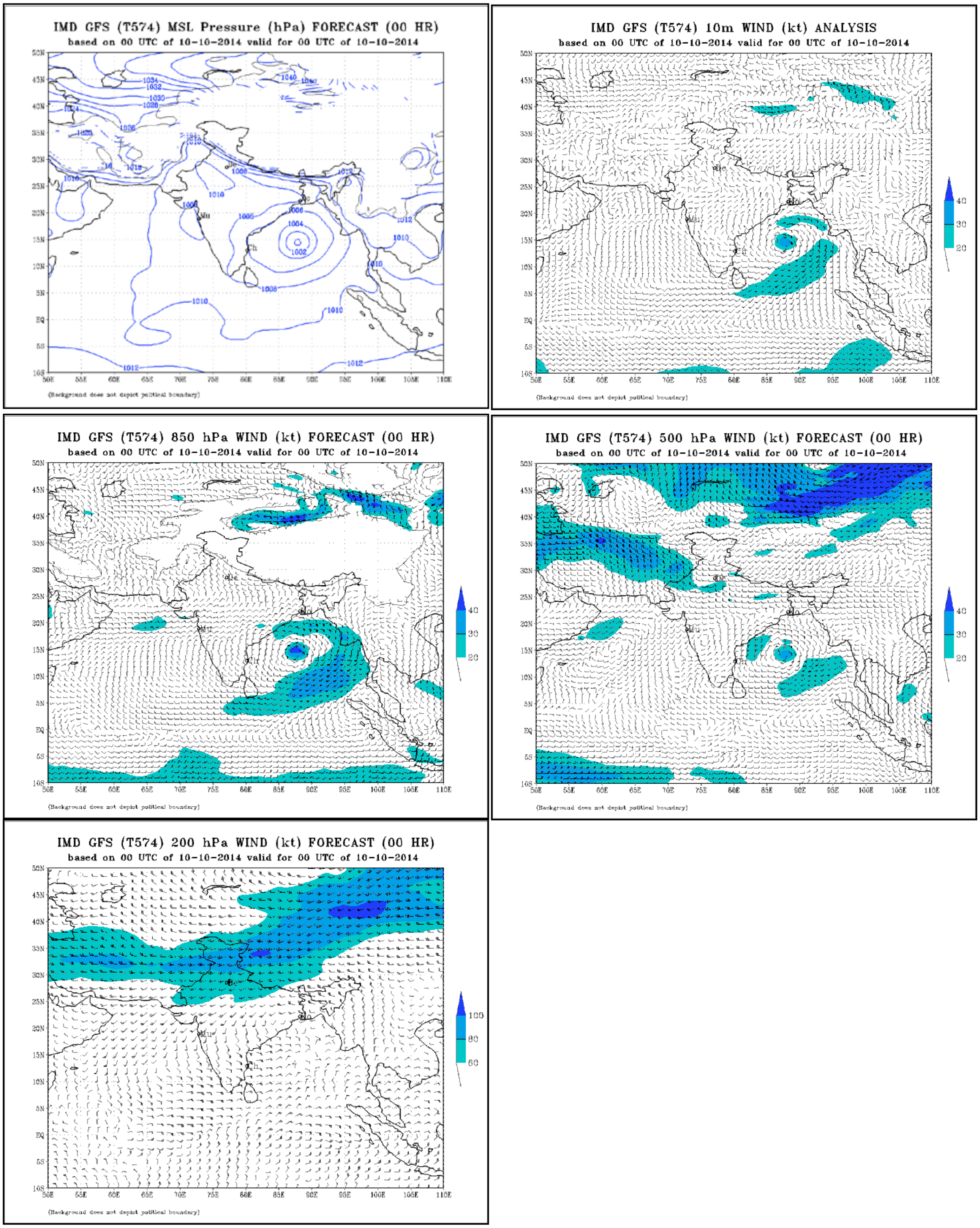


Fig. 2.6.12 (contd.)IMD-GFS Analysed charts on 10th MSLP Analysis, 10 m winds, 850 hPa winds, 500 hPa winds & 200 hPa winds

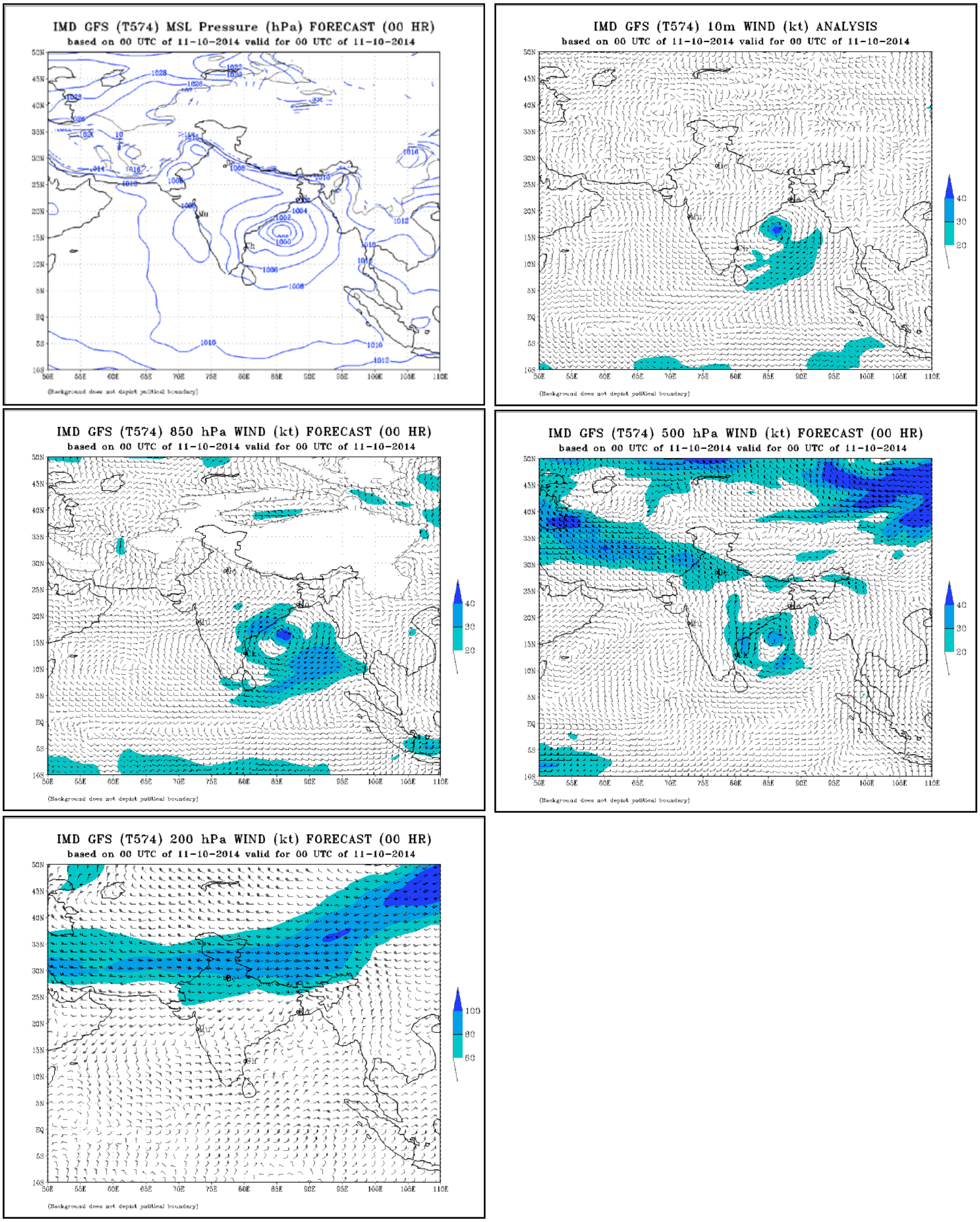


Fig. 2.6.12 (contd): IMD-GFS Analysed charts on 11th October 2014 MSLP Analysis, 10 m winds, 850 hPa winds, 500 hPa winds and 200 hPa winds

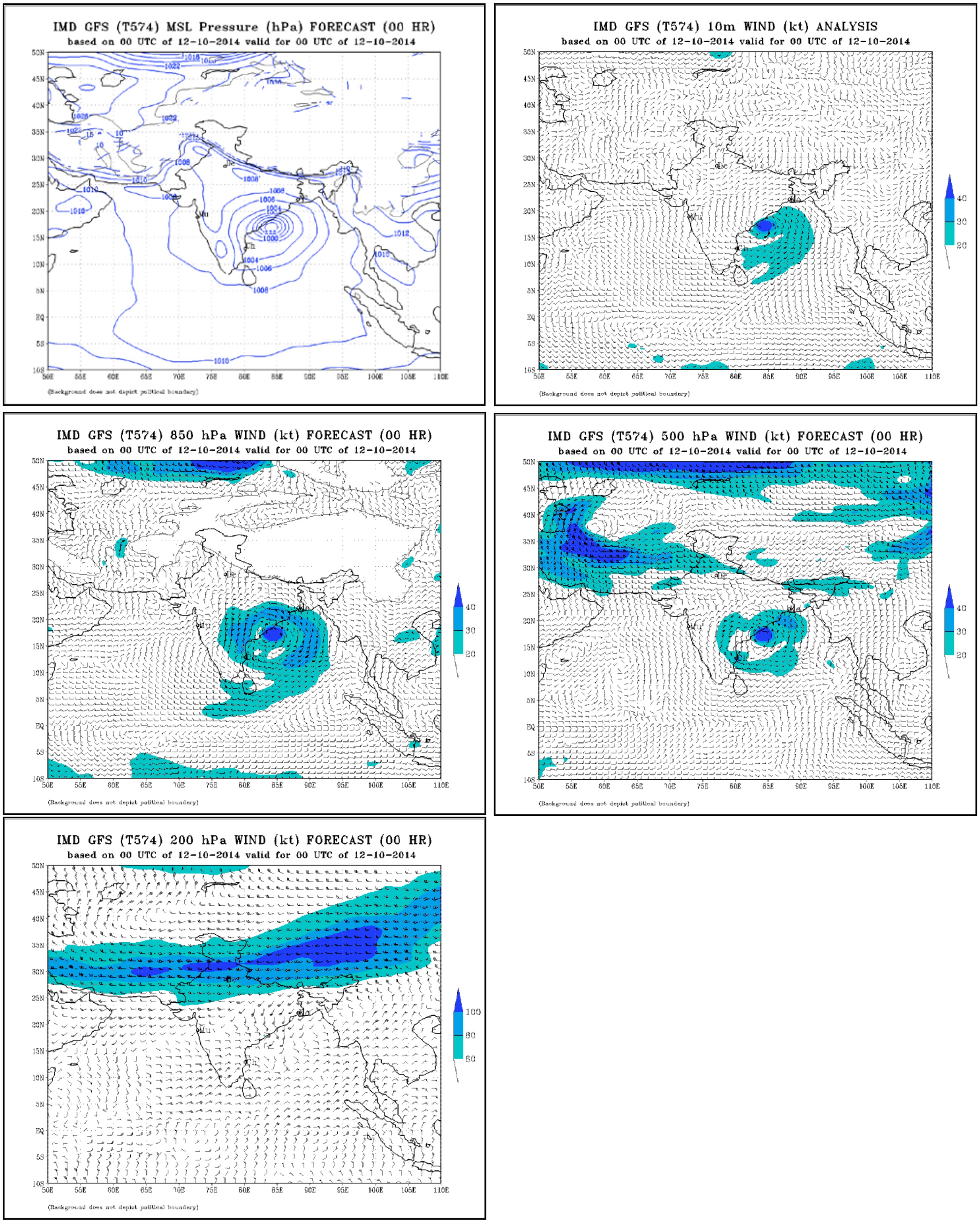


Fig. 2.6.12 (contd.) IMD-GFS Analysed charts on 12th October MSLP Analysis, 10 m winds, 850 hPa winds, 500 hPa winds & 200 hPa winds

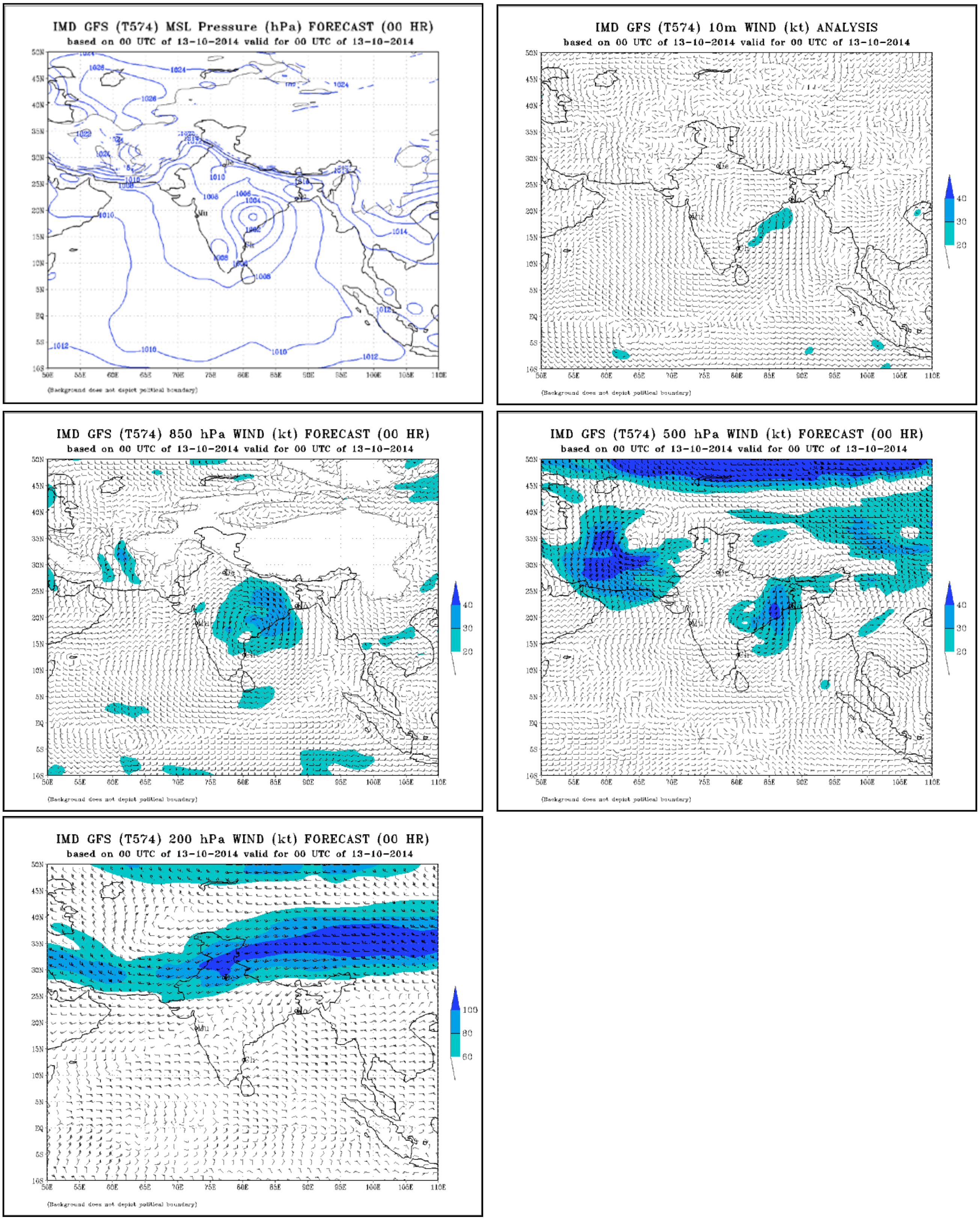


Fig. 2.6.12 (contd.) IMD-GFS Analysed charts on 13th October MSLP Analysis, 10 m winds, 850 hPa winds, 500 hPa winds & 200 hPa winds

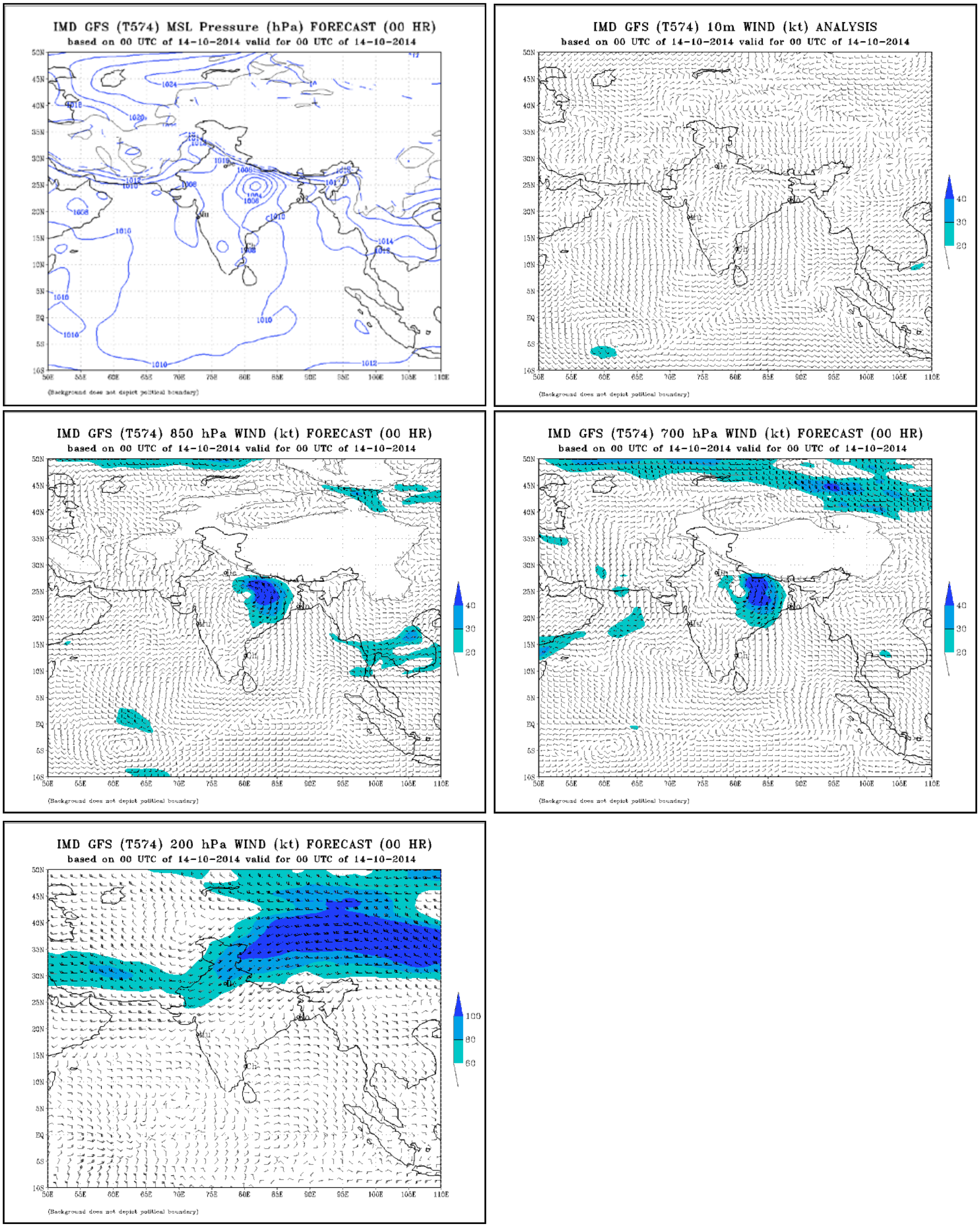


Fig. 2.6.12 (contd.) IMD-GFS Analysed charts on 14th October MSLP Analysis, 10 m winds, 850 hPa winds, 700 hPa winds & 200 hPa winds

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 2.6.4.1. 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 up to 300 hPa during the genesis phase and up to 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.

2.6.10 Realized Weather:

2.6.10.1. 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 0300 UTC 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.

12 October 2014

Andhra Pradesh: Itchapuram (dist Srikakulam) 14, Visakhapatnam Ap (dist Vishakhapatnam), Kalingapatnam (dist Srikakulam) 12 each, Visakhapatnam (dist Vishakhapatnam) 11, Pusapatirega (dist Vizianagaram), Vizianagaram (dist Vizianagaram), Ranasthalam (dist Srikakulam) 10 each, Nellimarla (dist Vizianagaram), Tekkali (dist Srikakulam), Palasa Mandal(arg) (dist Srikakulam) 9 each, Sompeta (dist Srikakulam), Palasa (dist Srikakulam), Cheepurupalli (dist Vizianagaram) 8 each, Mandasa (dist Srikakulam), Denkada (dist Vizianagaram), Garividi (dist Vizianagaram) 7 each

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

13 October 2014

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

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 2.6.4. The district-wise distribution of daily rainfall over Andhra Pradesh during 13-14 October 2014 is presented in Fig. 2.6.13.

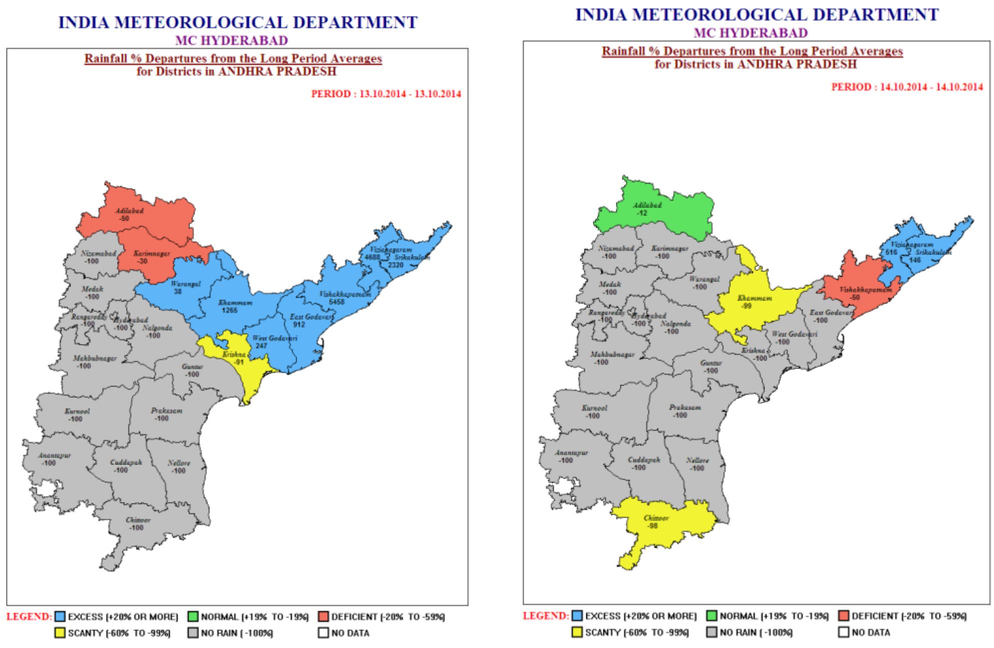


Fig. 2.6.13: District-wise distribution of daily rainfall over Andhra Pradesh during 13-14 October 2014

Table2.6.4: 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						
12.10.2014	PDN	259%	369%						
	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		
13.10.2014	PDN	931%	2437%	92%	1964%	1446%	252%		
	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
14.10.2014	PDN		98%		2070%	75%	310%	9792%	2225
	ACT (mm)						30.5		27.8
	NOR (mm)						1.4		0.6
15.10.2014	PDN						2078%		4535

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. 2.6.14.

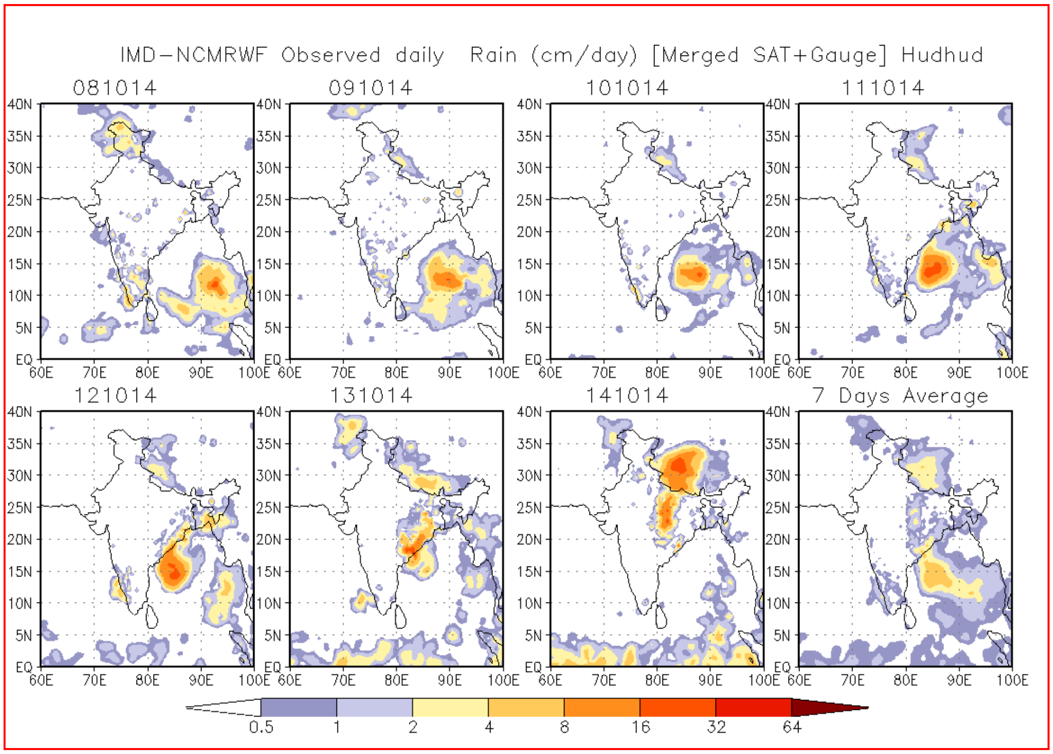


Fig. 2.6.9.14 IMD-NCMRWF satellite-gauge merged daily rainfall (in cm) during the period 08-14 October 2014 and the 7-day average rainfall during the same period.

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.

2.6.10.2 Gale Wind

Maximum gale wind of 185 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

2.6.10.3.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.

2.6.11. Damage due to Cyclone 'HUDHUD'

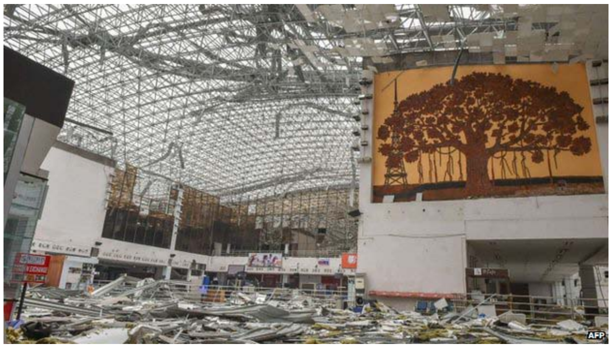
The VSCS, 'HUDHUD' mainly affected North Andhra Pradesh and adjoining south Odisha. Details of the damages in Andhra Pradesh are given in Table 2.6.5. As per the report of the Government of Andhra Pradesh. A few damage photographs are shown in Fig. 2.6.15

Table -2.6.5Damages associated with VSCS Hudhud

S No.	ITEM	Quantity
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	
	) Number of animal perished (no.)	2831
	) 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
	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)	80
	(b) Secondary schools (Partially/ully.)	237
	(c) Community Center (Partially)	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	
	Damaged looms	15
	Loss of raw materials / Goods in process / finished goods	32
9	Fisheries	
	Loss of Boat/missing	1110
	Catamaran	698
	Net	2129
10	Street vendors	10
	Loss of push carts(number)	85
11	Artisans’	70

(Source: Govt. of Andhra Pradesh)



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 uprooted electric poles

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

Fig. 2.6.15: Few Damage photographs associated with VSCS Hudhud

2.7 Very Severe Cyclonic Storm (VSCS) NILOFAR over the Arabian Sea(25-31 October 2014)

2.7.1. Introduction

The very severe cyclonic storm, Nilofar developed from a low pressure area which lay over southeast Arabian Sea in the morning of 21st October. It moved northwestwards and concentrated into a Depression in the early morning of 25th over westcentral and adjoining southwest Arabian Sea. It intensified into a Cyclonic Storm over the same region in the morning of 26th. It then moved nearly northwards and further intensified into a Severe Cyclonic Storm (SCS) over westcentral Arabian Sea in the early morning of 27th and into a Very Severe Cyclonic Storm (VSCS) around noon of the same day. It continued to move nearly northwards and reached its maximum intensity around midnight of 28th with wind speed of 205 kmph. It then moved north-northeastwards and started to weaken rapidly under the influence of high vertical wind shear, entrainment of dry and cold air from the north and relatively lower ocean thermal energy. It weakened into a Severe Cyclonic Storm during early hours of 30th October and into a Cyclonic Storm in the afternoon of 30th October. It weakened into a Deep Depression in the early hours and into a Depression in the early morning of 31st October. It weakened into a well marked low pressure area over northeast Arabian Sea off north Gujarat coast in the forenoon of 31st Oct.

The salient features of this system are as follows.

i. The track of the system was unique, as it initially moved northwestward on the day of formation and then re-curved northeastwards. It further moved nearly northwards very slowly up to 29th evening and then east-northeastwards.
ii. The estimated maximum sustained surface wind speed in association with the cyclone was about 110 kt (205 kmph).
iii. The estimated central pressure was 950 hPa with a pressure drop of 56 hPa at the centre compared to surroundings.
iv. It exhibited Rapid Intensification as well as Rapid Weakening. The maximum sustained wind increased from about 100 kmph in the early morning of 27th to about 205 kmph in the early evening of 28th (in 36 hours). It weakened rapidly from VSCS (wind speed of about 200 kmph) in the morning of 29th into SCS (wind speed of about 110 kmph) in the morning of 30th and further into a low pressure area (wind speed < 30 kmph) on 31st morning.
v. Though the re-curvature of the track could be predicted by NWP models 3 to 4 days in advance, there was large variation in the position and time of the landfall as well as re-curvature.
vi. Though the genesis, track and intensification/weakening were predicted by IMD with reasonable accuracy five days in advance, rapid intensification and rapid weakening prediction was very challenging.

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.

2.7.2 Monitoring and prediction of VSCS NILOFAR

The VSCS Nilofar was monitored & predicted continuously since its inception by the IMD. IMD could predict well in advance the genesis, intensification, weakening as well as the re-curvature of the track towards Gujarat coast. The VSCS Nilofar was monitored mainly with satellite observations, supported by meteorological buoys and ship observations. OMNI buoys deployed in the Arabian Sea captured the signals of the NILOFAR cyclone passage and the time series observations clearly exhibit the importance of the proximity of the location of the buoys to the cyclone track.

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 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.

2.7.3. Brief life history

2.7.3.1. Genesis

Under the influence of the active northeast monsoon, a cyclonic circulation extending up to mid – tropospheric level lay over Lakshadweep area and adjoining Kerala in the morning of 19th October. It lay over southeast Arabian Sea and adjoining Lakshadweep on 20th October. Under its influence, a low pressure area formed over southeast Arabian Sea in the morning of 21st October. It persisted over the same region and became well marked in the early morning of 23rd October. It concentrated into a Depression in the early morning of 25th October and lay centered at 0000 UTC of 25th over westcentral and southwest Arabian Sea near Lat. 12.5°N/ Long. 61.5°E. According to the satellite imagery intensity was T 1.5. The convection increased from 24th to 25th with increase in organization and depth of cloud. The associated cloud showed shear pattern with major convection being shifted to west of the low level circulation centre. The associated maximum sustained wind speed was 25 kts. However, the winds were higher in the northern sector due to prevailing northeast monsoon circulation. A ship located near Lat. 12.5°N/ Long. 60.3°E reported MSLP of 1001 hPa and surface wind speed of 330°/20 kts indicating the fact that areal extent of the strong winds in the northwestern sector was less compared to the northeast and southwest sector.

Considering the environmental condition, the SST was 28-30°C around the system centre prior to the genesis of Depression. Ocean thermal energy was 60-80 kJ/cm^2 and vertical wind shear was moderate 10-20 kts around the system centre. The low level convergence was about $15*10^{-5}s^{-1}$ and vorticity was about $200 *10^{-5}s^{-1}$. The upper level divergence was about $30*10^{-5}s^{-1}$. The low level relative vorticity and convergence as well as the upper level divergence increased from 24th to 25th. There was pole ward favourable outflow in association with an anti-cyclone to the east-northeast of the system. The upper tropospheric ridge at 200 hPa level ran along 15°N. The MJO was located in Phase 1 with amplitude greater than 1.

The observed track of the system is shown in fig.2.1.

2.7.3.2. Intensification and movement

In association with the favourable environmental and meteorological conditions as mentioned in previous section, the Depression moved north-northwestwards and intensified into a

Deep Depression at 0300 UTC of 26th over westcentral and adjoining southwest Arabian Sea near Lat. 14.0°N/ Long. 62.0°E. It intensified into a cyclonic storm over the same region at 0600 UTC of 26th. As the system was lying close to the ridge, it moved slowly northwards and intensified into an SCS over west central and adjoining southwest Arabian Sea at 2100 UTC of 27th and into a VSCS at 0600 UTC of the same day and lay centered over westcentral Arabian Sea near Lat. 14.9°N/ Long. 62.0°E. It continued to intensify further and reached the peak intensity with T 5.5 at 1800 UTC of 29th and lay centered over westcentral Arabian Sea near Lat. 17.6°N/ Long. 61.8°E.

The system exhibited Rapid Intensification as well as Rapid Weakening. The maximum sustained wind increased from about 100 kmph in the early morning of 27th to about 205 kmph in the evening of 28th (in 36 hours) because of low vertical wind shear and increase in vorticity. It weakened rapidly from VSCS (wind speed of about 200 kmph) in the morning of 29th into SCS (wind speed of about 110 kmph) in the morning of 30th and further into a low pressure area (wind speed < 30 kmph) on 31st morning under the influence of high vertical wind shear, entrainment of dry and cold air and relatively lower ocean thermal energy. Also the convection was highly sheared from the low level circulation centre. The best track parameters of VSCS 'NILOFAR' are shown in Table 2.7.1.

Table 2.7.1 Best track positions and other parameters of the Very Severe Cyclonic Storm, 'NILOFAR' over the Bay of Bengal during 25-31 October, 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
25/10/2014	0000	12.5/61.5	1.5	1004	25	3	**D**
	0300	12.5/61.5	1.5	1004	25	3	D
	0600	12.5/61.5	1.5	1004	25	3	D
	1200	13.0/61.0	1.5	1003	25	3	D
	1800	13.0/61.0	1.5	1003	25	3	D
26/10/2014	0000	14.0/62.0	1.5	1002	25	4	D
	0300	14.0/62.0	2.0	999	30	5	**DD**
	0600	14.1/62.0	2.5	998	35	6	**CS**
	0900	14.1/62.0	2.5	996	35	7	CS
	1200	14.2/62.0	2.5	994	40	8	CS
	1500	14.3/62.0	3.0	994	40	8	CS
	1800	14.4/62.0	3.0	994	45	10	CS
	2100	14.5/62.0	3.0	994	50	12	**SCS**
27/10/2014	0000	14.8/62.0	3.5	990	55	16	SCS
	0300	14.9/62.0	3.5	990	60	18	SCS
	0600	14.9/62.0	4.0	986	65	20	**VSCS**
	0900	14.9/62.0	4.0	984	65	22	VSCS
	1200	15.0/62.0	4.0	982	70	24	VSCS
	1500	15.1/62.0	4.0	981	70	25	VSCS
	1800	15.3/62.0	4.0	980	70	26	VSCS
	2100	15.6/61.8	4.0	979	75	27	VSCS
28/10/2014	0000	15.7/61.8	4.0	978	75	28	VSCS

	0300	15.8/61.7	4.0	977	75	29	VSCS
	0600	15.9/61.6	4.5	974	80	32	VSCS
	0900	16.3/61.6	5.0	966	90	40	VSCS
	1200	16.7/61.8	5.5	954	100	52	VSCS
	1500	17.2/61.8	5.5	952	105	54	VSCS
	1800	17.6/61.8	5.5	950	110	56	VSCS
	2100	18.0/61.8	5.5	950	110	56	VSCS
29/10/2014	0000	18.2/62.0	5.5	954	105	52	VSCS
	0300	18.7/62.0	5.0	958	100	48	VSCS
	0600	18.9/62.0	5.0	962	95	44	VSCS
	0900	19.0/62.0	5.0	968	90	40	VSCS
	1200	19.2/62.2	4.5	974	80	32	VSCS
	1500	19.4/62.5	4.0	980	70	26	VSCS
	1800	19.4/62.8	4.0	986	70	24	VSCS
	2100	19.4/63.1	3.5	988	60	20	**SCS**
30/10/2014	0000	19.5/63.6	3.5	990	60	18	SCS
	0300	19.8/64.1	3.0	994	50	14	SCS
	0600	20.2/64.3	3.0	998	45	10	SCS
	0900	20.2/64.5	2.5	1000	40	9	**CS**
	1200	20.5/64.6	2.5	1001	40	8	CS
	1800	20.6/64.7	2.5	1002	35	7	CS
	2100	20.7/65.0	2.0	1003	30	5	**DD**
31/10/2014	0000	20.7/65.1	1.5	1004	25	4	**D**
	0300	Weakened into a well-marked low pressure area over northeast Arabian Sea off Gujarat coast.					

2.7.4. 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. 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* √ pressure drop at the centre).

The lowest Estimated Central Pressure (ECP) of the system was 950 hPa at 1800 UTC of 28th Oct. with a pressure drop of 56 hPa. The estimated MSW was 110 kts. The variations in ECP and MSW are shown in Fig.2.7.1.

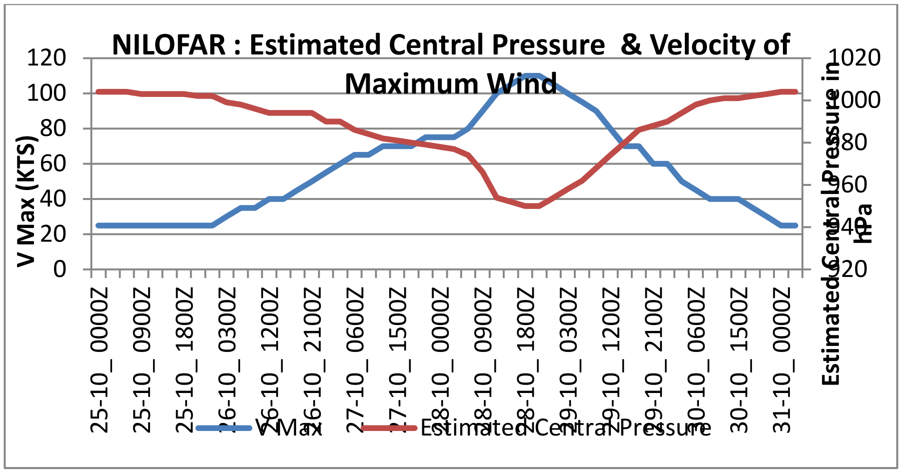


Fig. 2.7.1 Variations in ECP and MSW during VSCS Nilofar for the period 25 -31 Oct. 2014.

2.7.5 Characteristics observed by buoy

The buoys AD06, AD02 and AD07 were closer to the track. The buoys AD08, AD09 and AD10 were away from the cyclone track, with very less response in the met and ocean parameters. Table 2.7.2 shows the distance between NILOFAR cyclone track and OMNI buoy locations. Fig. 2.7.2-4shows the atmospheric air pressure, wind speed and significant wave height during the period 22 Oct. – 2 Nov. 2014.

Table -2.7.2: Distance between NILOFAR cyclone track and OMNI buoy locations

SI.No	Buoy ID	Distance between cyclone track and Buoy position
1	AD02	421 nm
2	AD04	876 nm
3	AD06	158 nm
4	AD07	417 nm
5	AD08	578 nm
6	AD09	897 nm
7	AD10	758nm

The Atmospheric Pressure showed a maximum drop observed at AD07 with recorded minimum pressure of 1004.46 hPa on October 26, 2014.

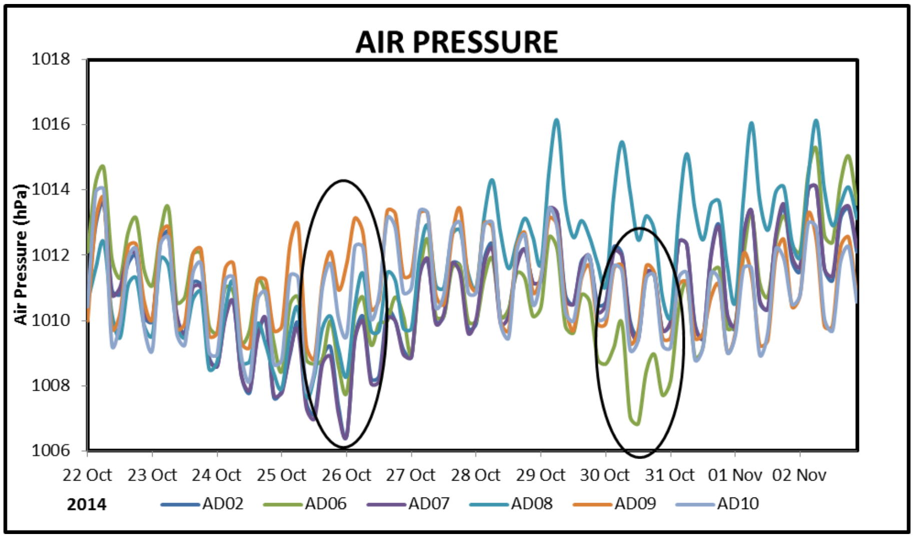


Fig. 2.7.2Atmospheric Pressure recorded by the buoys during 22 Oct. – 2 Nov. 2014

The buoy AD06 which was near the track of the cyclone recorded a maximum wind speed of 11.4 m/s on October 24, 2014 and 11.2 m/s on October 30, 2014.

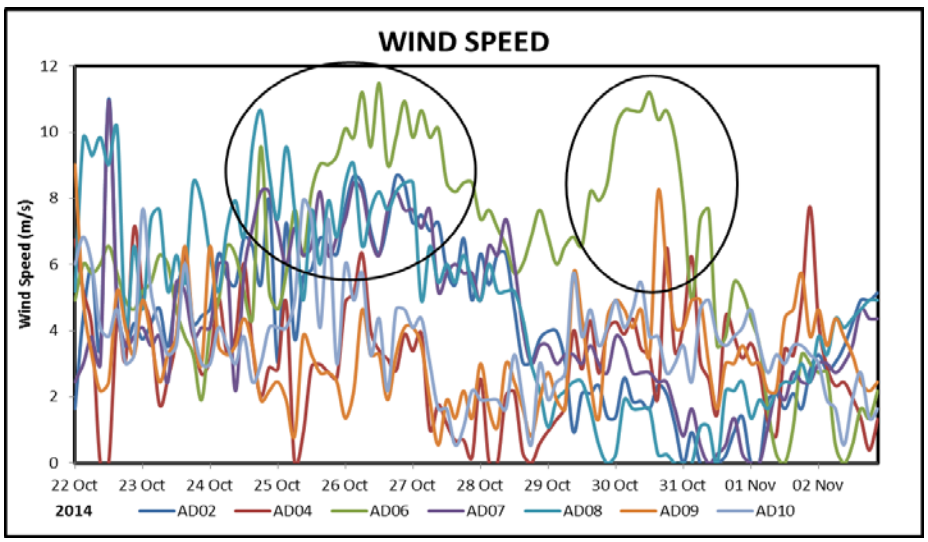


Fig. 2.7.3Wind speed recorded by the buoys during 22 Oct. – 2 Nov. 2014

The increase in significant wave height was recorded maximum at AD07 and AD06 location with a significant wave height of 3.22 m and 3.16 m on 26th and 30th October, 2014 respectively.

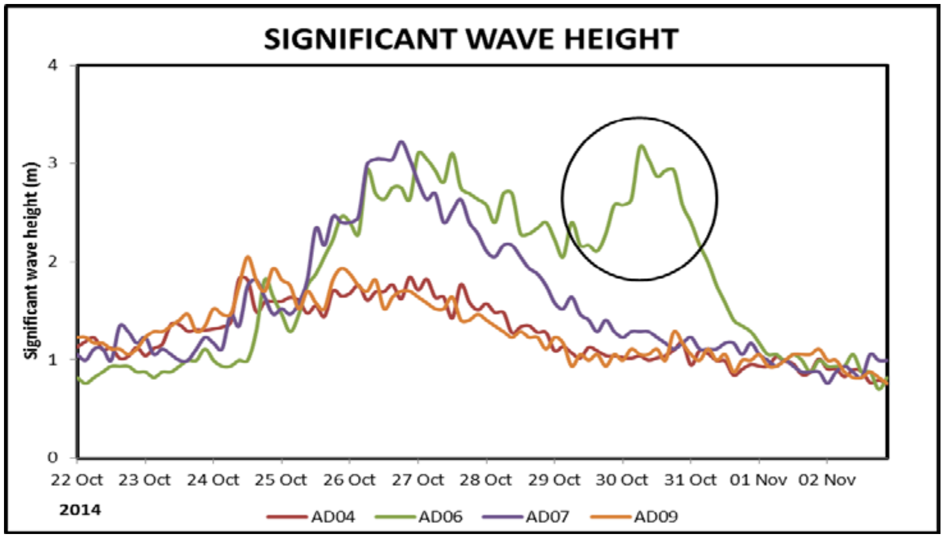


Fig. 2.7.4 Significant wave height recorded by the buoys during 22 Oct. – 2 Nov. 2014

2.7.6 Characteristic features observed through Satellite and RADAR

2.7.6.1 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 VSCS NILOFAR representing the life cycle of the cyclone are shown in Fig. 2.7.5 - 2.7.7.

According to INSAT-3D imageries and products, a low level circulation centre (LLCC) attained intensity of T.1.5 over westcentral Arabian Sea and adjoining east-central and south Arabian Sea on 25th/0000 UTC. Associated broken low and medium clouds with embedded intense to very intense convection extended over 8-10° laittude/longitude box around the vortex centre over the Arabian Sea and adjoining Indian Ocean. Convection increased gradually and started organising. The system attained intensity of T.2.0 at 0300 UTC of 26th. It further intensified to T.2.5 at 0600 UTC of 26th and convection organised into a curved band pattern with the lowest cloud top temperature of -93.0°C. It intensified to T.3.0 and T.3.5 at 26th/1500 UTC and 27th/0000 UTC respectively. The convection showed eye pattern from 0000 UTC of 27th. It attained intensity of T.4.0 and T.4.5 around 0600 UTC of 27th and 28th respectively and further attained its peak intensity of T.5.5 within next 6 hours (28th/1200 UTC). On 29th/0300 UTC the system started showing signs of weakening with ragged eye pattern and intensity T.5.0. By 29th/1500 UTC, its intensity decreased further to T.4.0. By 30th/0300 UTC, its T. No. became T.3.0. At 2100 UTC of 30th, its intensity was T.2.0 and on 31st/0000 UTC, it was T.1.5. During weakening phase the cloud pattern changed from eye pattern to curved band pattern and finally to shear pattern on 30th and 31st Oct. 2014.

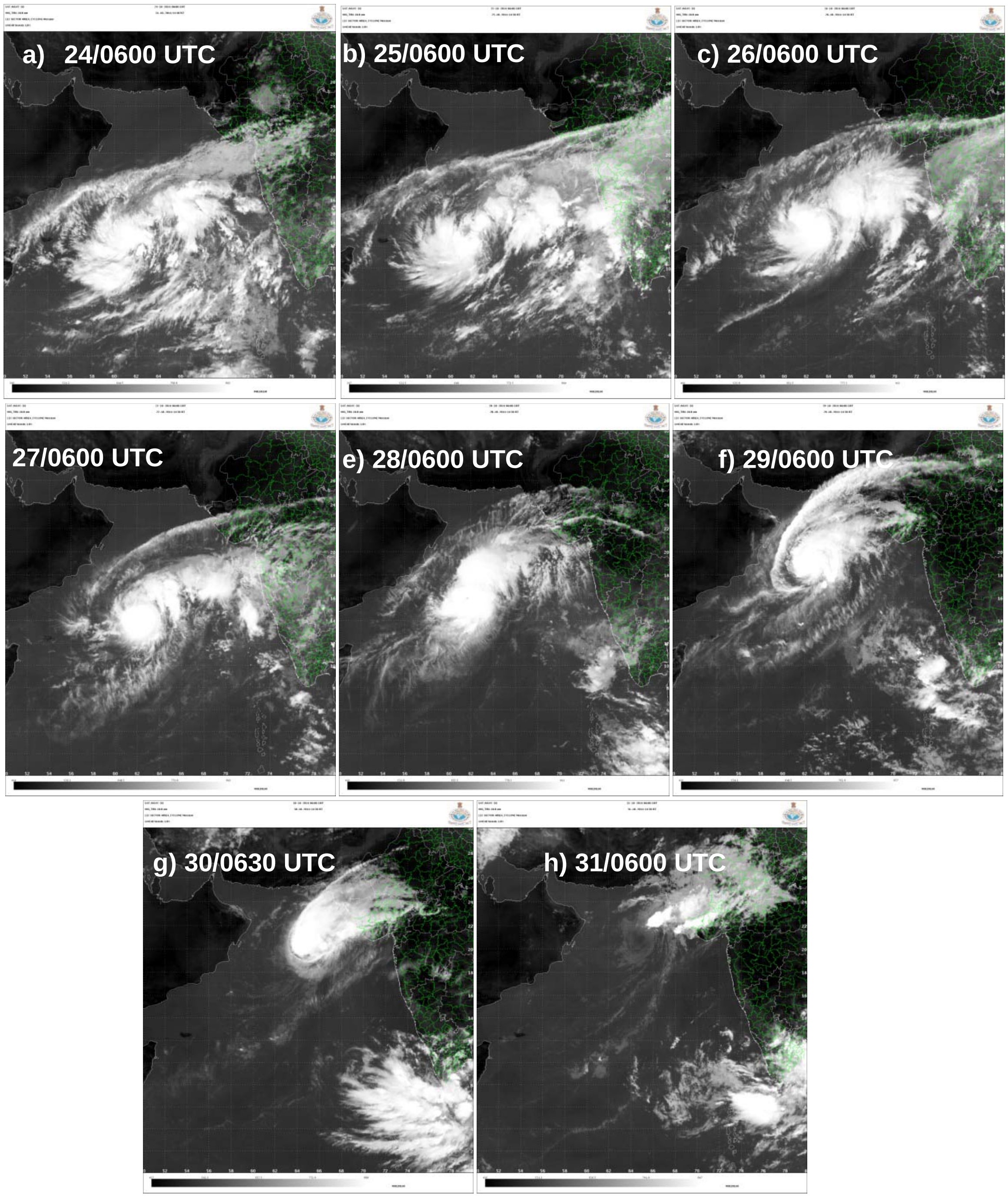


Fig. 2.7.5 Typical INSAT-3D IR imageries based on 0600 UTC in association with VSCS NILOFAR during 24-31 October 2014

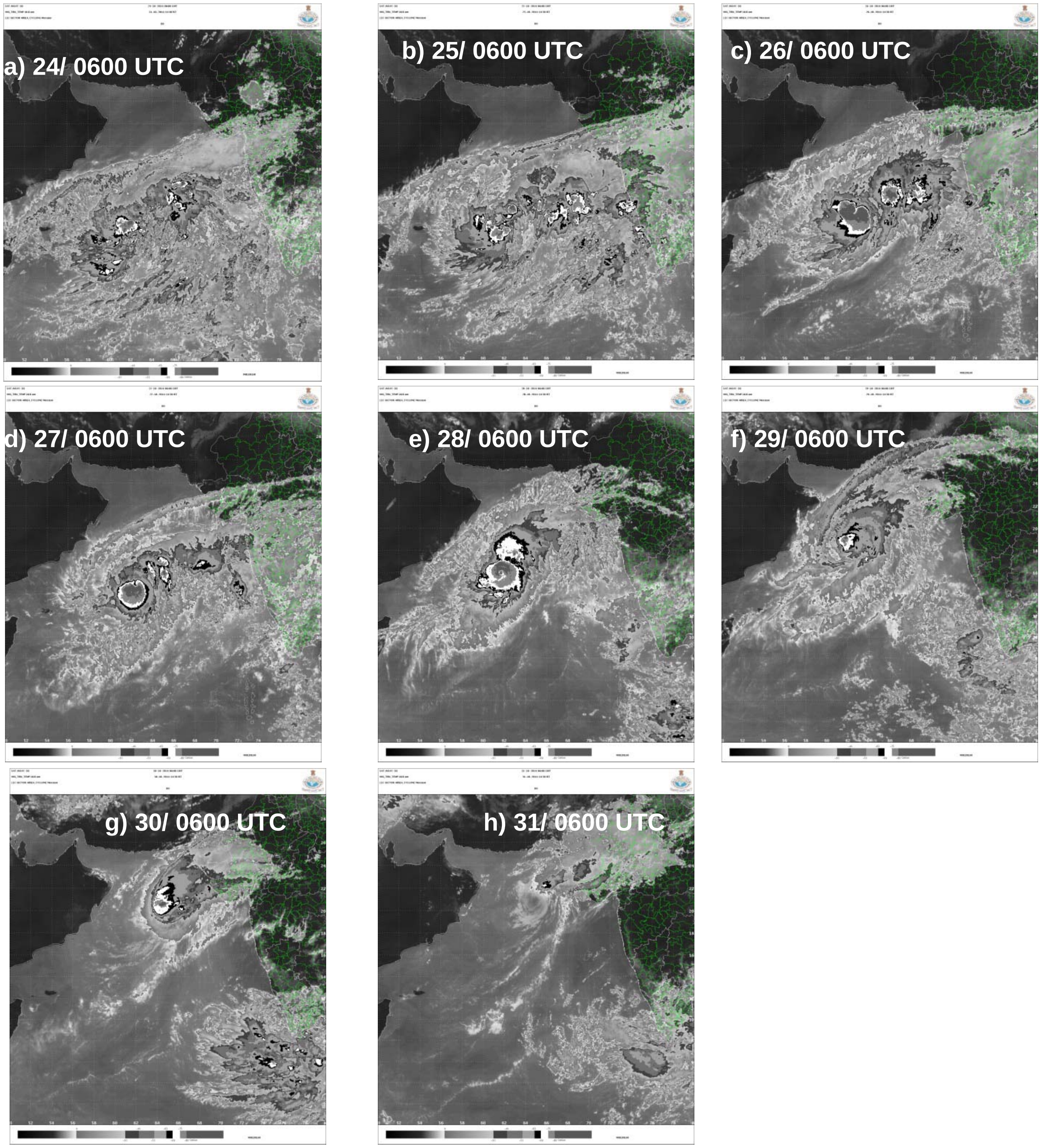


Fig. 2.7.7 INSAT-3D enhanced IR imageries in association with VSCS NILOFAR during 24-31 October 2014

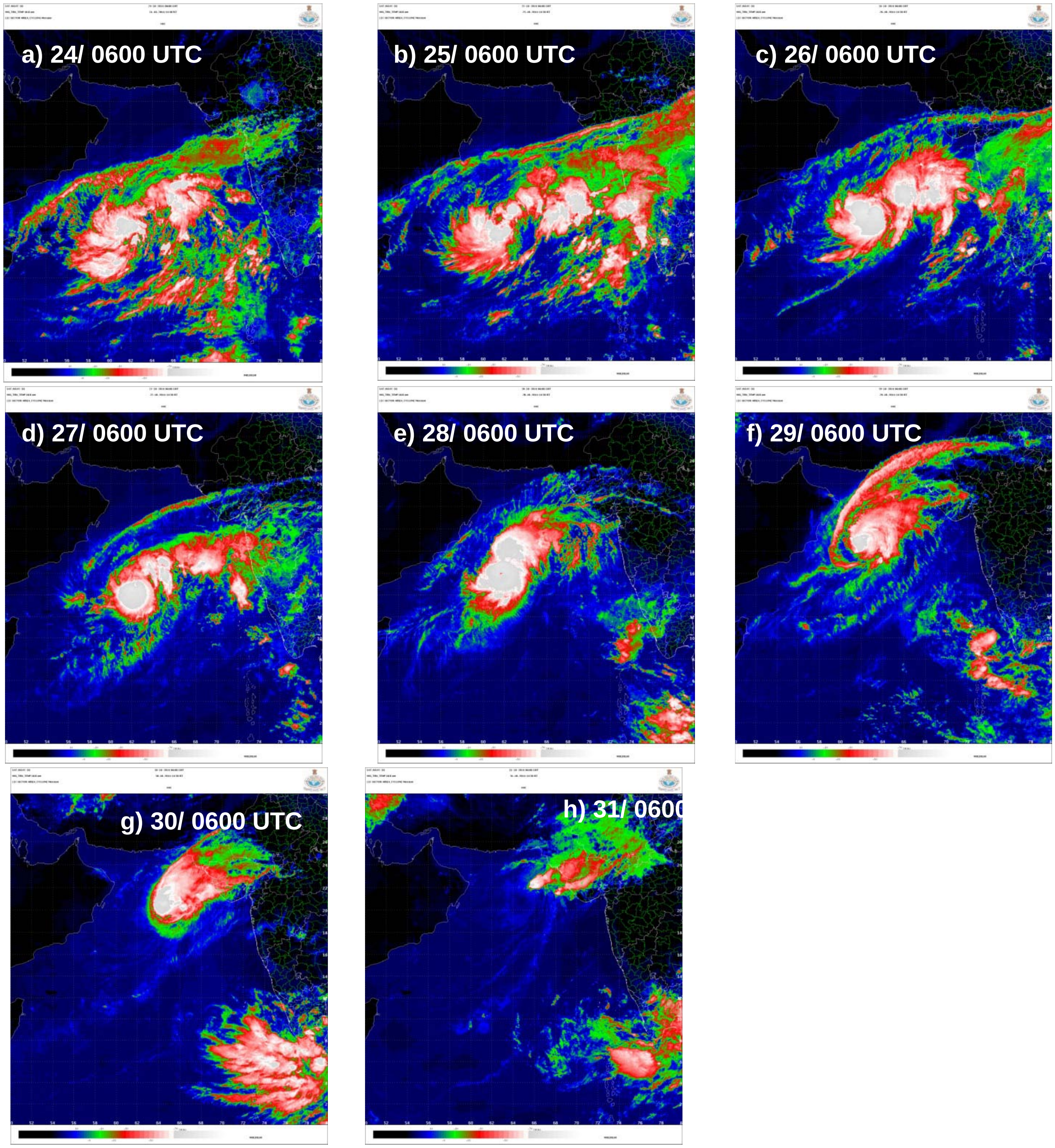


Fig. 2.7.7 INSAT-3D colored enhanced IR imageries based on 0600 UTC in association with VSCS NILOFAR during 24-31 October 2014

2.7.6.2 Features observed through RADAR

Cyclone Detection Radar (CDR) Bhuj could monitor the system on 31st Oct. as the system came in its range. Due to weakening of the system the characteristic features like location and intensity could not be detected with RADAR. However, the convection in association with the system lying to the right of the system centre was well captured in the RADAR imagery as shown in Fig. 2.7.8.

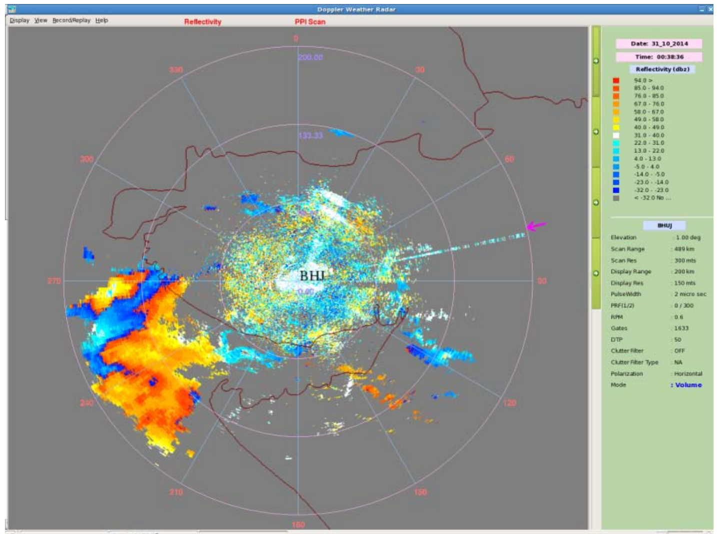


Fig. 2.7.8: RADAR Imagery from CDR Bhuj based on 0000 UTC of 31st Oct. 2014

2.7.7. Dynamical features

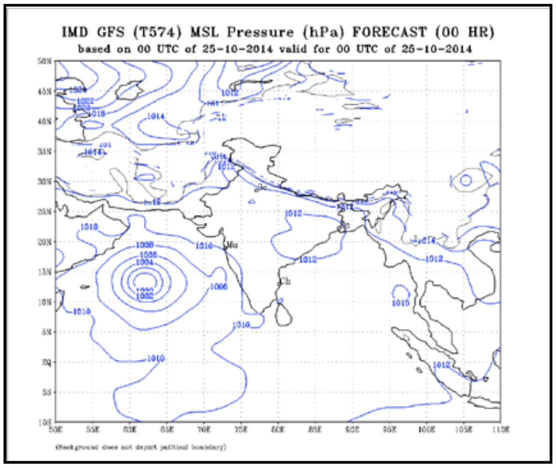
To analyse the dynamical features, the Mean Sea Level Pressure (MSLP), surface winds at 10 m height and winds at 850, 500 and 200 hPa levels during the period 25 – 31 October 2014 are presented in Fig. 2.7.9 based on IMD-GFS analysis.

The maximum wind at lower level was oriented north-south and active northeast monsoon flow prevailed to the north during genesis stage i.e., 25th Oct. The wind speed was little bit higher in the northern sector. Hence the wind distribution was asymmetric. While the size of the gale wind gradually increased with intensification of the system and continued to be asymmetric, the core wind became symmetric when system intensified into VSCS on 27th Oct. However, with the weakening of the system from 29th Oct., the size of the gale wind decreased in the northeast and southeast sector.

During 26-28th, the VSCS Nilofar was sandwiched between two anti-cyclonic circulation, one lying to the southeast and another to the west-northwest of the system centre. As a result, during 26-28th the system nearly moved northwards with very slow speed. At the same time it provided a very low vertical wind shear (5-10 kts) which resulted in rapid intensification.

A trough in the upper tropospheric westerly approached from west which led to increase in the westerlies in the storm region from 29th Oct. 2014. Subsequently, as the system moved to the north of the ridge line it was steered northeastwards from 29th onwards towards Gujarat and adjoining Pakistan coast. However, as it moved northeastwards, it encountered high vertical wind shear, entrainment of dry and cold air towards to the core due to mid-latitude westerlies. Hence, it started weakening rapidly over the sea itself before reaching the Gujarat coast.

The analysis could very well capture the genesis and track of the system. However, the rapid intensification and rapid weakening before reaching coast could not be detected reasonably.



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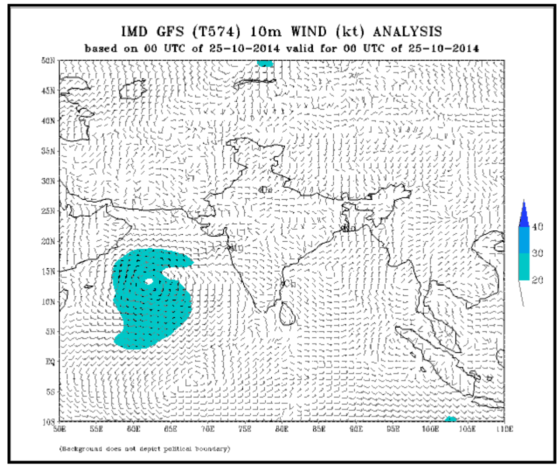

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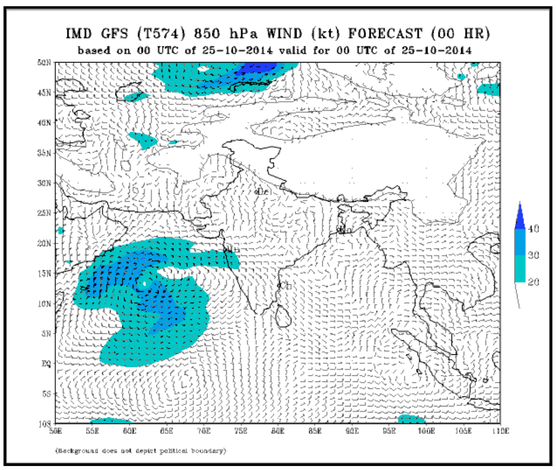

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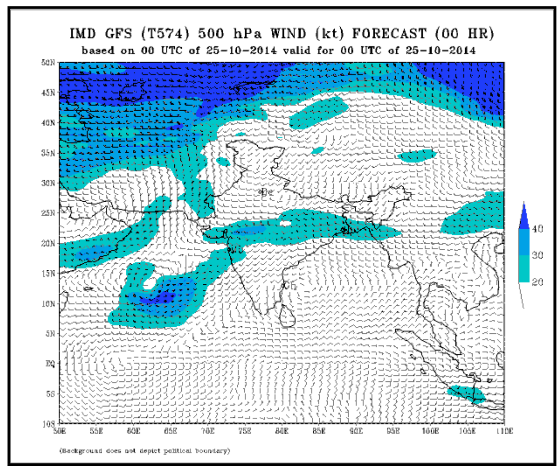

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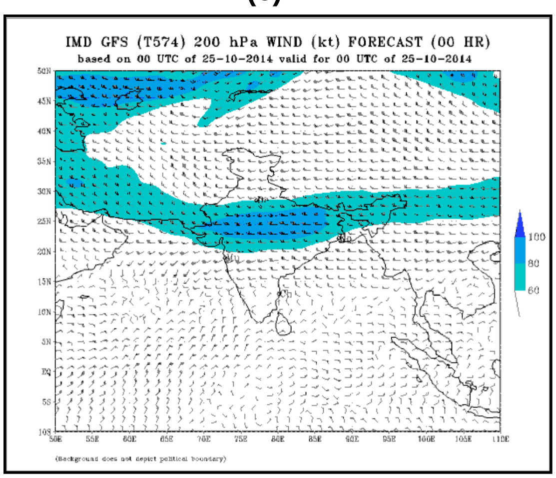
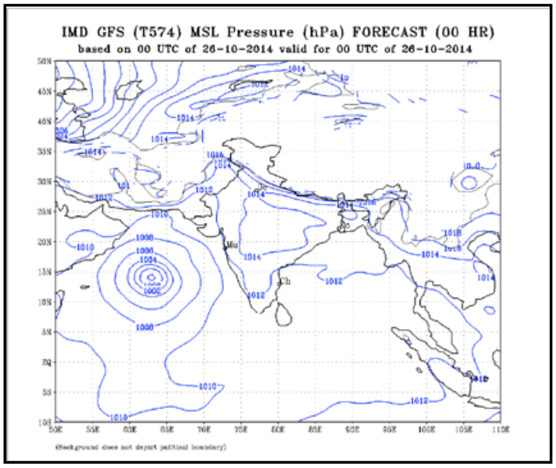


(e)

Fig. 2.7.9 IMD-GFS Analysed charts on 25th 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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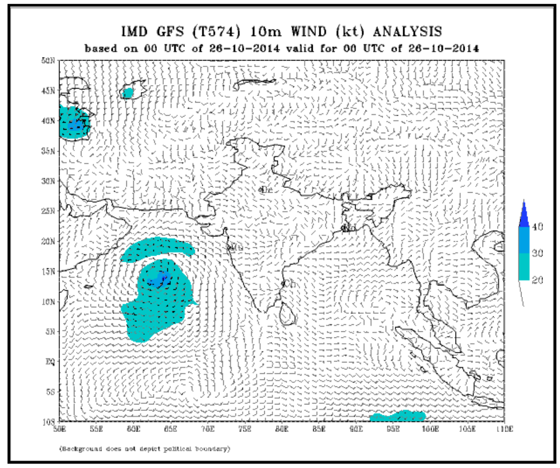

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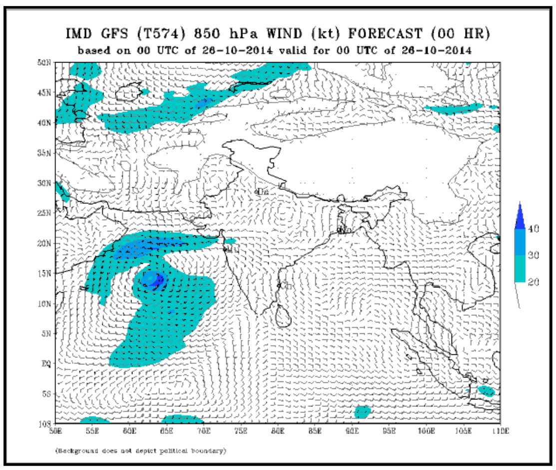

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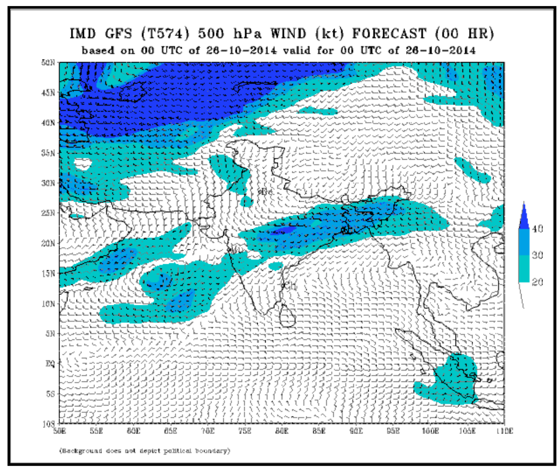

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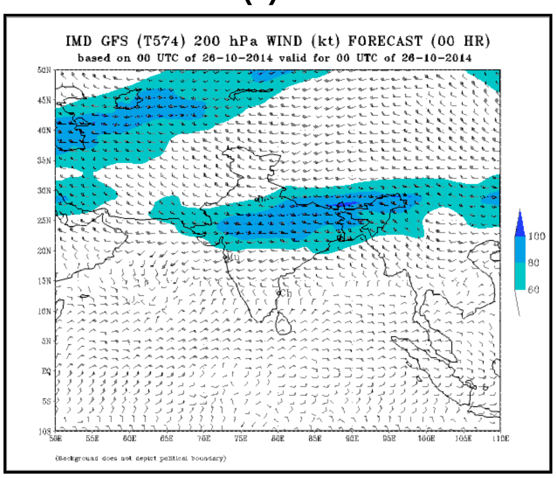
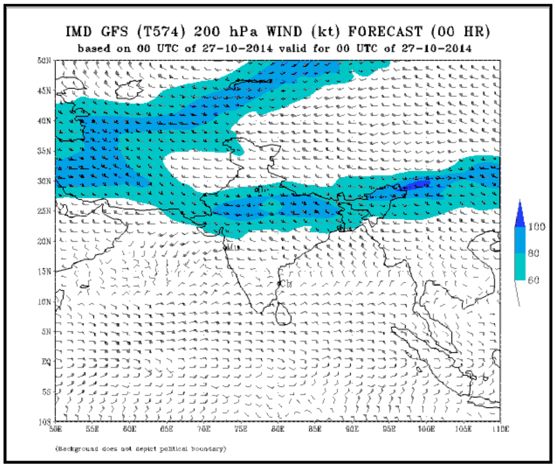


(e)

Fig. 2.7.9 (contd.) IMD-GFS Analysed charts on 26th 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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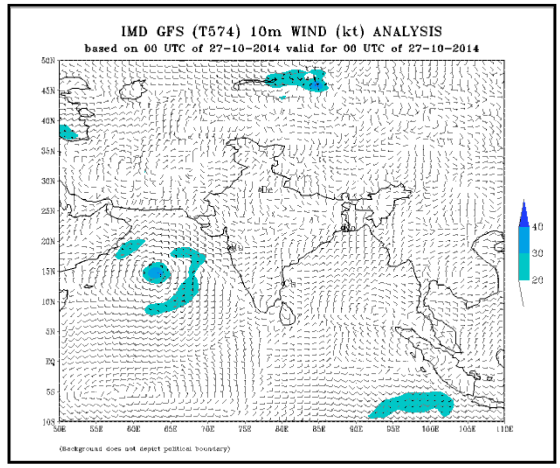

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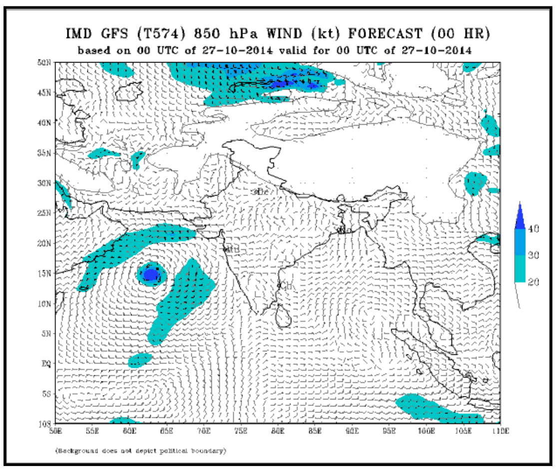

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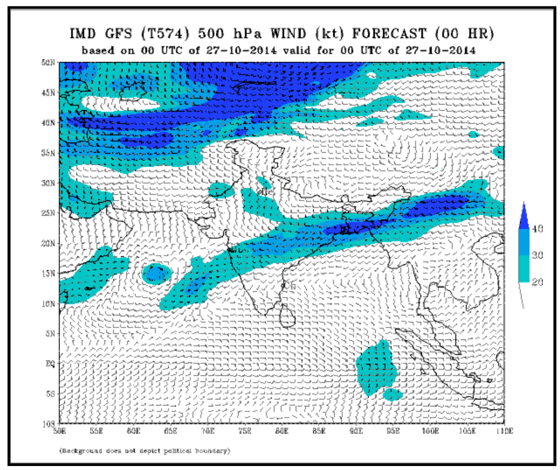

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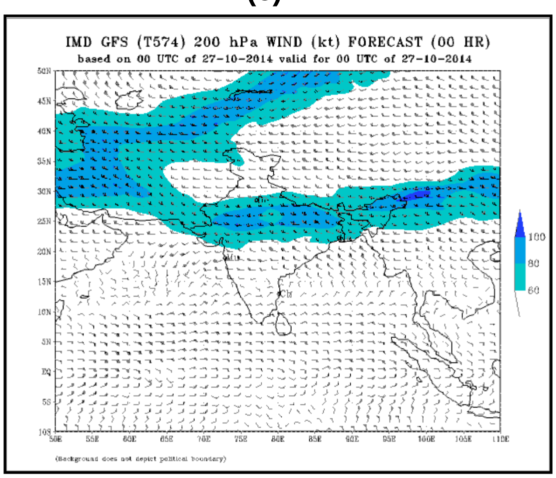
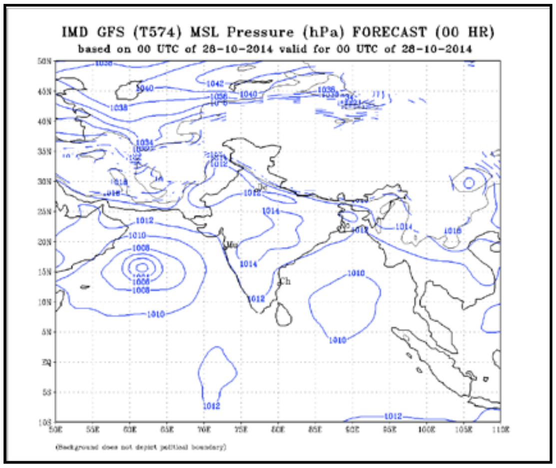


(e)

Fig. 2.7.9 (contd) IMD-GFS Analysed charts on 27th 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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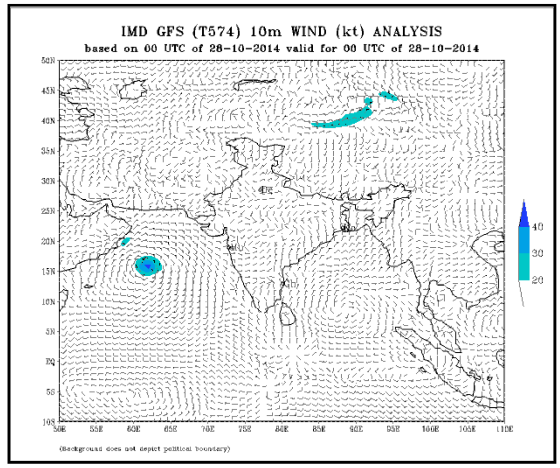

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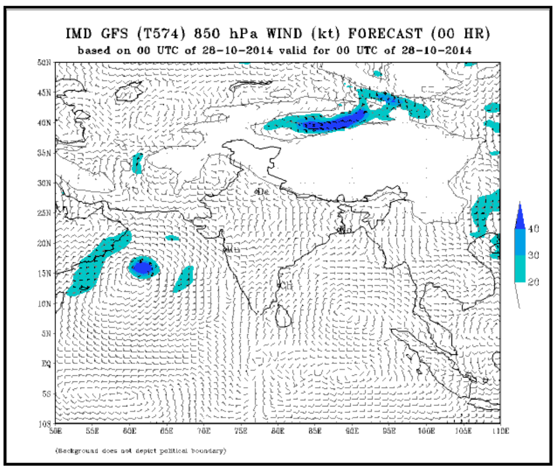

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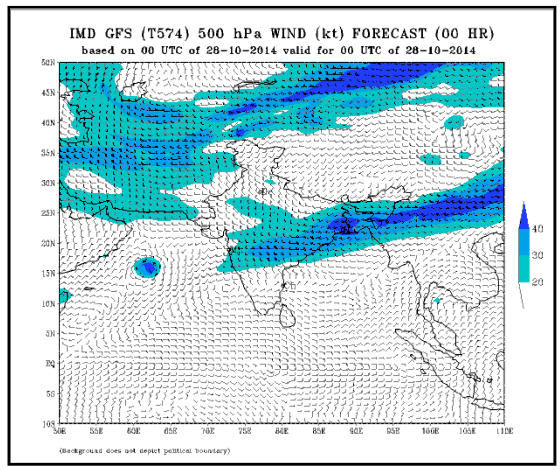

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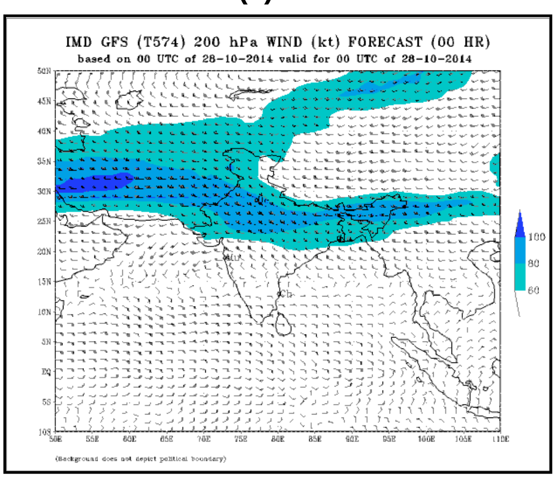

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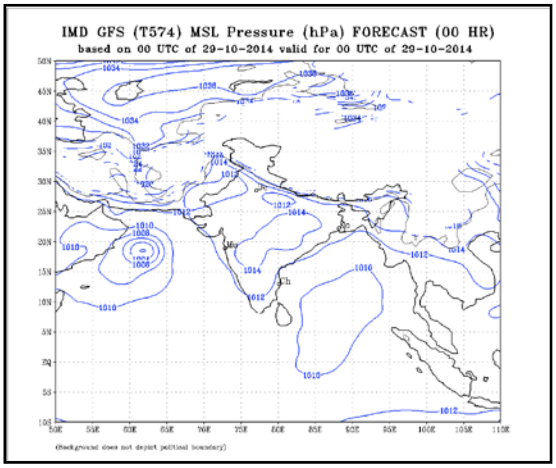
Fig. 2.7.9 (contd.) IMD-GFS Analysed charts on 28th October 2014 (a)MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



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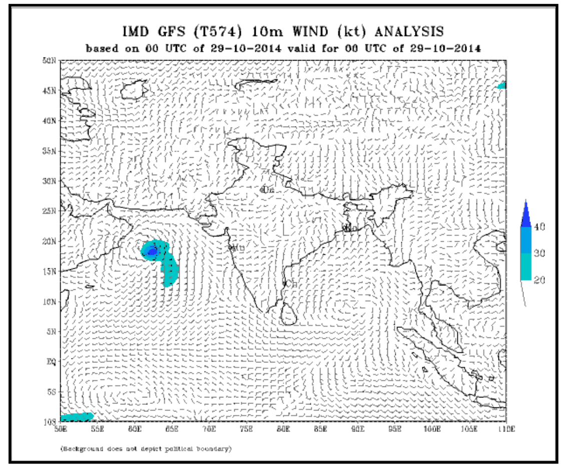

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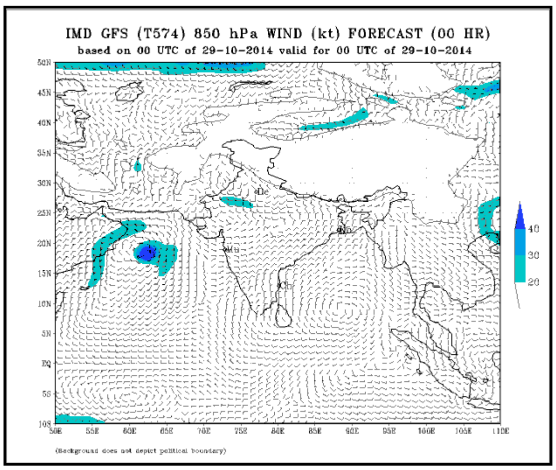

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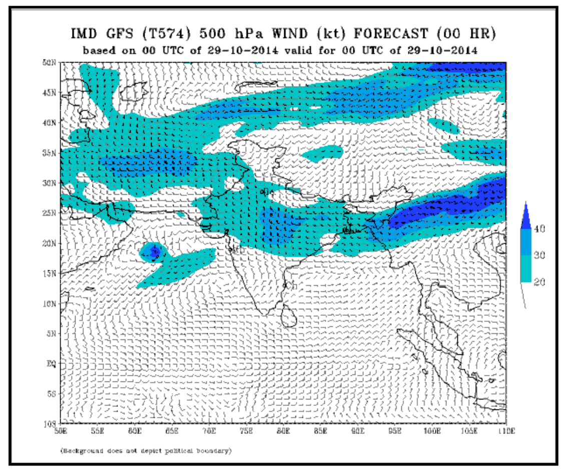

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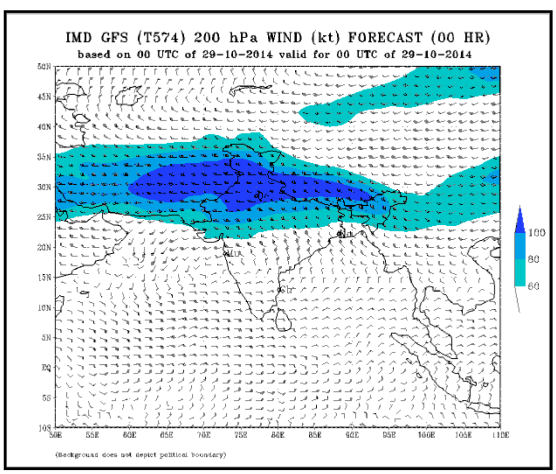
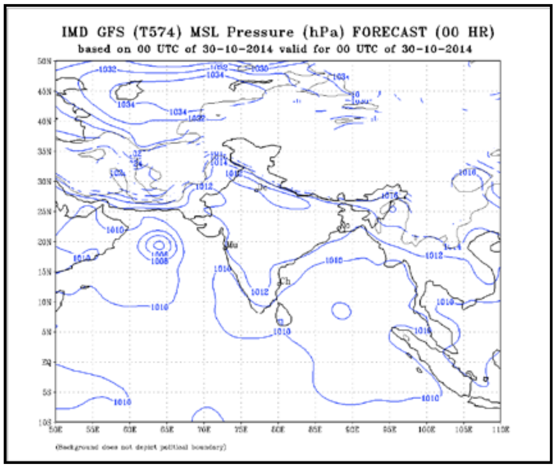


(e)

Fig. 2.7.9 (contd.) IMD-GFS Analysed charts on 29th 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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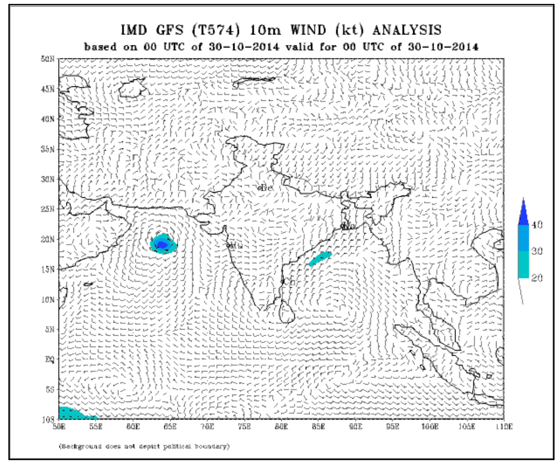

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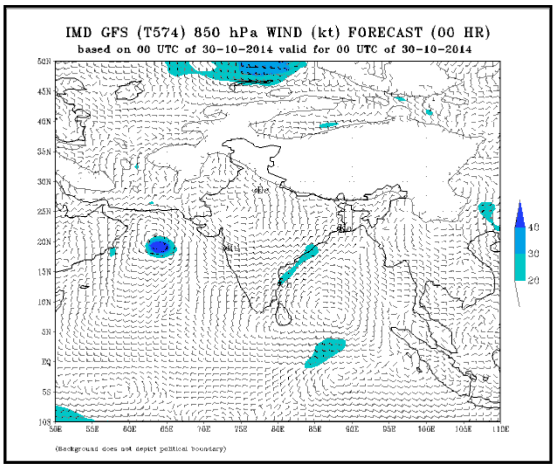

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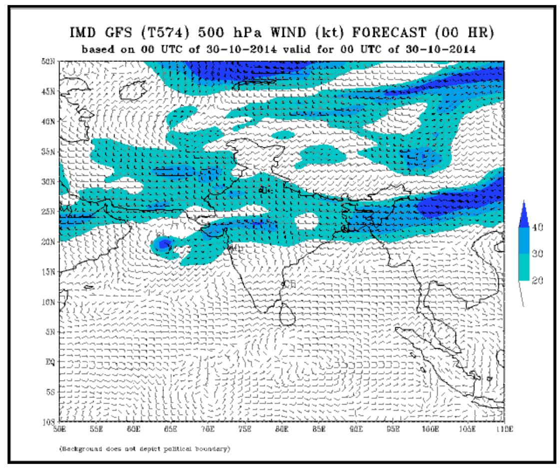

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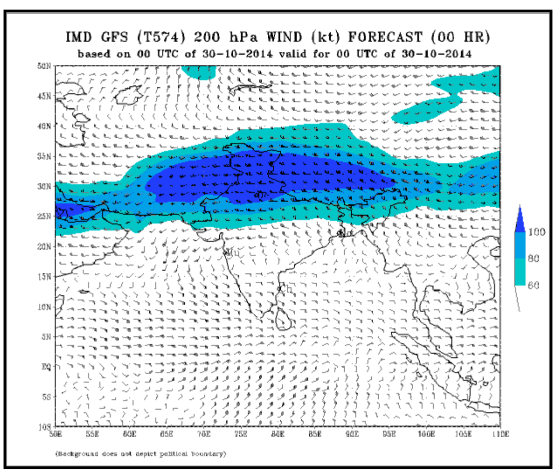
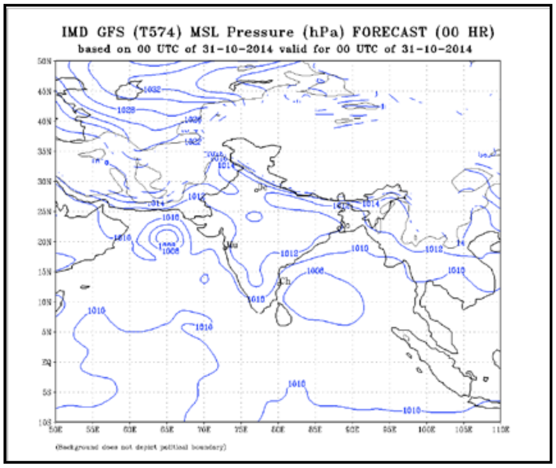
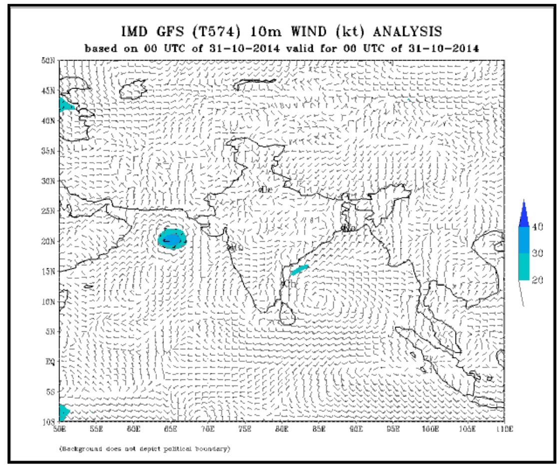


(e)

Fig. 2.7.9 (contd.) IMD-GFS Analysed charts on 30th October 2014 (a)MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds



(a)



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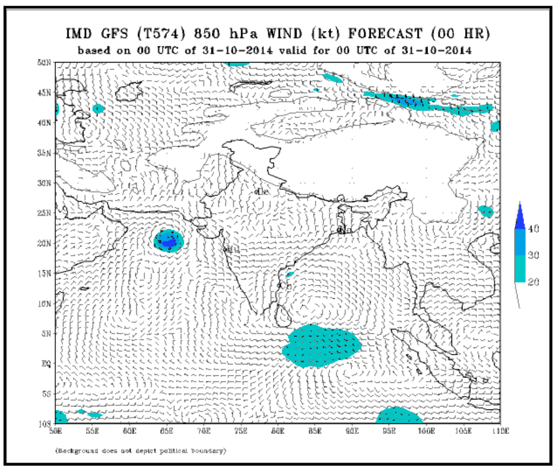

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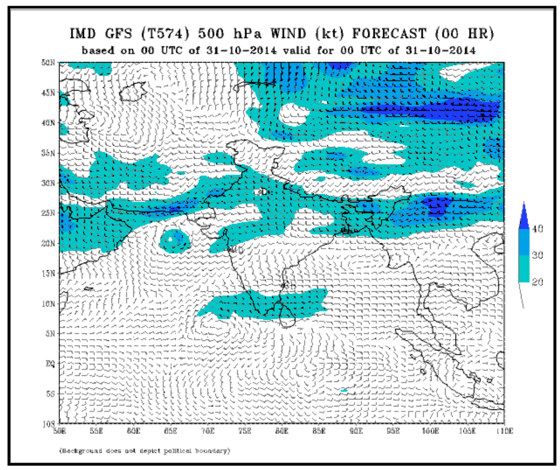

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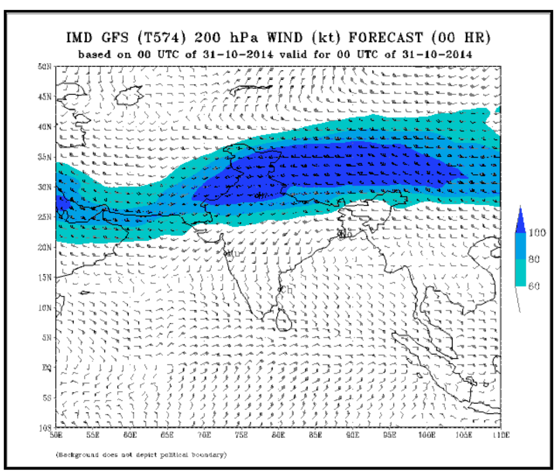

(e)

Fig. 2.7.9 (contd.) IMD-GFS Analysed charts on 31th October 2014 (a)MSLP Analysis, (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds

2.7.8. Realized Weather:

2.7.8.1. Heavy rainfall due to NILOFAR:

Under the influence of TC NILOFAR, Konkan and Goa region experienced widespread rain with heavy rainfall at isolated places on 25th, widespread rain with heavy to very heavy rainfalls at a few places on 26th. However, as the system started to weaken rapidly over the sea itself on 30th/31st, without crossing the coast significant rainfall was not realised over the Gujarat. Rainfall realised in association with the TC NILOFAR during the period 25-31 October 2014 is furnished below:

24 hrs cumulative rainfall amounts ≥(7cm) ending of 0300 UTC of date realised in association with passage of TC NILOFAR' during 25-31 October 2014are as follow

25 October 2014

Konkan & Goa:

Margaon-12

26 October 2014

Konkan & Goa:

Margao-29, Marmugao, Mapusa& Panjim-14 each, Ponda-12, Dabolim N.A.S.- Navy-11, Quepem-11, Sanguem-10, Pernem-8, Vengurla-7.

Madhya Maharashtra:

Chandgad-7

Rainfall associated with the TC NILOFAR 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 TC NILOFAR during the period 25 -31 October 2014 as well as the 7-day average rainfall during the same period are furnished in Fig. 2.7.10.

As can be seen, during the period 26-27 October, when the system was in its intensification phase, rainfall was observed over a wide area covering about 8-10° latitude / longitude belt in the vicinity of the TC centre and mainly in the northeast sector of the TC centre. Rainfall of the order of 2 - 8 cm are observed in the outer storm area covering regions of Konkan and Goa and adjoining areas of Madhya Maharashtra and Marathwada. However, after the recurvature on 29th, associated with the weakening of the system, area of rainfall activity during 29 October – 1st Nov is decreased to about 5° latitude/ longitude belt. No rainfall is observed over Gujarat region as the system weakened rapidly over the sea itself on 31st Oct. and 1st Nov. 2014.

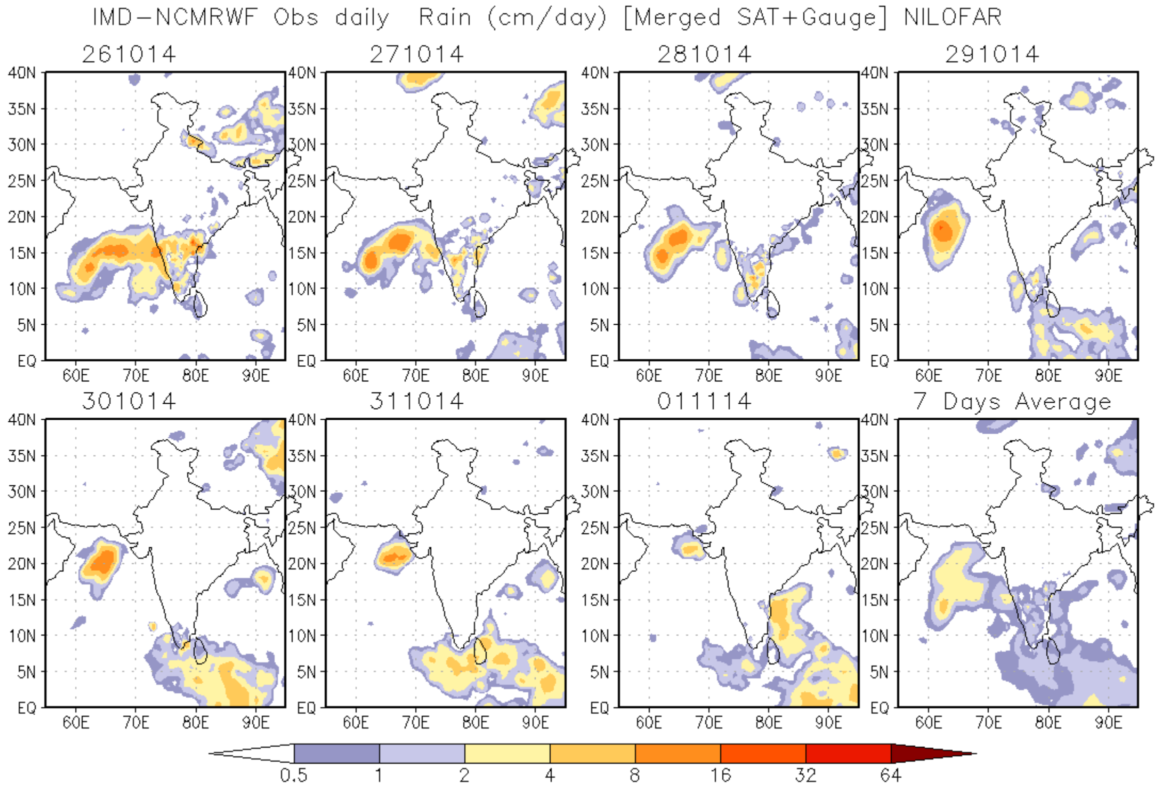

Fig. 2.7.10 IMD-NCMRWF satellite-gauge merged daily rainfall (in cm) during the period 25 October – 1 November 2014 and the 7-day average rainfall during the same period.

2.7.8.2 Gale Wind

As the system weakened over the sea, no gale wind was reported. However, strong winds with speed of 30 kmph at 0905 UTC and 25 kmph at 1258 IST was recorded by High Wind Speed Recorders (HWSRs) at Dwarka and Okha respectively on 31st Oct. (Fig.2.7.11).

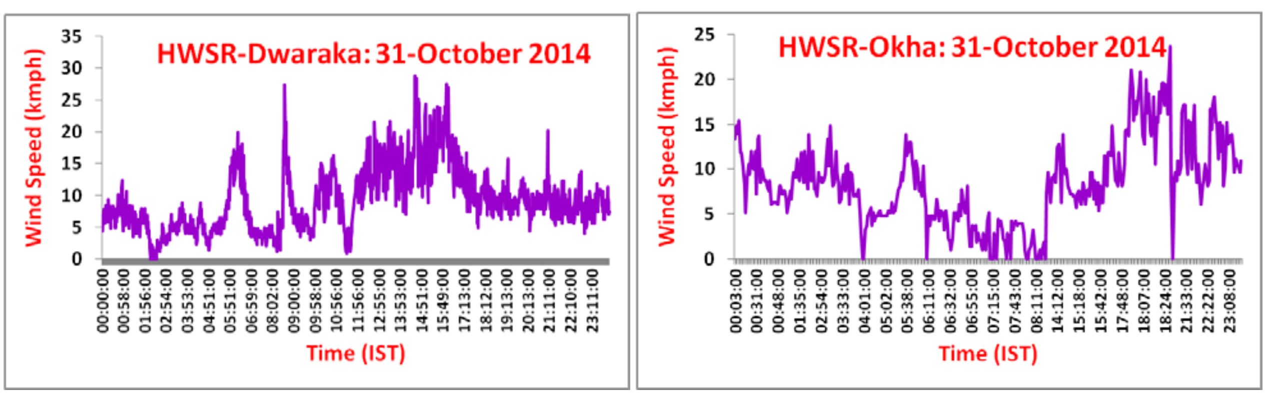

Fig. 2.7.11: Time series of wind speed recorded by HWSR at Dwarka and Okha on 31st October 2014.

2.7.8.3. Storm Surge

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

2.7.8.4 Damage due to Cyclone 'NILOFAR'

No damage has been reported due to this system.

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

2.8.1. 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.

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.

2.8.2. 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.

2.8.3. Brief life history

2.8.3.1 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/0900 UTC 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 0900 UTC 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.

2.8.3.2. 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 0300 UTC 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 0300 UTC 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 0300 UTC 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-2.8.1 and Fig.2.1.

2.8.4. 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*√ pressure drop at the centre).

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 0300-1200 UTC of 06th November, 2014 with a pressure drop of 6 hPa. The estimated MSW was 30 knots (55 kmph) at 0300 UTC of 06th.

Table2.8.1 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					

November, 2014

2.8.5 Characteristic features observed through Satellite and RADAR

2.8.5.1 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.2.8.1 - 2.8.3.

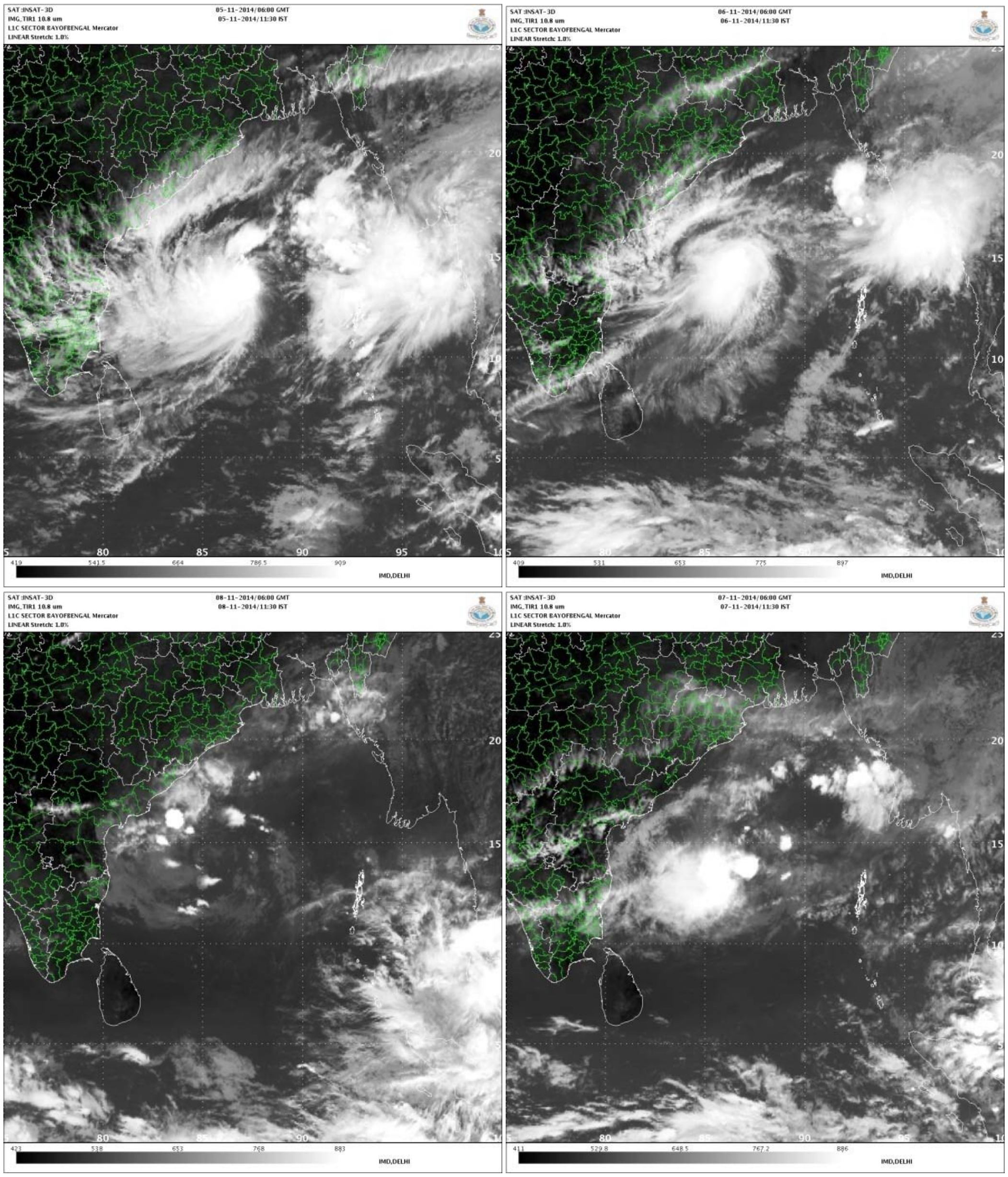

Fig. 2.8.1: Typical INSAT-3D IR imageries based on 0600 UTC in association with Deep Depression during 05-08 November 2014

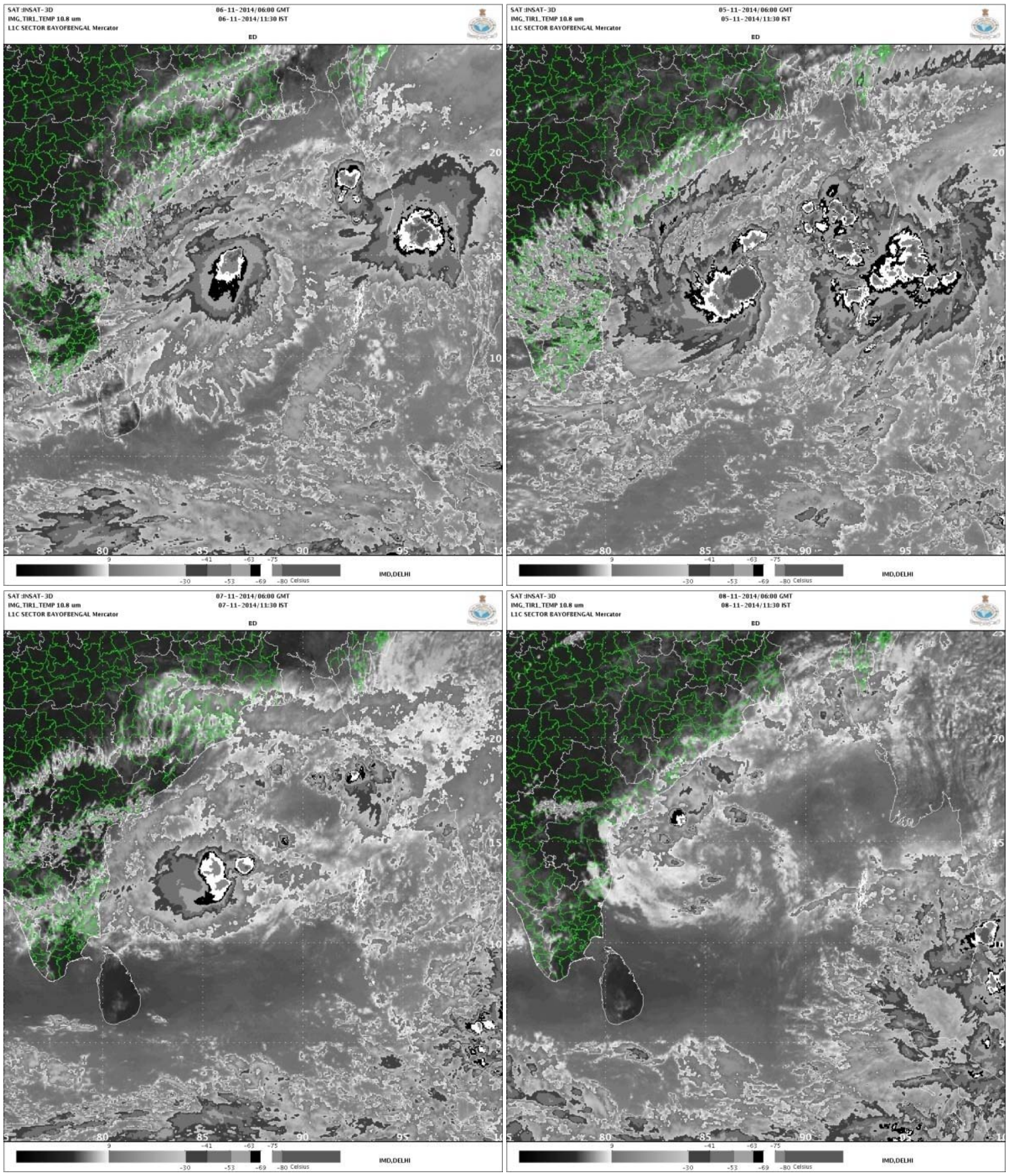

Fig. 2.8.2 INSAT-3D enhanced IR imageries based on 0600 UTC in association with Deep Depression during 05-08 November 2014

As per the satellite imagery of 05th/0900 UTC, 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 1200 UTC 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.

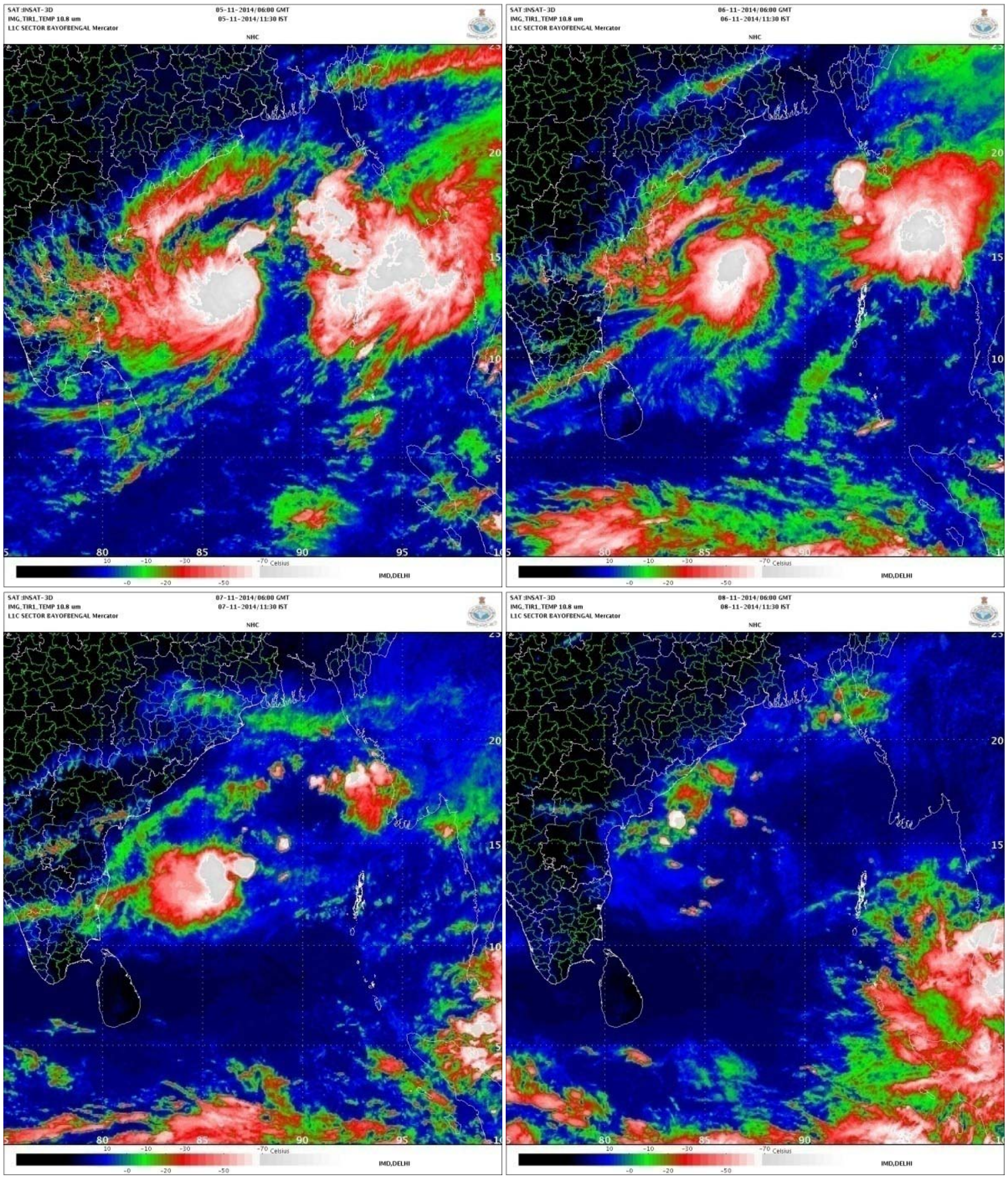

Fig. 2.8.3 INSAT-3D colored enhanced IR imageries based on 0600 UTC in association with Deep Depression during 05-08 November 2014

The lowest cloud top temparature (CTT) was -93°C. At 0300 UTC 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/0300 UTC, indicated intensity of T.1.5 and pattern changed to shear pattern. Further at 1200 UTC of 7th, satellite based intensity was T.1.0.

2.8.5.2 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 DWR Machilipatnam for day ending 0300 UTC during the period 08-10th November 2014 is shown in Fig.2.8.4.

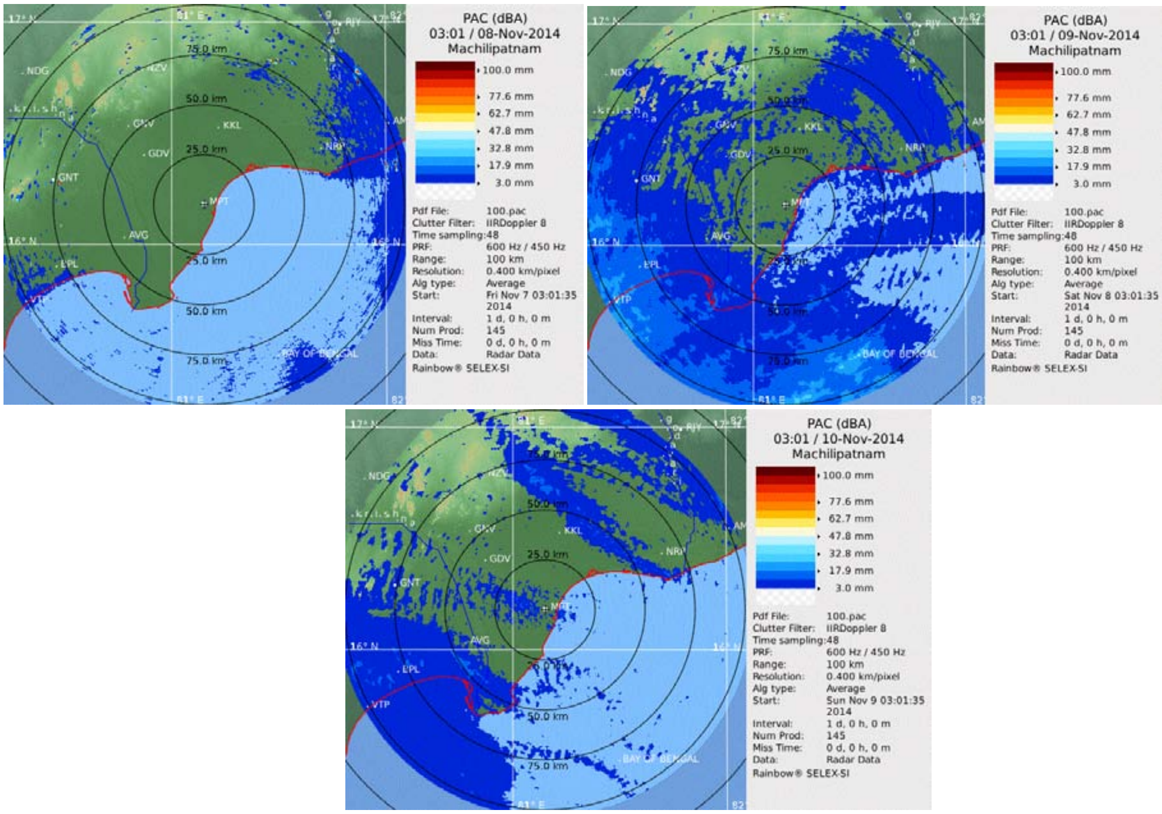

Fig.2.8.4DWR MPT 24-hr accumulated precipitation product for 08-10th November 2014 ending 0300 UTC.

2.8.6. 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.2.8.5.(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.

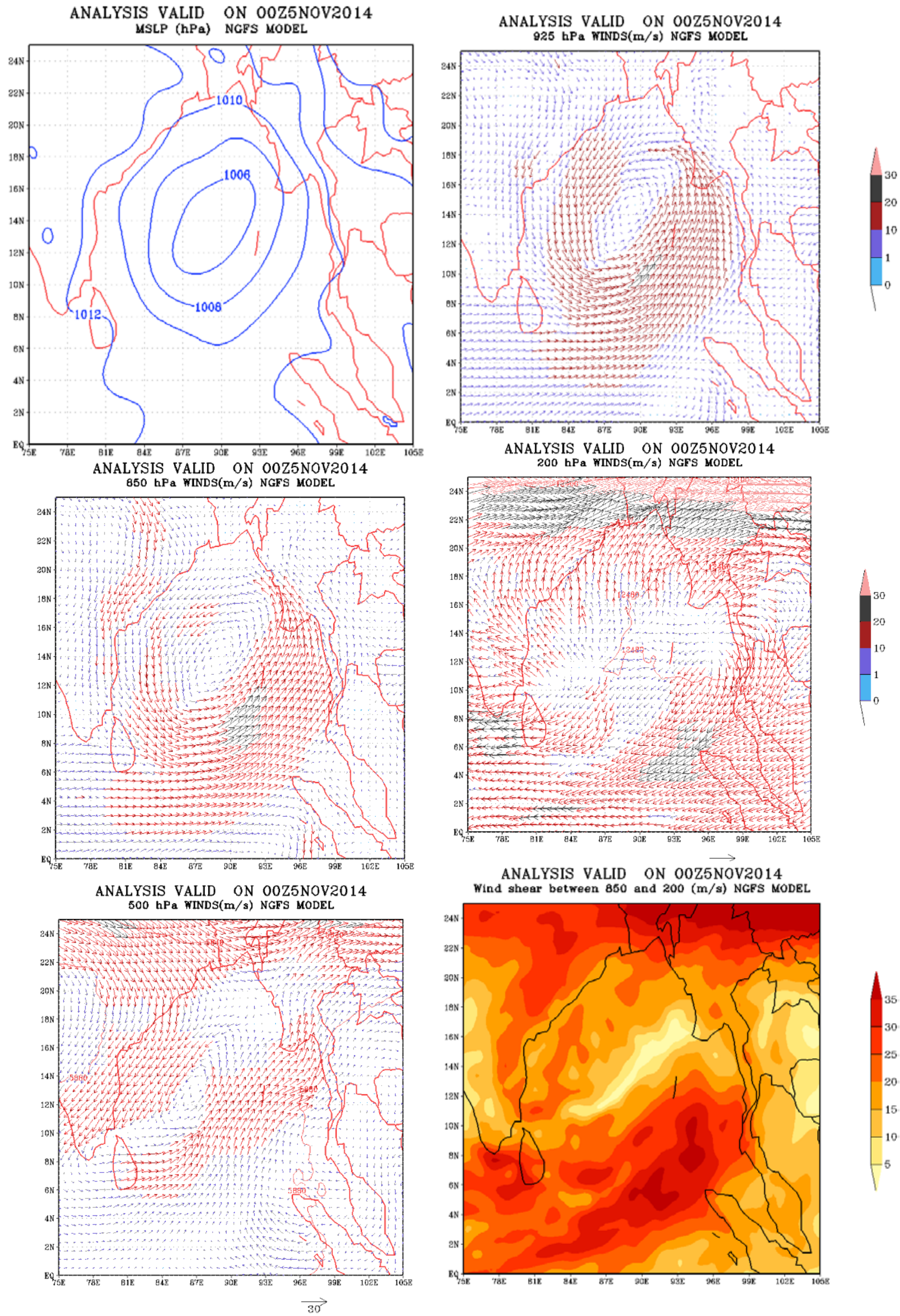

Fig. 2.8.5a NCMRWF-NGFS model analysis fields of MSLP, winds at 925, 850, 500 & 200 hPa levels and vertical wind shear (between 850 and 200 hPa) based on 05th November 2014 / 0000 UTC

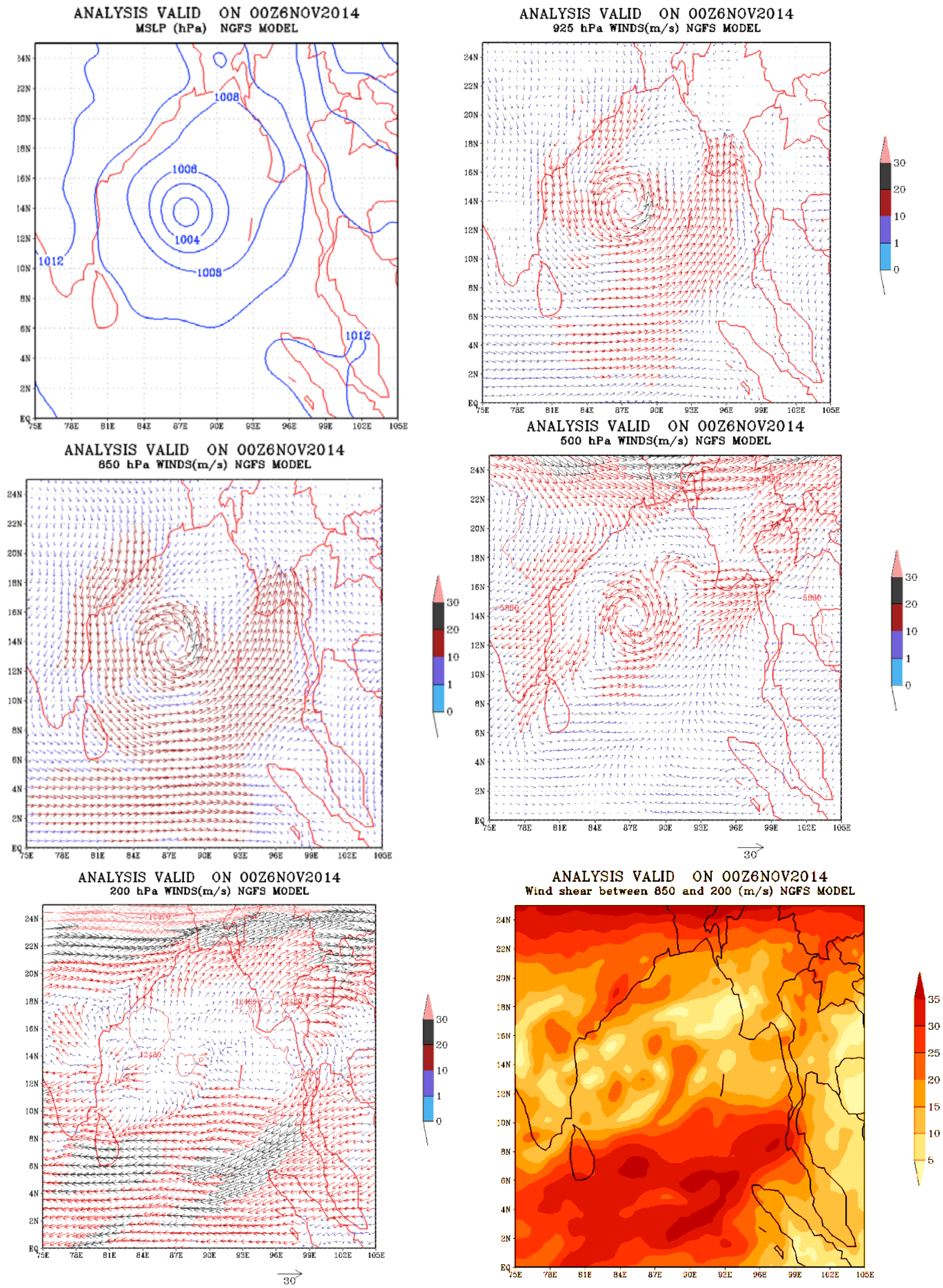

Fig. 2.8.5b Same as Fig.6a, but based on 06th November 2014 / 0000 UTC

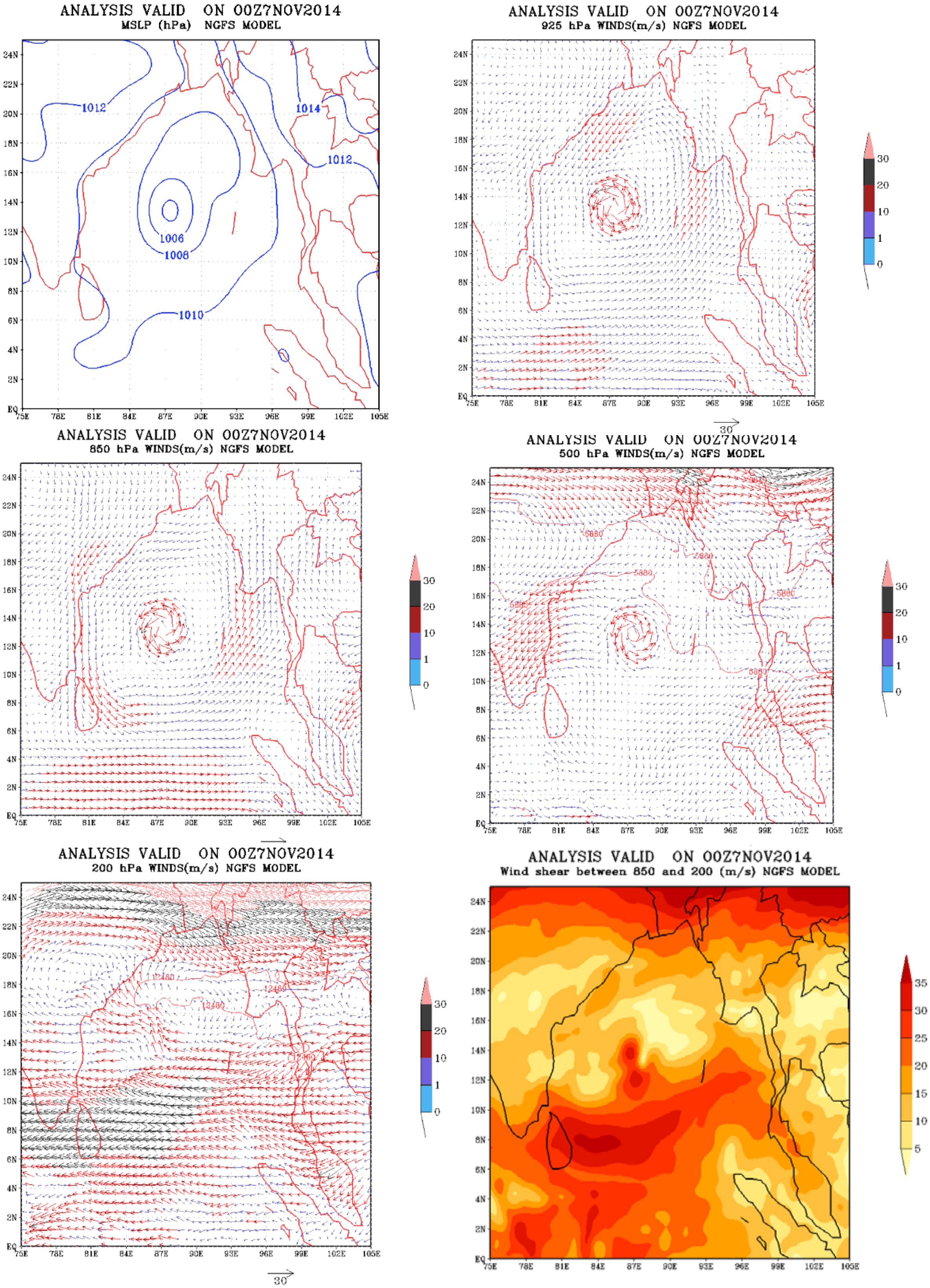

Fig. 2.8.5c: Same as Fig.6a, but based on 07th November 2014 / 0000 UTC

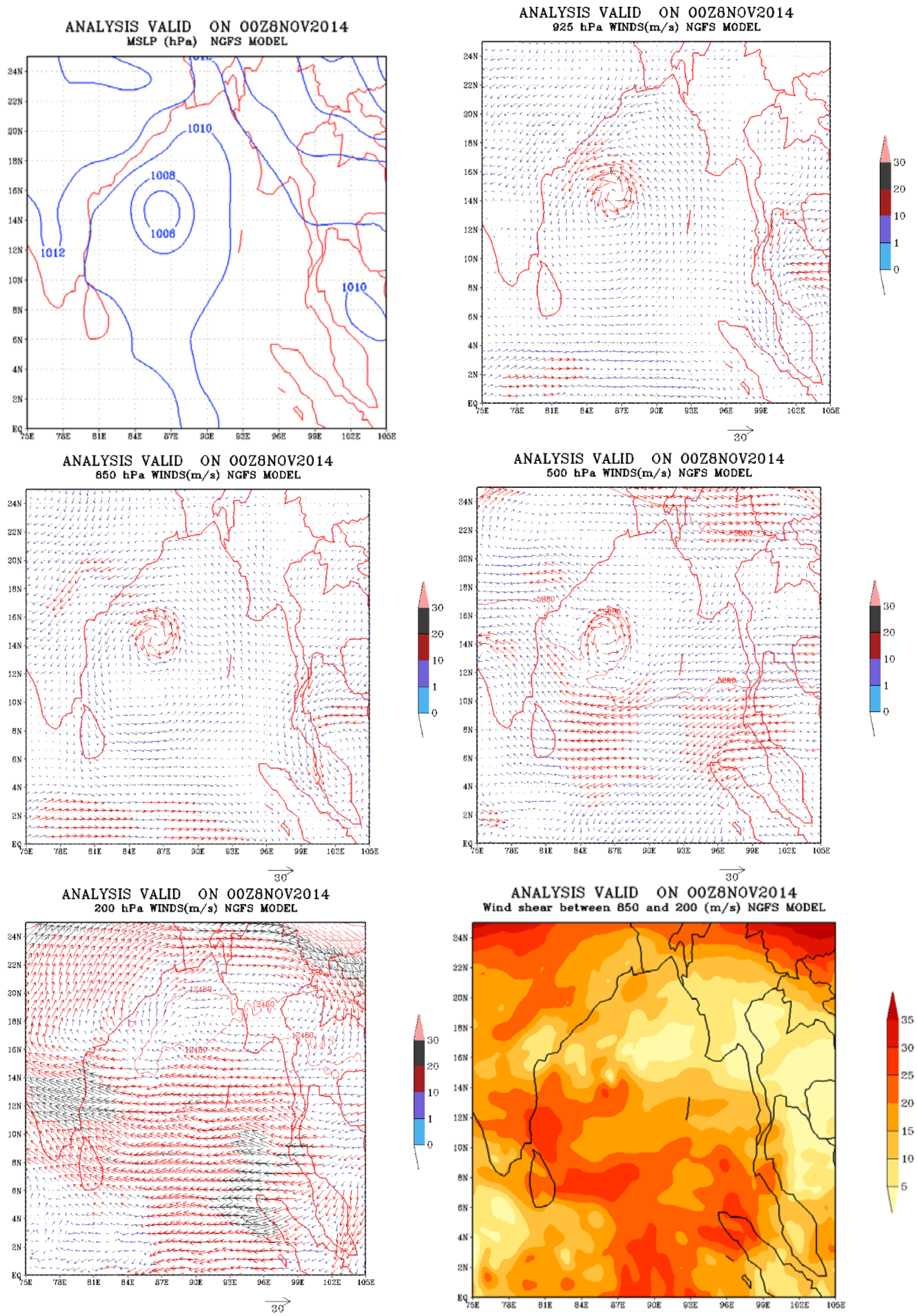

Fig. 2.8.5d: Same as Fig.6a, but based on 08th November 2014 / 0000 UTC

2.8.7. Realised Weather:

2.8.7.1. 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. 2.8.6.

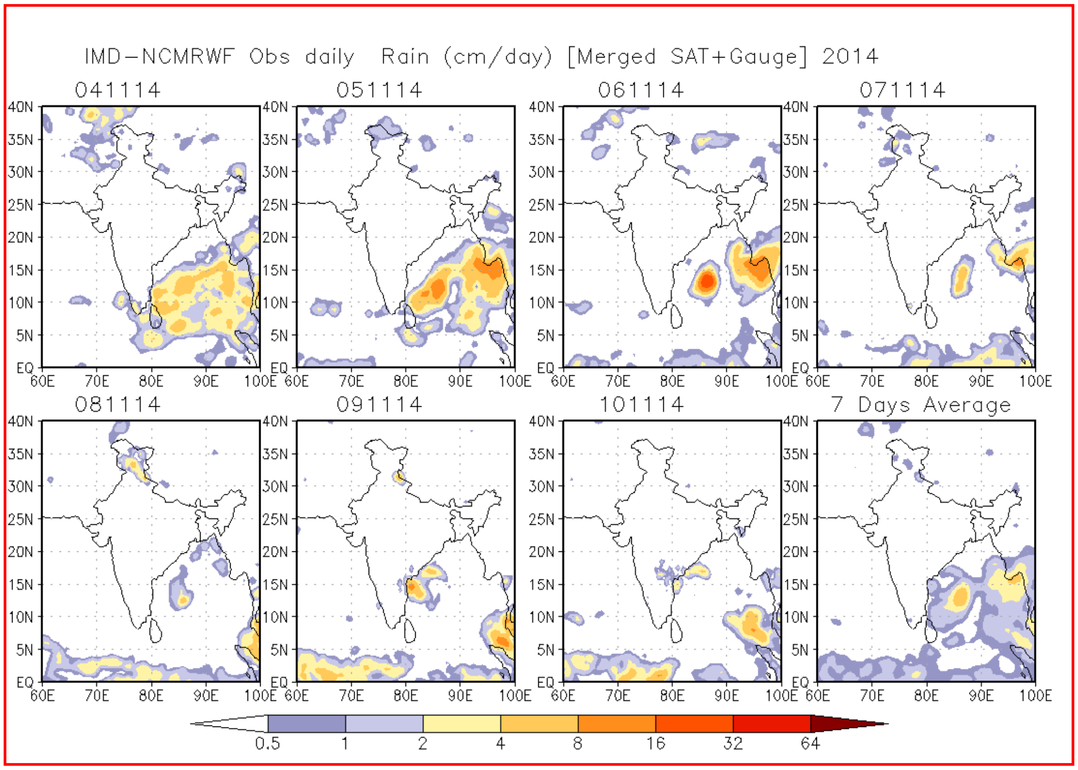

Fig. 2.8.6 IMD-NCMRWF satellite-gauge merged daily rainfall (in cm) during the period 04-10 November 2014 and the 7-day average rainfall during the same period.

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 activity is seen in isolated / a few places over Andhra Pradesh on 9th and 10th <25% of area gets (Description of spatial rainfall distribution: Isolated (one or two places) 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).

2.8.7.2 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 0700 UTC of 9th. Kavali(AWS) and Darsi(AWS) recorded 22 kmph at 0400 UTC and 0800 UTC of 9th respectively.

2.8.7.3. Storm Surge

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

2.8.7.4. Damage

No damage has been reported due to this system.

CHAPTER-III

Performance of operational NWP models for forecasting tropical cyclones over the North Indian Ocean during the year 2014

3.1 Introduction:

India Meteorological Department (IMD) operationally runs two regional models, WRF and HWRF for short-range prediction and one Global model 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. The HWRF model (resolution 27 km and 9 km) is used for cyclone track prediction in case of cyclone situation in the north Indian Ocean. IMD also makes use of NWP products prepared by some other operational NWP Centers like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), UKMO (UKMet), JMA (Japan Meteorological Agency). 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 "dynamical statistical models". It comprises of five forecast components, namely (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) statistical Cyclone intensity prediction (SCIP), (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 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 viz. IMD-GFS, GFS (NCEP), ECMWF, UKMO 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. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclones during 2013 are presented and discussed for three cyclones formed during 2014.

3.2. Cyclonic storm 'NANAUK" over the Arabian Sea during 10-14 June 2014

3.2.1 Grid point analysis and forecast of GPP

120, 96, 72, 48, 24 hour forecast and 00 hour (Analysis) of Genesis Potential Parameter (GPP) based on 0000 UTC of 05^{th}, 6^{th}, 7^{th}, 8^{th}, 9^{th} and 10th June 2014 valid for 0000 UTC of 10 June 2014 (Fig. 3.1(a) to Fig.3.1(f)) indicate cyclogenesis over the east-central Arabian Sea where a deep depression formed on that day.

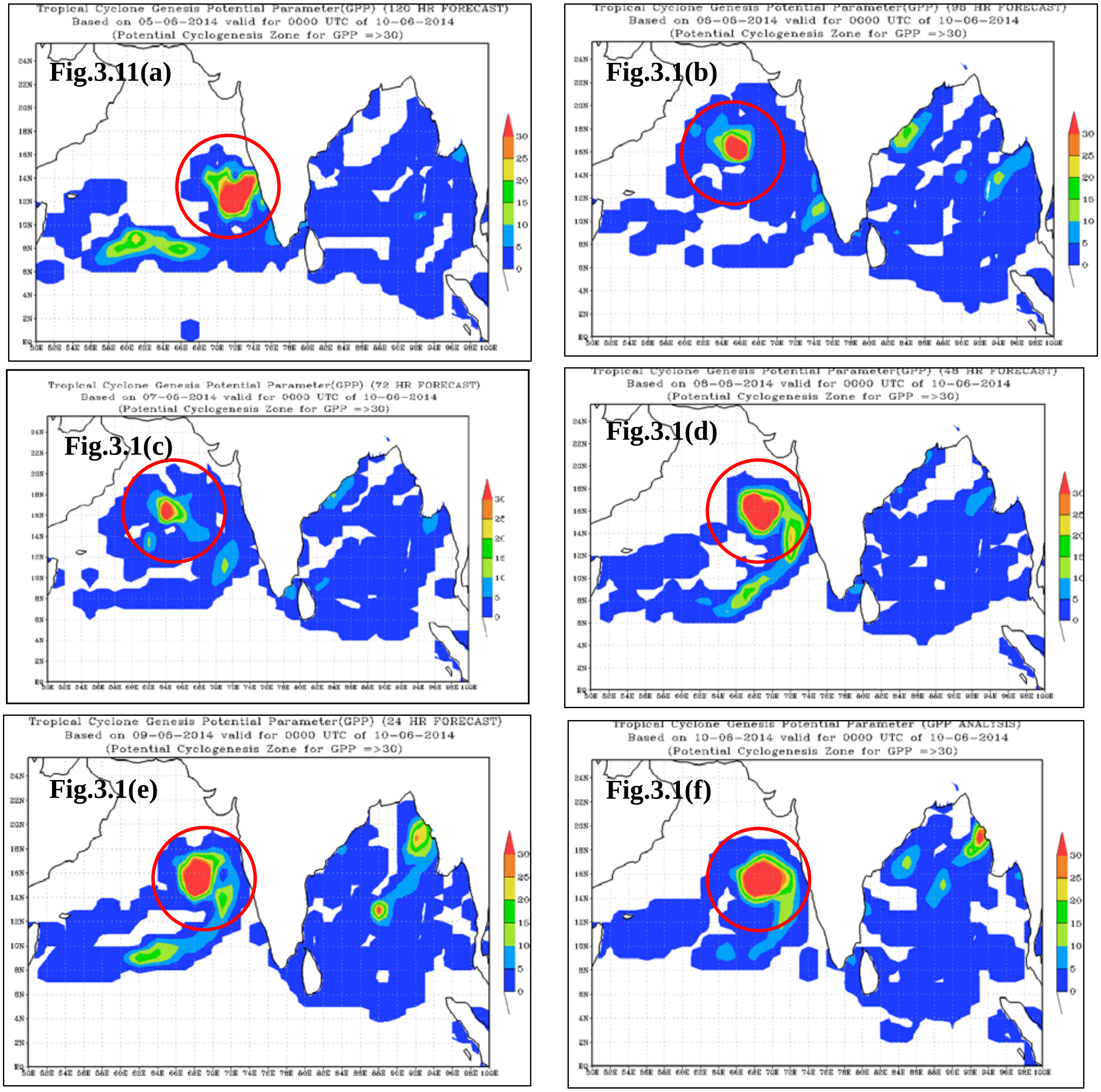

Fig.3.1(a-f) Forecasts and Fig. 3.1(f) Analysis of Genesis Potential Parameter (GPP) based on 0000 UTC of 05th to 10th June 2014.

3.2.2 Individual NWP models & EPS based Multi Model Ensemble (MME) track forecast, SCIP Intensity and RI Index

MME track forecast and intensity forecast based on:

0000 UTC of 11 June 2014 (Fig.3.2(a)) shows landfall on Oman Coast, at about 0300 UTC of 15 June 2014. 1200 UTC of 11 June 2014 (Fig. 3.2(b)) shows weakening into depression over sea. 0000 UTC of 12 June 2014 (Fig. 3.2(c)) shows weakening into depression over sea. 1200 UTC of 12 June 2014 (Fig. 3.2(d)) shows weakening into depression over sea. 0000 UTC of 13 June 2014

(Fig. 3.2(e)) shows weakening into depression over sea.

SCIP Intensity: The 12-hourly Intensity prediction by SCIP model as given below shows that the Depression over Andaman Sea would intensify into a tropical cyclone and weaken thereafter (Fig.3.2). Probability of Rapid Intensification (RI) for the cyclone Nanauk was low to moderate Fig.3.2

Track Predictions by various NWP models for cyclone NANAUK are shown in Fig 3.3. the track prediction based on EPS are shown in Fig 3.4

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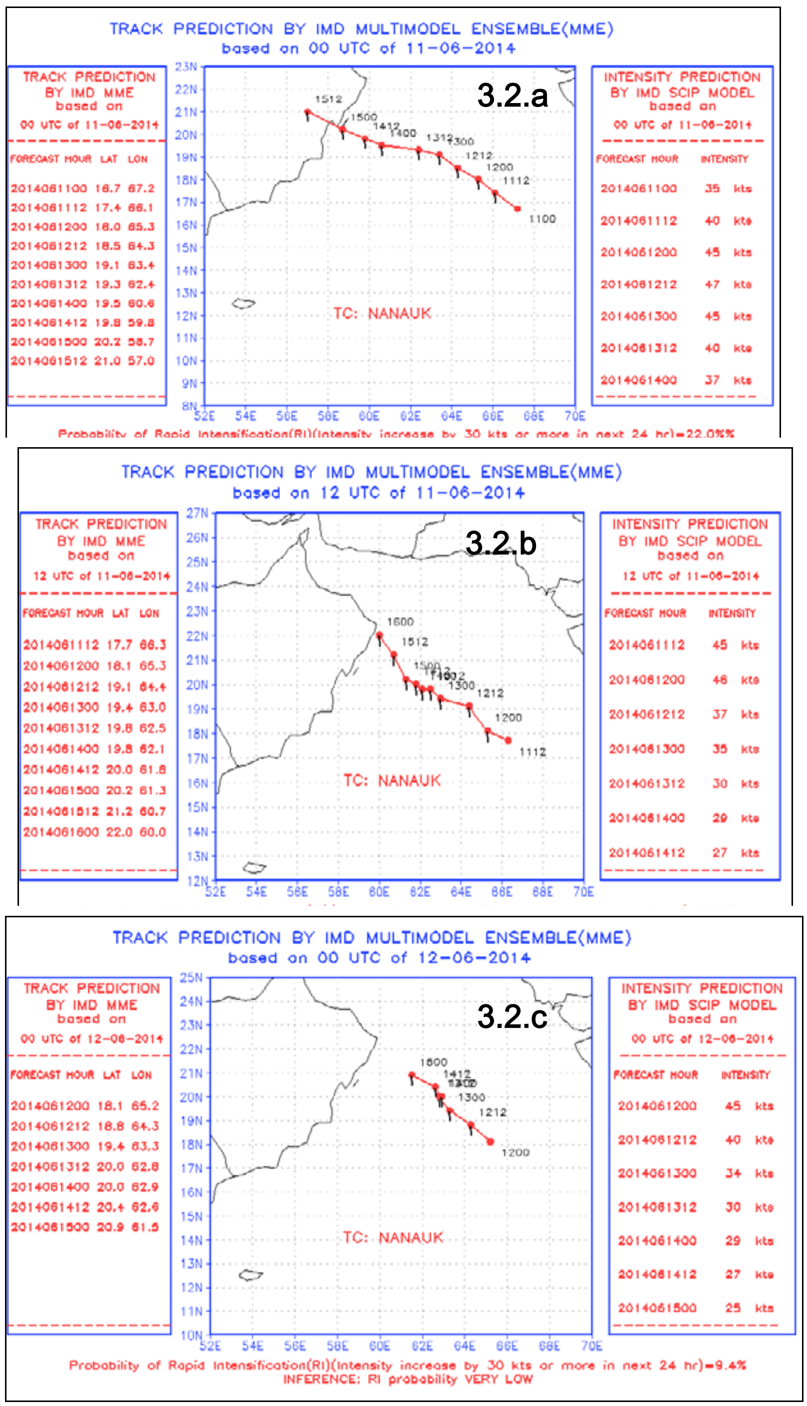
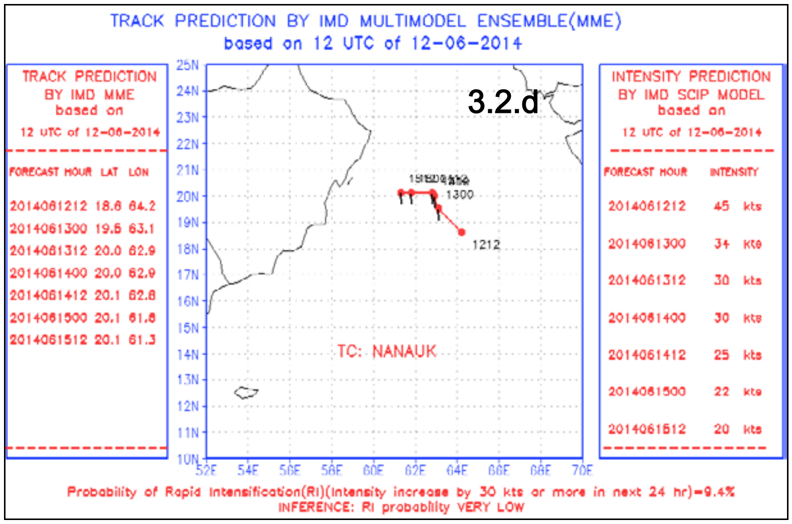




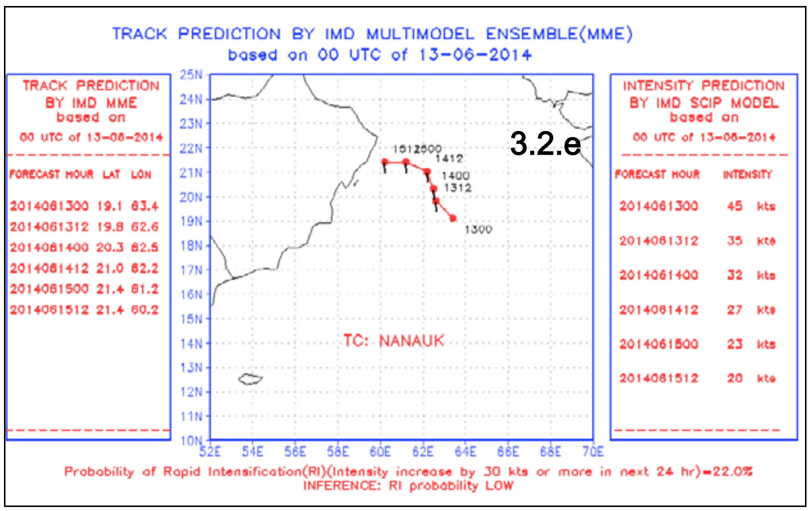


Fig. 3.2(a-e) MME track forecast based on 11th (0000 UTC), 11th (1200 UTC), 12th (0000 UTC), 12th (1200 UTC) and 13th (0000 UTC) of June 2014 along with Intensity (SCIP) and Rapid intensification (RI) forecast for cyclone NANAUK

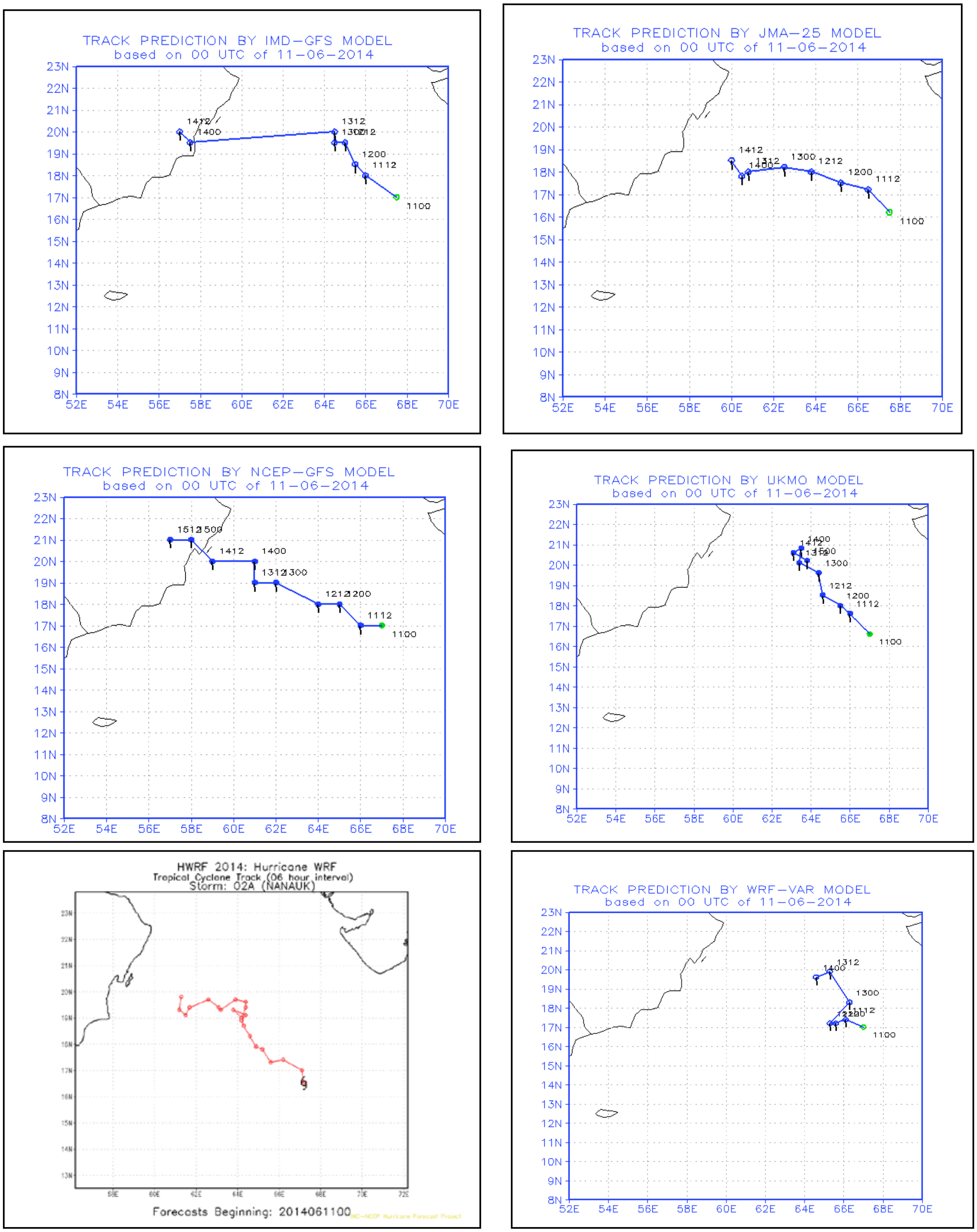


Fig 3.3.a. Track forecast for cyclone NANAUK based on 00 UTC of 11.06.2014

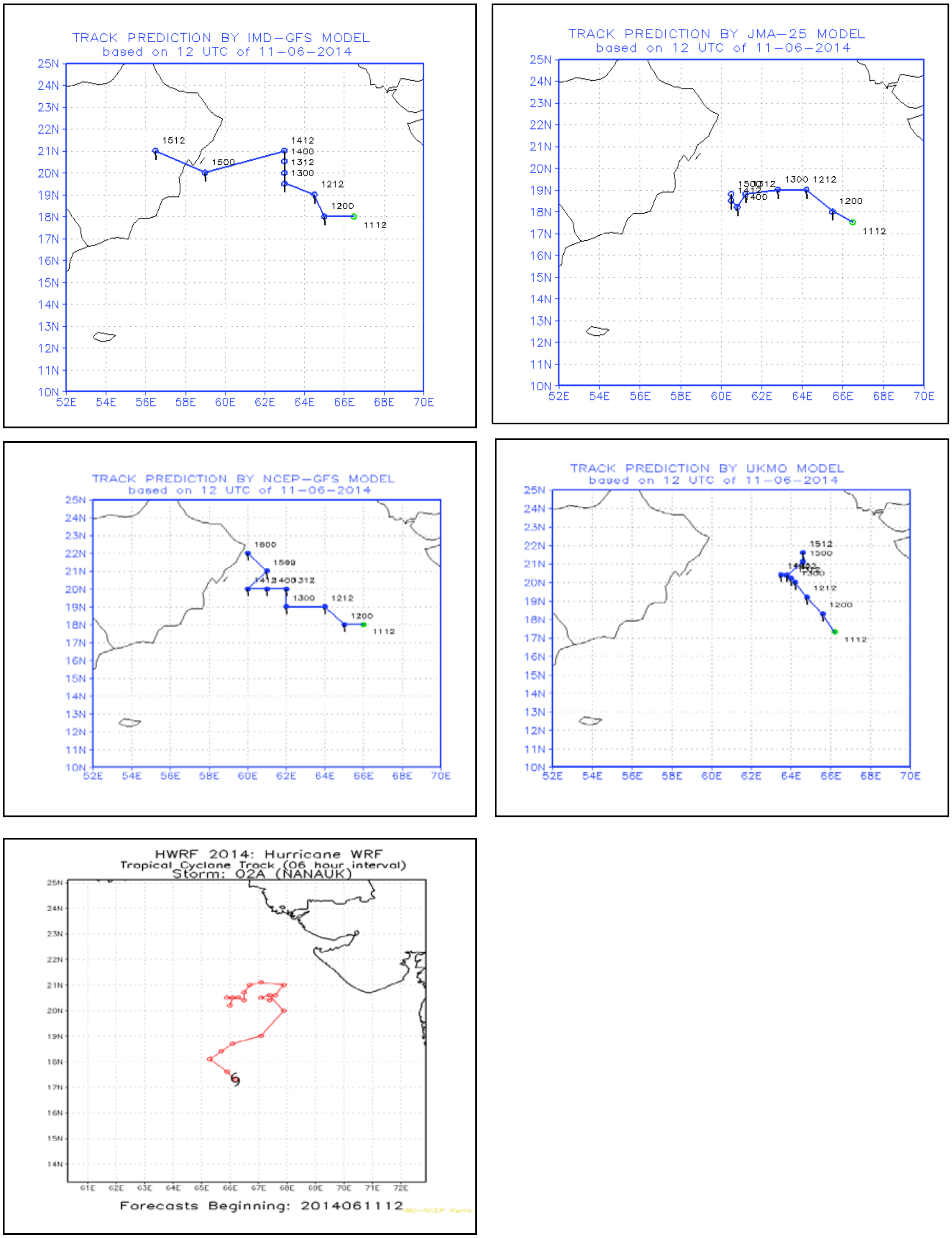


Fig 3.3.b. Track forecast for cyclone NANAUK based on 12 UTC of 11.06.2014

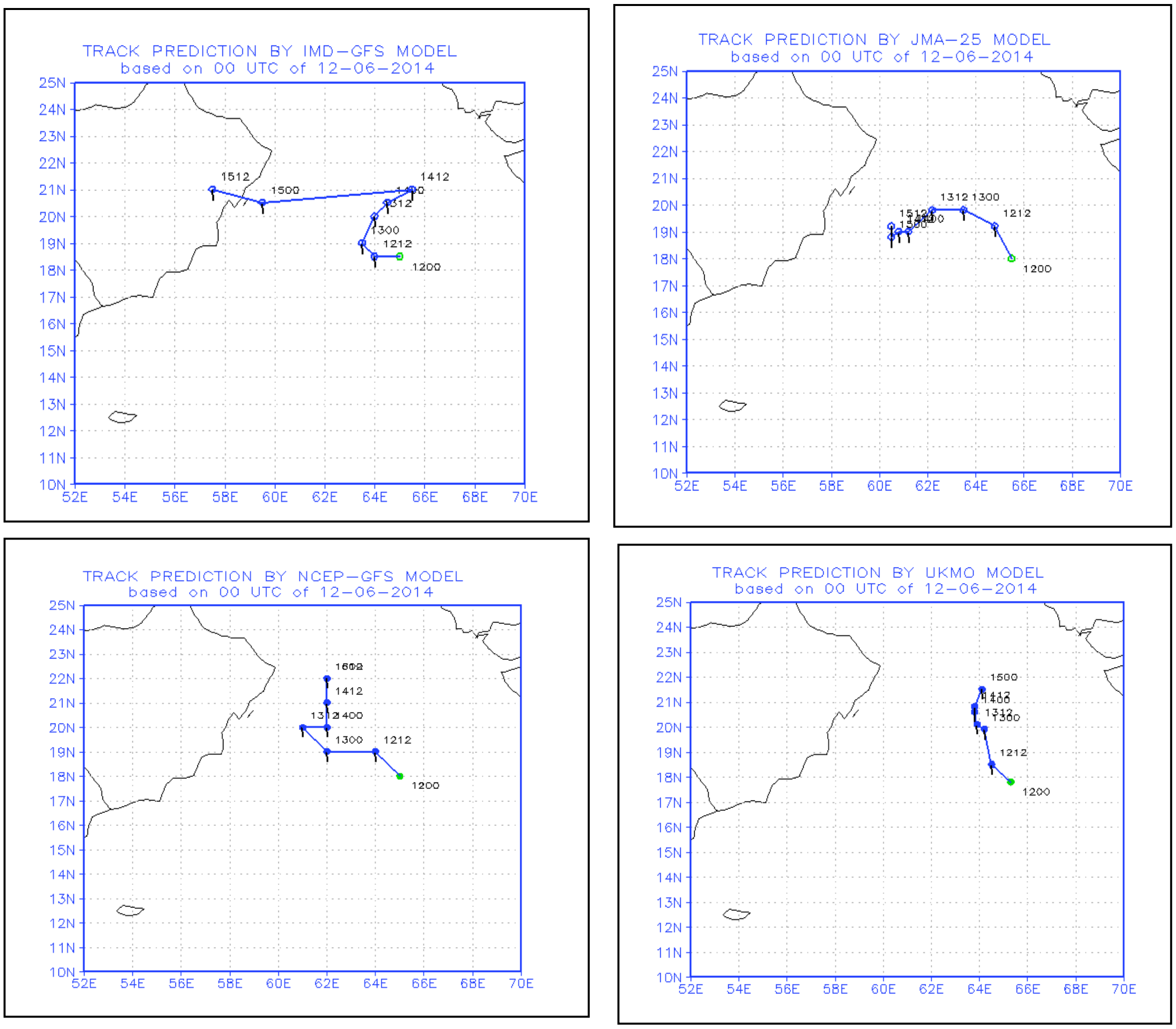


Fig.3.3.c. Track forecast for cyclone NANAUK based on 00 UTC of 12.06.2014

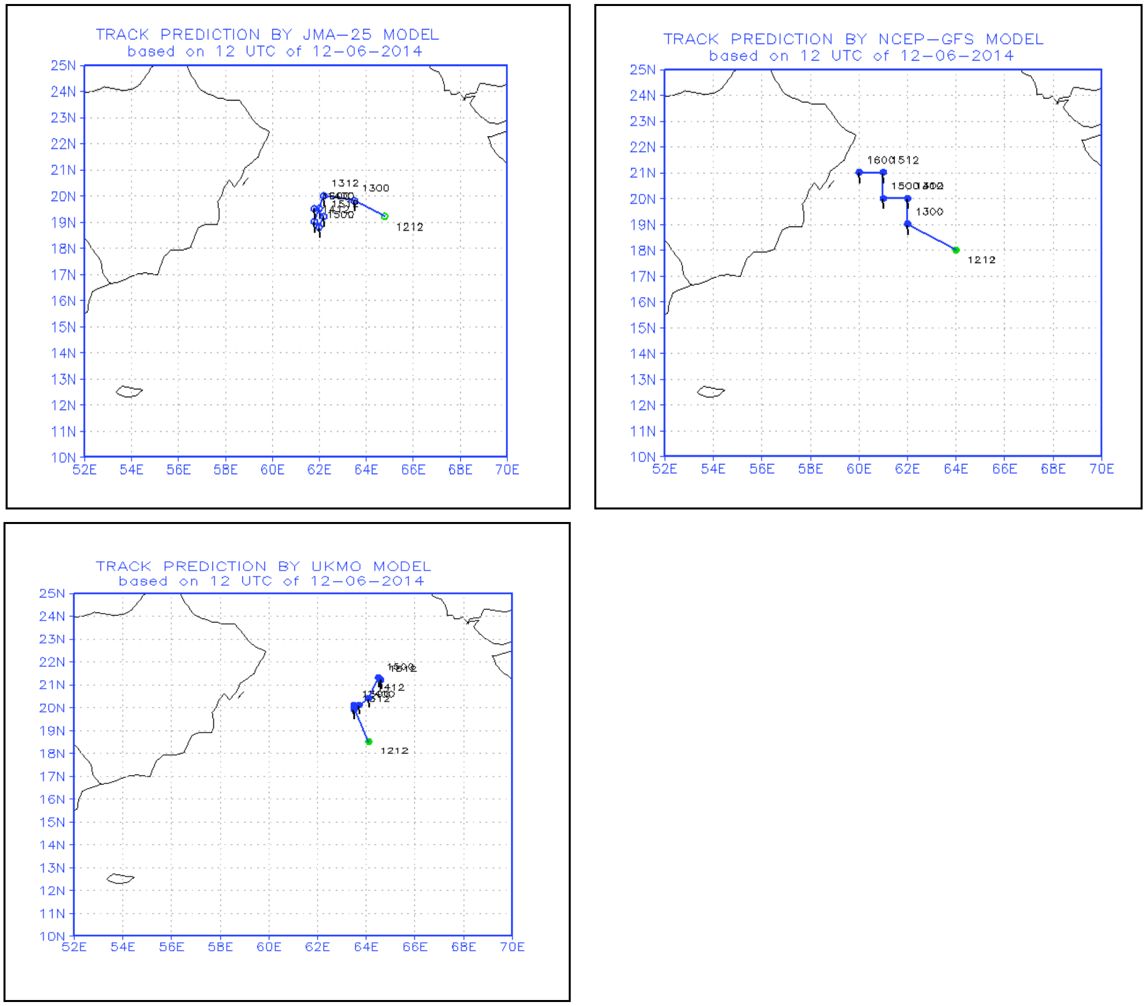


Fig.3.3.d. Track forecast for cyclone NANAUK based on 12 UTC of 12.06.2014

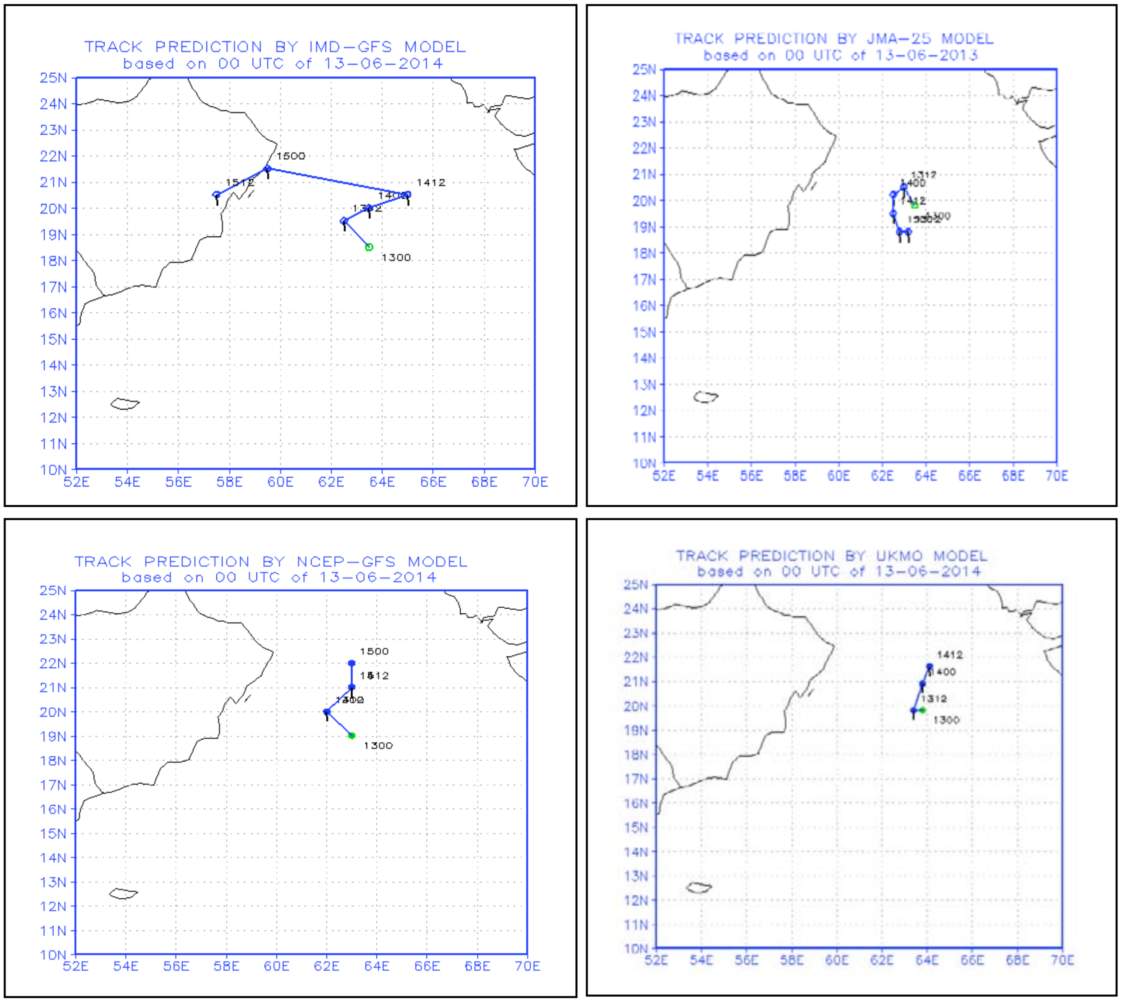


Fig 3.3.e. Track forecast for cyclone NANAUK based on 00 UTC of 13.06.2014

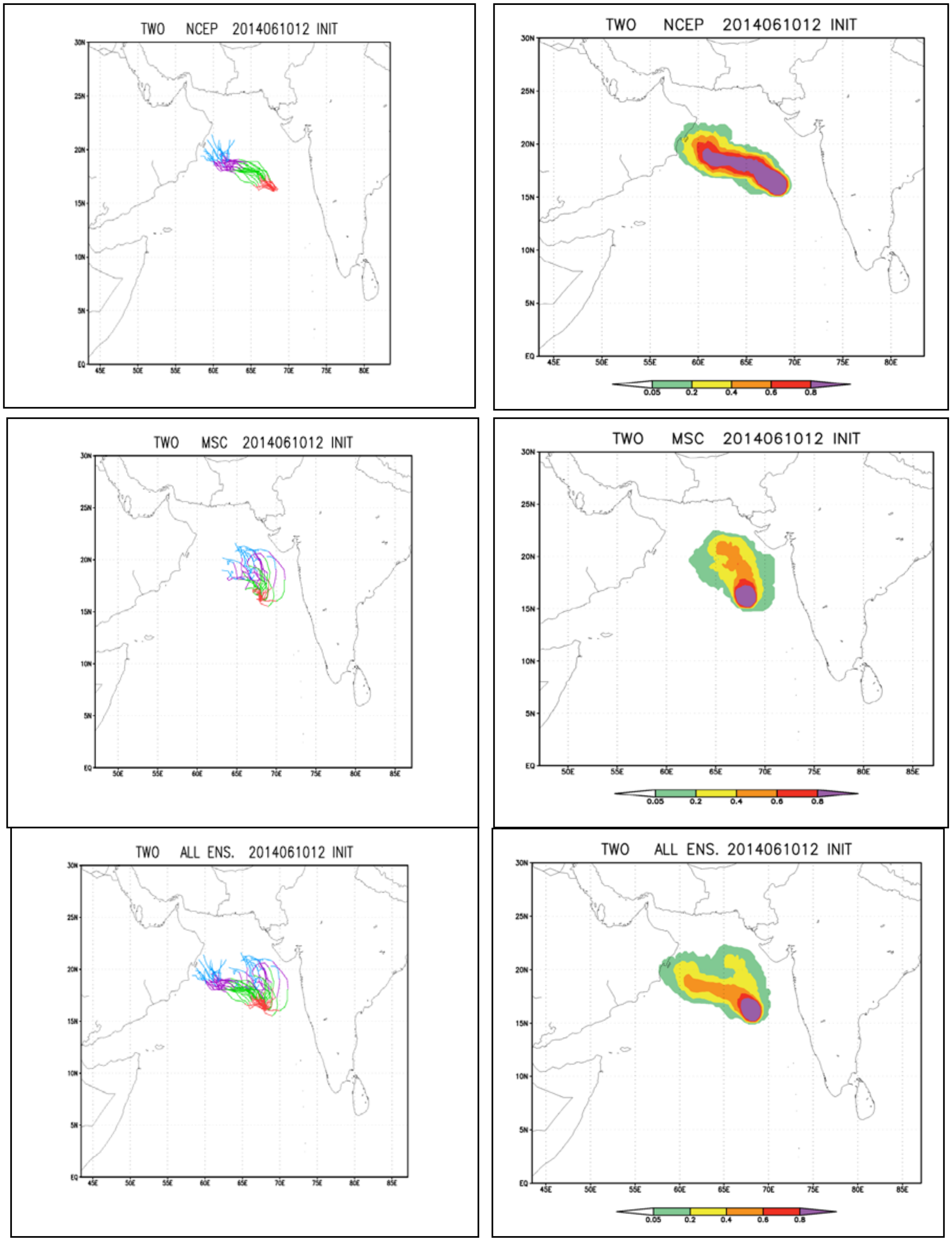


Fig.3.4 (a) EPS forecast for cyclone Nanauk based on 0000 UTC 10.06.2014

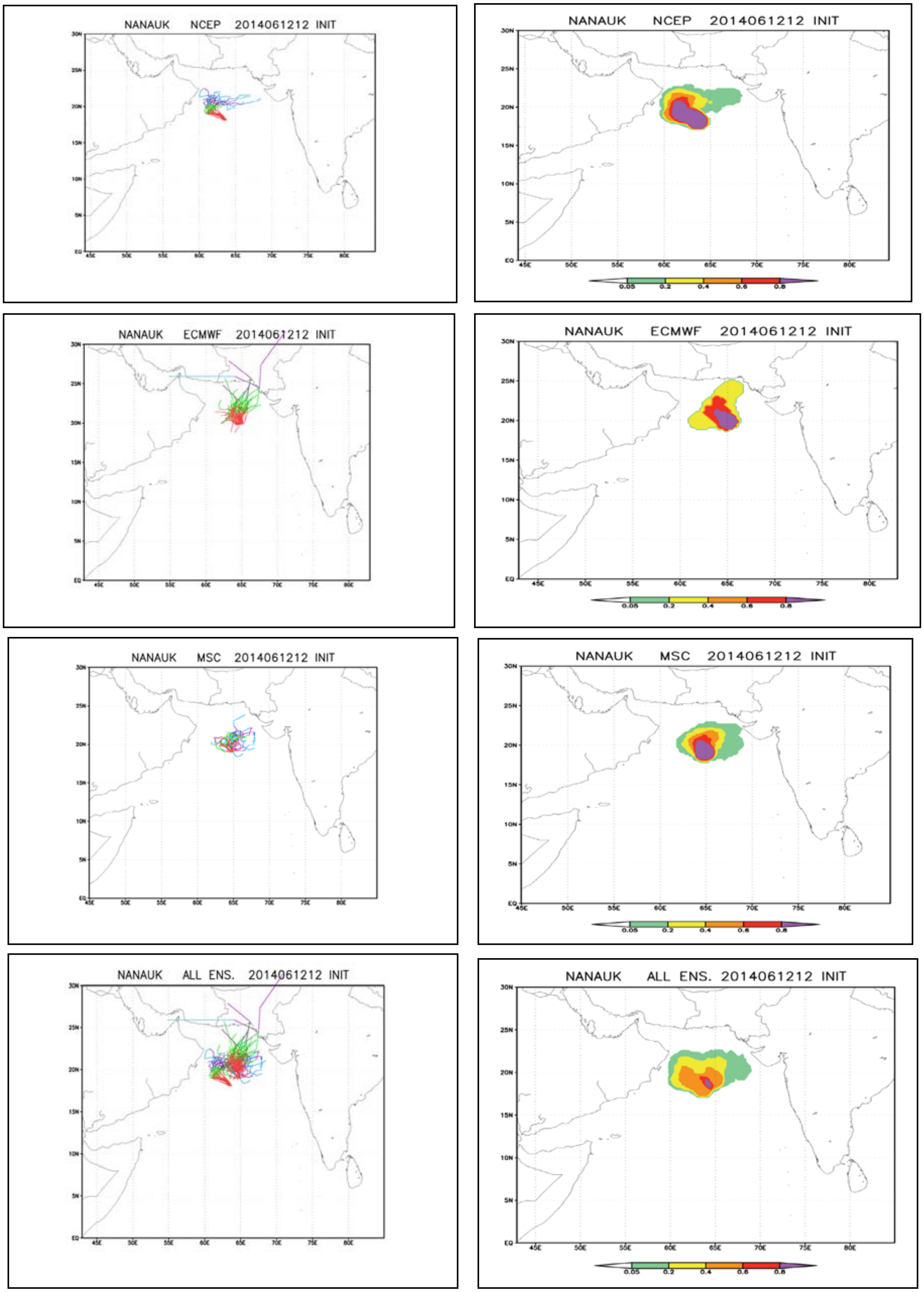


Fig.3.4 (b) EPS forecast for cyclone Nanauk based on 1200 UTC 12.06.2014

3.2.3 Forecast Performance

Fig.3.4 (b): EPS forecast for cyclone Nanauk based on 1200 UTC 12.06.2014

3.2.3. Track Prediction error

Direct position errors (DPE), cross track (CT) and along track (AT) component of track forecast are calculated based on the following Fig. 3.5 adapted from Heming (1994).

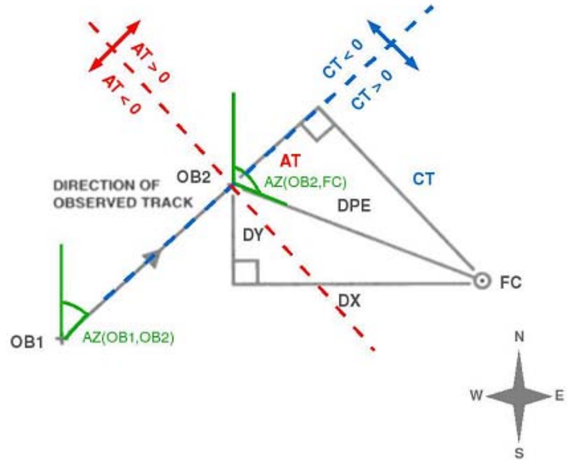


Fig.3.5: Types of positional forecast errors. DPE represents the direct positional error, CT is the cross track component, AT the along track component. DX represents the longitudinal component and DY is the latitudinal component. (Adapted from Heming (1994))

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the MME forecast are presented in the Table 1, Table 2 and Table 3 respectively.

3.2.3.1 Direct position Error (DPE)

Average track forecast error DPE was highest for WRF (about 220 km at 24 h, 339 km at 48 h, 289 km in 72h) and JMA (about 94 km at 12 h to 339 km at 72 h). The 72 h average DPE of IMD-GFS was also very high at 483 km. IMD-WRF and IMD-GFS 12 h average DPE were lowest at 45 km and 49 km respectively. Overall average DPE was lowest for NCEP-GFS and MME up to 48 h (between 53 km and 89 km). The DPE for NCEP-GFS was lowest (about 118 km) at 72 h. The DPE for MME was below 80 km up to 60 h forecast (Table-3.1). The DPE of all models are shown in Fig.3.6.

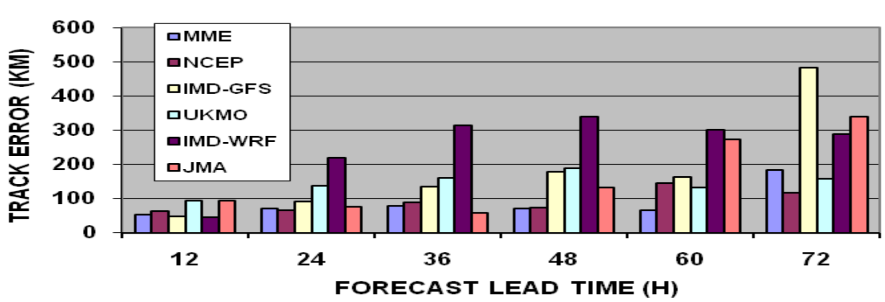


Fig. 3.6: Average track forecast errors (DPE) of NWP models for cyclone NANAUK

Table-3.1. Average track forecast errors (DPE) in km for cyclone NANAUK

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-GFS	49(5)	93(5)	136(4)	178(3)	162(2)	483(1)
IMD-WRF	45(5)	220(5)	314(4)	339(3)	301(2)	289(1)
JMA	94(5)	76(5)	59(4)	134(3)	273(2)	339(1)
NCEP-GFS	64(5)	67(5)	89(4)	73(3)	145(2)	118(1)
UKMO	95(5)	138(5)	161(4)	189(3)	133(2)	159(1)
IMD-MME	53(5)	72(5)	79(4)	71(3)	67(2)	184(1)

(Number of forecasts verified)

3.2.3.2 Cross Track Error (CTE)

Average cross track error (CTE) was lowest for 12 h forecast for IMD-WRF and IMD-GFS at 15 km and 28 km respectively followed by NCEP-GFS (42 km) and IMD-MME (48 km). The average CTE was overall largest for UKMO, IMD-GFS and JMA. The average CTE of NCEP-GFS was lowest up to 48 h and for IMD-MME it was less than 70 km up to 60 h. The CTE of all models are shown in Fig. 3.7.

Table-3.2. Average cross track error (CTE) in km for cyclone NANAUK

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-GFS	28	80	103	135	105	374
IMD-WRF	15	61	105	136	130	91
JMA	83	64	44	127	270	333
NCEP-GFS	42	31	40	23	132	108
UKMO	82	127	124	149	88	123
IMD-MME	48	66	57	39	50	178

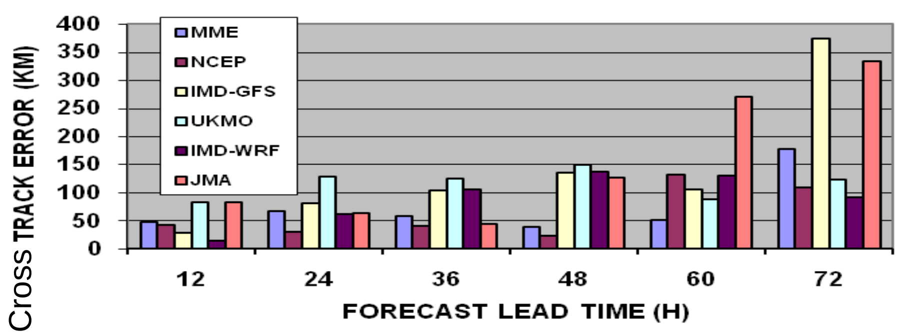


Fig.3.7: Average cross track errors (CTE) of NWP models for cyclone NANAUK

3.2.3.4 Along Track Error (ATE)

Average along track error (ATE) was highest for WRF (about 41 km at 12 h, 204 km at 24 h, 310 km at 48 h, 274 km at 72 h). The ATE for JMA, NCEP-GFS and IMD-MME was less than 80 km for all the hours. The ATE for MME was the best at about 13 km at 12 h to 47 km at 72 h (Table-3.3). The ATE of all models is shown in Fig. 3.8.

Table-3.3. Average along track error (ATE) in km for cyclone NANAUK

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-GFS	29	43	66	113	124	305
IMD-WRF	41	204	294	310	264	274
JMA	39	23	35	38	41	61
NCEP-GFS	39	53	78	66	59	48
UKMO	33	48	95	112	98	101
IMD-MME	13	19	44	44	44	47

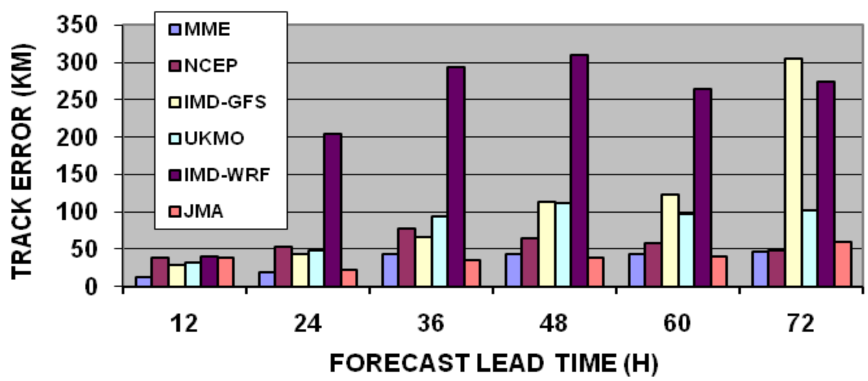


Fig.3.8: Average along track errors (ATE) of NWP models for cyclone NANAUK

3.2.3.3 Intensity prediction error of SCIP model

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP is shown in Fig.3.9. The SCIP model could predict the non-intensification of tropical cyclone NANAUK further into severe stage. Moreover, in all its predictions it could indicate the impending weakening of the system over the sea.

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP forecast error is presented in Table-3.4 and Table-3.5. Intensity forecasts by SCIP show that forecasts were reasonably good up to 48 h

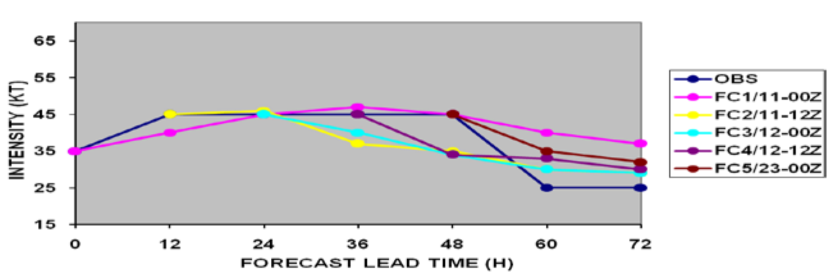


Fig.3.9: Intensity forecasts of SCIP model for cyclone NANAUK

Table-3.4 AAE (knots) for cyclone NANAUK (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	6.4(5)	6.8(5)	5.5(4)	3(3)	9.5(2)	12(1)

Table-3.5 RMSE (knots) for cyclone NANAUK (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	7.4(5)	7.7(5)	6.2(4)	3.7(3)	11.0(2)	12.0(1)

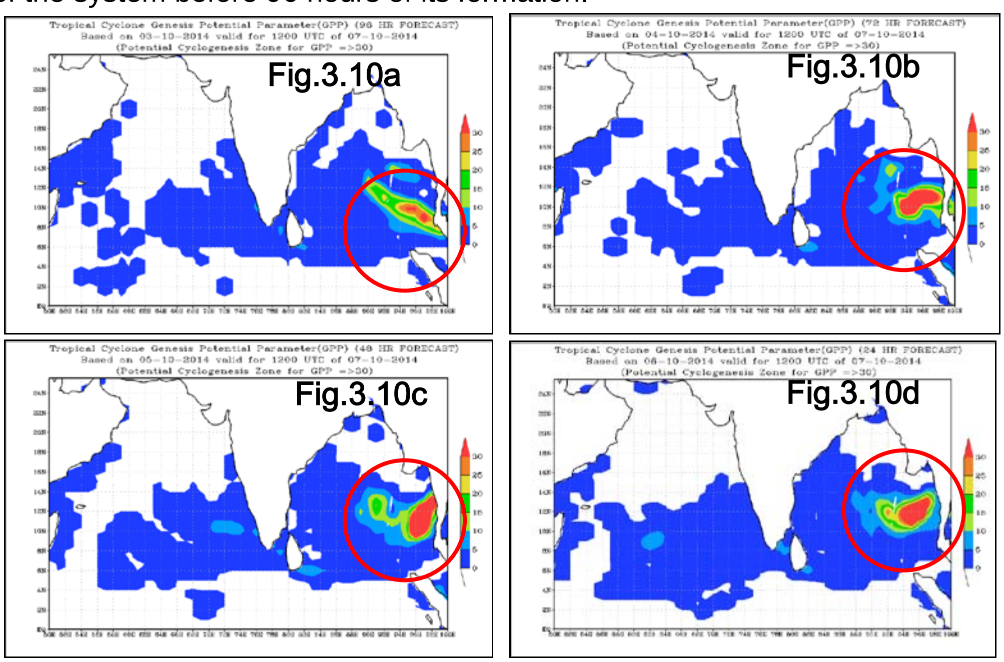
3.2.3.4 Rapid intensification (by RI-Index) forecast error

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour. RI-Index could predict NON-OCCURENCE of Rapid Intensification of cyclone NANAUK during its lifetime.

3.3 Cyclonic storm HUDHUD over the Bay of Bengal during (7-14) October 2014

3.3.1 forecast based on GPP

Grid point analysis and forecasts of GPP (Fig.3.10(a-e)) shows that it could predict the formation and location of the system before 96 hours of its formation.



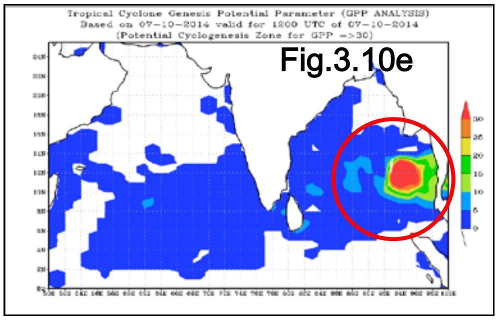


Figure.3.10 (a-e): Predicted zone of cyclogenesis for cyclone HUDHUD.

The area average analysis of GPP is shown Fig.3.11 (a-d)

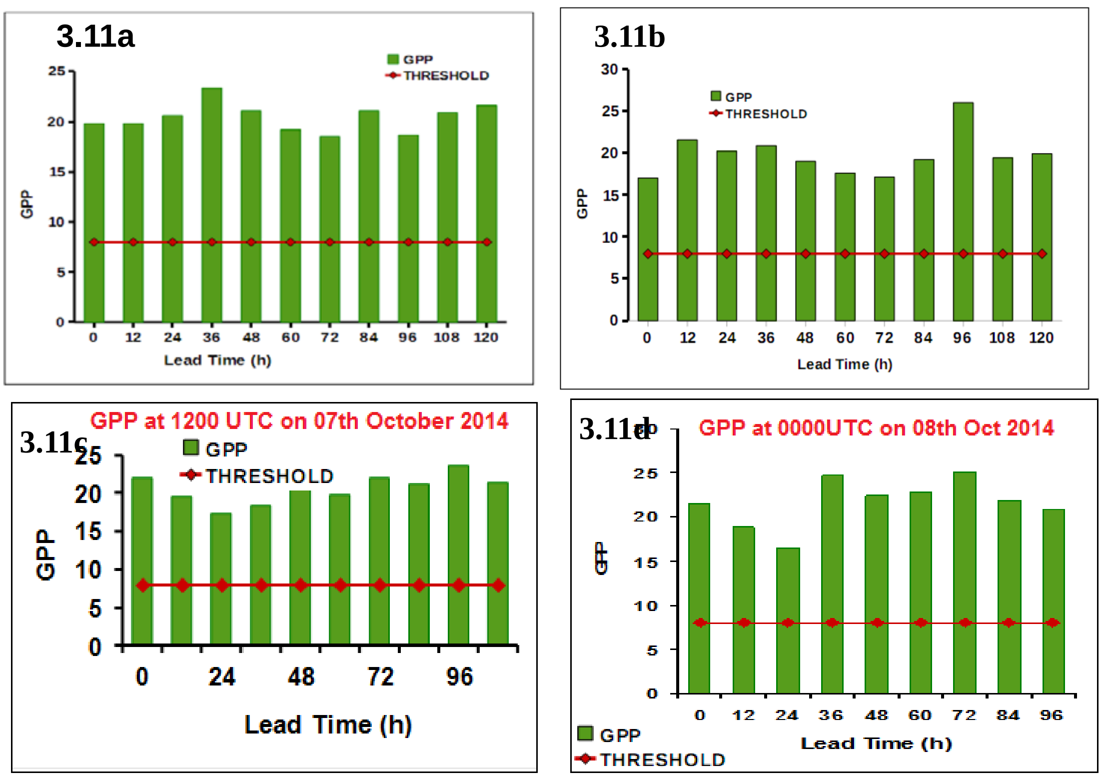


Fig. 3.11(a-d) Area average analysis of GPP based on 0000 UTC of 06 & 07 at 1200 UTC of 07 and 08 Oct 2014 with initial T.No of 1.0 each.

Conditions for: (i) Developed system C.T.3.0: Threshold value of GPP ≥ 8.0

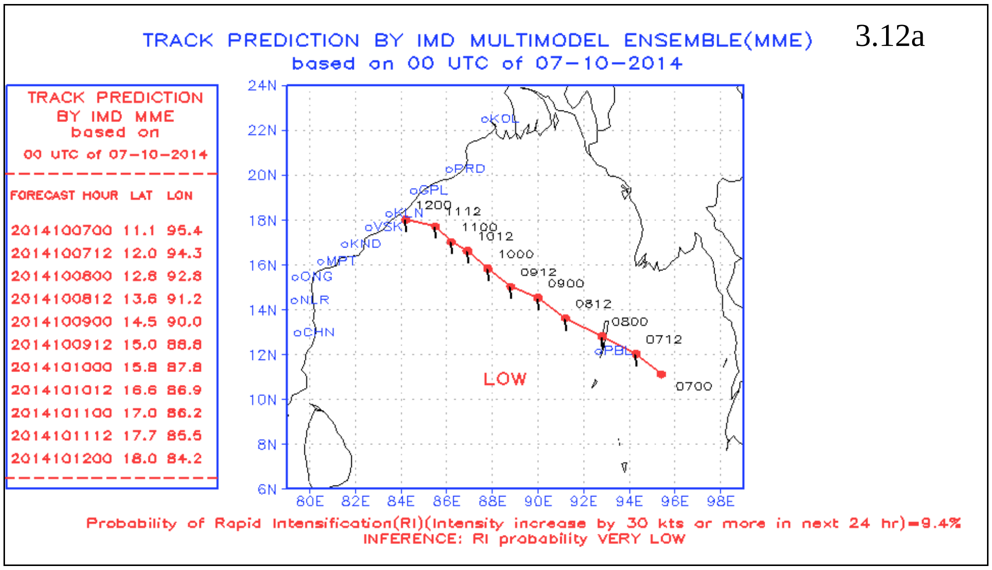
(ii) Non-developed system C.T.3.0: Threshold value of GPP < 8.0

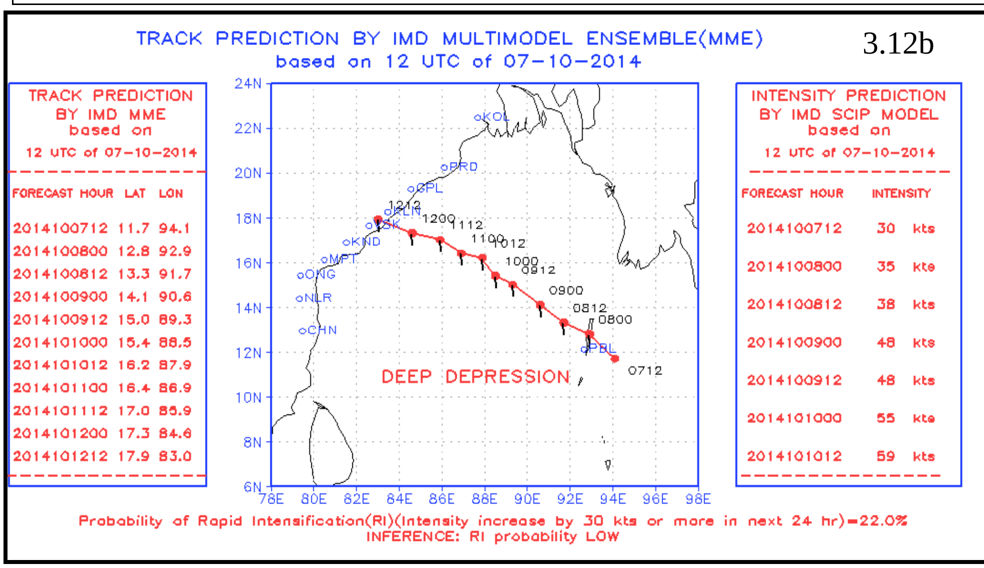
Analysis and forecasts of GPP (Fig.3(a-d)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone). Thus it predicted potential to intensify into a cyclone at early stages of development (T.No. 1.0 to 2.0).

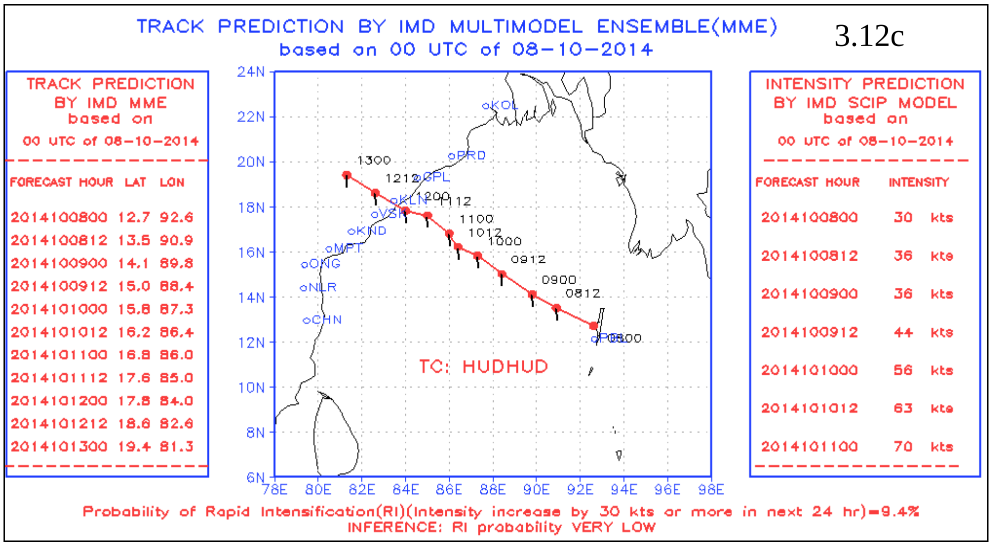
3.3.2. Track predicting by individual NWP models, MME & EPS

The track prediction by MME are shown in Fig 3.12, by individual models is in Fig 3.13 and by GPS in Fig.3.14

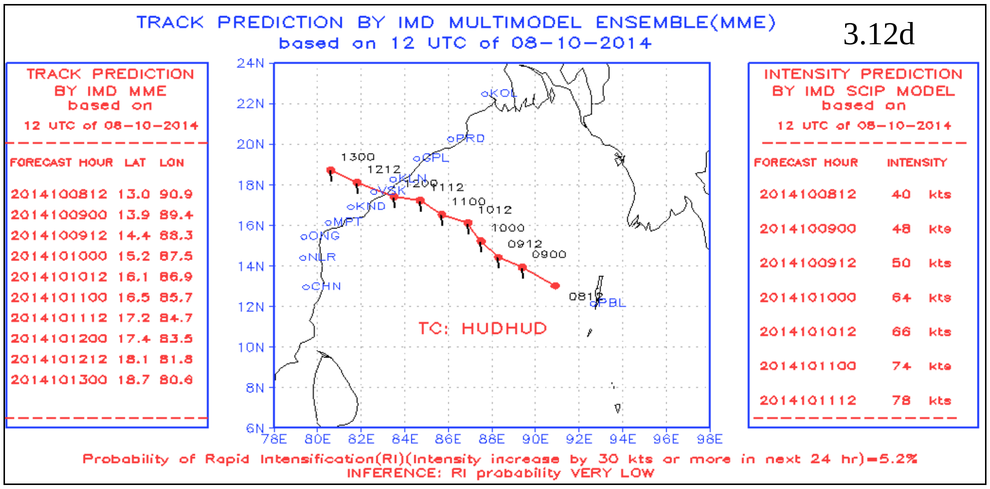
Consensus track prediction by MME for cyclone Hudhud



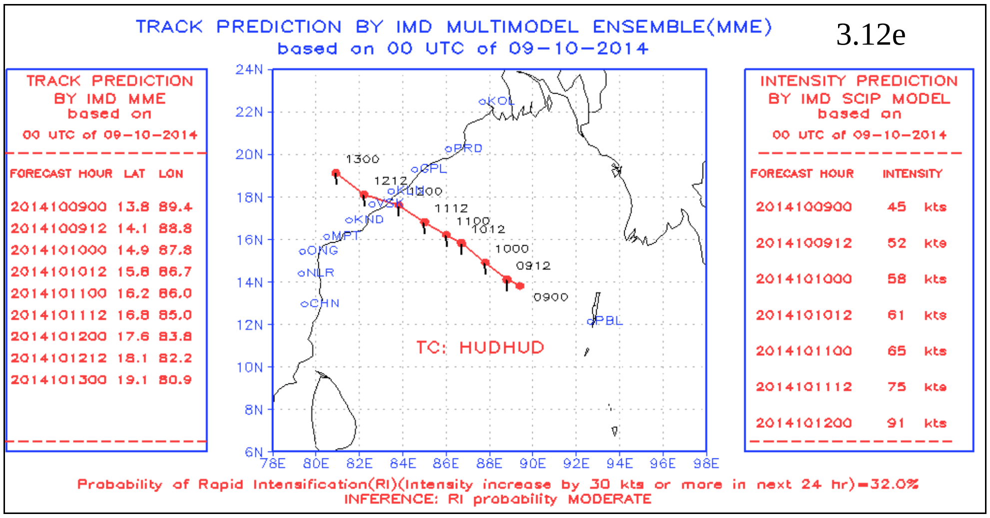




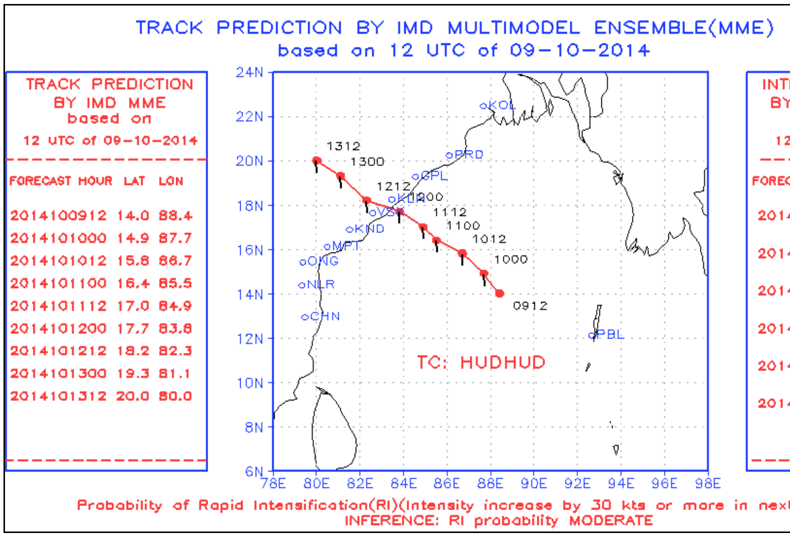
3.12c



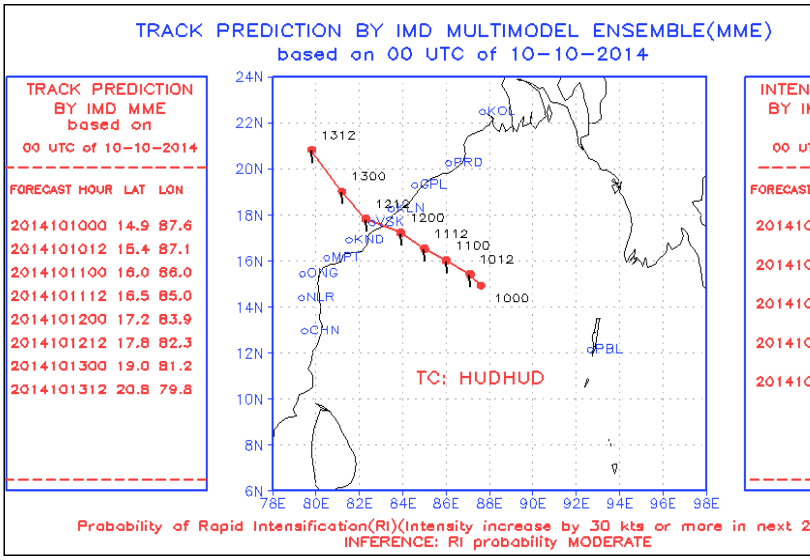
3.12d



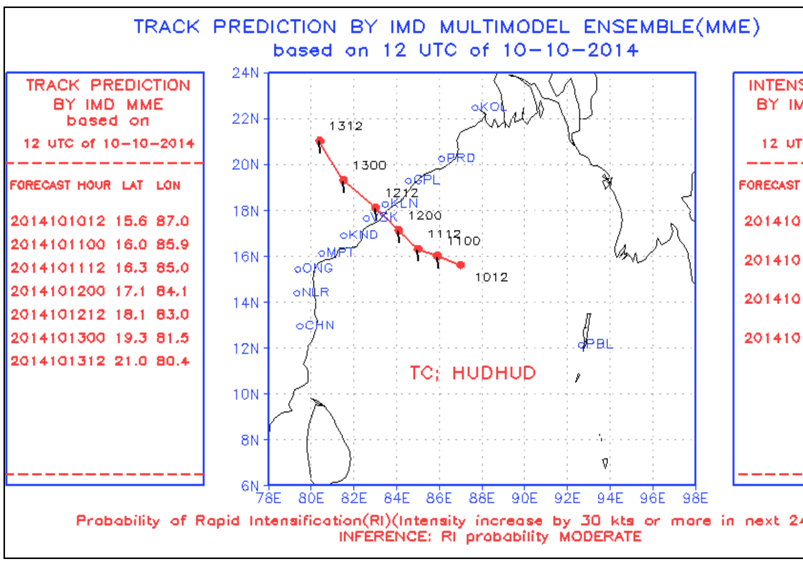
3.12e



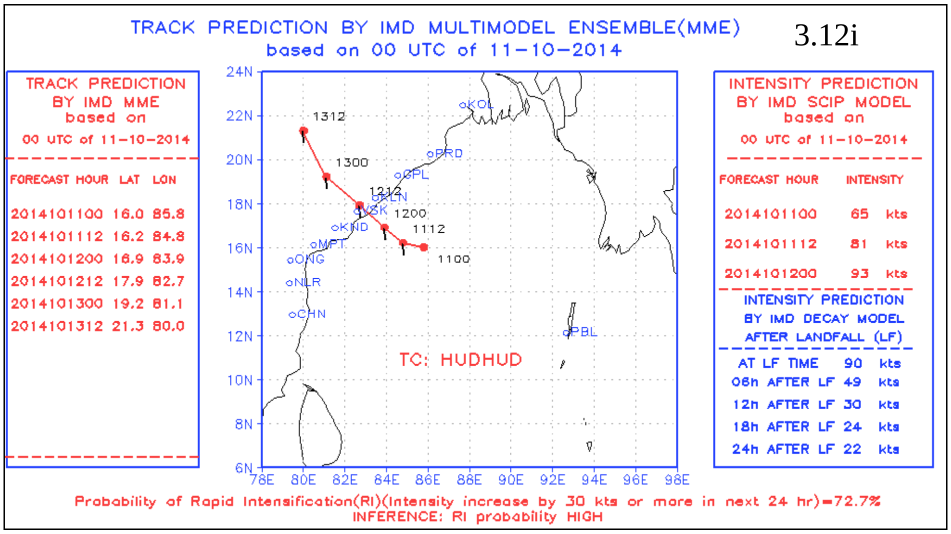
3.12f

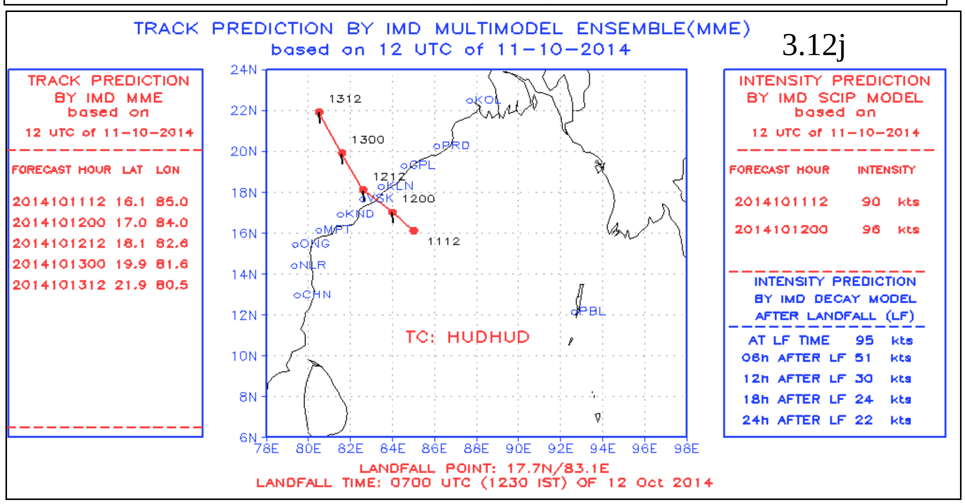


3.12g



3.12h





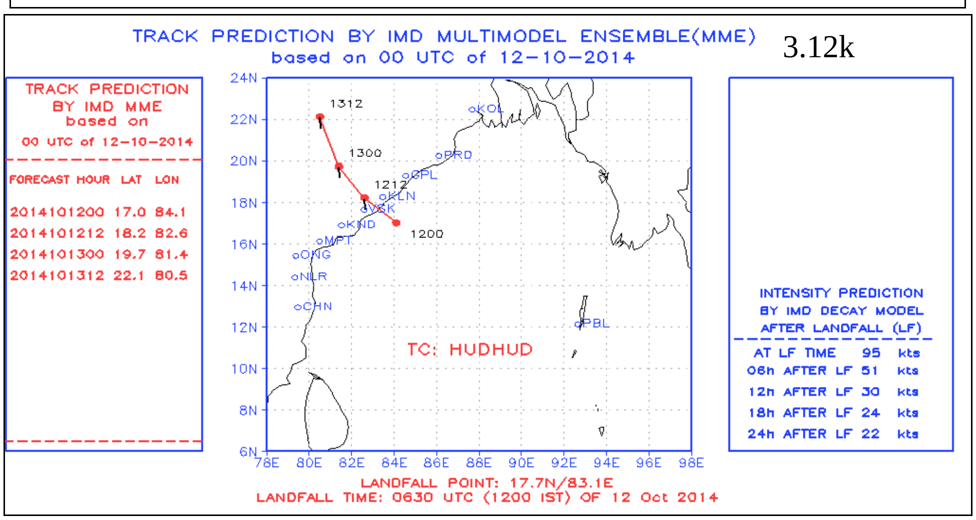


Fig.3.12 (a-k): Track prediction by MME for cyclone HUDHUD

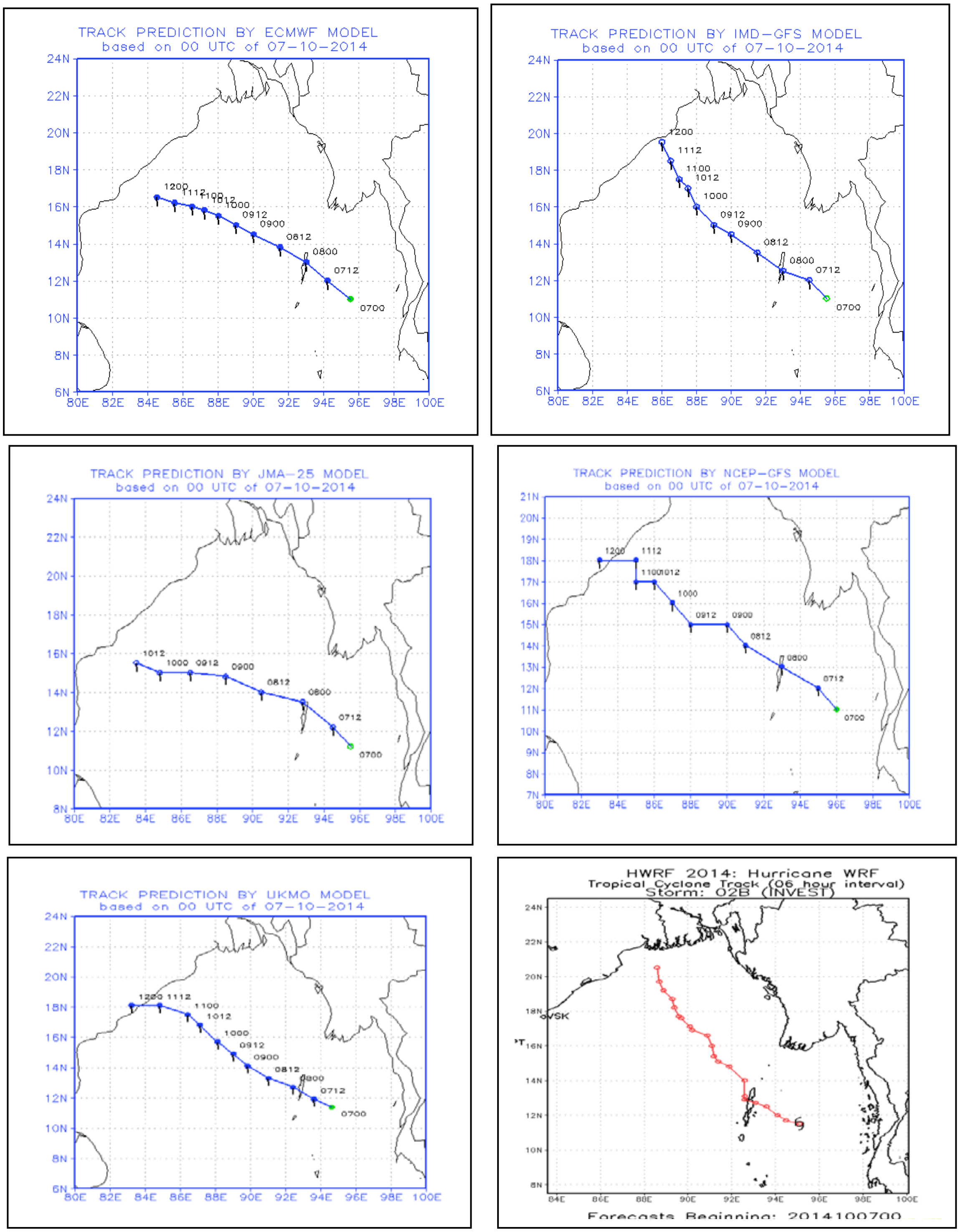


Fig.3.13 (a). Track forecast by NWP models for cyclone HUDHUD based on 00 UTC of 07.10.2014

Track prediction by NWP model for cyclone HUDHUD

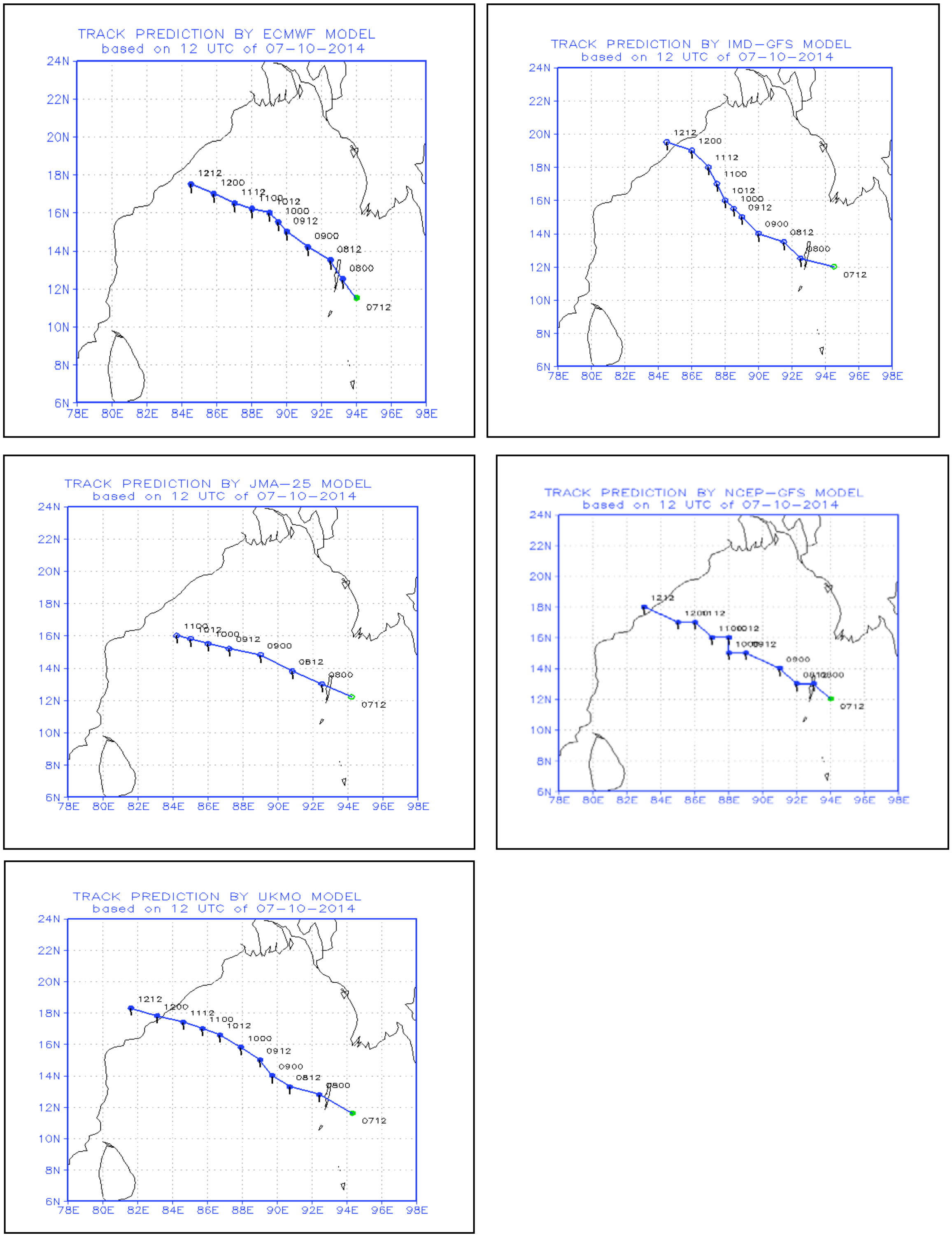


Fig 3.13 (b). Track forecast by NWP models for cyclone HUDHUD based on 12 UTC of 07.10.2014

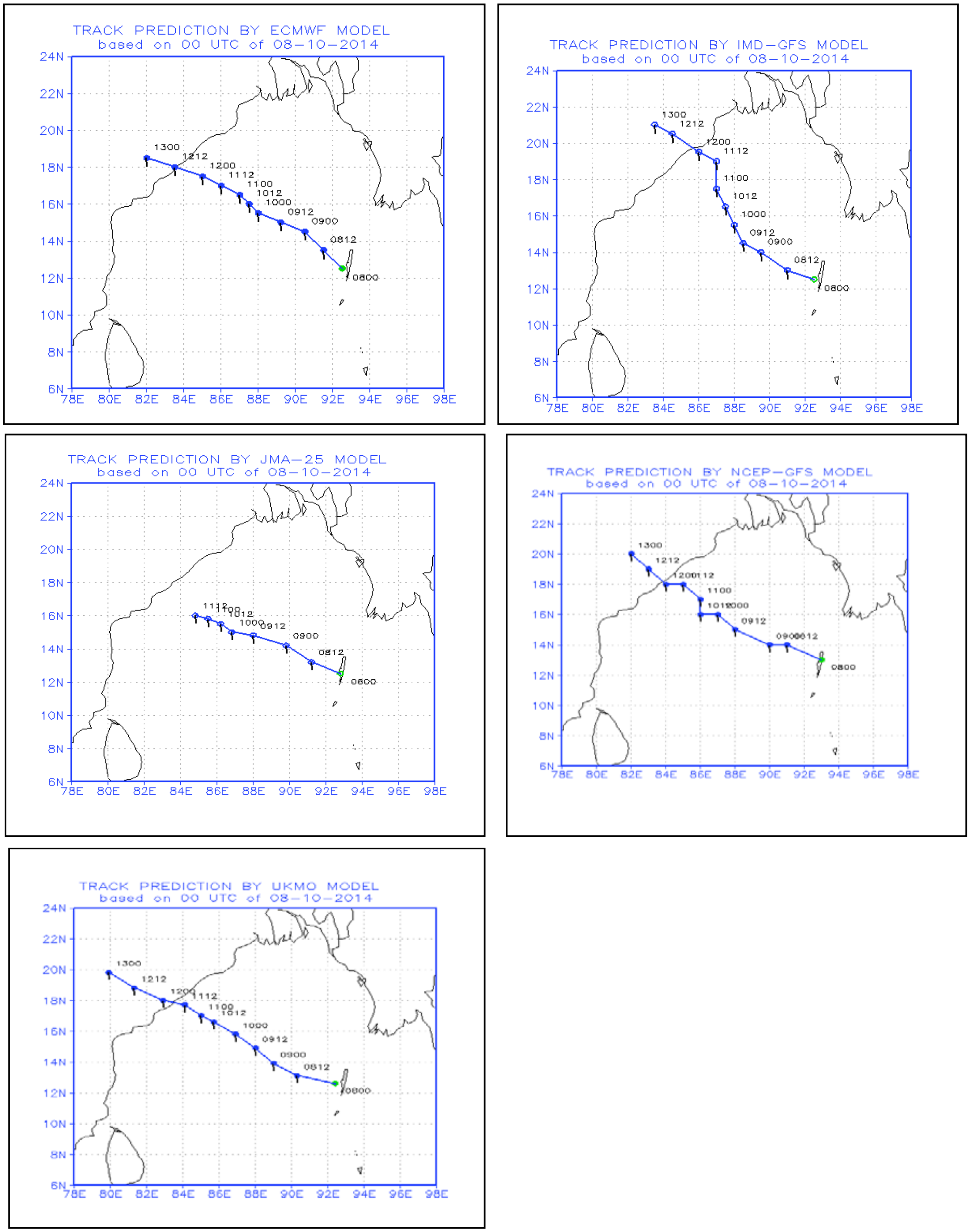


Fig.3.13(c). Track forecast by NWP models for cyclone HUDHUD based on 00 UTC of 08.10.2014

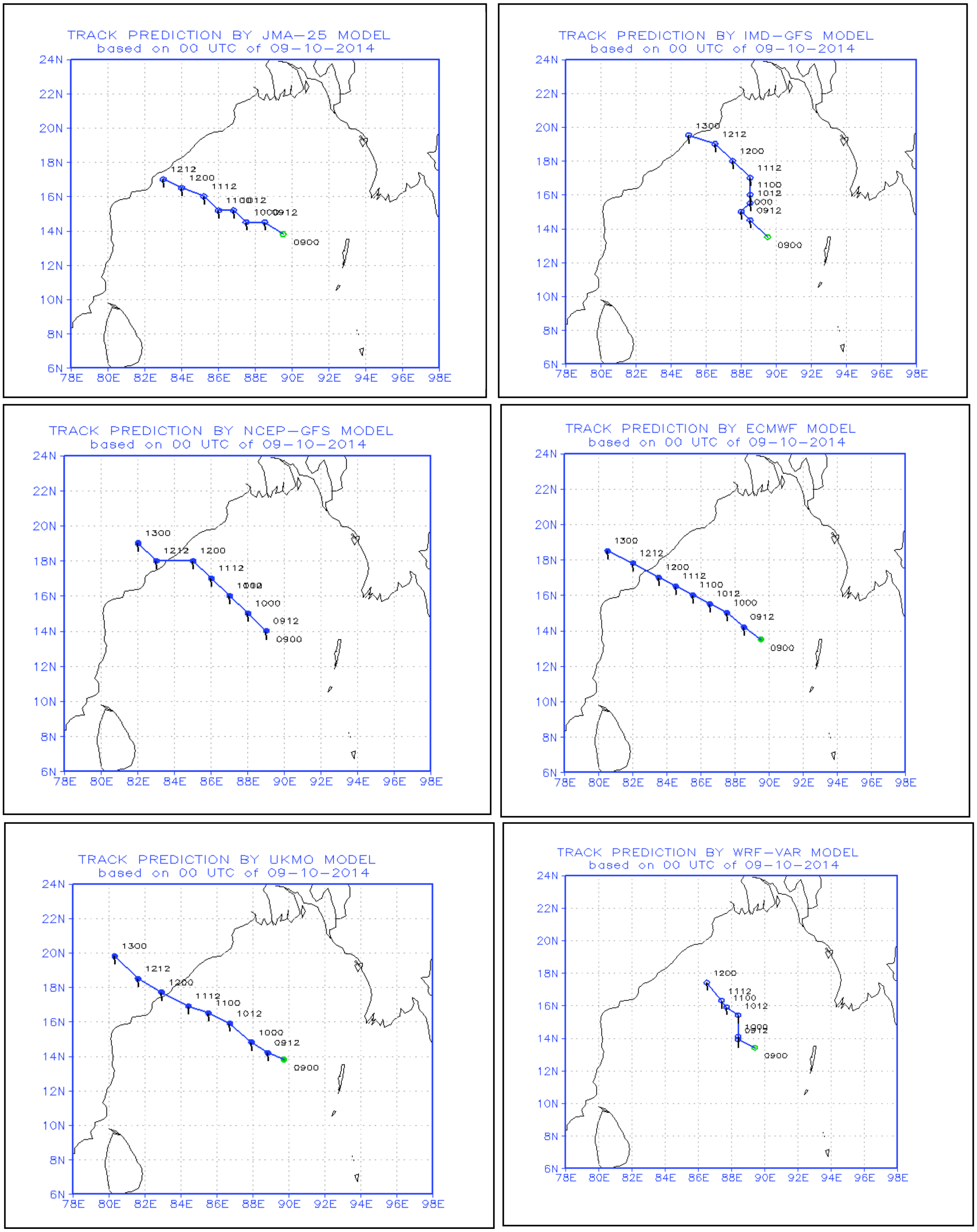


Fig.3.13(d). Track forecast by NWP models for cyclone HUDHUD based on 00 UTC of 09.10.2014

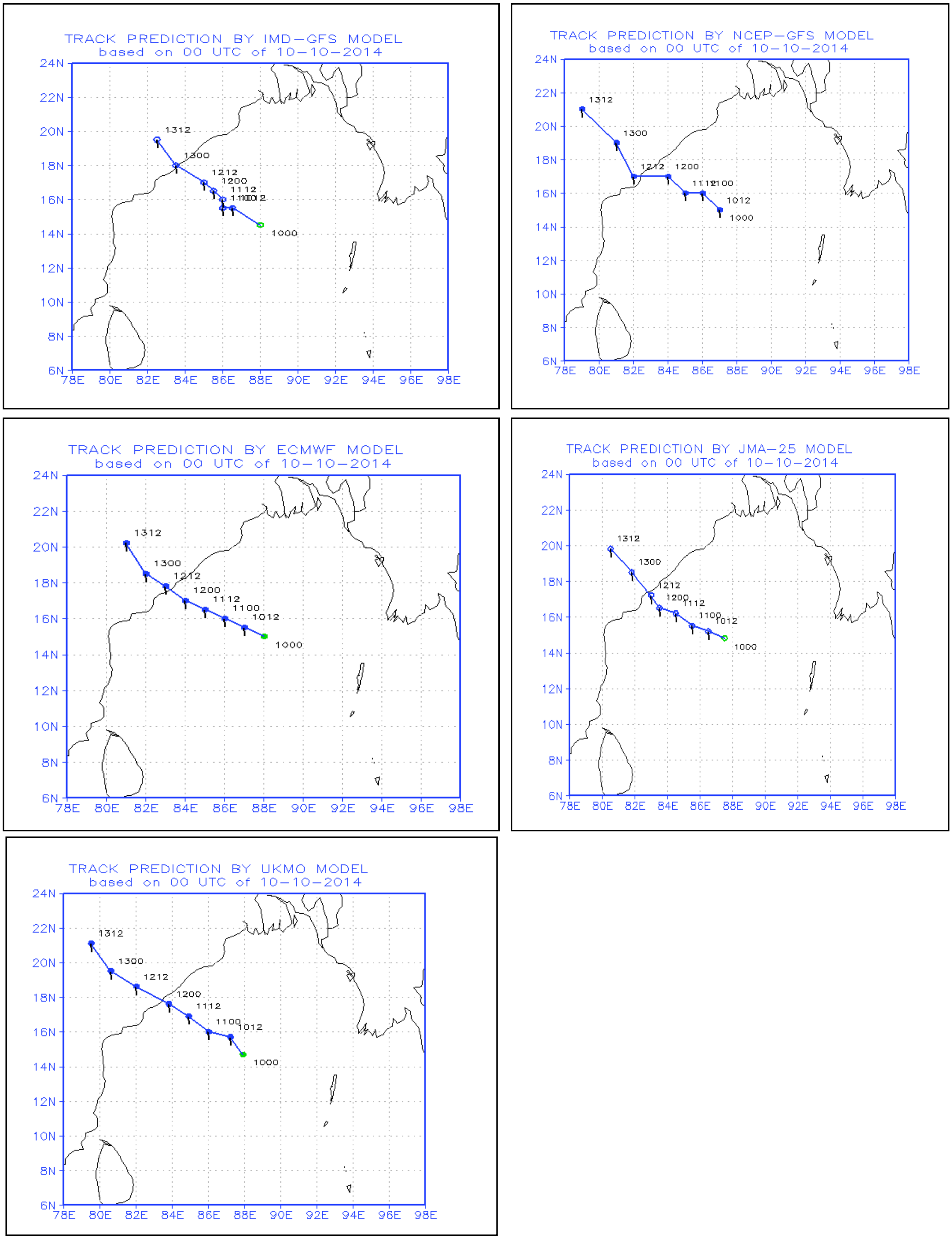


Fig.3.13.e. Track forecast by NWP models for cyclone HUDHUD based on 00 UTC of 10.10.2014

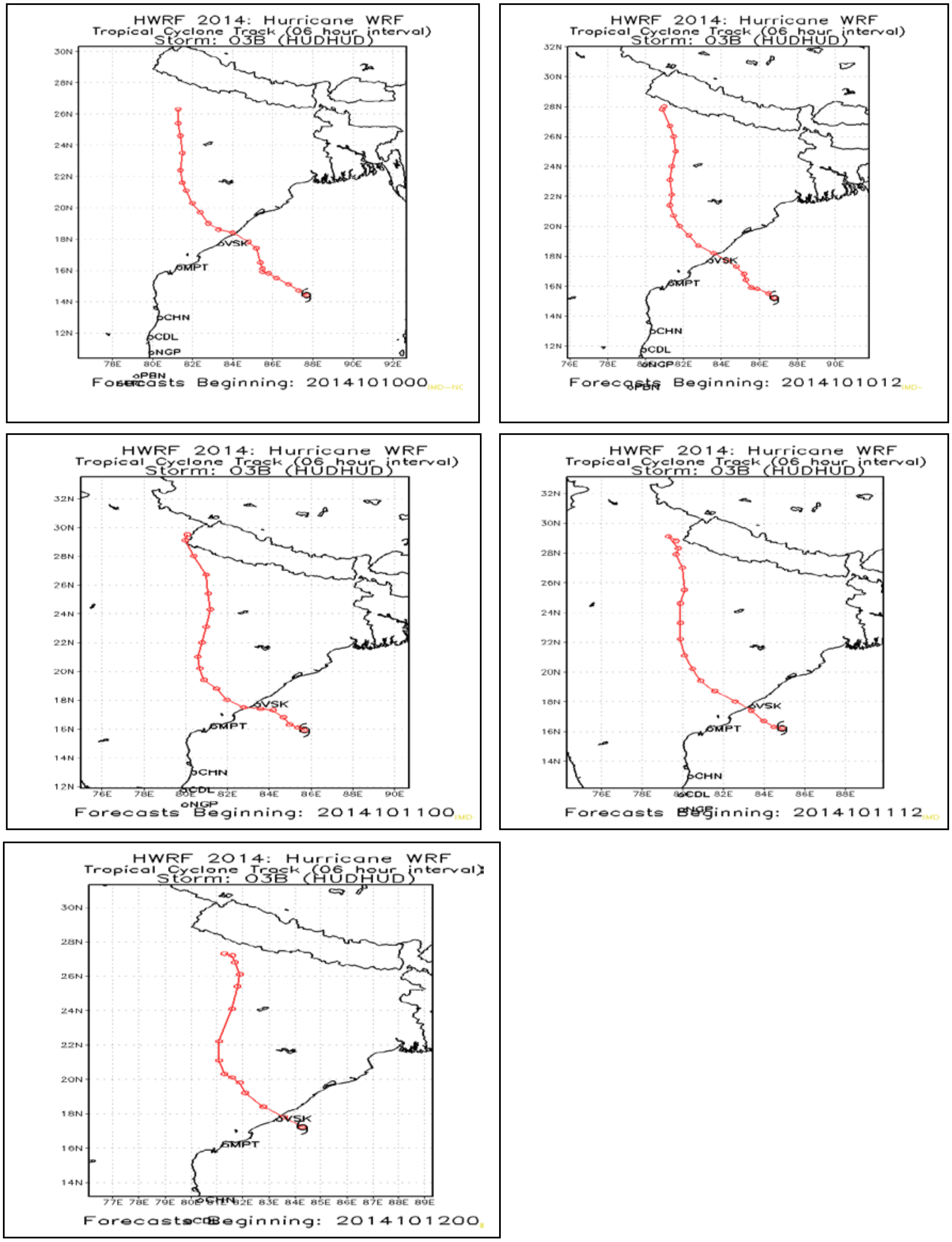
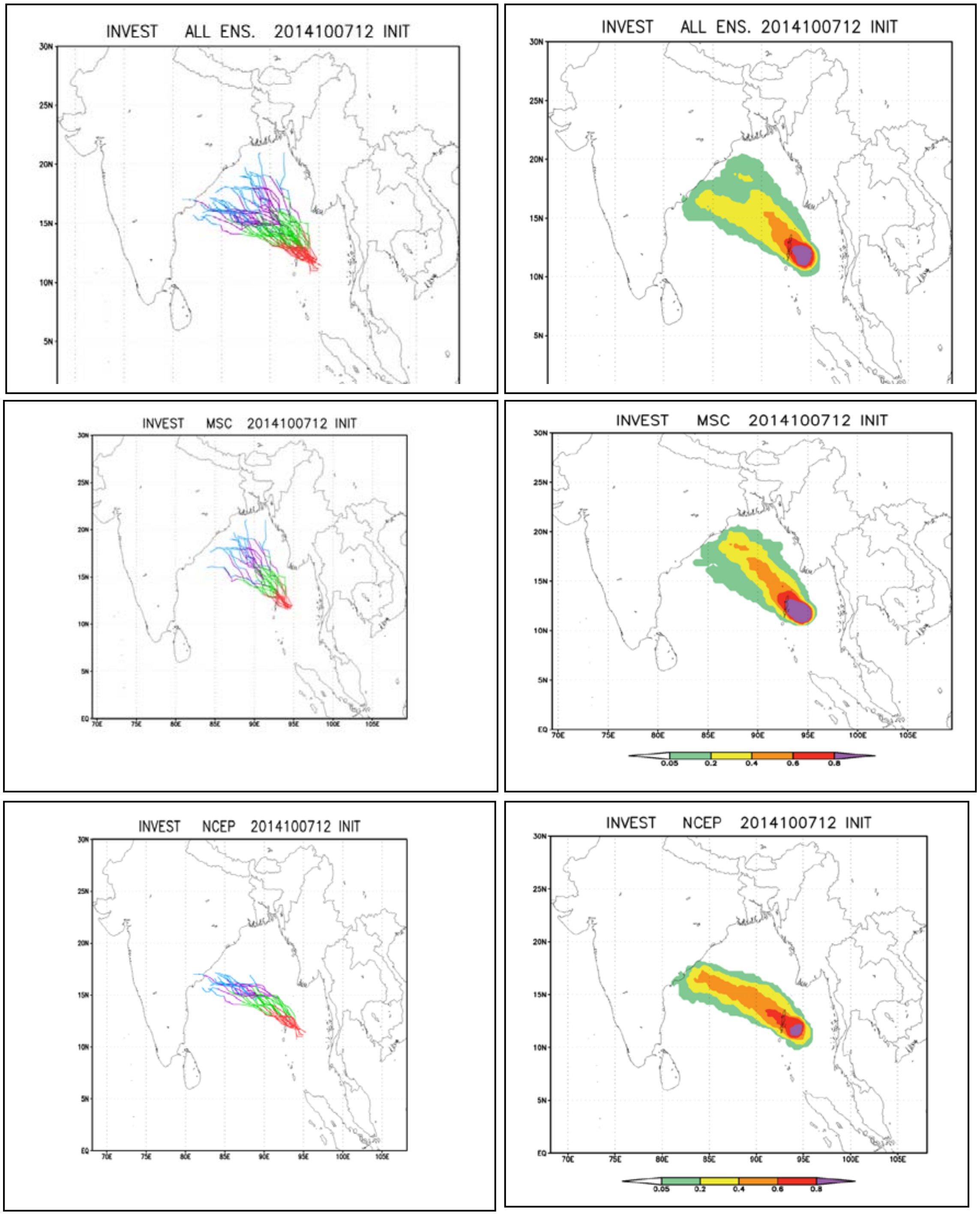


Fig.3.13(f). Track prediction by HWRF model for cyclone HUDHUD



3.14 (a). EPS based track and strike probability based on 1200 UTC 07.10.2014

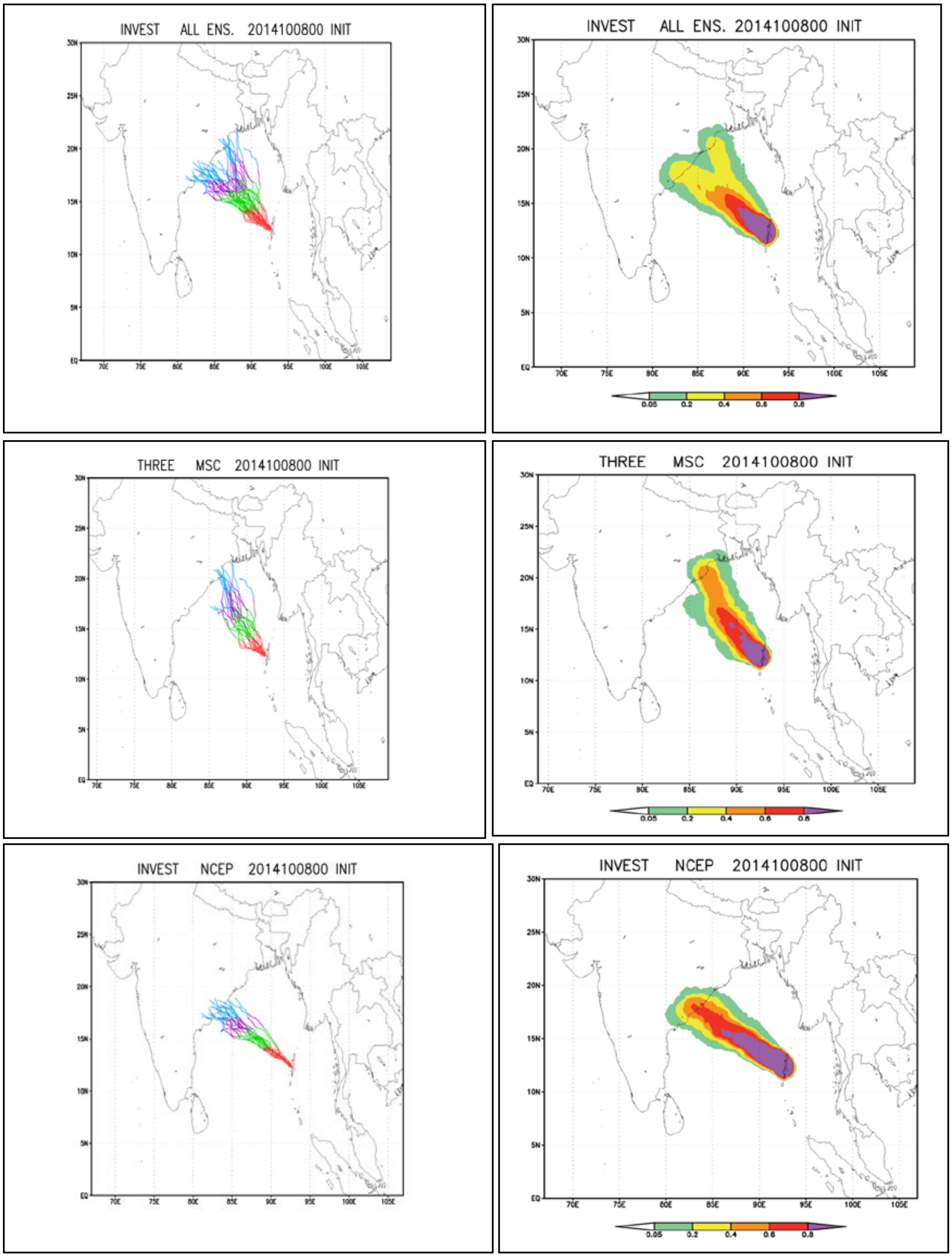


Fig.3.14 (a-d): EPS based forecast track & strike probability based on 07.10.2014 (1200 UTC), 08.10.2014 (0000 UTC), 08.10.2014 (1200 UTC), 09.10.2014 (0000 UTC) initial data (Contd.,)

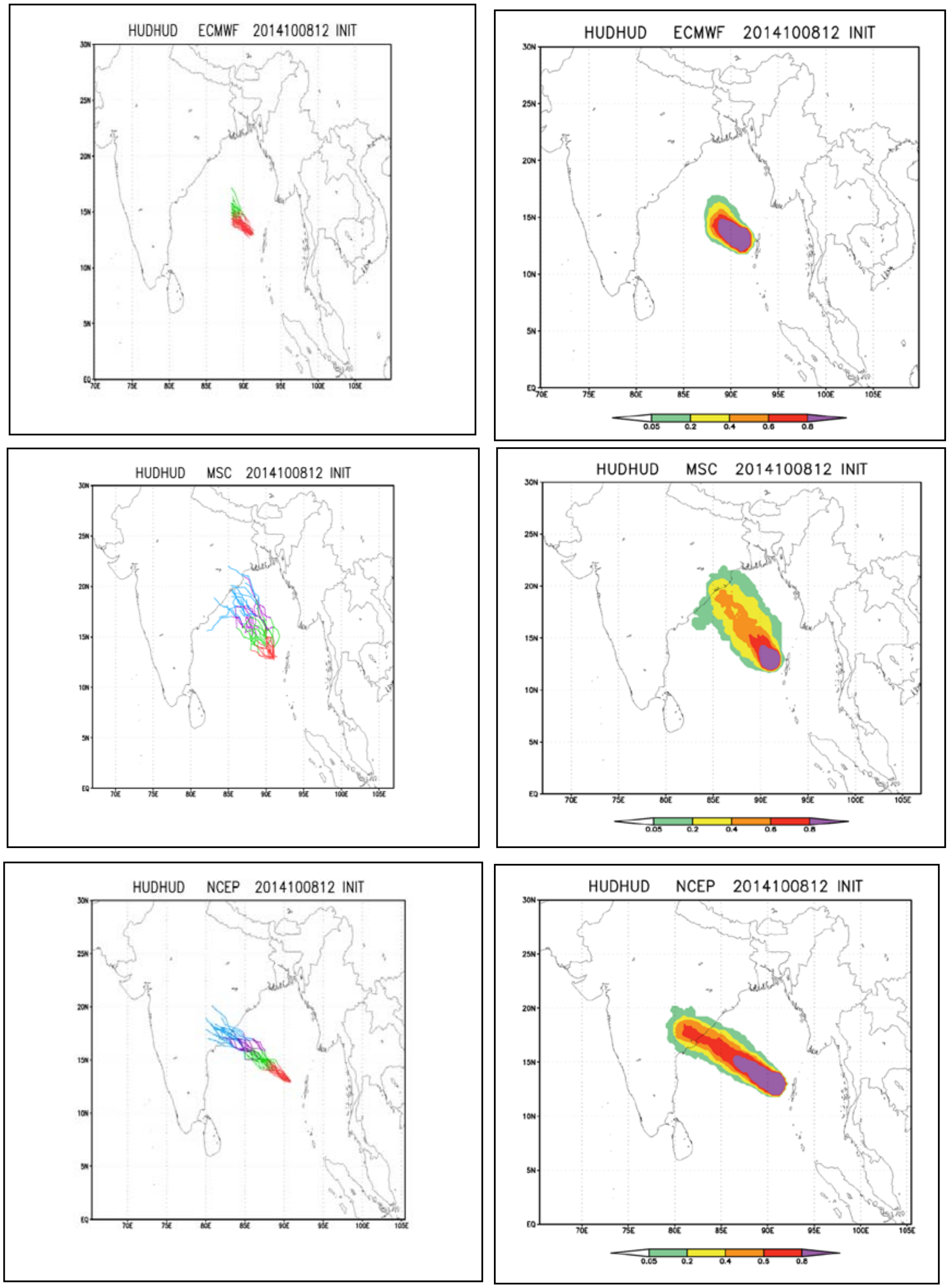


Fig.3.14 (a-d): EPS forecasts track & strike probability based on 07.10.2014 (1200 UTC), 08.10.2014 (0000 UTC), 08.10.2014 (1200 UTC), 09.10.2014 (0000 UTC) initial data (Contd.,)

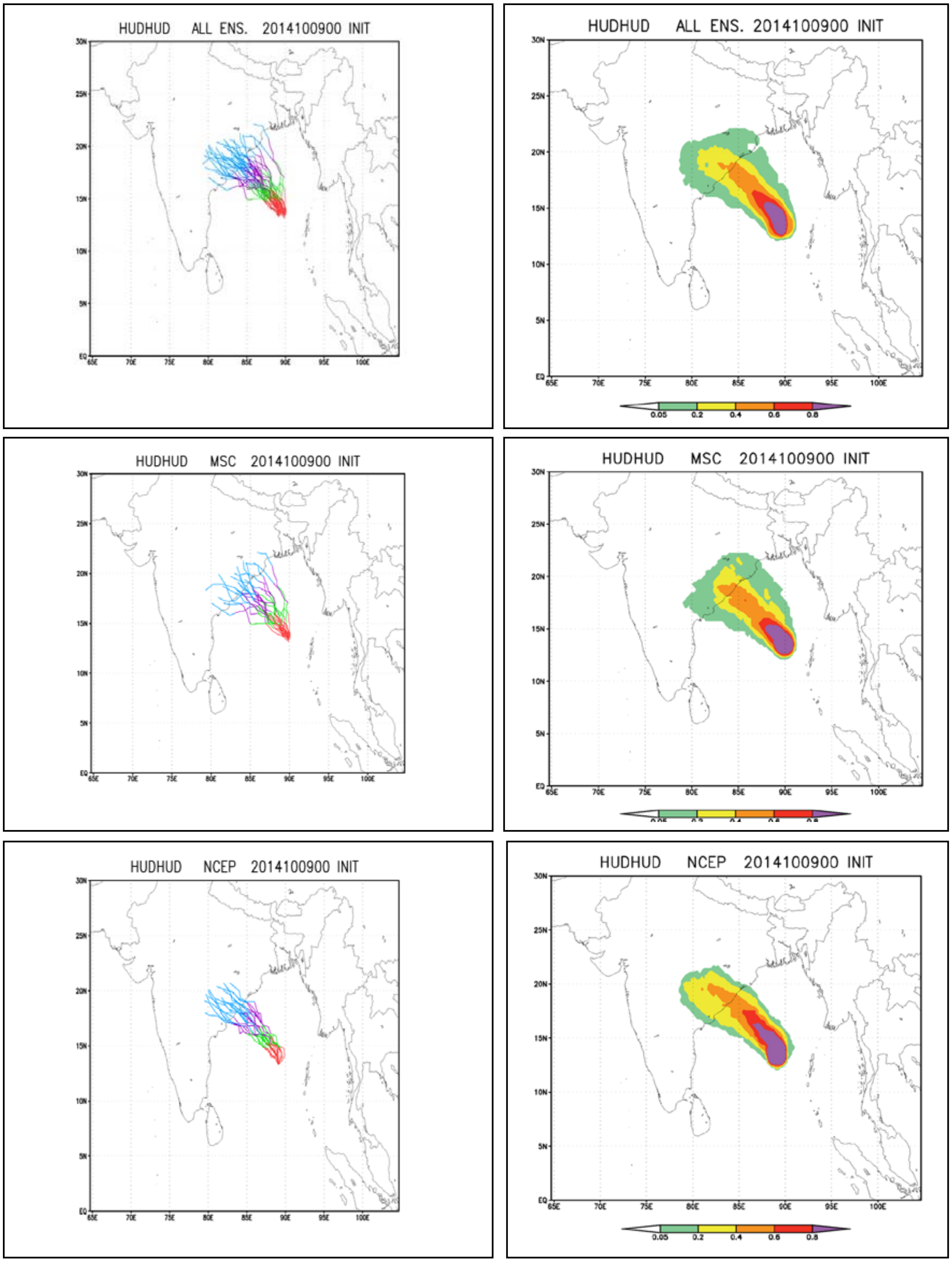


Fig.3.14 (a-d): EPS based forecasts track & strike probability based on 07.10.2014 (1200 UTC), 08.10.2014 (0000 UTC), 08.10.2014 (1200 UTC), 09.10.2014 (0000 UTC) initial data

3.3.3. Track prediction error for cyclone HUDHUD

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the MME forecast are presented in the Table 3.6, Table 3.7 and Table 3.8 respectively.

3.3.3.1 Direct position Error (DPE):

Average DPE was highest for IMD-GFS (about 47 km at 12 h to 302 km at 108 h) and IMD-WRF (about 46 km at 12 h to 222 km at 72 h). Average DPE for all other models are similar and ranged from about 40 km at 12 h to 172 km at 108 h). The DPE for MME was found more consistent and ranged from 40 km at 12 h to 49 km at 120 h with maximum 123 km at 96h (Table-3.6). HWRF model forecast errors are computed for available data based on 00 UTC of 10 October 2014 to 00 UTC of 12 October 2014 only (later half of the life period of the cyclone). The DPE of all models are shown in Fig. 3.15.

Table-3.6. Average track forecast errors (DPE) in km of NWP models for cyclone HUDHUD (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)

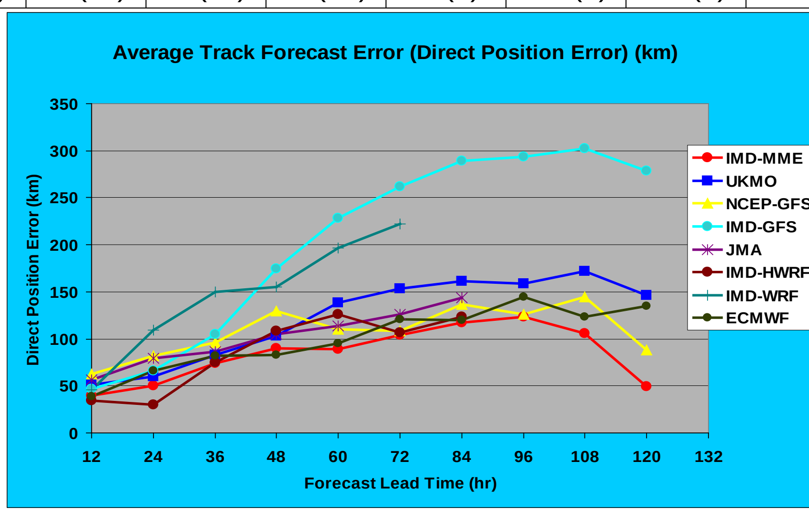


Fig. 3.15: Average track forecast errors (DPE) of NWP models

3.3.3.2 Cross Track Error (CTE): Average cross track error (CTE) was highest for IMD-GFS (about 33 km at 12 h to 187 km at 72 h). Average CTE for all other models are similar and ranged from about 40 km at 12 h to 123 km at 108 h). The CTE for MME ranged from 34 km at 12 h to 35 km at 120 h with maximum 106 km at 96h (Table-3.7). The CTE of all models are shown in Fig. 3.16.

Table-3.7. Average cross track error (CTE) in km of NWP models for cyclone HUDHUD

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	33	48	52	96	139	167	219	239	287	267
IMD-WRF	26	54	67	48	47	69	-	-	-	-
JMA	42	55	56	57	42	53	77	-	-	-
NCEP-GFS	46	51	55	103	86	96	99	91	123	37
UKMO	36	47	55	61	82	95	94	73	68	41
ECMWF	34	50	59	68	68	93	91	116	73	53
IMD-HWRF	23	23	50	88	101	44	34	-	-	-
IMD-MME	34	40	53	75	74	86	94	106	98	35

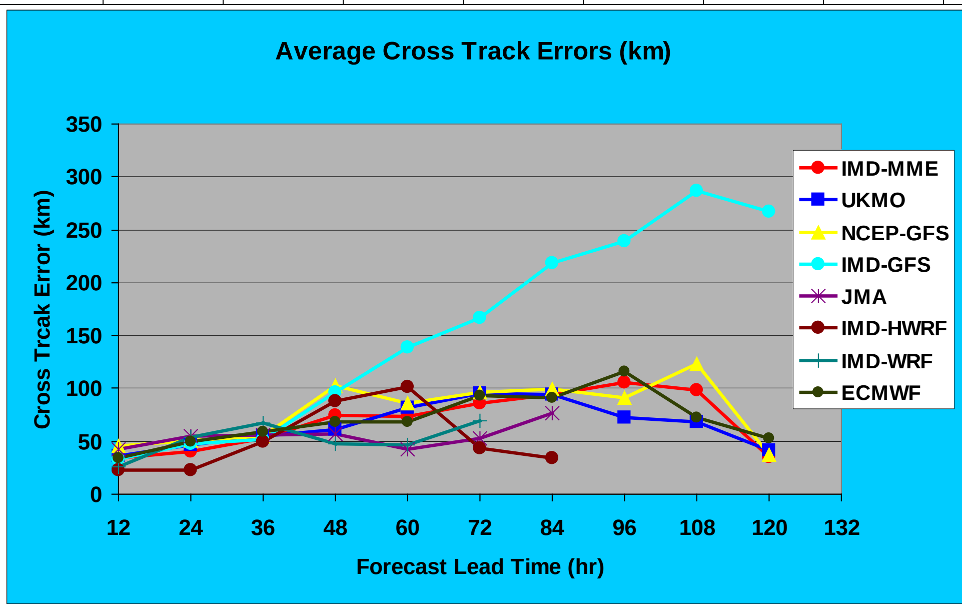


Fig. 3.16: Average cross track errors (CTE) of NWP models

Along Track Error (ATE): Average along track error (ATE) was highest for IMD-WRF (about 34 km at 12 h to 195 km at 72 h). There is wide variation of average CTE for all other models. The ATE for MME was found more consistent and ranged from 16 km at 12 h to 29 km at 120 h with maximum 57 km at 84h (Table-3.8). The ATE of all models is shown in Fig. 3.17.

Table-3.8: Average along track error (ATE) in km of NWP models for cyclone HUDHUD

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	26	37	81	129	158	168	150	142	79	77
IMD-WRF	34	85	122	140	188	195	-	-	-	-
JMA	31	44	56	71	98	97	110	-	-	-
NCEP-GFS	33	53	71	64	50	40	84	67	56	66
UKMO	28	30	50	72	96	100	109	107	137	139
ECMWF	15	39	43	40	54	66	69	64	81	121
IMD-HWRF	19	15	54	60	67	96	118	-	-	-
IMD-MME	16	25	42	43	42	44	57	40	25	29

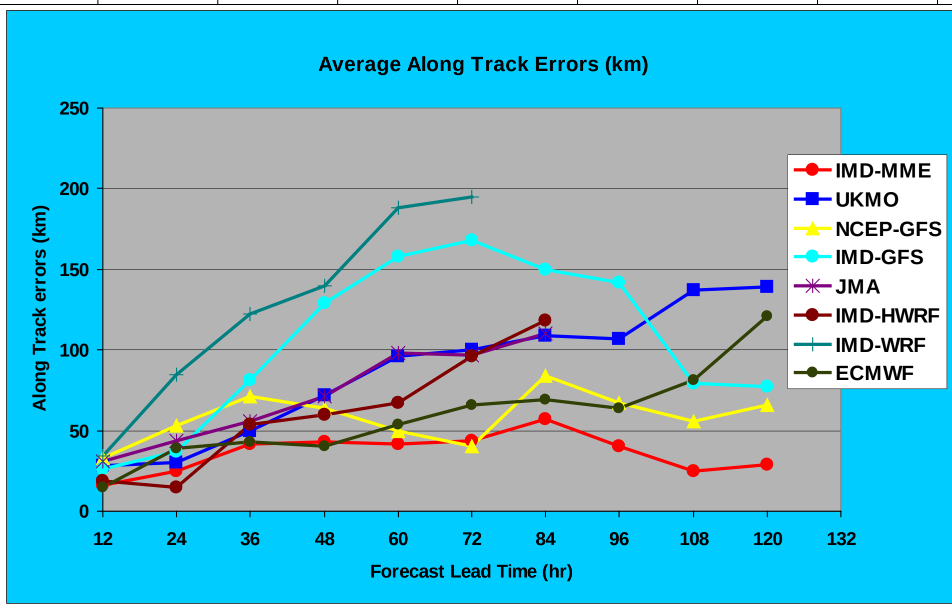


Fig. 3.17: Average along track errors (ATE) of NWP models for cyclone HUDHUD

3.3.4. Landfall Point Error: Landfall point forecasts errors of MME at Andaman Island and at Visakhapatnam at different forecast lead times is presented in Table-3.9 and Table-3.10 respectively. Landfall point forecasts errors of NWP model at Visakhapatnam at different forecast lead times (Fig. 3.18) show that some model predicted north of actual landfall point and some predicted south of actual landfall point with a maximum limit upto about 336 km towards north and up to 123 km towards south. Under this wide extent of landfall point forecasts, MME could predict near actual landfall point (Visakhapatnam) consistently.

Table-3.9. Landfall Point and Landfall time error for cyclone HUDHUD (at Andaman Island) of MME forecasts

Forecast based on	Forecast Lead Time (hr)	Landfall Point Error (km)	Landfall Time Error
06 UTC/06.10.2014	51	45	1 hr Early
00 UTC/07.10.2014	27	45	3 hrs Early
12 UTC/07.10.2014	15	45	3 hrs Early

Table-3.10. Landfall point forecast errors (km) of NWP Models for east coast of India at different lead time (hour) for cyclone HUDHUD ('+' 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

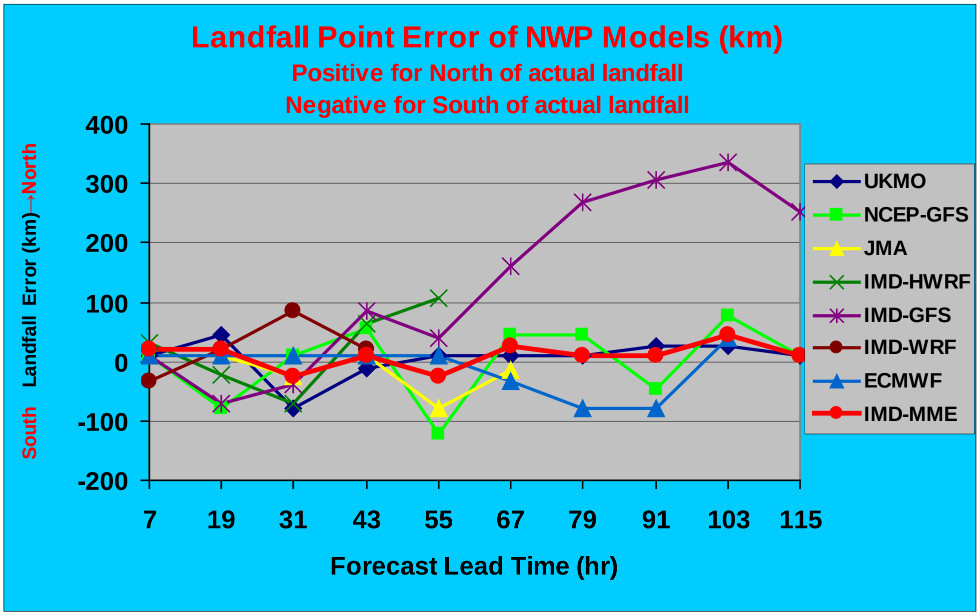


Fig. 3.18: Landfall point error (hr) of NWP Models for cyclone HUDHUD on east coast of India.

3.3.5 Landfall Time Error: Landfall time forecasts errors of NWP model at different forecast lead times (Fig. 3.19, Table 3.9, 3.10) show that some model predicted earlier than actual landfall time and some predicted delayed than actual landfall time with a maximum limit upto 17 hr delayed and up to 10 hr earlier than actual landfall time. Under this wide extent of landfall time forecasts, MME landfall time error was consistently low (Table-3.11). Average land fall time error (Fig. 3.19) shows that MME landfall time forecast error is least (1.9 hr) compared to other models.

Table-3.11. Landfall time forecast errors (hour) at different lead time (hr) for cyclone HUDHUD ('+' 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	0	-4	-4	-4	-4	2

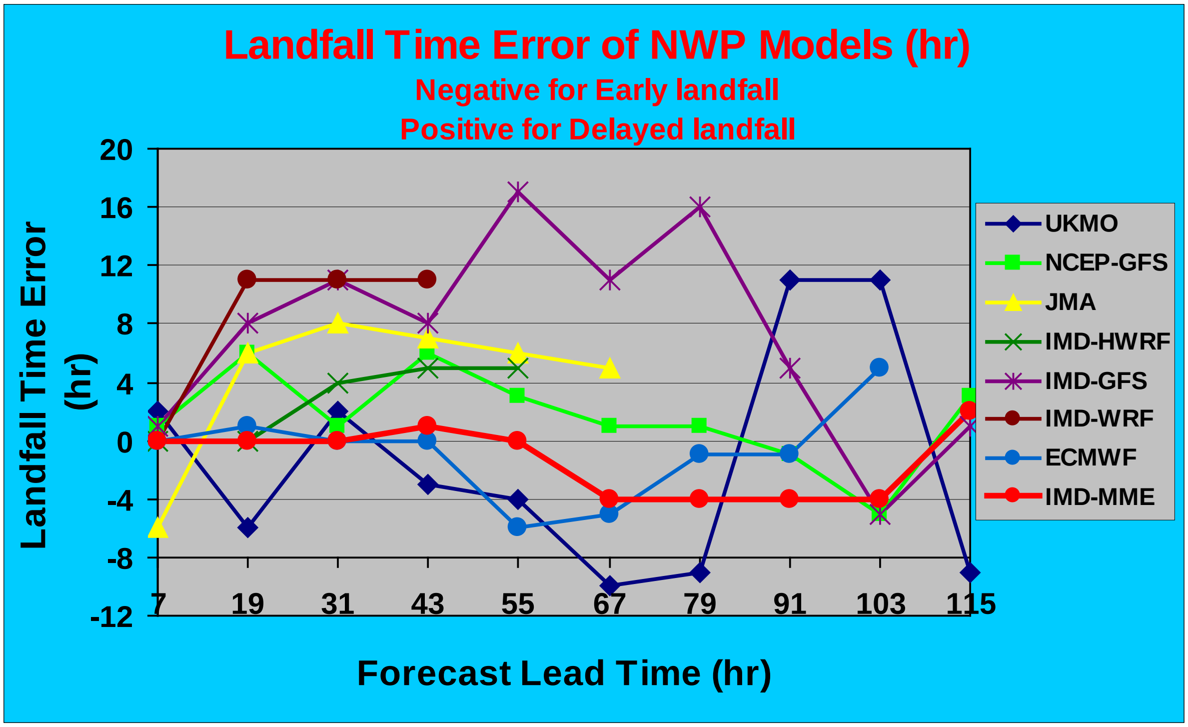


Fig.3.19: Landfall time error (km) of models at different lead time (hr) for cyclone HUDHUD

3.3.6 Intensity prediction for cyclone HUDHUD by SCIP & HWRF models

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig. 3.20 and Fig. 3.21 respectively. Fig. 3.20 shows that the SCIP model could able to predict the intensity of the very severe cyclonic storm HUDHUD with a great accuracy at all stages of forecast. HWRF forecast based on 00 UTC of 10 October 2014 to 00 UTC of 12 October 2014 shows HWRF model could able to predict the intensity of the very severe cyclonic storm HUDHUD.

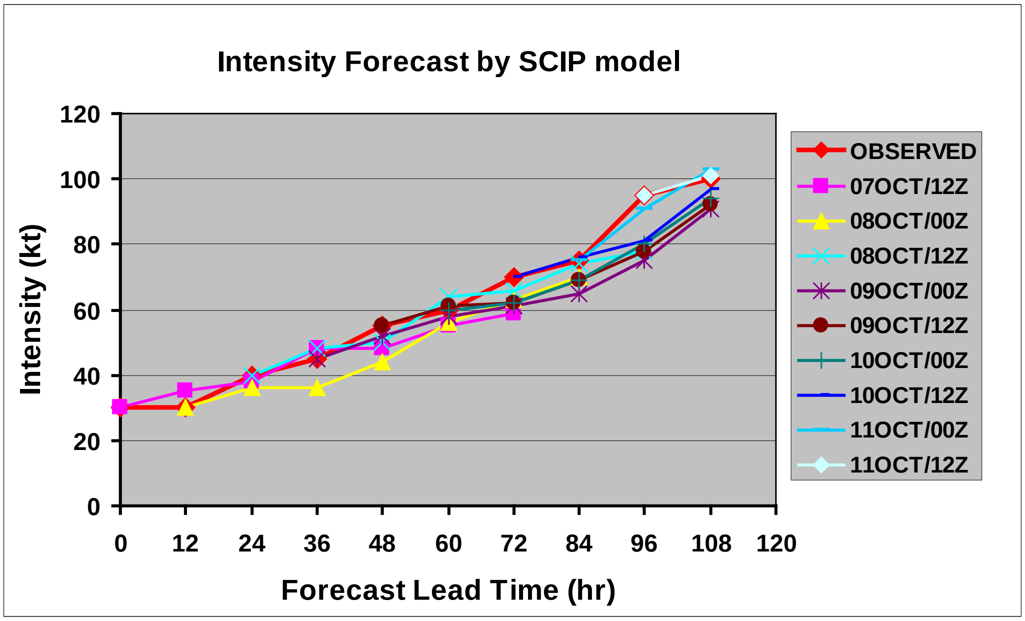


Fig. 3.20. Intensity forecasts of SCIP model for cyclone HUDHUD

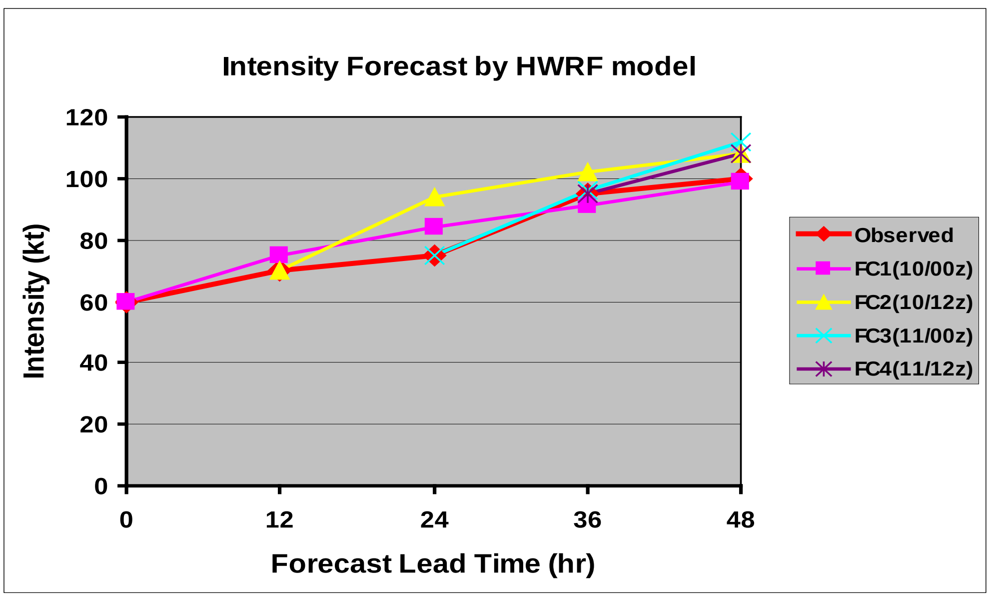


Fig.3.21: Intensity forecasts of HWRF model for cyclone HUDHUD

Average absolute error (AEE) and Root mean square error (RMSE) of SCIP and HWRF intensity forecast error is presented in the following Table-3.12 and Table-3.13.

Table-3.12 Average absolute errors of SCIP and HWRF model for cyclone HUDHUD (Intensity forecasts prior to landfall (0700 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)	-	-

(Number of forecasts verified is given in the parentheses)

Table-3.13 Root Mean Square (RMSE) errors of SCIP and HWRF model for cyclone HUDHUD

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)	-	-

(Number of forecasts verified is given in the parentheses)

3.3.7 Landfall intensity prediction by models

Landfall intensity predicted by SCIP model in 3 days before landfall (from 0000 UTC of 09 October 2014) shows that the model could predict the landfall intensity (Fig. 3.22) as well as increase in intensity (kt) during high intensification phase (00 UTC of 11.10.2014 to 00 UTC of 12.10.2014) of very severe cyclonic storm with a great success.

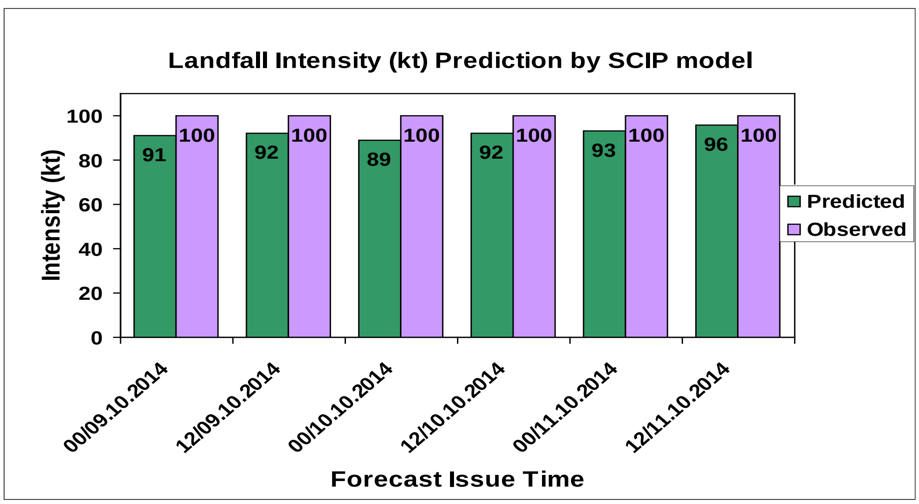


Fig. 3.22: Landfall Intensity (kt) prediction by SCIP Model for cyclone HUDHUD

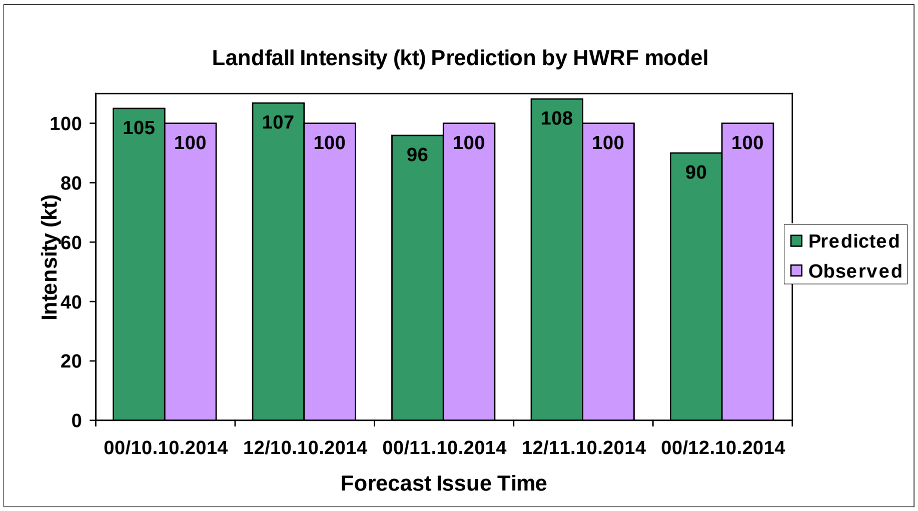


Fig. 3.23: Landfall Intensity (kt) prediction by HWRF Model for cyclone HUDHUD

Landfall intensity predicted by **HWRF** model in 2 days before landfall (from 0000 UTC of 10 October 2014) shows that the model could predict the landfall intensity (Fig. 3.23) of the very severe cyclonic storm with a great success.

3.3.8. Probability of Rapid intensification (by RI-Index)

RI-Index predicted high probability of Rapid Intensification during the period 00 UTC of 11.10.2014 to 00 UTC of 12.10.2014 though there was to change of 25 knots in 24 hrs (Table. 3.14)

Table-3.14 Probability of Rapid intensification for cyclone HUDHUD

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h
00 UTC/07.10.2014	09.4 %	VERY LOW	5
00 UTC/08.10.2014	9.4 %	VERY LOW	15
00 UTC/09.10.2014	32.0 %	MODERATE	15
00 UTC/10.10.2014	32.0 %	MODERATE	15
00 UTC/11.10.2014	72.2 %	HIGH	25

3.3.9. Decay after landfall

Decay (after landfall) prediction curve (6-hourly up to 24 hr) (Fig. 3.24)) shows good agreement to observed decay except at 12h. However in 12 hr forecast the error was about 10 knots with under prediction by the model.

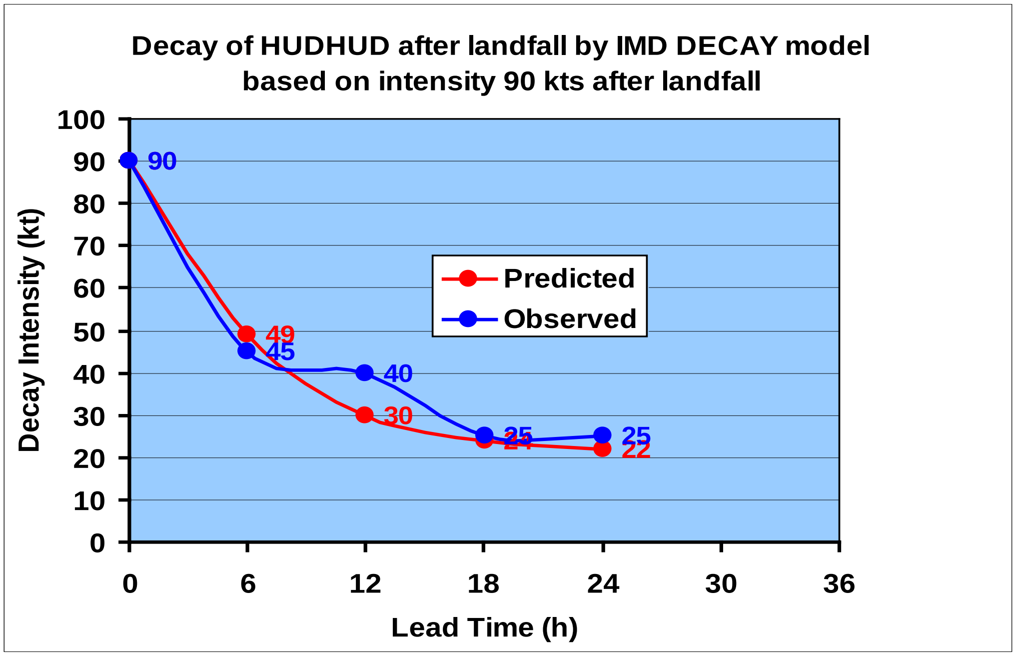


Fig. 3.24. Decay after landfall of cyclone HUDHUD

Ensemble track and strike probability forecast based on 12 UTC 07.10.2014 to 00 UTC 09.10.2014 shows that MSC predicted towards south Odisha coast, NCEP predicted towards north Andhra Pradesh coast and all ensemble shows wide variation over north Andhra Pradesh coast to Odisha coast.

3.4. Cyclonic storm NILOFAR over the Arabian Sea during (25-31) October 2014

3.4.1. Genesis forecast for cyclone NILOFAR by GPP

Fig. 1(a-f) below shows the predicted zone of formation of cyclogenesis.

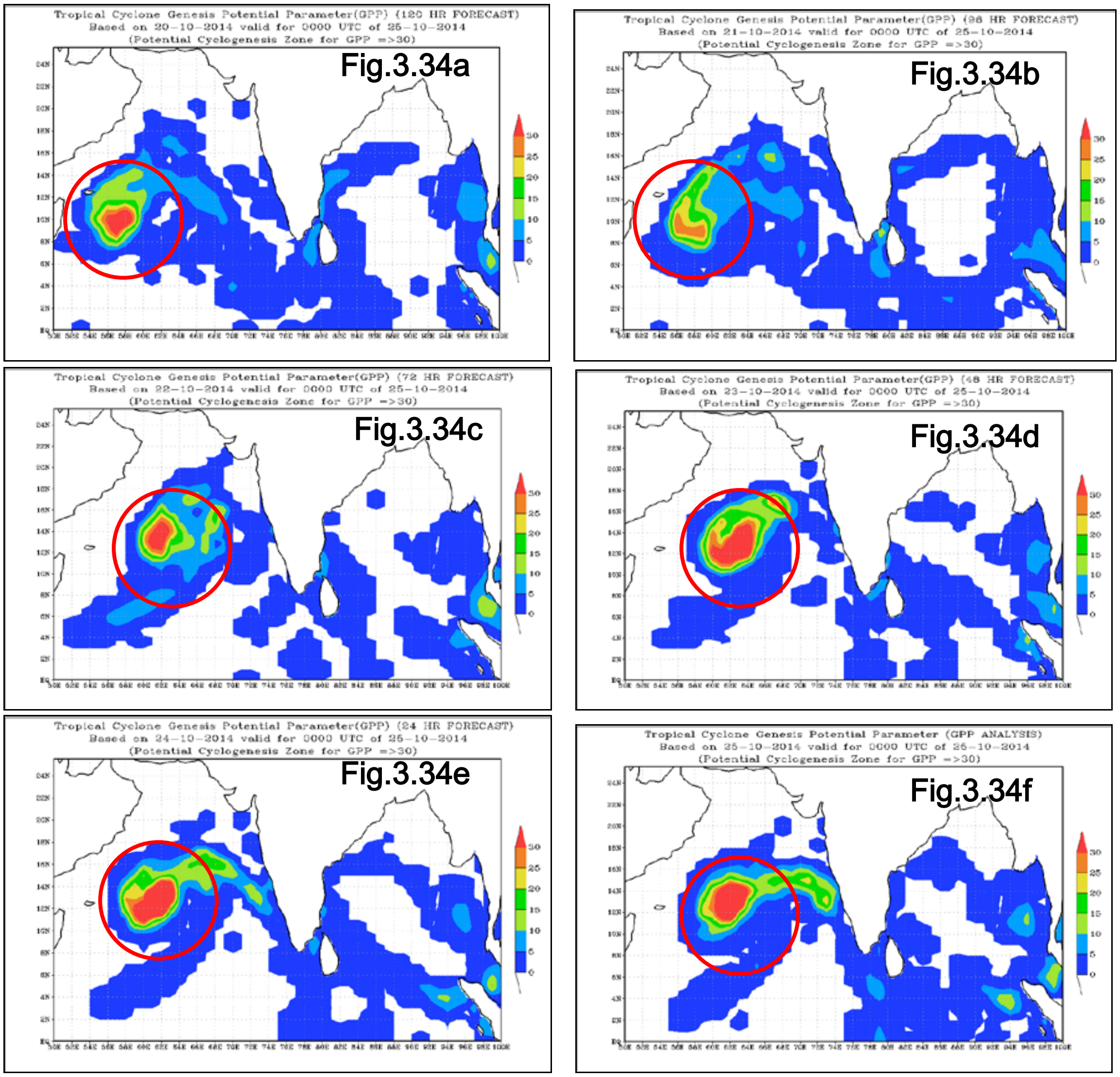


Figure 3.25(a-f): Predicted zone of cyclogenesis for cyclone NILOFAR.

Conditions for: (i) Developed system: Threshold value of GPP ≥ 8.0

(ii) Non-developed system: Threshold value of GPP < 8.0

The Area average analysis and forecast of GPP for cyclone NILOFAR. Fig.3.26 shows that GPP ≥ 8.0 (threshold value for intensification into cyclone T.3.0) at early stages of development (T.No. 1.0 to 1.5).

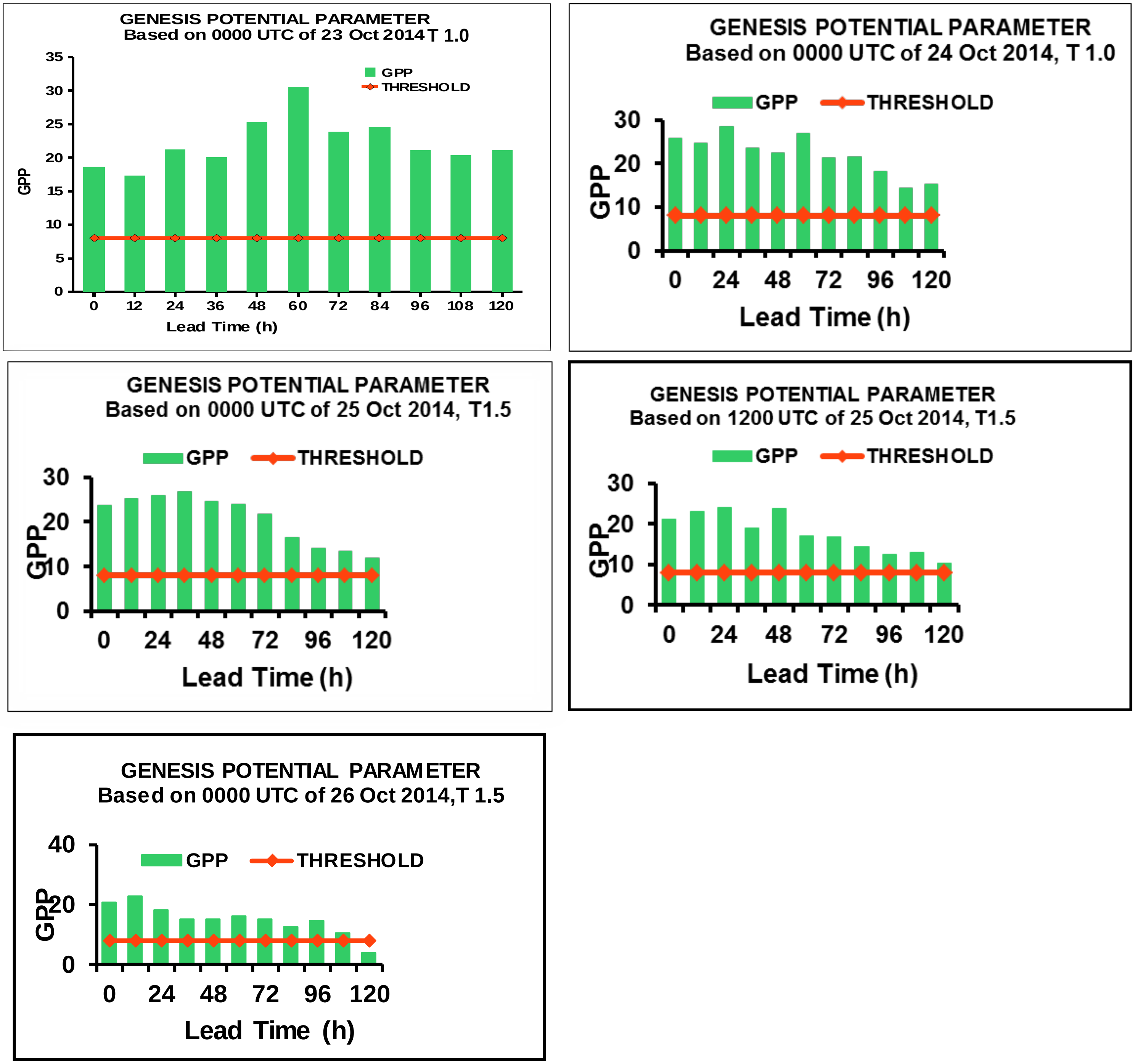
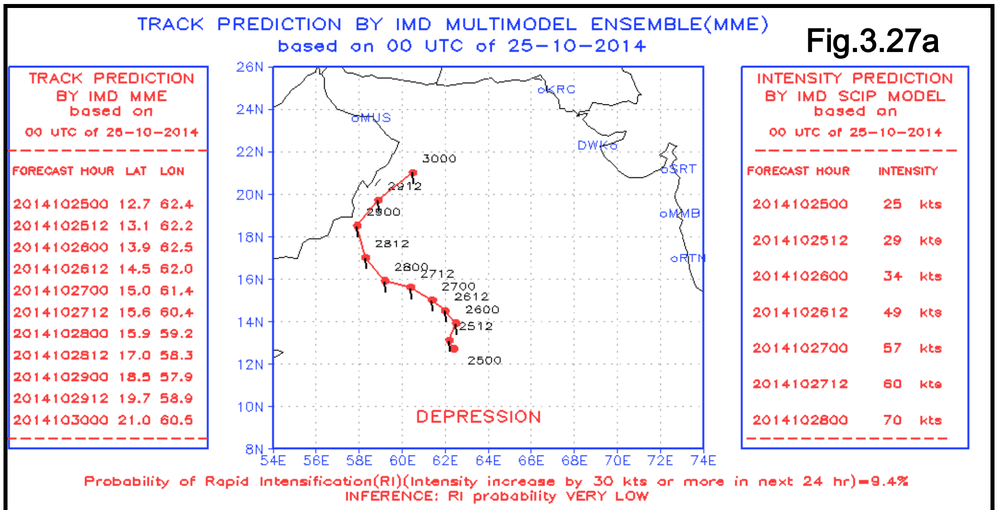
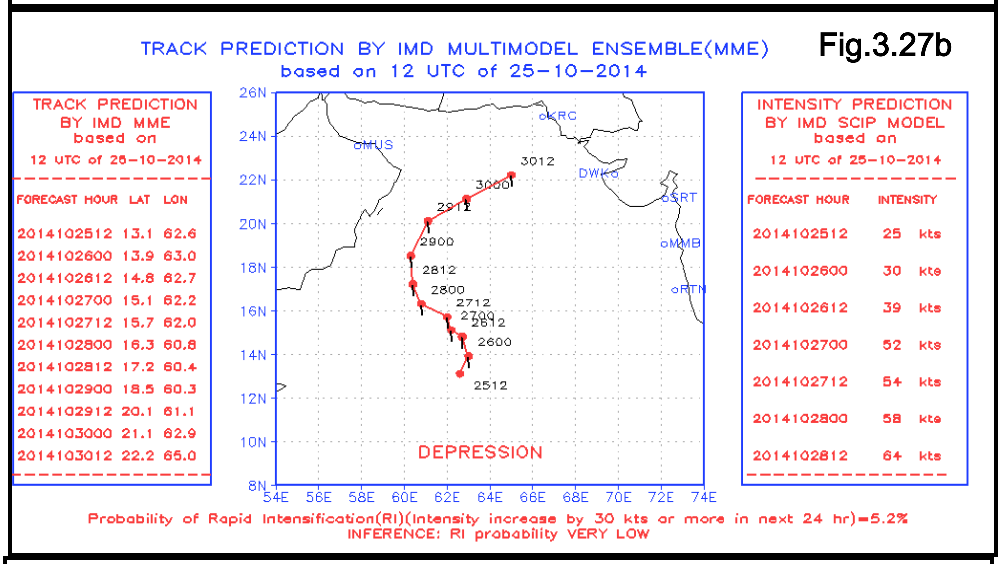


Fig.3.26 Area average analysis of GPP

3.4.2. Track prediction by individual MME, NWP models and EPS for Cyclone NILOFAR

The track forecast by MME individual NWP models and EPE are shown in Fig.3.27, 3.28 and 3.29 respectively





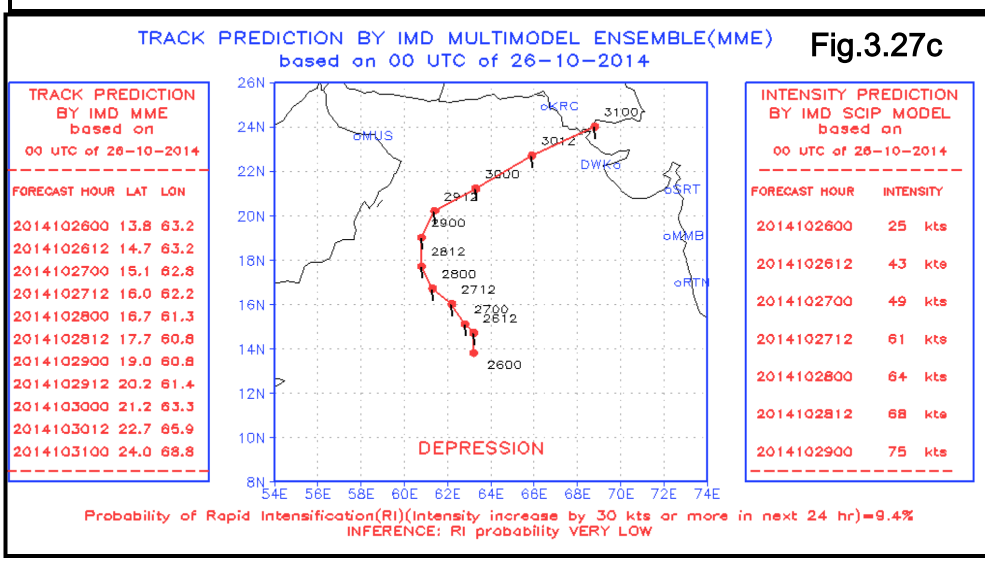
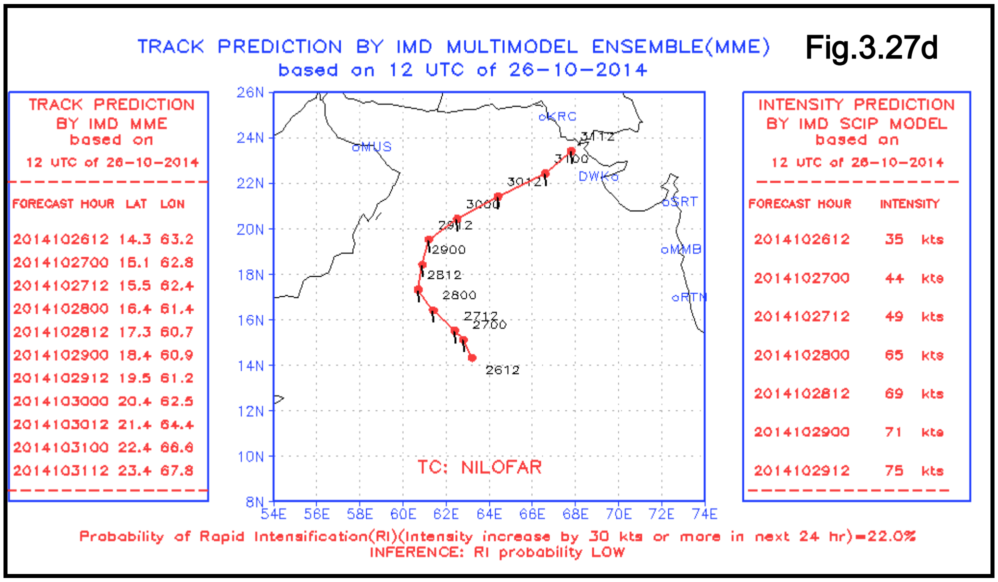
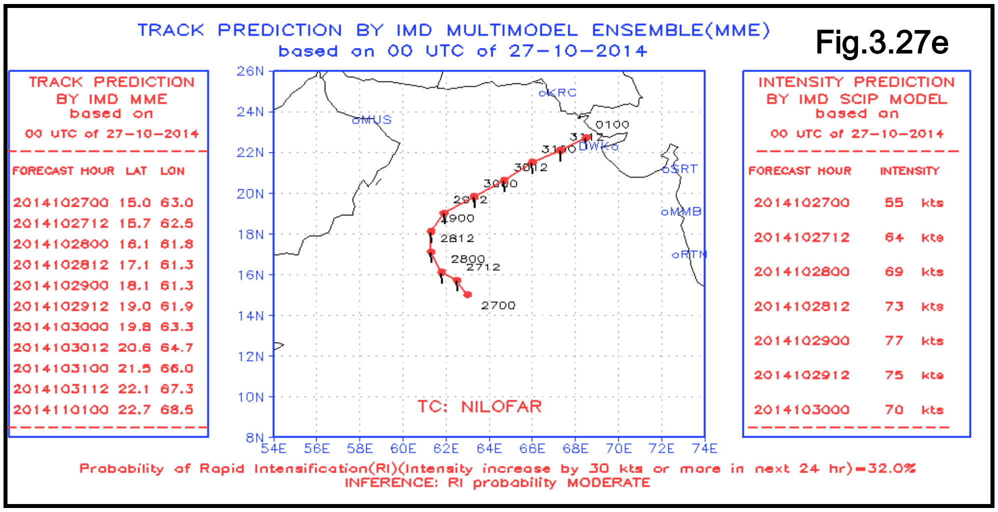


Fig. 3.36(a-k) (contd): Track prediction by MME and Intensity forecast by SCIP model for cyclone NILOFAR





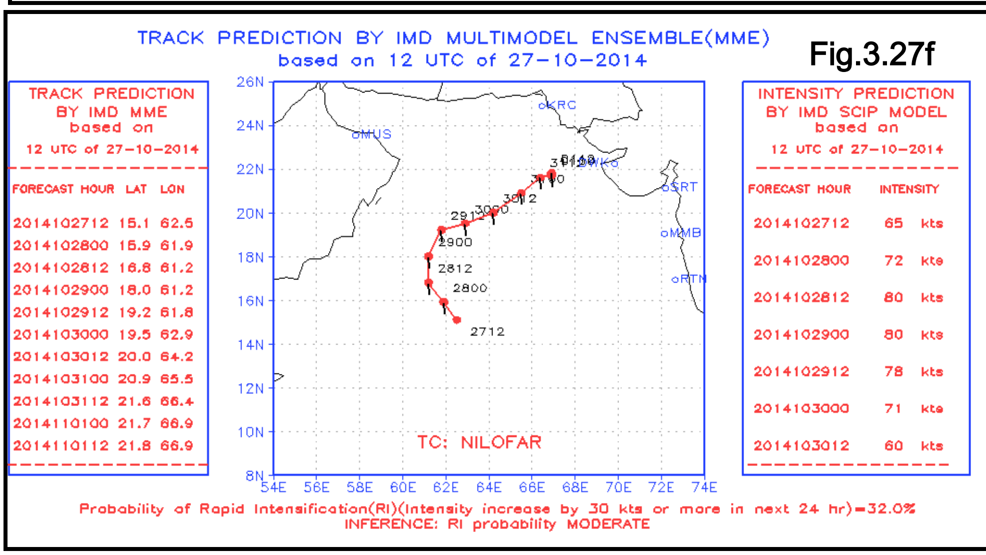
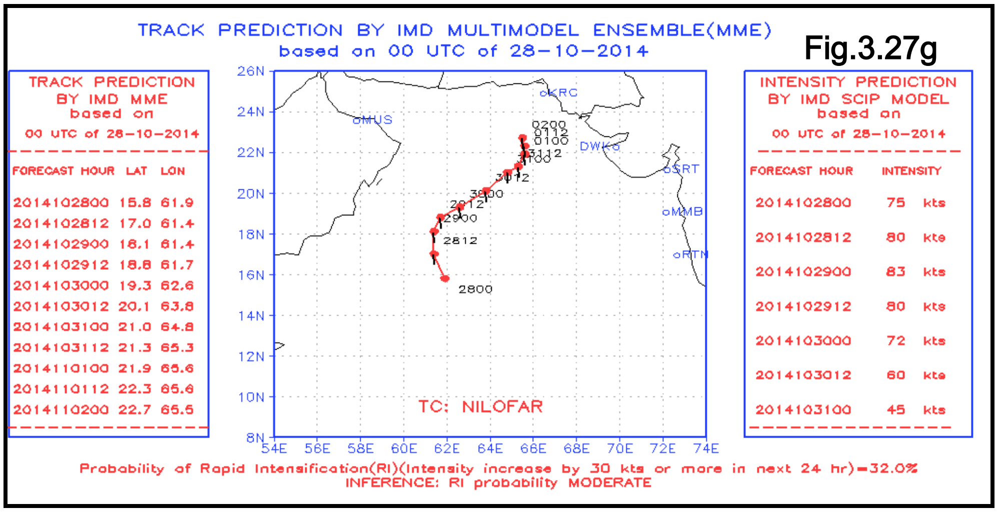
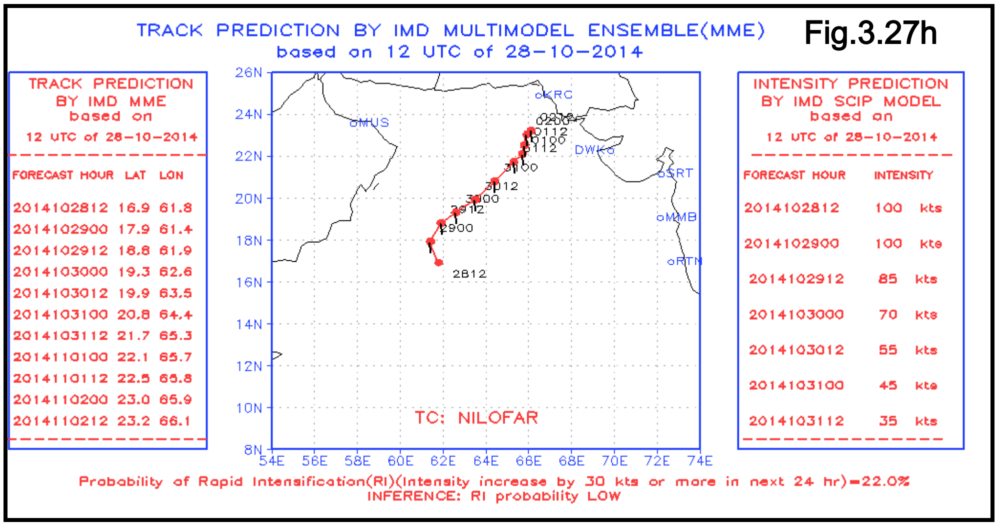


Fig. 3.36(a-k) (contd): Track prediction by MME and Intensity forecast by SCIP model for cyclone NILOFAR





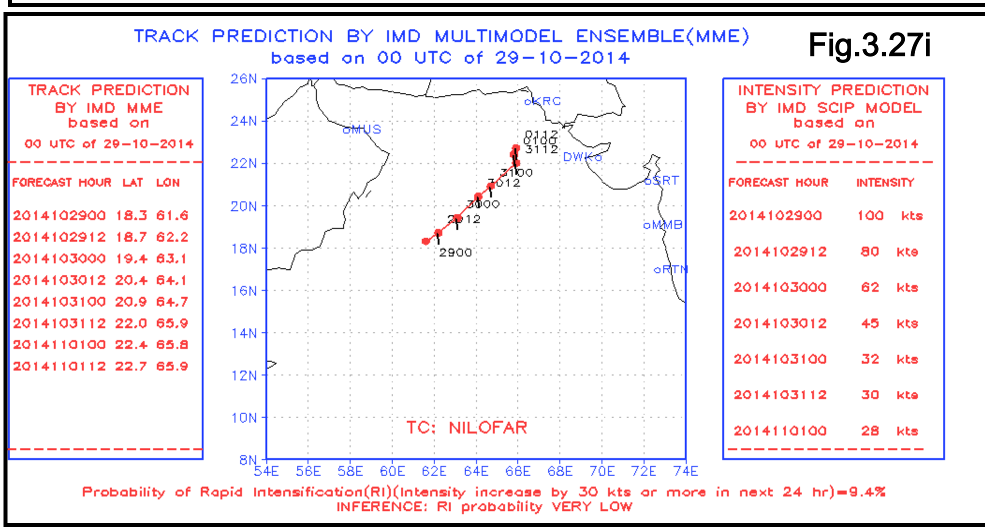
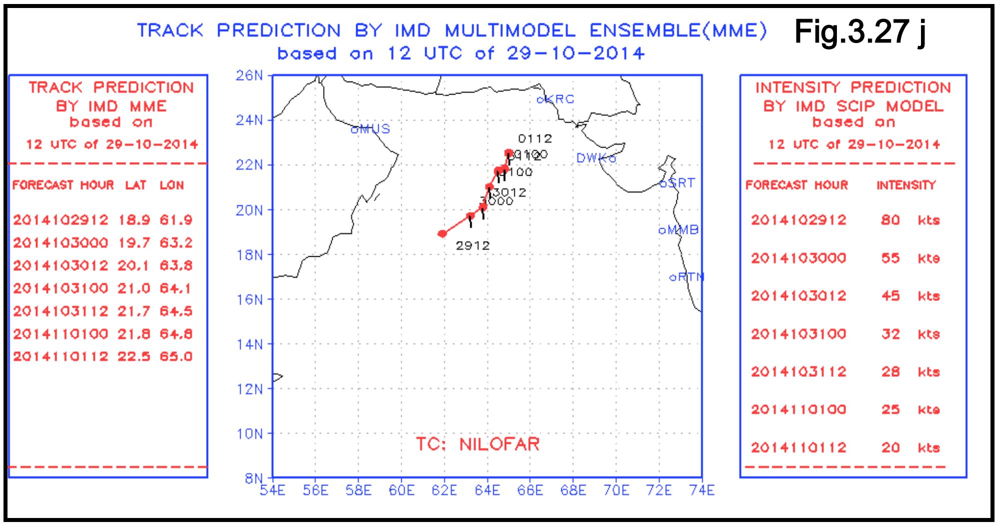


Fig. 3.36(a-k)(contd): Track prediction by MME and Intensity forecast by SCIP model for cyclone NILOFAR



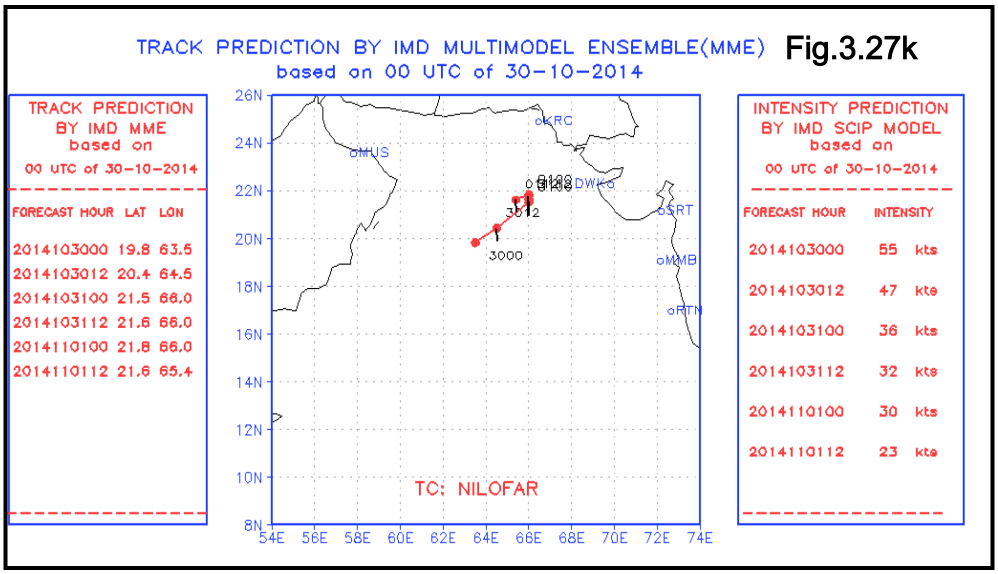


Fig. 3.36(a-k): Track prediction by MME and Intensity forecast by SCIP model for cyclone NILOFAR

Track prediction by NWP models for cyclone NILOFAR are shown in Fig.3.28

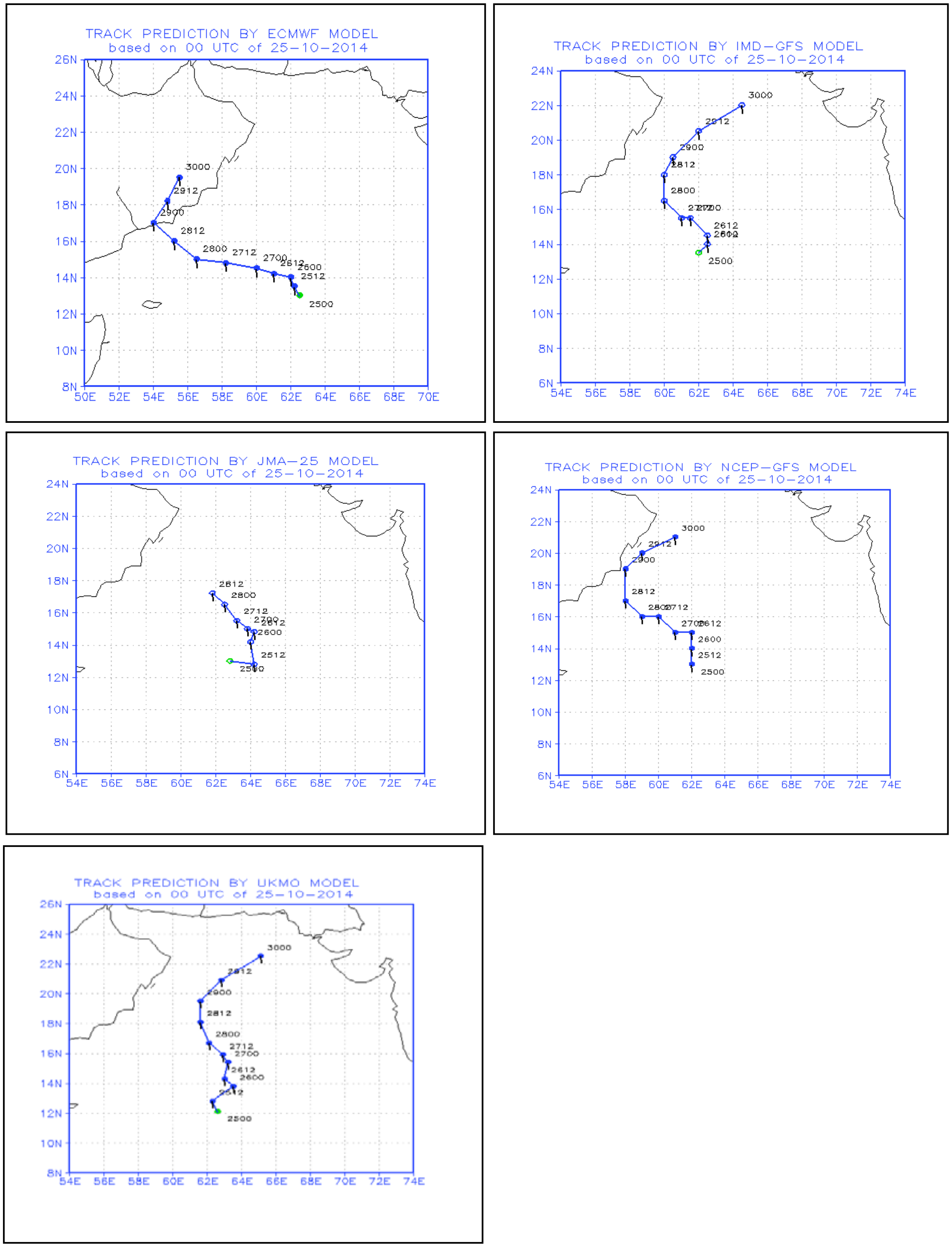


Fig.3.28 a. Track forecast for cyclone NILOFAR based on 00 UTC of 25.10.2014

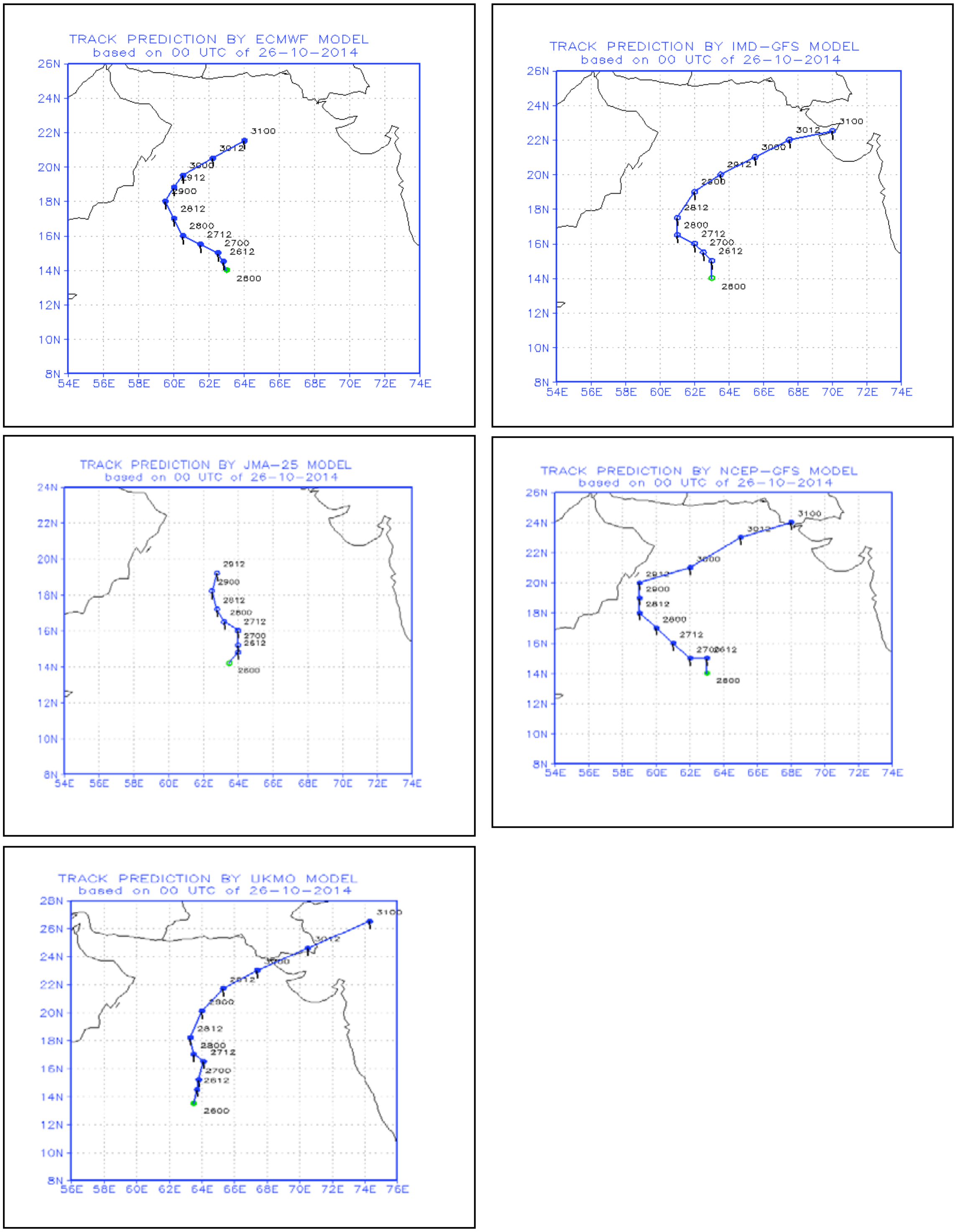


Fig.3.28 b. Track forecast for cyclone NILOFAR based on 00 UTC of 26.10.2014

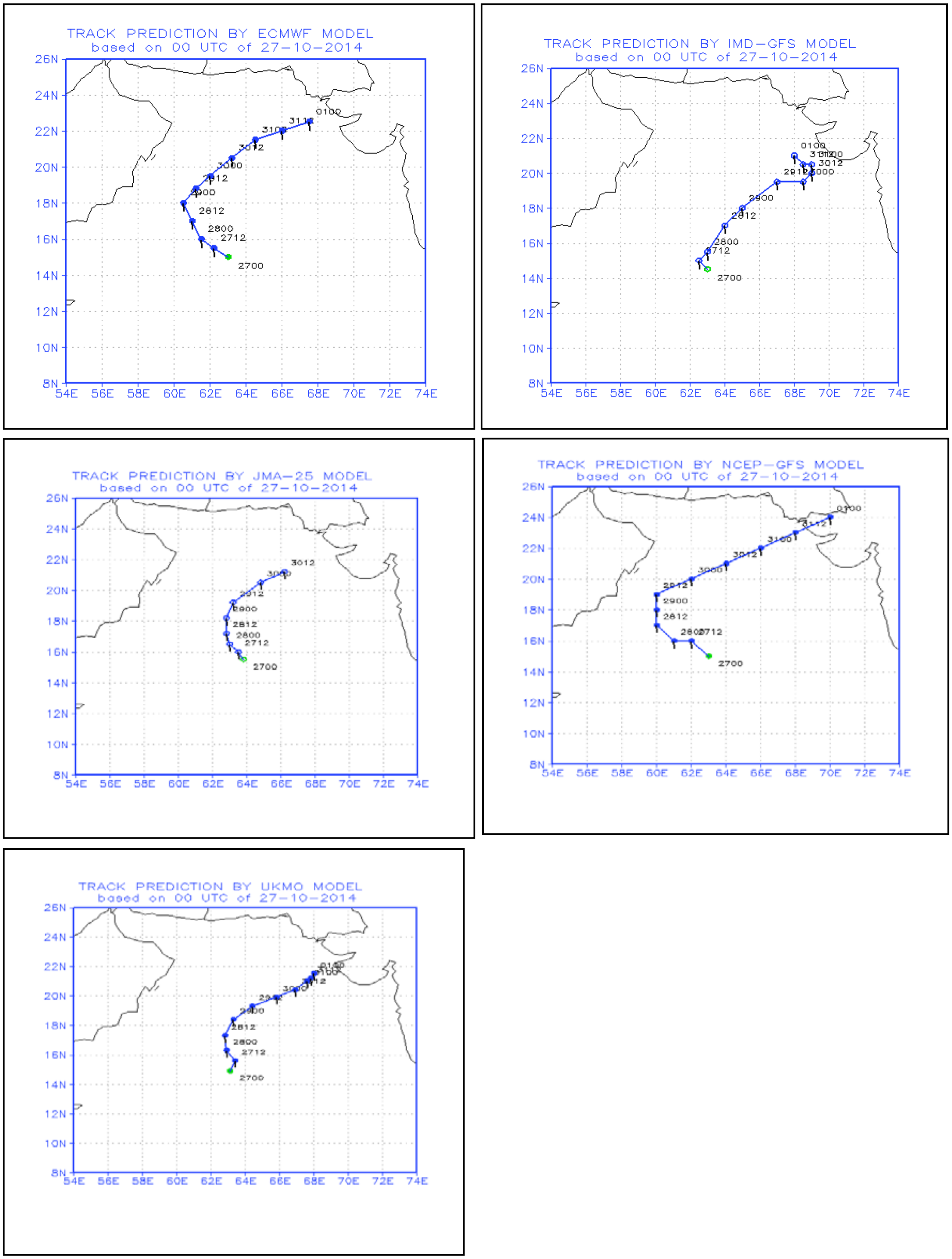


Fig.3.28 c. Track forecast for cyclone NILOFAR based on 00 UTC of 27.10.2014

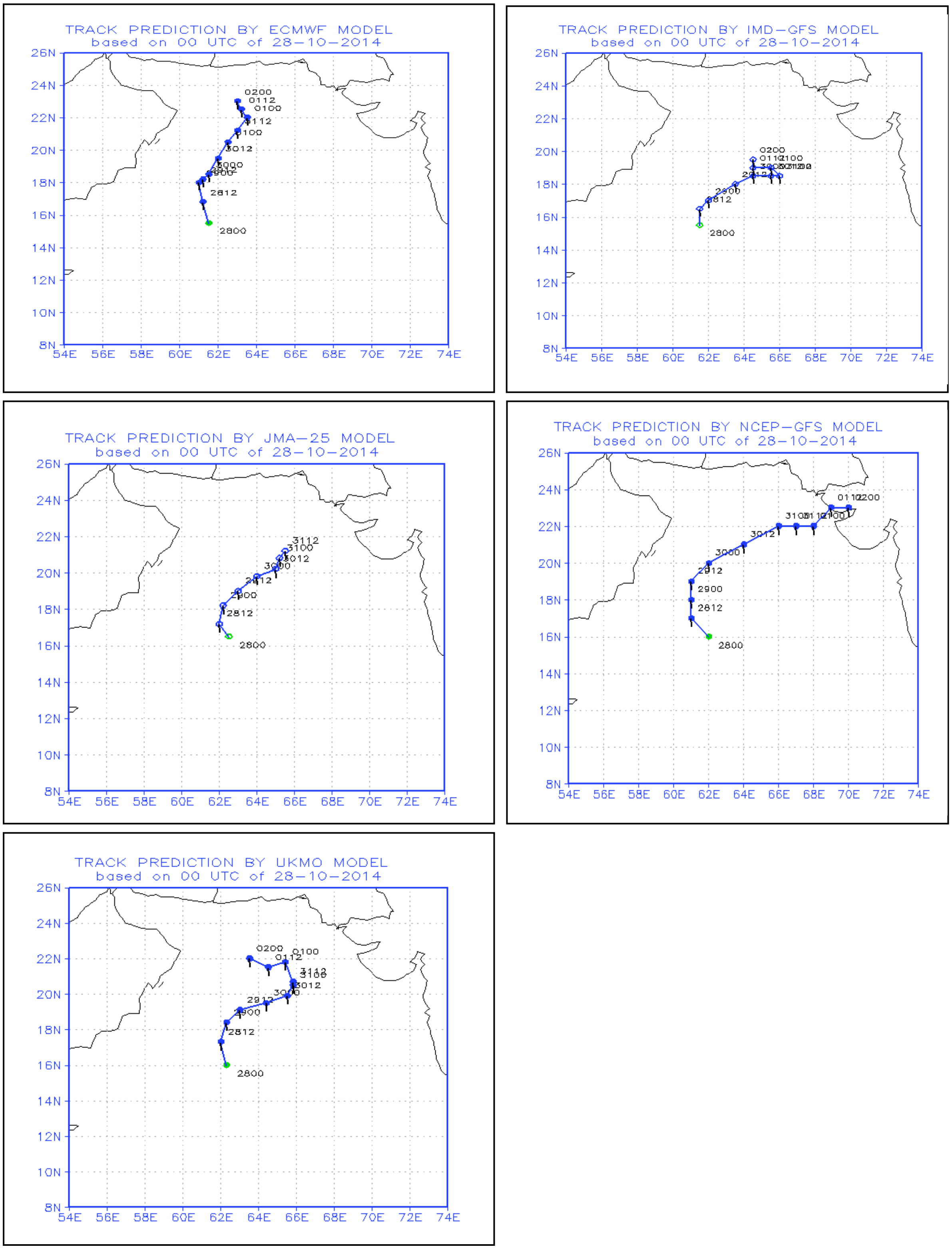


Fig.3.28 d. Track forecast for cyclone NILOFAR based on 00 UTC of 28.10.2014

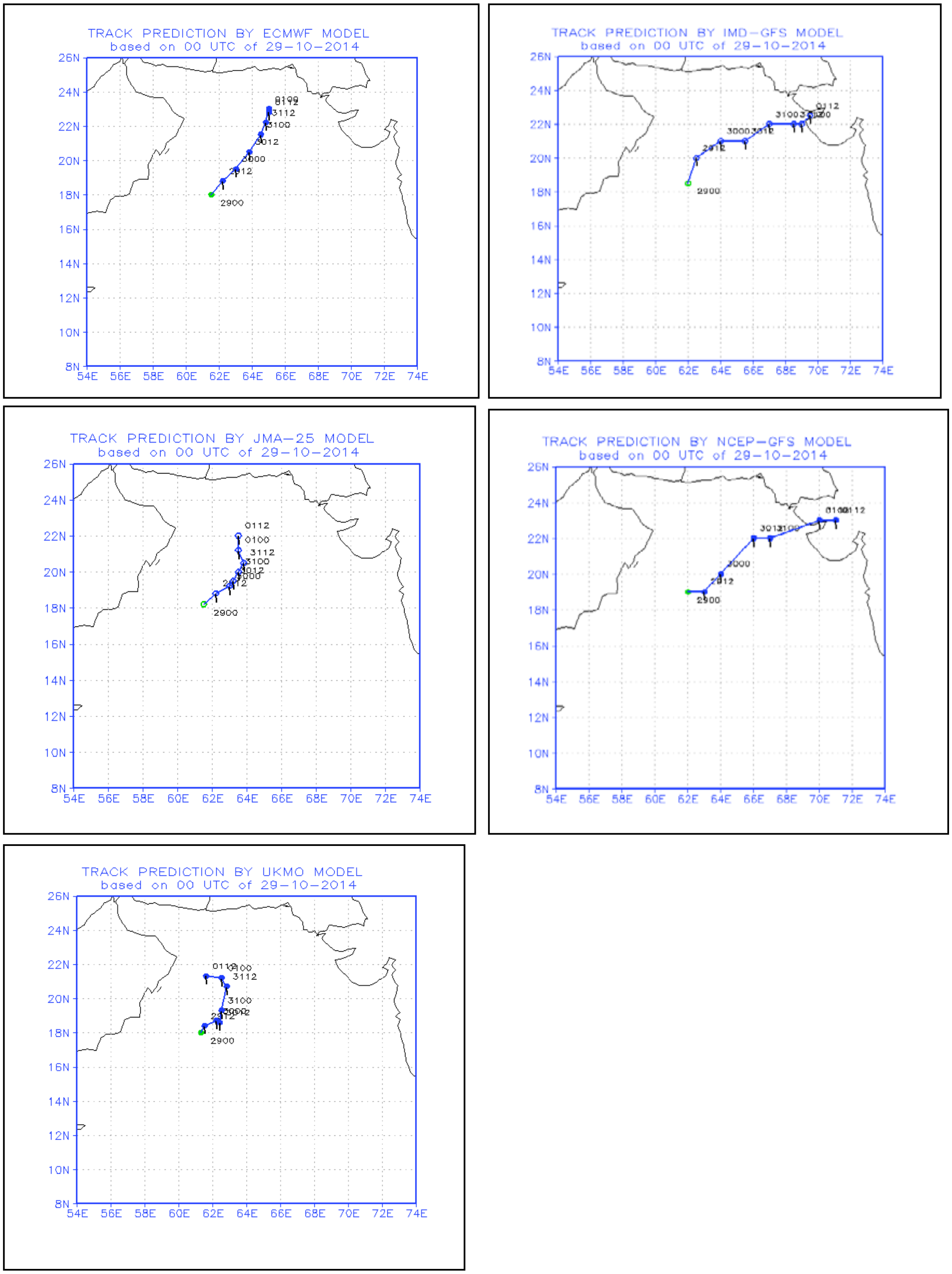


Fig.3.28 e. Track forecast for cyclone NILOFAR based on 00 UTC of 29.10.2014

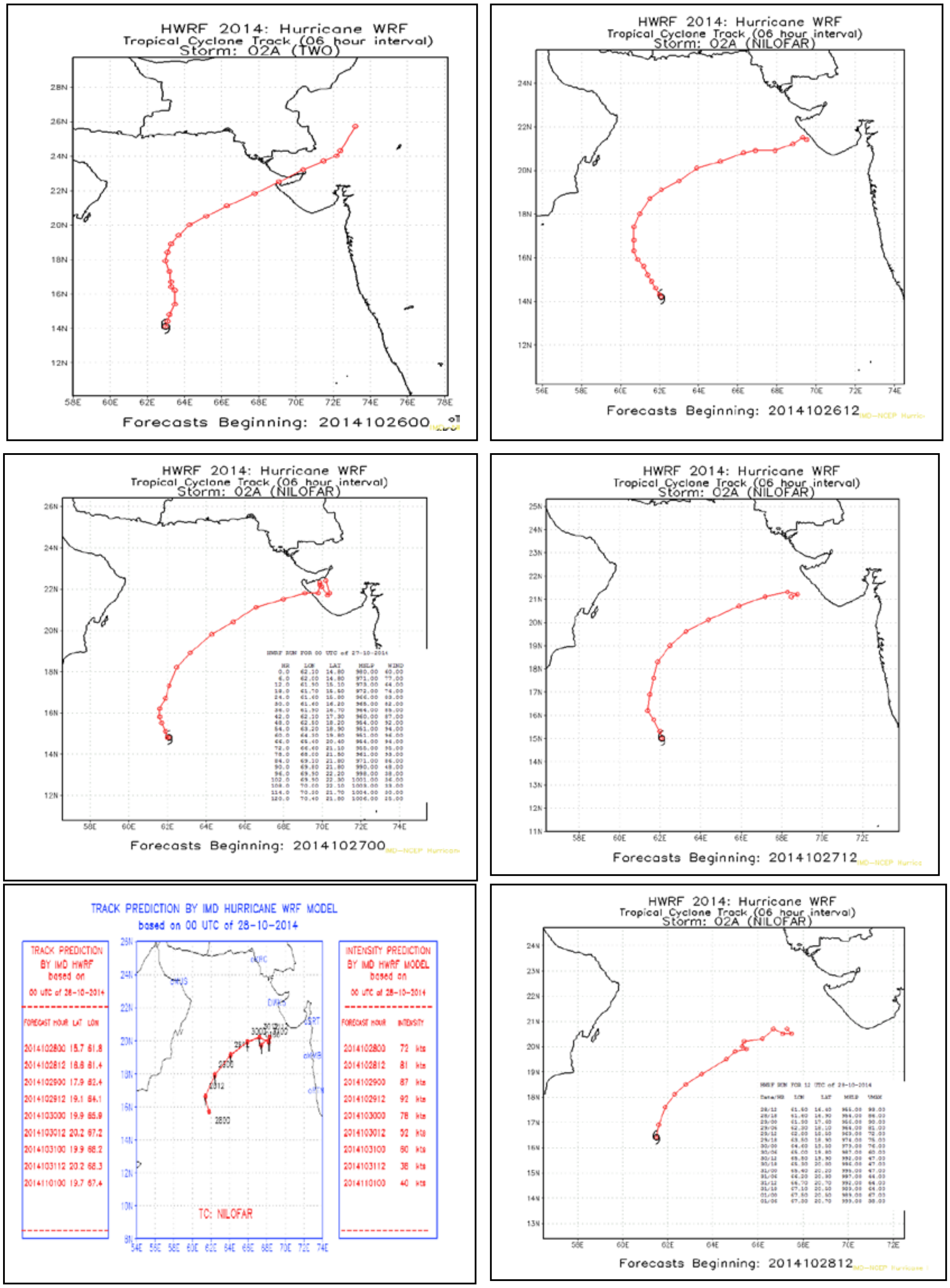


Fig.3.28 (f): Track prediction by HWRF model for cyclone NILOFAR

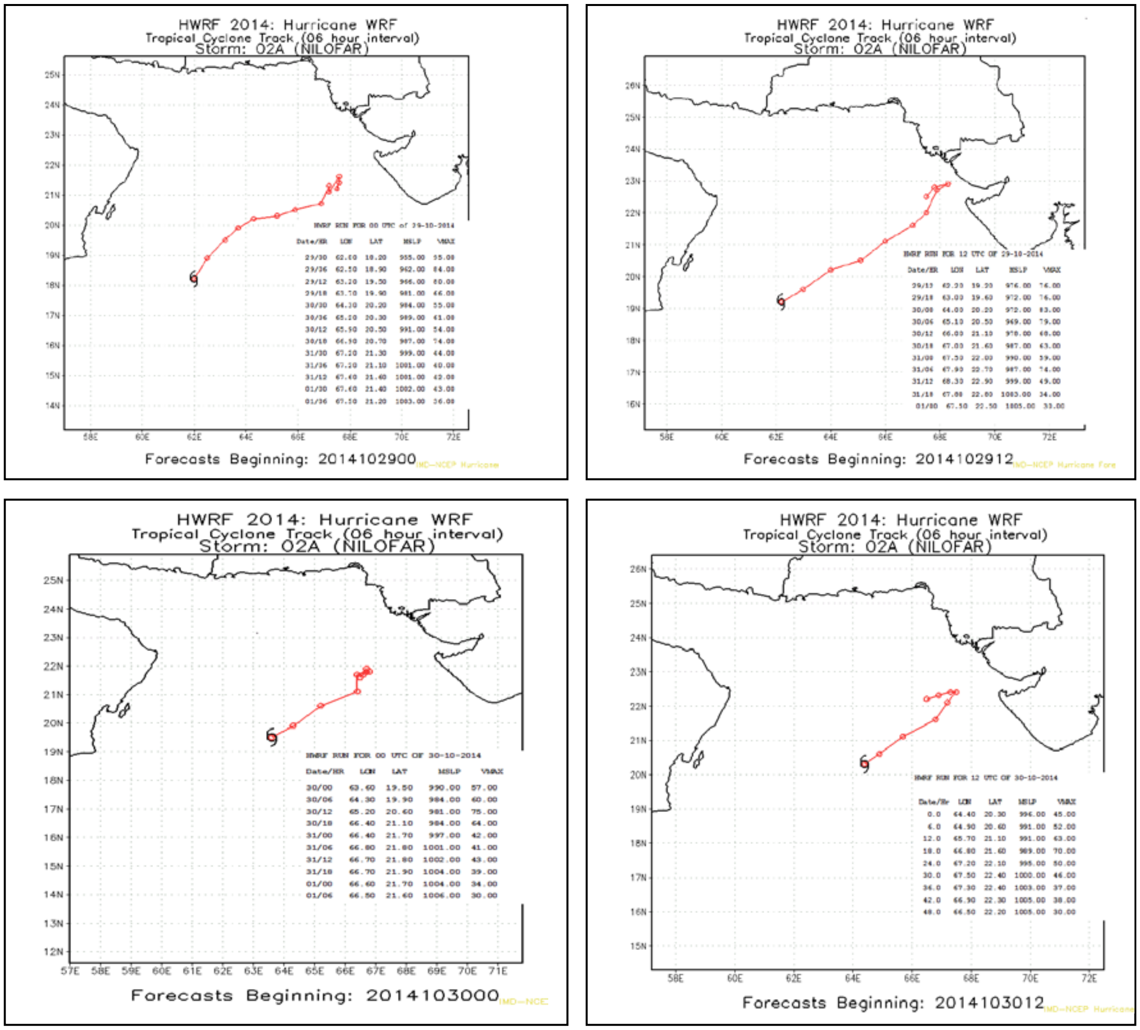


Fig.3.28 (f) (contd..): Track prediction by HWRF model for cyclone NILOFAR

The track forecast error of different models are shown in Table 3.15. it can be seen that, the error, more relatively large for all time seek for all the models. It may be due to unique track of the cyclone which could not be picked up by the models. Comparing individual models performance of NWP –GFS was better for 24 and 48 hr forecasts MME, performed better than individual models .

3.4.3 Track forecast error of NWP products for cyclone, Nilofar

Table-3.15. Average track forecast errors (DPE) in km for cyclone NILOFAR

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	85(11)	111(11)	134(10)	171(9)	214(8)	261(7)	254(6)	259(5)	257(4)	392(3)
IMD-WRF	86(11)	107(11)	189(10)	320(9)	477(8)	645(7)	-	-	-	-
JMA	150(11)	151(11)	167(10)	156(9)	130(8)	82(7)	99(6)	-	-	-
NCEP-GFS	87(11)	80(11)	156(10)	184(9)	242(8)	255(7)	331(6)	313(5)	282(4)	342(3)
UKMO	113(10)	140(10)	166(10)	189(9)	185(8)	205(7)	275(6)	385(5)	560(4)	754(3)
ECMWF	80(11)	97(11)	131(10)	192(9)	243(8)	293(7)	304(6)	361(5)	376(4)	440(3)
IMD-HWRF	66(10)	106(9)	136(8)	165(7)	207(6)	284(5)	349(4)	455(3)	543(2)	849(1)
IMD-MME	76(11)	75(11)	77(10)	90(9)	108(8)	123(7)	152(6)	202(5)	266(4)	362(3)

(No. of forecasts verified)

3.4.4. Intensity (kt) prediction by SCIP and HWRF Model for cyclone NILOFAR

The error statistics for CIP & HWRF models are shown in Table 3.16 @3.17 respectively it can be seen that the performance was relatively for with very high error for different forecast time scales. It is due to the fact that cyclone, Nilofar exhibited rapid intensification and rapid weakening over the sea. Which could not be predicted well by the models.

Table-3.16 Average absolute errors of SCIP and HWRF model for cyclone NILOFAR (Number of forecasts verified is given in t he parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	6.3(11)	9.8(11)	10.5(10)	13.8(9)	18.6(8)	18.0(7)	-	-	-	-
IMD-HWRF	17.4(10)	11.7(9)	14.0(8)	14.6(7)	19.0(6)	24.8(5)	28.3(4)	30.3(3)	22.5(2)	5.0(1)

Table-3.17 Root Mean Square (RMSE) errors of SCIP and HWRF model for cyclone NILOFAR (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	8.1(11)	12.3(11)	13.4(10)	16.8(9)	21.0(8)	21.2(7)	-	-	-	-
IMD-HWRF	21.5(10)	14.0(9)	16.4(8)	15.2(7)	22.3(6)	29.5(5)	30.2(4)	34.7(3)	27.3(2)	5.0(1)

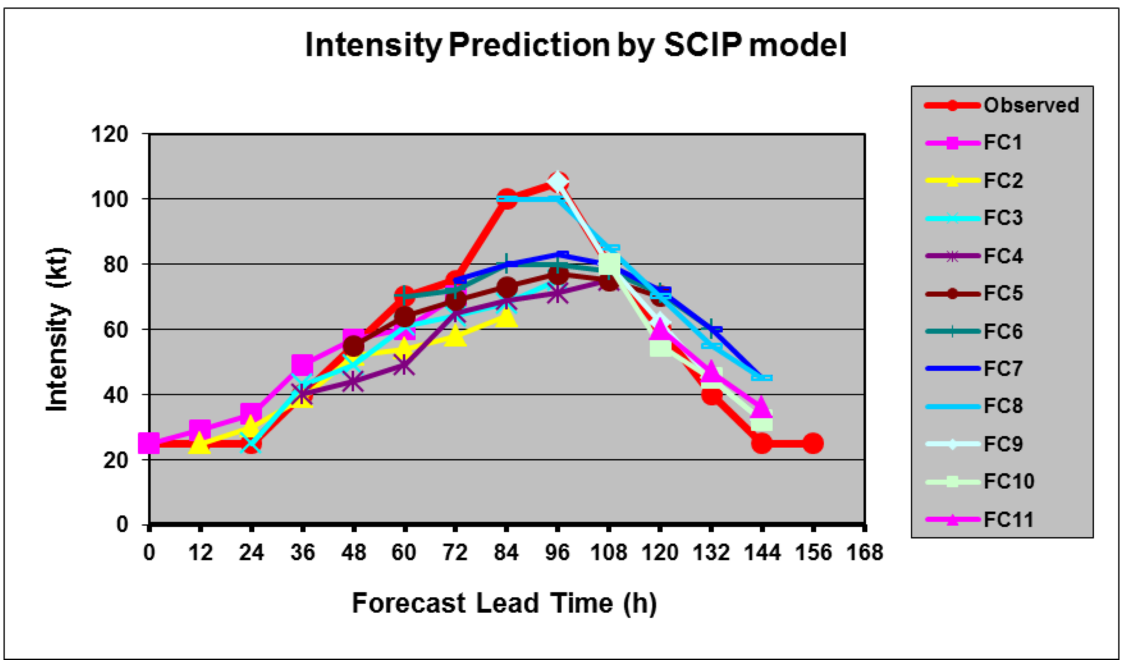


Fig.3.30: Intensity (kt) prediction by SCIP Model for cyclone NILOFAR

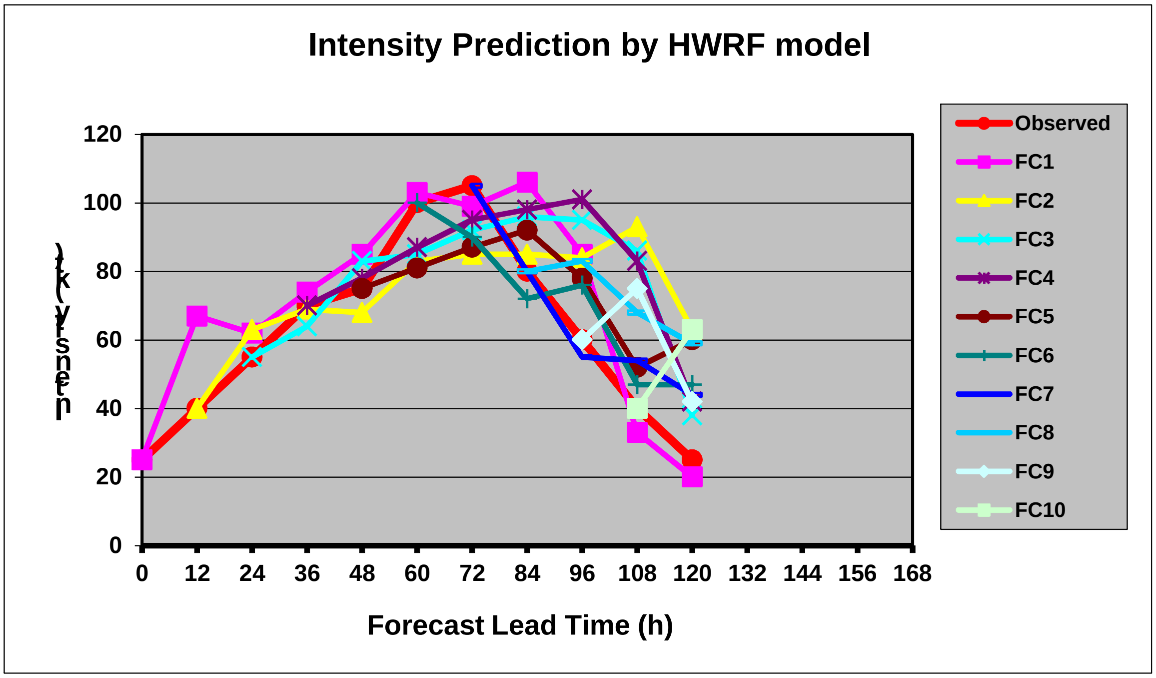


Fig. 3.31: Intensity (kt) prediction by HWRF Model

Intensity predicted by SCIP model (11 forecasts) and HWRF model (10 forecasts) shows that both the models could predict the intensification phase as well as decay phase of the very severe cyclonic storm NILOFAR. Fig 3.30 & 3.31 though the intensity error was high.

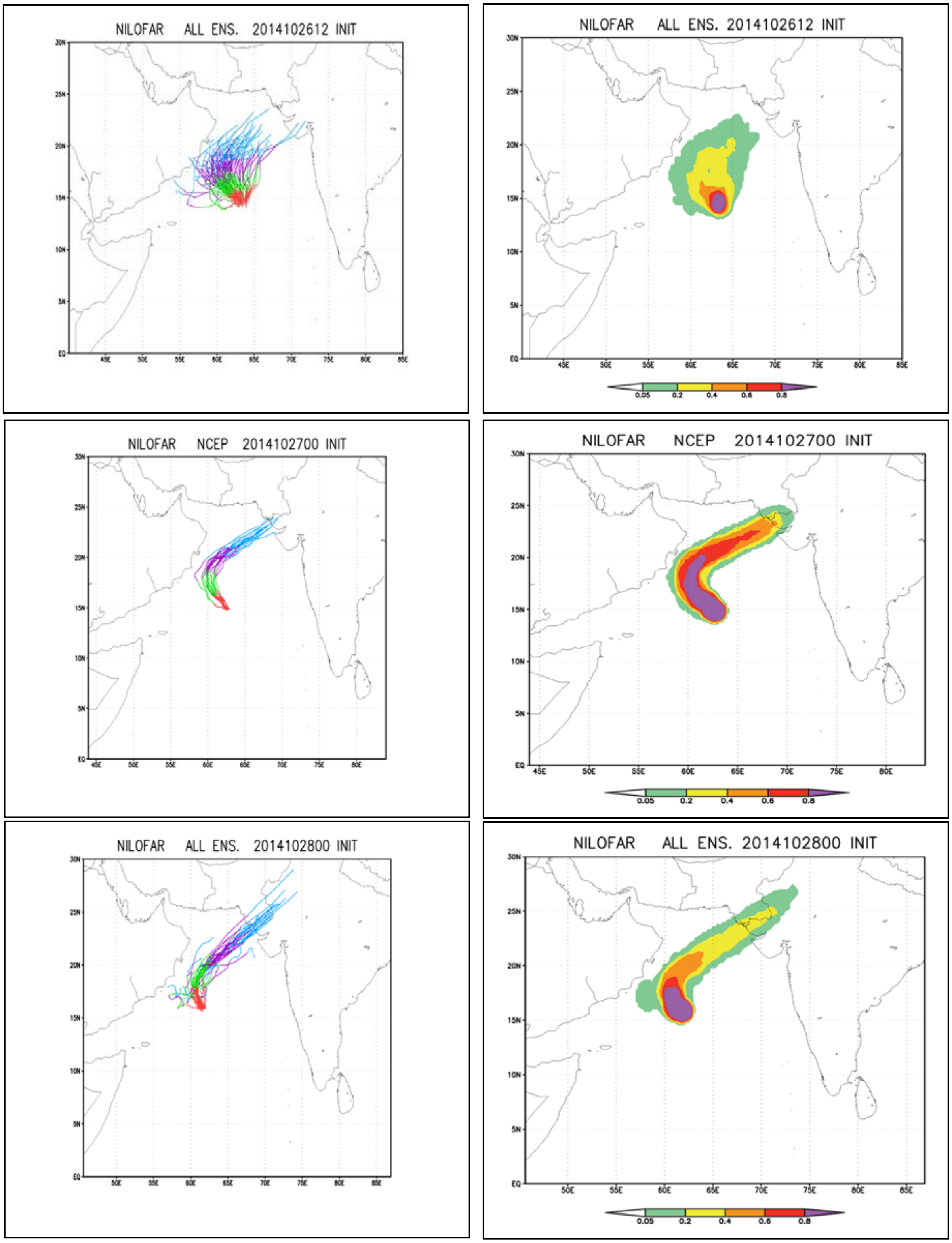


Fig.3.29: EPS based track and strike probability forecasts based on 0000 and 1200 UTC of 26-29th October 2014

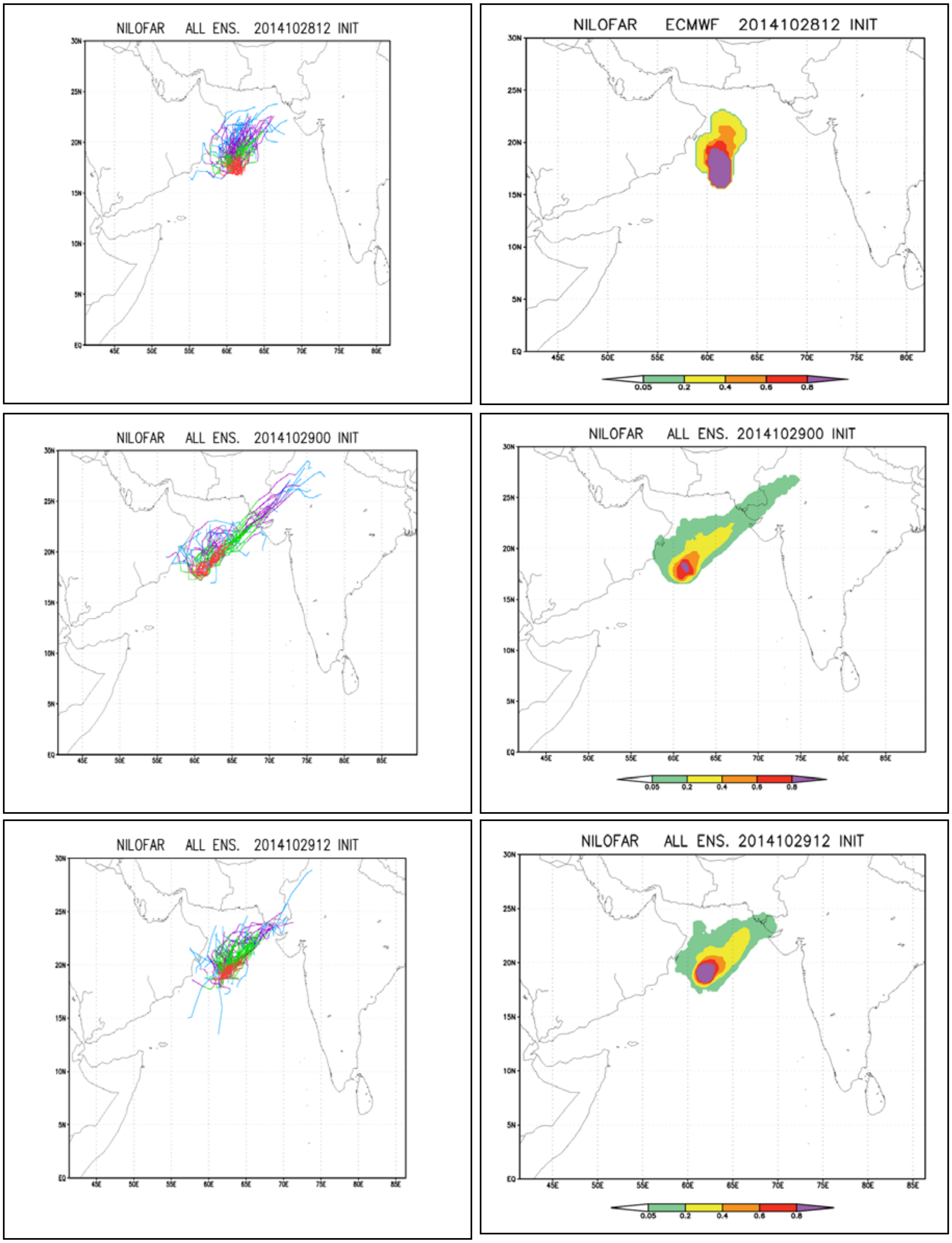


Fig.3.29 contd: EPS based track and strike probability forecasts based on 0000 and 1200 UTC of 26-29th October 2014

3.5. Deep Depression over the Bay of Bengal during 5-8 November 2014

3.5.1. Genesis forecast by GPP

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.

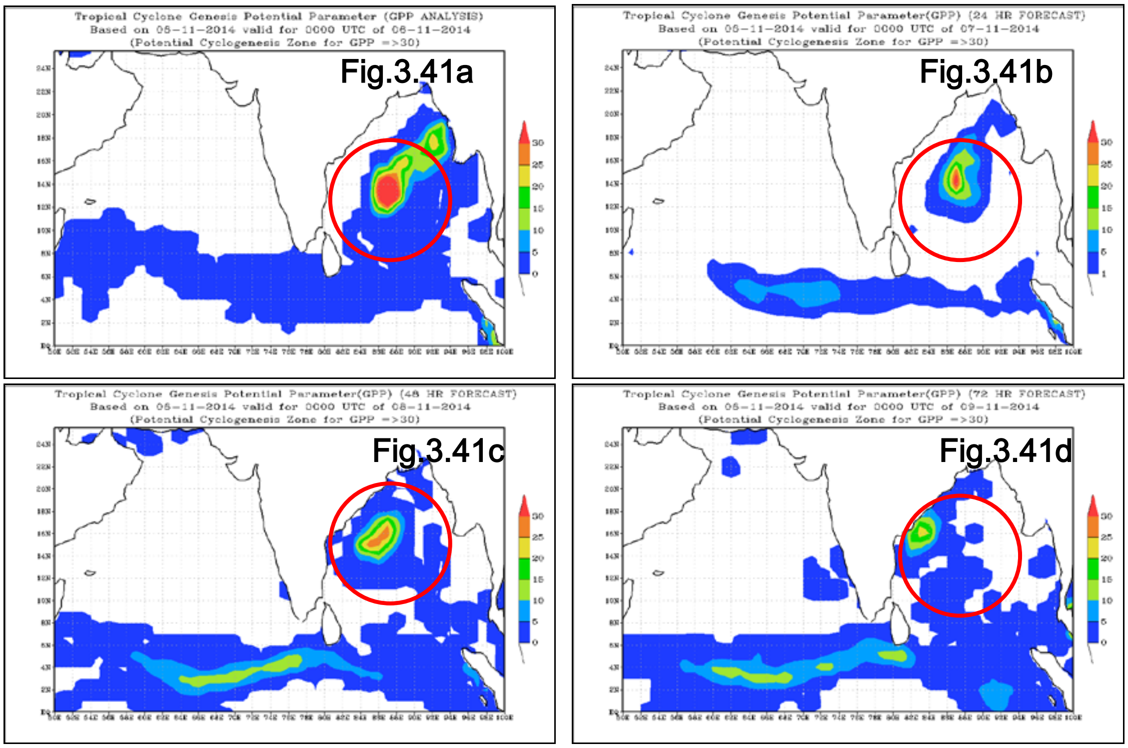


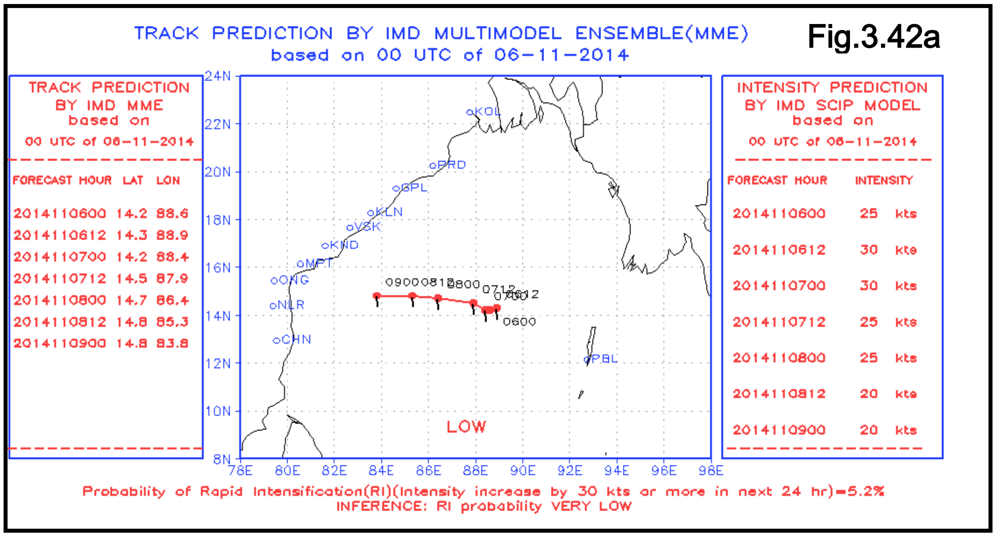
Fig. 3.32(a-d): Predicted zone of cyclogenesis.

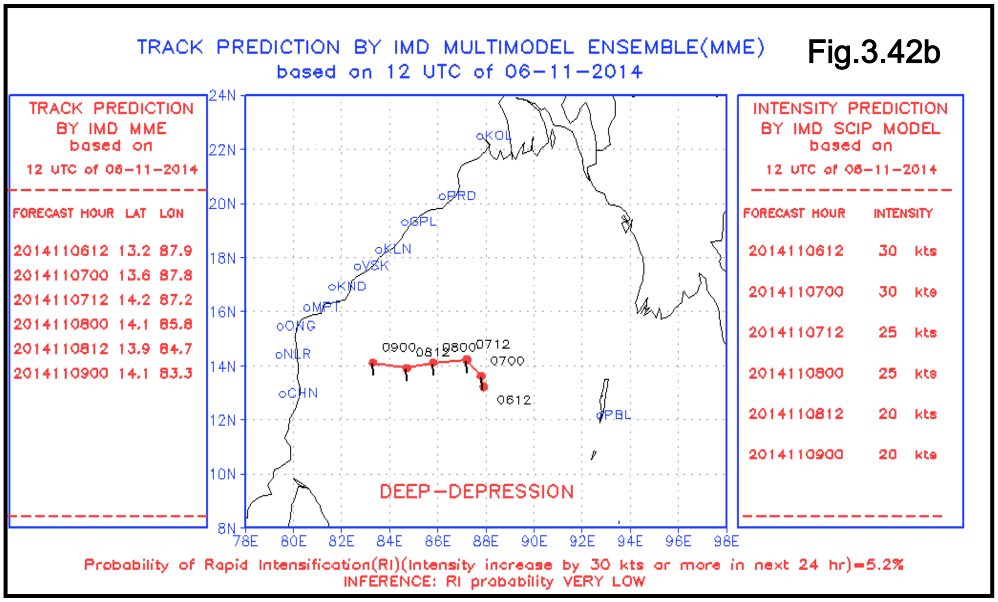
3.5.2. Consensus track prediction by individual NWP models and MME for Deep Depression

MME track forecast based on 0000 UTC of 6 November, 1200 UTC of 6 November 2014 and 0000 UTC of 7 November 2014 suggested westward movement Fig 3.33 the average track forecast errors for different models are shown in Table.3.18.

3.5.3 Intensity prediction by models

Analysis of SCIP intensity forecast and various thermo-dynamical parameters of Genesis Potential Parameter (GPP) ***suggested decay of the system over the Sea Table.3.19.***





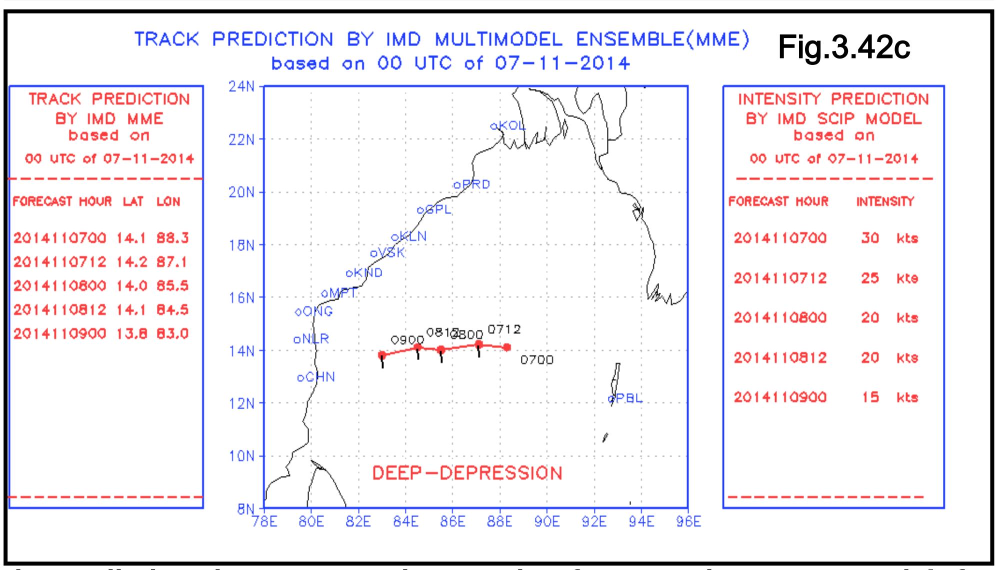


Fig. 3.33: Track prediction by MME and Intensity forecast by SCIP model for Deep Depression

Table-3.18. Average track forecast errors (Direct Position Error) in km for Deep Depression

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)

(Number of forecasts verified)

3.5.3. Intensity (kt) prediction by SCIP Model for Deep Depression

Table-3.19 Average absolute errors (AAE) and Root Mean Square (RMSE) errors of SCIP model

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

(Number of forecasts verified is given in the parentheses)

3.6. Annual average track and intensity forecast errors for cyclonic storms during 2014

3.6.1. Mean track forecast error (km) – 2014

The annual average track forecast errors (DPE) of various models for the systems NANAUK, HUDHUD, NILOFAR, and DEEP DEPRESSION (5-8 November 2014) over the North Indian Seas during the year 2014 are shown in Table 3.20. The 24 hr track forecast errors is less than 100 km for all models except IMDWRF, JMA and UKMO, 48 hr track forecast errors is less than 150 km for all models except IMDGFS and IMDWRF, 72hr track forecast errors is more than 200 km except JMA, NCEP, UKMO, 96hr track forecast errors is more than 250 km for all models except NCEP, and ECMWF, 120hr track forecast errors is more than 300 km for all models except for NCEP and ECMWF. The track forecast error of MME shows that MME was superior to all models, and forecast errors ranged from 58 km at 12h to 205 km at 120h Table.3.20.

Table-3.20: annual average track forecast errors (DPE) of various models for the year 2014

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	62 (28)	89 (28)	125 (26)	178 (23)	215 (19)	275 (16)	273 (13)	278 (11)	289 (8)	336 (6)
IMD-WRF	62 (27)	129 (27)	192 (25)	248 (22)	326 (19)	411 (16)	-	-	-	-
JMA	105 (28)	115 (28)	118 (26)	127 (23)	137 (19)	120 (16)	123 (13)	-	-	-
NCEP-GFS	70 (30)	79 (30)	118 (27)	142 (23)	169 (19)	173 (16)	226 (13)	211 (11)	214 (8)	215 (6)
UKMO	85 (29)	106 (28)	126 (27)	150 (23)	157 (19)	176 (16)	214 (13)	272 (10)	366 (80	450 (6)
ECMWF	66 (25)	87 (25)	105 (23)	133 (20)	165 (17)	201 (15)	205 (13)	243 (11)	249 (8)	288 (6)
IMD-HWRF	55 (15)	78 (14)	112 (13)	144 (11)	180 (9)	233 (7)	303 (5)	455 (3)	543 (2)	849 (1)
IMD-MME	58 (30)	66 (30)	75 (27)	86 (23)	95 (19)	118 (16)	133 (13)	159 (11)	186 (8)	205 (6)

(Number of forecast verified given in the parentheses)

3.6.2 Annual Mean Intensity forecast error during 2014

I. SCIP model -2014

The annual average intensity forecast errors of SCIP model are shown in Table 3.21.

Table-3.21: The annual average intensity forecast errors knots of SCIP for all the systems during 2014

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
AAE	4.7(28)	7.4(27)	7.4(24)	8.6(21)	13.9(15)	15.0(12)
RMSE	6.3	9.5	10.1	12.1	16.9	17.8

*Number of forecast verified is given in the parentheses

II. HWRF model -2014

The annual average intensity forecast errors for 2014 are shown in Table 3.22 for HWRF model.

Table-3.22: Annual average intensity forecast errors of HWRF for the cyclones HUDHUD, and NILOFAR during 2014

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84h	96h	108h	120h
AAE	14.8(14)	11.1(12)	12.4(10)	12.9(8)	19.0(6)	24.8(5)	28.3(4)	30.3(3)	22.5(2)	5.0(1)
RMSE	19.0	13.0	14.9	14.2	22.3	29.5	30.2	34.7	27.3	5.0

(Number of forecast verified is given in the parentheses)

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CHAPTER-IV
PERFORMANCE OF RSMC, NEW DELHI
IN TRACK AND INTENSITY PREDICTION OF CYCLONES
DURING 2014

4.1. Introduction

The Cyclone Warning Division/ Regional Specialised Meteorological Centre (RSMC)-Tropical Cyclone, IMD, New Delhi mobilised all its resources for monitoring and prediction of cyclonic disturbances (CDs) over the north Indian Ocean during 2014. A cyclonic disturbance is considered as a TC over NIO, when the associated maximum sustained surface wind (MSW) is 34 knots or more as per the classification adopted by IMD. It corresponds to the definition of tropical storms over other Ocean basins like Pacific and Atlantic Oceans. Detailed classification of TCs into Cyclonic storm (CS), severe cyclonic storm (SCS), very severe cyclonic storm (VSCS) and super cyclonic storm (SuCS) are given in cyclone manual published by IMD (2013).

It issued 3 hourly forecast and warning/advisory bulletins to various national and international disaster management agencies including National Disaster Management (NDM), Ministry of Home Affairs (MHA), concerned state Govt. and other users in regular intervals. It also issued advisories to World Meteorological Organisation (WMO)/Economic and Social Cooperation for Asia and the Pacific (ESCAP) Panel member countries including Bangladesh, Myanmar, Thailand, Pakistan, Oman, Sri Lanka and Maldives during cyclone period. As tropical cyclone advisory centre (TCAC), it also issued tropical cyclone advisories with effect from the stage of deep depression for international civil aviation purpose as per the requirement of international civil aviation organization (ICAO). Detailed standard operation procedure (SOP) are given in IMD (2013)

IMD continuously monitored, predicted cyclogenesis, track, intensity and structure of cyclones. The genesis forecast in probabilistic term was issued from 01 June 2014. 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 warning issued regularly. 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 ≥ 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's website regularly. The storm surge guidance was provided as and when required to the member countries of WMO/ESCAP Panel as per the recommendation of Panel on Tropical Cyclone (PTC) held during March, 2009 at Muscat, Oman based on IITD model. The prognosis and diagnosis of the systems were described in the special tropical weather outlook and tropical cyclone advisory bulletins since 2008. The TCAC bulletin was also sent to Asian Disaster Risk reduction (ADRR) centre of WMO at Hong Kong like previous years.

The statistics of bulletins issued by IMD, New Delhi with respect to cyclonic disturbances is presented in sec.4.2. The performance of RSMC-New Delhi in track and intensity prediction of the cyclones during 2014 are analysed and discussed in sec.4.3.

4.2. Bulletins issued by IMD

The following are the statistics of bulletins issued by IMD in association with the cyclonic disturbances during 2014

Bulletins issued during ‘Nanauk'

Bulletins for national disaster management agencies	:	27
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	26
Tropical cyclone advisory for international civil aviation	:	12

Bulletins issued during ‘Hudhud’

Bulletins for national disaster management agencies	:	55
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	35
Tropical cyclone advisory for international civil aviation	:	23

Bulletins issued during ' Nilofar '

Bulletins for national disaster management agencies	:	48
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	47
Tropical cyclone advisory for international civil aviation	:	21

Bulletins issued for all cyclones during 2014

Bulletins for national disaster management agencies	:	75
RSMC bulletin for WMO/ESCAP Panel member countries (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	73
TCAC bulletin for international civil aviation	:	33

Bulletins issued for all cyclonic disturbances (depression and above) during 2014

Bulletins for national disaster management agencies	:	171
RSMC bulletin for WMO/ESCAP Panel member countries: (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	134
TCAC bulletin for international civil aviation	:	61

4.3. Performance of Operational Track, intensity and landfall forecast

The performance of operational genesis, track and intensity forecasts issued by IMD, New Delhi for three cyclones and two deep depressions during 2014 are described below.

4.3.1. Deep Depression over Bay of Bengal (4 – 7th January, 2014)

The landfall forecasts issued in connection with the depression over Bay of Bengal (4 – 7th January, 2014) have been verified.It was about 55 km or less for all forecasts ranging from 12-48 hrs and the results are shown in the Table 4.1. The heavy rainfall warning issued by IMD along with the actual heavy rainfall is givenin Table 4. 2.

Table 4.1.Landfall forecast error for Deep Depression over Bay of Bengal (04-07 January, 2014)

Hours	Forecast landfall point		Actual Landfall point		Error (Kms)	Time		
	Lat ^{0}N	Long ^{0}E	Lat ^{0}N	Long ^{0}E		Landfall Forecast time	Actual landfall time	Error (hrs)
12	9.25	80.5	9.2	80.8	57	6th 00.30 UTC	6th 05.30 UTC	-5
24	9.5	80.5	9.2	80.8	47	5th 18.30 UTC	**6th 05.30 UTC**	-11
36	9.5	80.5	9.2	80.8	47	5th 12.30 UTC	**6th 05.30 UTC**	-17
48	9.2	80.5	9.2	80.8	33	5th 12.30 UTC	**6th 05.30 UTC**	-17

Error = forecast - actual

Table 4.2. Heavy Rainfall Warning Verification for the Deep Depression over Bay of Bengal (04-07 January, 2014)

Date & time	Warning issued	24 hours rainfall realized at 0300 UTC of date (cm)
04/01/2014 0300 UTC	Isolated heavy to very heavy falls over south coastal Tamil Nadu and isolated heavy fall over south interior Tamil Nadu commencing from 6th January 2014.	Nil.
05/01/2014 0300 UTC	Isolated heavy falls south Tamil Nadu on 6th and isolated heavy to very heavy falls on 7th January 2014.	
06/01/2014 0300 UTC	isolated heavy falls over south Tamil Nadu during next 24 hours and isolated heavy to very heavy falls during subsequent 24 hours.	
07/01/2014 0300 UTC	Isolated heavy falls over south coastal Tamil Nadu during next 24 hours.	

4.3.2 Depression overBayofBengal (21–23May, 2014)

4.3.2.1. Heavy rainfall warning

The heavy rainfall and squally wind warning issued by IMD along with the actual heavy rainfall is given in Table 4.3 & 4.4.

Table 4.3.Verification of heavy rainfall warning issued by IMD for depression over Bay of Bengal (21-23 May, 2014)

Date&time	Warningissued	24 hours rainfall realized at 0300 UTC of date (cms)
21/05/2014 0300UTC	Isolated heavy to very heavy falls over Andaman and NicobarI slands during next48 hrs.	26.5.2014 Heavy to very heavyrainfall at a few places over coastal Andhra Pradesh, Odisha. Isolated heavy to very heavy rainfall over West Bengal
22/05/2014 0300UTC	Nil	
23/05/2014 0300UTC		
24/05/2014 0300UTC		
25/05/2014 0300UTC	Heavy rainfall would occur at isolated places over coastal Odisha during nex t72hrs.	
26/05/2014 0300UTC	Heavy to very heavy rainfall would occur at a few places with extremely heavy falls at isolated places over Odisha, and heavy rainfall would occur at isolated places over north coastal Andhra Pradesh, sub Himalayan west Bengal & Sikkim and south Chatisgarh	27.5.2014 Heavy to very heavy rainfall at a few places with isolated extremely heavy rainfall over Odisha and isolated heavy rainfall over West Bengal

4.3.2.2. Wind warnings:

The squally wind warning issued by IMD and realized wind are shown in Table 4.4.

Table4.4.squallywindwarningissuedbyIMD and realisedwind

Date & time	Warning issued	Observed wind
21/05/2014 0300 UTC	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Andaman and Nicobar Islands during next 48 hrs.	40 -50 KMPH over the sea and Andaman & Nicobar Islands
22/05/2014 0300 UTC	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Andaman Islands during next 24 hrs	
23/05/2014	Strong winds speed reaching 40-50 kmph gusting to 60 kmph would prevail along and off Andaman Islands during next 24 hrs	

4.3.3: Cyclonic Storm (CS) 'NANAUK' over the Arabian Sea (10-14 June 2014)

4.3.3.1. Track forecast error

In the first bulletin issued in the afternoon of 10th June, 2014 , when the system was a depression over east central Arabian sea, it was predicted that the system would move north-northwestwards and intensify further into a deep depression and move west-northwestwards towards Oman coast. In the second bulletin issued on 10th June it was predicted that the system would intensify into a cyclonic storm.

The average track forecast error is shown in Table 4.5. It was about 79 km, 89 km and 94 km respectively for 24, 48 and 72 hr forecast respectively against the long period average of 124, 202 and 268 km based on the period of 2009-2013. The operational track forecast skill for this cyclone is shown in Table 4.6.The track forecast skill as compared to climatology and persistence (CLIPER) model forecast was about 54%, 74% and 84% for 24, 48 and 72 hr forecasts respectively.

Table 4.5. Operational average track forecast error of IMD of 'NANAUK'

Lead Period	Track Forecast Error (km)	Long period average (2009-2013)
12	48.0(11)	68.5
24	78.8(10)	124.1
36	81.2(08)	163.8
48	89.0(06)	202.1
60	77.5(04)	233.8
72	94.2(02)	268.2

Figures in the parentheses show the number of six hourly forecasts verified

Table 4.6. Operational Track Forecast Skill (%) of cyclonic storm, Nanuak.

Lead period (hrs)	Track forecast skill	Long period skill (2009-2013)
12	43.8(11)	31.2
24	54.1(10)	35.9
36	67.9(08)	43.9
48	74.1(06)	52.6
60	84.2(04)	58.1
72	84.9(02)	61.8

Figures in the parentheses show the number of six hourly forecasts verified

4.3.3.2. Intensity forecast error

The intensity forecast errors (average absolute error (AAE) and root mean square error (RMSE)) of IMD for cyclonic storm, **'NANAUK'** are shown in Table 4.7. The AAE was about 13, 30 and 28 knots against the long period average of 16, 23 & 27 knots based on the period of 2009-2013 for 24, 48 & 72 hr forecasts respectively. The average RMSE was about 14, 32 and 28 knots against the long period average of 21, 28 and 31 knots respectively for the same period. Though the AAE was higher than long period average for 36-72 hr forecasts and RMSE was higher for 48-72 hr forecasts, the forecast was skillful as compared to persistence forecast as shown in Table 4.7. The higher intensity error in the lead period of 36-72 hrs may be attributed to the poor guidance from numerical models, as most of the models could not predict intensity accurately.

The intensity forecast skills are shown in Table 4.8. The Skill in terms of improvement in AAE with respect to persistence forecast is about 9%, 27% and 66% respectively for 24, 48 and 72 hr forecasts. Similarly, the skill in terms of improvement in RMSE with respect to persistence forecast is about 12%, 26% and 67% respectively for 24, 48 and 72 hr forecasts.

Table 4.7. Operational average intensity forecast error of IMD of 'NANAUK'

Lead Period	Intensity Forecast Error (knots)		Long period Average (2009-2013): Absolute Error (knots)	Long period Average (2009-2013): RMS Error (knots)
	Absolute error	Root mean square error		
12	6.1(11)	7.5(11)	10.4	14.0
24	13.2(10)	14.1(10)	15.7	20.5
36	20.4(08)	21.6(08)	20.5	25.2
48	30.2(06)	32.0(06)	22.5	27.6
60	33.1(04)	34.5(04)	23.5	26.4
72	28.4(02)	28.4(02)	26.7	30.8

Figures in the parentheses show the number of six hourly forecasts verified

Table 4.8. Operational Intensity Forecast skill (%)of cyclonic storm, Nanauk

Lead period (hrs)	Skill in term of Absolute Error (%)	Skill in term of RMS Error (%)
12	-19.6(11)	1.3
24	9.0(10)	12.4
36	16.7(08)	13.3
48	27.0(06)	25.9
60	51.5(04)	49.4
72	66.4(02)	66.7

Figures in the parentheses show the number of six hourly forecasts verified

4.3.3.3 Heavy Rainfall, Wind Warning and Storm surge warning

The heavy rainfall warning issued by IMD along with the actual heavy rainfall is given in Table 4.9. The strong wind forecast along with actual wind is presented in Table 4.10. It may be mentioned that the heavy rainfall and wind due due to the cyclone could not be predicted well in advance with good accuracy. As initially, it was predicted that the cyclone would weaken at the time of landfall and later it was predicted that the cyclone would weaken over the sea, storm surge was not predicted by the RSMC, New Delhi

Table 4.9: Heavy rainfall warning issued by IMD and realized rainfall

Date	Forecast heavy rainfall	Actual heavy rainfallending at 0300 UTC of date.
10. 06.2014 (0900 UTC)	Isolated heavy falls over coastal Karnataka, Kerala and Lakshadweep during next 24 hrs	11.06.2014 Isolated heavy falls over coastal Karnataka and Kerala

11. 06.2014 (0300 UTC)	Isolated heavy falls over coastal Karnataka, Kerala and Lakshadweep during next 24 hrs	12.06.2014 Isolated heavy falls over coastal Karnataka, Kerala and Lakshadweep
11. 06.2014 (2100 UTC)	Isolated heavy falls over coastal Karnataka, Kerala and Lakshadweep during next 24 hrs	13.06.2014 Isolated heavy falls over coastal Karnataka and Kerala

Table 4.10. Wind forecast along with actual wind in connection with Cyclonic Storm Nanauk

Date	Forecast wind (kmph)	Actual wind (kmph)
10. 06.2014 (0900 UTC)	Strong wind of 35-45 kmph gusting to 55 kmph would prevail along and off south Gujarat, Konkan and Goa coasts	Strong wind of 35-45 kmph prevailed along and off south Gujarat, Konkan and Goa coasts
11. 06.2014 (0000 UTC)	Strong wind of 35-45 kmph gusting to 55 kmph would prevail along and off south Gujarat, Konkan and Goa coasts	
12. 06.2014 (0000 UTC)	Strong wind of 35-45 kmph gusting to 55 kmph would prevail along and off south Gujarat, Konkan and Goa coasts	
13. 06.2014 (0000 UTC)	Strong wind of 35-45 kmph gusting to 55 kmph would prevail along and off south Gujarat, Konkan and Goa coasts	
14. 06.2014 (0000 UTC)	Strong wind of 30-40 kmph gusting to 50 kmph would prevail along and off south Gujarat, Konkan and Goa coasts	

4.3.4. Land Depression over Odisha and adjoining areas of Gangetic West Bengal (21st - 23rd July 2014)

The heavy rainfall warning issued by IMD along with the realised rainfall is given in the Table 4.11.

Table 4.11.Verification of heavy rainfall warning in association with land depression

Date (Time in UTC)	Heavy rainfall warning	Heavy rainfall realized at the end of 0300 UTC of date
21.07.2014 (0300)	Extremely heavy rainfalls- Isolated places over Chhattisgarh Heavy to very heavy rainfall at a few places – Odisha east Madhya Pradesh.and Chhattisgarh Heavy to very heavy rainfall at Isolated places - Vidarbha and Jharkhand	Date.22.07.2014: Extremely heavy at isolated places of Odisha and Chhattisgarh. Heavy to very heavy rainfall at a few places-Vidarbha east Madhya Pradesh.Odisha Chhattisgarh Heavy rainfall at isolated places - Jharkhand, West Uttar Pradesh and east Rajastahan.
22.07.2014 (0300))	Extremely heavy rainfalls- Isolated places over - Chhattisgarh and Vidarbha. Heavy to very heavy rainfall at a few places - Madhya Pradesh Chhattisgarh and Vidarbha. Heavy rainfall would occur at isolated places over Odisha.	23.07.2014: Extremely heavy rainfalls- Isolated places over – Vidarbha and West Madhya Pradesh Heavy to very heavy rainfall at a few places- Chhattisgarh west and east Madhya Pradesh and Gujarat.

		Heavy rainfall at isolated places over east Rajasthan
23.07.2014 (0300)	Extremely heavy rainfalls- Isolated places over – Madhya Maharashtra Heavy to very heavy rainfall at a few places west Madhya Pradesh, Madhya Maharashtra Heavy rainfall at isolated places east Madhya Pradesh, Gujarat, and Vidarbha	Date.:24.07.2014: Extremely heavy rainfalls- Nil Heavy to very heavy rainfall at a few places-Madhya Maharashtra, Gujarat and west Madhya Pradesh Heavy rainfall at isolated places Vidarbha and east Rajasthan.

4.3.5. Deep Depression over Bay of Bengal during 3-7 August, 2014

The heavy rainfall warning issued by IMD along with the realised rainfall is given in the Table 4.12.

Table 4.12. Verification of heavy rainfall warning in association with Deep Depression over Bay of Bengal during 3rd - 7th Aug 2014

Date (Time in UTC)	Heavy rainfall warning	Heavy rainfall realized at the end of 0830 Hrs of the date
03.08.2014 (0300)	Heavy to very heavy rainfall at isolated places- Odisha. Heavy rainfall at isolated places - Gangetic West Bengal and Chhattisgarh.	04.08.2014: Heavy to very heavy rainfall at a few places with extremely heavy at isolated places– Odisha, Gangetic West Bengal. Heavy rainfall would occur at isolated places- Chhattisgarh.
04.08.2014 (0300)	Extremely heavy falls at isolated places- Chhattisgarh and Odisha. Heavy to very heavy rainfall at isolated places – east Madhya Pradesh, Vidarbha and Jharkhand, Chhattisgarh, Odisha. Heavy rainfall at isolated places- East Uttar Pradesh, Gangetic West Bengal, Madhya Maharashtra	05.08.2014: Extremely heavy falls at isolated places- Odisha. Heavy to very heavy rainfall at isolated places- Chhattisgarh, east Madhya Pradesh and Vidarbha, Odisha. Heavy rainfall at isolated places- Gangetic West Bengal, Jharkhand, Madhya Maharashtra, East Rajasthan and west Madhya Pradesh
05.08.2014 (0300)	Extremely heavy falls at isolated places - Madhya Pradesh, Vidarbha and Chhattisgarh. Heavy to very heavy rainfall at isolated places - Odisha and Jharkhand. Heavy rainfall at isolated places - South Uttar Pradesh, East Rajasthan, and Madhya Maharashtra.	Date.06.08.2014: Extremely heavy falls: Nil Heavy to very heavy rainfall at a few places – Madhya Pradesh, East Rajasthan Heavy to very heavy rainfall at isolated places -Chhattisgarh, Vidarbha, West Uttar Pradesh Heavy rainfall at isolated places - Madhya Maharashtra.
06.08.2014 (0300)	Extremely heavy falls at isolated places - West Madhya Pradesh.	Date.07.08.2014: Extremely heavy falls at isolated places-

	Heavy to very heavy rainfall at isolated places – East Rajasthan, Gujarat. Heavy rainfall at isolated places -Uttar Pradesh and East Madhya Pradesh.	east Rajasthan. Heavy to very heavy rainfall at isolated places-West MP and West Rajasthan, East Rajasthan Heavy rainfall at isolated places-Gujarat
07.08.2014 (0300)	Heavy to very heavy rainfall at isolated places -East Rajasthan. Heavy rainfall at isolated places- West Rajasthan, West Madhya Pradesh, Gujarat.	Date.08.08.2014: Very heavy rainfall -Nil. Heavy rainfall at isolated places-West and East Rajasthan, , Gujarat.

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

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 140 kmph gusting to 155 kmph 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.

4.3.6.1 Operational landfall forecast error

The operational landfall forecast error varied from 2 to 20 km for 12 to 72 hrs forecast (Table 4.13.). 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.4.1.

4.3.6.2. Operational track forecast error and skill of VSCS, Hudhud.

The operational average track forecast errors are shown in Table 4.14. It was less than 100 km for all forecast time scales upto 108 hrs.

4.3.6.3. Operational Intensity forecast error and skill

The operational intensity forecast error in terms of AAE and RMSE is presented in Table 4.16. The AAE 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 4.17.). Considering the RMSE, it varied from 11 kt to 22 kt 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 4.13. 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	-	-

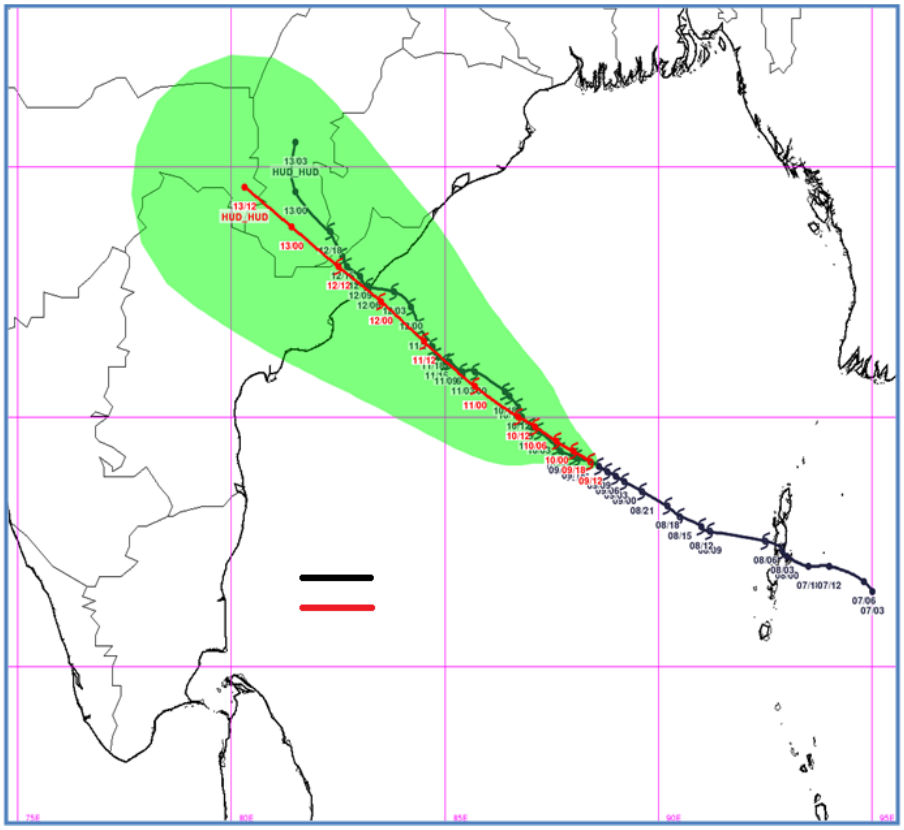

Fig.4.1.An example of forecast and actual track along with cone of uncertainty issued on 9th October 2014.

Table 4.14. Operational Track Forecast Error (km) of VSCS, 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 4.15. Operational Track Forecast Skill (%)of VSCS, HUDHUD

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.

Table 4.16. Operational Intensity forecast errors of VSCS, HUDHUD

Lead period (hrs)	**AAE (knots)**	**RMSE (knots)**	**Long period Average (2009-2013):AAE (knots)**	**Long period Average (2009-2013): RMSE (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 –4.17. Operational Intensity Forecast skill (%)of VSCS, HUDHUD

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.

4.3.6.4 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 4.18 to 4.20. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table–4.18.Verification of Heavy Rainfall warning

<table>
<tr><th>Date/ Time(UTC)</th><th>Forecast Rainfall</th><th>Observed Rainfall</th></tr>
<tr><td>06.10.14
(0300)</td><td>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.</td><td rowspan="3">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:</td></tr>
<tr><td>07.10.14/
(0300)</td><td>Andaman and Nicobar Islands: Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (>=25 cm) would occur over during subsequent 48 hours.</td></tr>
<tr><td>08.10.14/
(0300)</td><td>(i) Andaman and Nicobar Islands:
Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (≥25 cm) during next 24 hours.
(ii) North Andhra Pradesh and South Odisha:
Heavy to very heavy falls at a few places with isolated extremely heavy falls over south Odisha</td></tr>
</table>

<table>
<tr><td></td><td>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.</td><td rowspan="5">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 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</td></tr>
<tr><td>09.10.14/ (0300)</td><td>North Andhra Pradesh and South Odisha coasts: Heavy to very heavy falls at a few places and isolated extremely heavy falls 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.</td></tr>
<tr><td>10.10.14/ (0300)</td><td>North Andhra Pradesh and South Odisha coasts: Heavy to very heavy falls at a few places and isolated extremely heavy falls would occur over West & East Godavari, Visakhapatnam, Vizianagaram & 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></tr>
<tr><td>11.10.14/ (0300)</td><td>Andhra Pradesh and Odisha coasts: Heavy to very heavy falls 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,</td></tr>
</table>

	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.	at isolated places. **15 October 2014:** Bihar: Heavy to very heavy rainfall at isolated places. East Uttar Pradesh: Heavy to very heavy rainfall at isolated places. Sub-Himalayan West Bengal & Sikkim: Isolated heavy rainfall.
13.10.14/ (0300)	Isolated heavy falls 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 to very heavy falls over Chhattisgarh & adjoining east Madhya Pradesh and interior Odisha during next 24 hrs and over East Uttar Pradesh, Jharkhand & Bihar during next 48 hrs.	
14.10.14/ (0300)	Heavy to very heavy falls 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.	

Table 4.19. Verification of Gale Wind Forecast

Date/ Time(UTC)	**Gale wind Forecast**	**Recorded wind**
06.10.14 (0300)	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 **09 October 2014:** Port Blair: 60 kmph **10 October 2014:** Port Blair: 64
07.10.14/ (0300)	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.	
08.10.14/ (0300)	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.	kmph **11 October 2014:** Machilipatnam: 88 kmph Visakhapatnam: 74 kmph **12 October 2014:** Visakhapatnam: 185kmph
09.10.14/ (0300)	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.	
10.10.14/ (0300)	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).	
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/ (0300)	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/ (0300)	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 4.19. Verification of Storm Surge Forecast issued by IMD

Forecast Storm surge above astronomical tide and area to be affected	Actual Storm Surge
09.10.14/0300 UTC 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) **10.10.14/0300 UTC** 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.

4.3.7. Very Severe Cyclonic Storm (VSCS) NILOFAR over the Arabian Sea (25-31 October 2014)

Following are the salient features of the bulletins issued by IMD (Table 4.21.).

Table 4.21. Salient features of the bulletins issued by IMD

Date and Time(UTC)	Current Status	Forecast issued
20.10.2014 (0300)	Cyclonic circulation over southeast Arabian Sea	A low pressure area may form over South Arabian Sea during next 48 hours and may subsequently concentrate into a depression
21.10.2014 (0300)	Low pressure area over southeast Arabian Sea	Likely to become well-marked low during next 48 hours.
23.10.2014 (0300)	Well-marked low pressure area over southeast and adjoining eastcentral Arabian Sea.	It would concentrate into a depression during next 24 hours. It would move initially northwestwards and may intensify into a cyclonic storm.

25.10.2014 (0000)	Depression over westcentral and adjoining southwest Arabian Sea	It would intensify into a deep depression within next 24 hrs and may intensify further into a cyclonic storm during subsequent 24 hrs. It would move initially west-northwestwards.
26.10.2014 (0300)	Deep Depression over westcentral and adjoining southwest Arabian Sea.	It would intensify into a Cyclonic Storm during next 12 hrs and into a severe cyclonic storm during subsequent 24 hrs and subsequently into a very severe cyclonic storm. It would move initially north-northwestwards during next 48 hrs and then recurve northeastwards towards North Gujarat and adjoining Pakistan coast. While moving towards north Gujarat coast, it would weaken into a severe cyclonic storm with wind speed of 90-100 kmph.
27.10.2014 (0000) UTC	Severe Cyclonic Storm over westcentral and adjoining southwest Arabian Sea	It would intensify further into a Very Severe Cyclonic Storm (130-140 kmph gusting to 155 kmph) during next 24 hrs. It would move initially northwards during next 24 hrs and then recurve northeastwards and cross North Gujarat and adjoining Pakistan coast around Naliya by 31st October as a severe cyclonic storm with wind speed of 100-110 kmph.
28.10.2014 (0600)	Very Severe Cyclonic Storm over westcentral Arabian Sea.	Maximum wind speed would be 160-170 kmph gusting to 185 kmph. It would cross North Gujarat and adjoining Pakistan coast around Naliya by 01st November Forenoon. As the system would come closer to Gujarat coast, it would weaken and cross the coast as a Cyclonic Storm (80-90 kmph).
28.10.2014 (1200)	Very Severe Cyclonic Storm over westcentral Arabian Sea.	Maximum wind speed: 200-210 kmph gusting to 230 kmph.
29.10.2014 (0300)	Very Severe Cyclonic Storm over westcentral Arabian Sea.	As the system would come closer to Gujarat coast, it would weaken and cross the coast as a marginal Cyclonic Storm with wind speed of 60-70 kmph gusting to 80 kmph.
29.10.2014 (1200)	Very Severe Cyclonic Storm over westcentral Arabian Sea.	As the system comes closer to Gujarat coast, it would weaken into a depression near North Gujarat coast by 31st October evening

4.3.7.1. Operational landfall forecast error

The system dissipated over the sea. However, a figure depicting the forecast track alongwith cone of uncertainty is shown below (Fig.4.2):

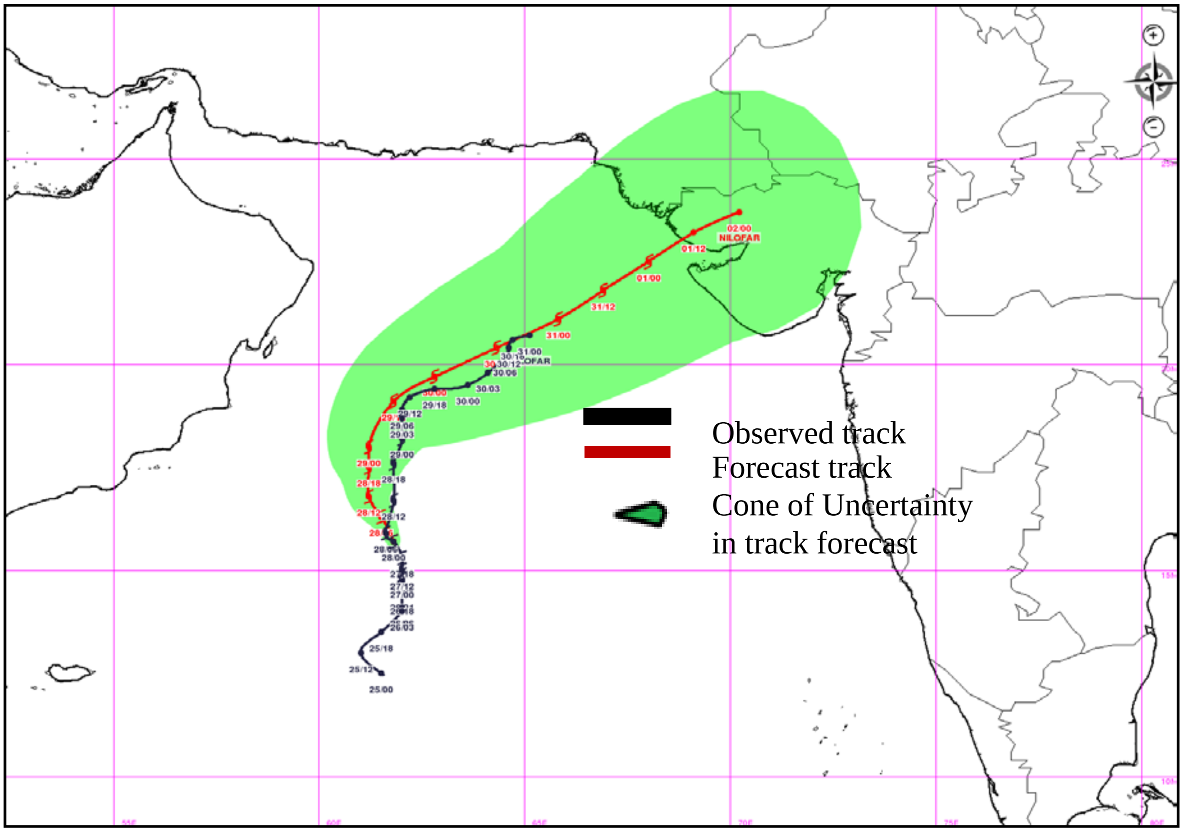

Fig. 4.2.An example of forecast track along with cone of uncertainty based on 0000UTC of 28th October 2014.

4.3.7.2. Operational track and intensity forecast error and skill

The operational average track forecast errors and skill are shown in Table 4.22. It was less than 100 km for the forecast time scales up to 60 hrs. The track forecast skill varied from 59% to 89 % for various time scales and was significantly higher than long period average.

The operational intensity forecast error in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 4.23. The AE varied from about 10 knots to 24 knots in different time scales. However, comparing the skill, the skill in intensity forecast compared to persistence forecast varied from 17% to 84% for different lead periods and has been significantly higher as compared to long period average skill (Table 4.23). Considering the RMSE, it varied from 13 knots to 27 knots for different forecast time scales. The skill varies from 25% to 83% and is significantly higher than the long period average skills.

Table 4.22. Operational average track forecast errors and skill of VSCS, Nilofar

Lead Period	**Track forecast error(km)**	**Track forecast skill (%) with reference to climatology and**	**Long period Average based on 2009-13**

(hrs)		persistence forecast	Track forecast error (km)	Track forecast skill (%)
12	64.7(17)	59	68.5	31.2
24	90.5 (15)	72	124.1	35.9
36	80.4 (13)	84	163.8	43.9
48	94.1 (11)	86	202.1	52.6
60	93.8 (9)	89	233.8	58.1
72	166.1 (7)	83	268.2	61.8
84	223.5 (5)	81	-	-
96	221.7 (3)	83	-	-
108	275 (1)	74	-	-

-: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. 120 hr forecast could not be verified as the cyclone dissipated over the sea.

Table -4.23. Operational Intensity forecast errors (knots) of VSCS, Nilofar

Lead period (hrs)	Absolute Error	Root mean square (RMS) Error	Long period Average (2009-2013):	
			Absolute Error	RMS Error
12	10.0	12.8	10.4	14.0
24	17.1	19.6	15.7	20.5
36	23.7	27.4	20.5	25.2
48	23.9	27.4	22.5	27.6
60	21.6	25.4	23.5	26.4
72	17.4	19.3	26.7	30.8
84	15.3	17.5	-	-
96	22.2	22.5	-	-
108	21.8	21.8	-	-

Table –4.24. Operational Intensity Forecast skill (%)of VSCS, Nilofar

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	16.9	24.8	10.4	14.0
24	31.7	47.5	15.7	20.5
36	34.4	54.1	20.5	25.2
48	57.9	67.1	22.5	27.6
60	58.7	59.1	23.5	26.4
72	75.4	77.0	26.7	30.8
84	84.1	83.5	-	-
96	11.9	76.4	-	-
108	75.8	75.8	-	-

4.3.7.3. Adverse weather forecast verification of VSCS, Nilofar

The adverse weather warning verification is presented in Table 4.25-.26

Table 4.25.Gale wind forecast verification of VSCS, Nilofar

Date/ Time(IST)	**Gale wind Forecast**	**Recorded wind**
26.10.2014/ 1430	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would commence along and off Gujarat coast from 30th October morning.	**Gujarat:** **31st** October 2014 Dwarka recorded 30 kmph at 1435 IST and Okha recorded 25 kmph at 1828 IST Deesa recorded wind speed of 20 kmph.
27.10.2014/ 0530	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would commence along and off Gujarat coast from 30th October morning and would become 100-110 kmph gusting to 125 kmph at the time of landfall	
28.10.2014/ 0530	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would commence along and off Gujarat coast from 31st October night and would become 80-90 kmph gusting to 100 kmph at the time of landfall.	
29.10.2014/ 0830	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would commence along and off Gujarat coast from 31st October and would become 60-70 kmph gusting to 80 kmph at the time of landfall.	
29.10.2014/ 1730	Squally wind speed reaching 40-50 kmph gusting to 60 kmph would prevail along and off Gujarat coast on 31st October.	
31.10.2014/ 0230	Squally wind speed reaching 35-45 kmph gusting to 55 kmph would prevail along and off Gujarat coast today the 31st October.	

Table 4.26. Heavy rainfall forecast verification of VSCS, Nilofar

Date/ Time(IST)	Forecast Rainfall	Observed Rainfall
26.10.2014/ 1430	Isolated heavy to very heavy falls along coastal districts of Saurashtra and Kutch from 30th morning.	**Gujarat**: No rainfall due to weakening of the system over the sea itself
27.10.2014/ 0530	Isolated heavy to very heavy falls along coastal districts of Saurashtra and Kutch from 30th morning. Intensity would increase gradually with heavy to very heavy falls at a few places and isolated extremely heavy falls from the night of 30th.	
28.10.2014/ 0530	Isolated heavy to very heavy falls along coastal districts of Saurashtra and Kutch from 31st night.	
29.10.2014/ 1730	Isolated heavy to very heavy falls over all districts of Saurashtra and Kutch and North Gujarat on 30th and 31st October.	
30.10.2014/ 0830	Isolated heavy to very heavy falls over Kutch and coastal districts of Saurashtra during next 48 hrs. Isolated heavy falls over remaining districts of Saurashtra, north Gujarat and southwest Rajasthan during the same period.	
31.10.2014/ 0230	Isolated heavy to very heavy falls over Kutch and coastal districts of Saurashtra during next 24 hrs. Isolated heavy falls over remaining districts of Saurashtra, north Gujarat and southwest Rajasthan during the same period.	
31.10.2014/ 0830	Moderate rainfall at many places over Kutch and Saurashtra during next 24 hrs	

The severe cyclonic storm, Nilofar had a unique characterstic, along with rapid intensification and rapid weakening. Though this track could be predicted well with reasonable accuracy, the intensity was over predicted especially during its rapid weakening phase. Of course, the weakening of the cyclone was indicated in the bulletin even when the cyclone was in intensification phase. Due to over prediction of intensity during rapid weakening phase, there was over warning of wind and rainfall over Saurastra & Kutch coast. These aspects of rapid weakening near the coast before landfall need further improvement. However, as it was expected to weaken while reaching the coast, no surge was predicted by IMD.

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

The salient features of the bulletins issued by IMD are furnished in Table 4.27.

Table 4.27. Salient features of the bulletins issued by IMD for Deep Depression over bay of Bengal (5-8 Nov 2014)

Date and Time(UTC)	Current Status	Forecast issued
05.11.2014 (0900)	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 (0300)	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 (0300)	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 (0600)	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.

4.3.8.1. 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.

4.3.8.2. Operational track and intensity forecast error and skill

The operational average track forecast errors and skill are shown in Table 4.28. 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 4.29(a-b). The 12hr intensity forecast error is greater than the persistence forecast error and hence the 12hr intensity forecast skill is negative.

Table 4.28 Operational average track forecast errors and skill for Deep Depression over bay of Bengal (5-8 Nov 2014)

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 4.29a Operational Intensity forecast errorsfor Deep Depression over Bay of Bengal (5-8 Nov 2014)

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 4.29b. Operational Intensity Forecast skill (%) for Deep Depression over Bay of Bengal (5-8 Nov 2014)

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

4.3.6.3 Adverse weather forecast verification for Deep Depression over Bay of Bengal (5-8 Nov 2014)

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 4.28-4.30.

Table 4.28.Gale wind forecast verification for Deep Depression over Bay of Bengal (5-8 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 4.29. Rainfall forecast verification for Deep Depression (05-08 November 2014)

Date/ Time(IST)	**Forecast Rainfall**	**Observed Rainfall (cm)**
05.11.2014/ 1430	Isolated heavy to very heavy falls over Andaman & Nicobar Islands during the next 48 hours.	Nil
06.11.2014/ 0530	Isolated heavy to very heavy falls over Andaman during the next 24 hours.	

06.11.2014/ 0830	Nil	
07.11.2014/ 0830	Nil	
08.11.2014/ 0530	Nil	
08.11.2014/ 0830		

4.4. Annual Performance cyclone landfall, Track and intensity forecast

The annual tropical cyclone track forecast error has been calculated for the year 2014.The annual average track forecast error (Fig.4.3a) has been 76 km, 86 km and 114 km, respectively for 24, 48 and 72hrs against the long period average error of 124, 202 and 268 km based on data of 2009-2013. The 96 and 120 hr track forecast error were 135 and 203 km respectively which are also very less. Also the track forecast skills compared to climatology and persistence forecast (Fig.4.3b) are 66%, 82% and 85% respectively for the 24, 48 and 72 hrs lead period which is much higher than long period average of 2009-2013 (36%,53% & 62% respectively). The landfall forecast error varied from 2 to 20 km for 12 to 72 hrs forecast (Table 4.31). The landfall time error was also very less varying from 1 to 4 hrs. Similarly, the annual average intensity forecast error (Fig.4a) has been 15 nautical miles per hour (knots), 22 knots and 21 knots respectively for 24, 48 and 72 hrs lead period of forecast against the long period average of 16, 23 and 27 knots. The skill compared to persistence forecast (Fig.4b) were 38%, 52% and 63% respectively which is also much higher than the long period average of 16%, 23% and 27% respectively.

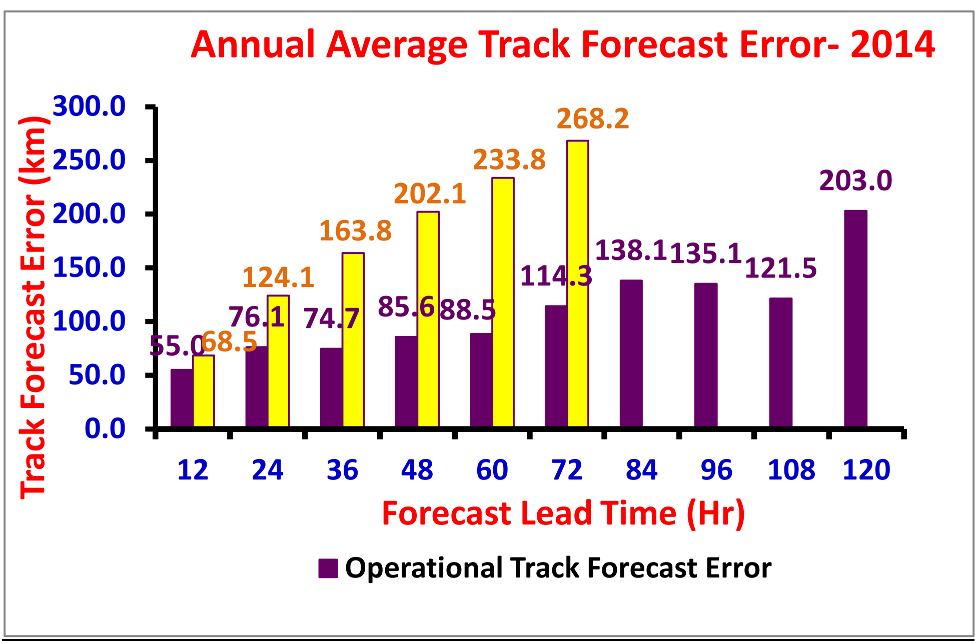

Fig.4.3a. Annual Average Track Forecast Error-2014

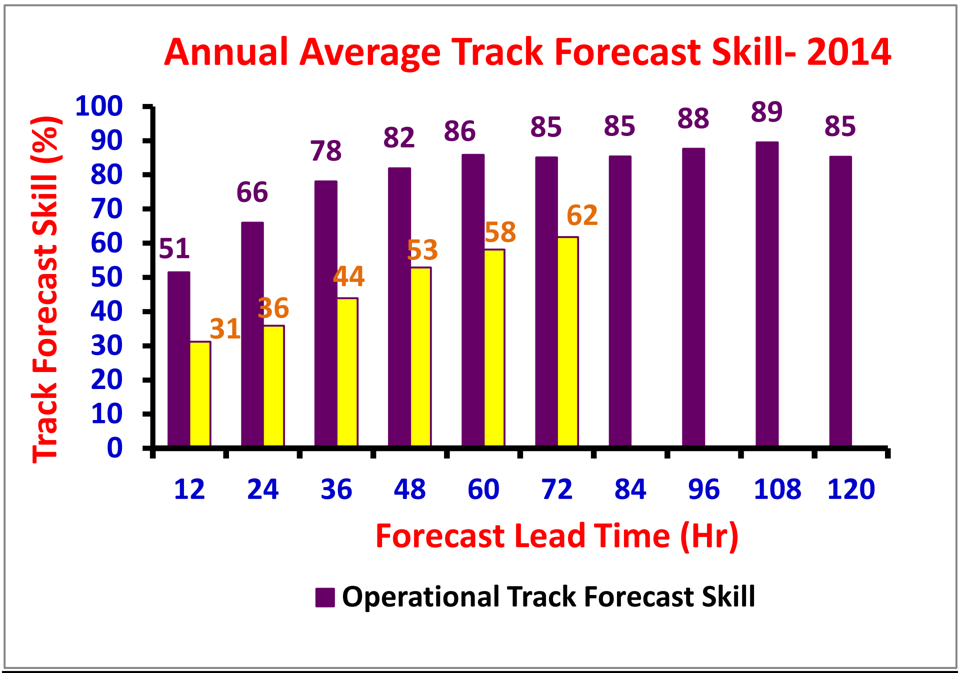

Fig.4.3b. Annual Average Track Forecast Skill-2014

Table 4.31. Operational landfall point and time forecast errors

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	39	2
31	20	0 h	75	4
43	17	4 h early	95	8
55	04	4 h early	97	7
67	08	3 h early	84	4
79	02	1 h early	124	2
91	24	3 h early	-	-
103	40	3 h early	-	-

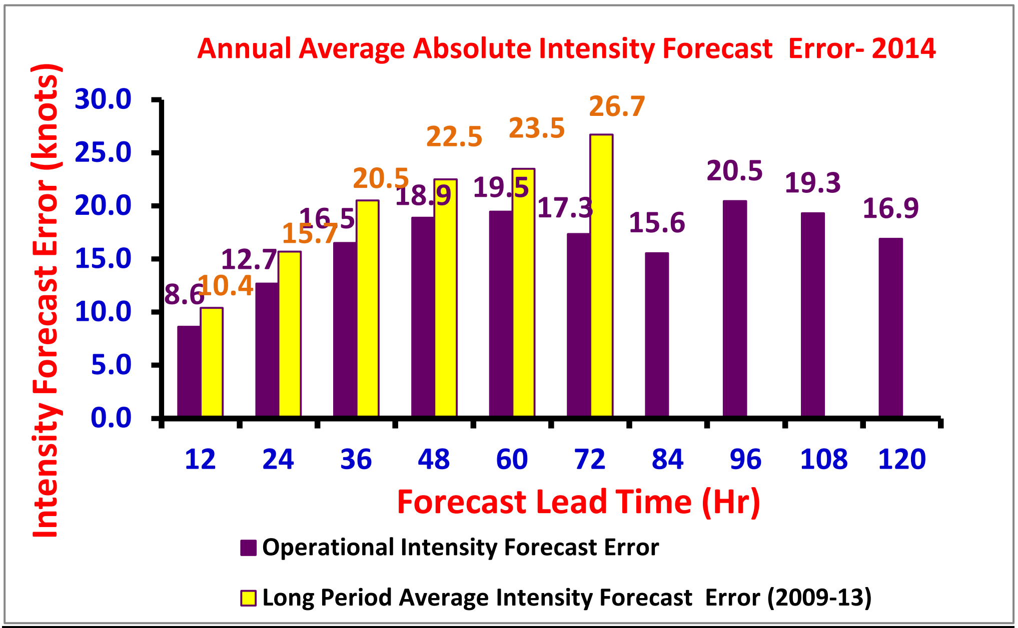

Fig. 4.4a. Annual Average Absolute Intensity Forecast Error-2014

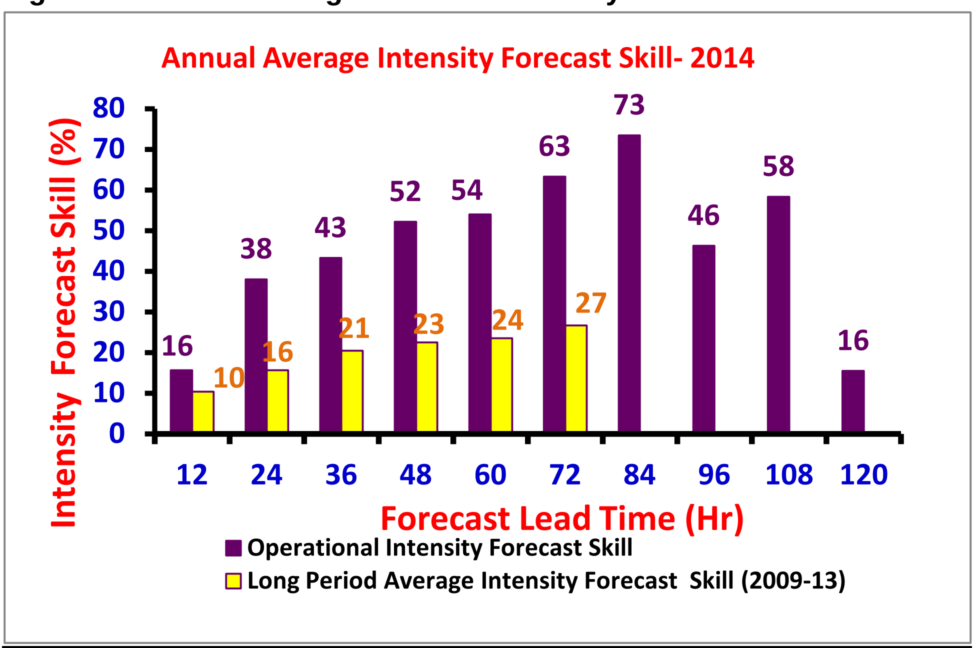

Fig. 4.4b. Annual Average Intensity Forecast Skill-2014

4.5. Interannual variation

4.5.1. Landfall forecast error

The landfall point and time forecast errors of cyclones over north Indian Ocean during 2003-14 are shown in Fig.4.5 (a and b). It is found that the errors are decreasing significantly in recent years. The 12 and 24 hr landfall point forecast errors have reduced at the rate of 14 and 29 km per year. Similarly the landfall time forecast error has reduced at the rate of 0.2 and 0.5 hr per year for 12 and 24 hr forecasts respectively during 2003-14.

4.5.2. Track forecast error and skill

The track forecast errors and skill as compared to climatology and persistence (CLIPER) model based forecast errors of cyclones over north Indian Ocean during 2003-14 are shown in Fig.4.6 (a and b). It is found that the errors are decreasing significantly in recent years. The 12 and 24 hr track forecast errors have reduced at the rate of 4.7 and 7.6 km per year. Similarly the track forecast skill has improved at the rate of 7.4% and 4.2% per year for 12 and 24 hr forecasts respectively during 2003-14.

4.5.3. Intensity forecast error and skill

The intensity forecast errors and skill as compared to persistence based forecast errors of cyclones over north Indian Ocean during 2003-14 are shown in Fig.4.7 and 4.8(a and b). It is found that the errors are decreasing in recent years. However, the rate of decrease is less than that of track forecast error.The 12 and 24 hrs intensity forecast errors have decreased a the rate of 0.2 knot and 0.6 knot for year 2014 respectively considering both AE and RMSE. The 12 and 24 intensity forecasts skills have improved at the rate of 1.4% and 4.9% respectively considering AE and 2.6% and 4.5% respectively considering the RMSE during 2005-14.

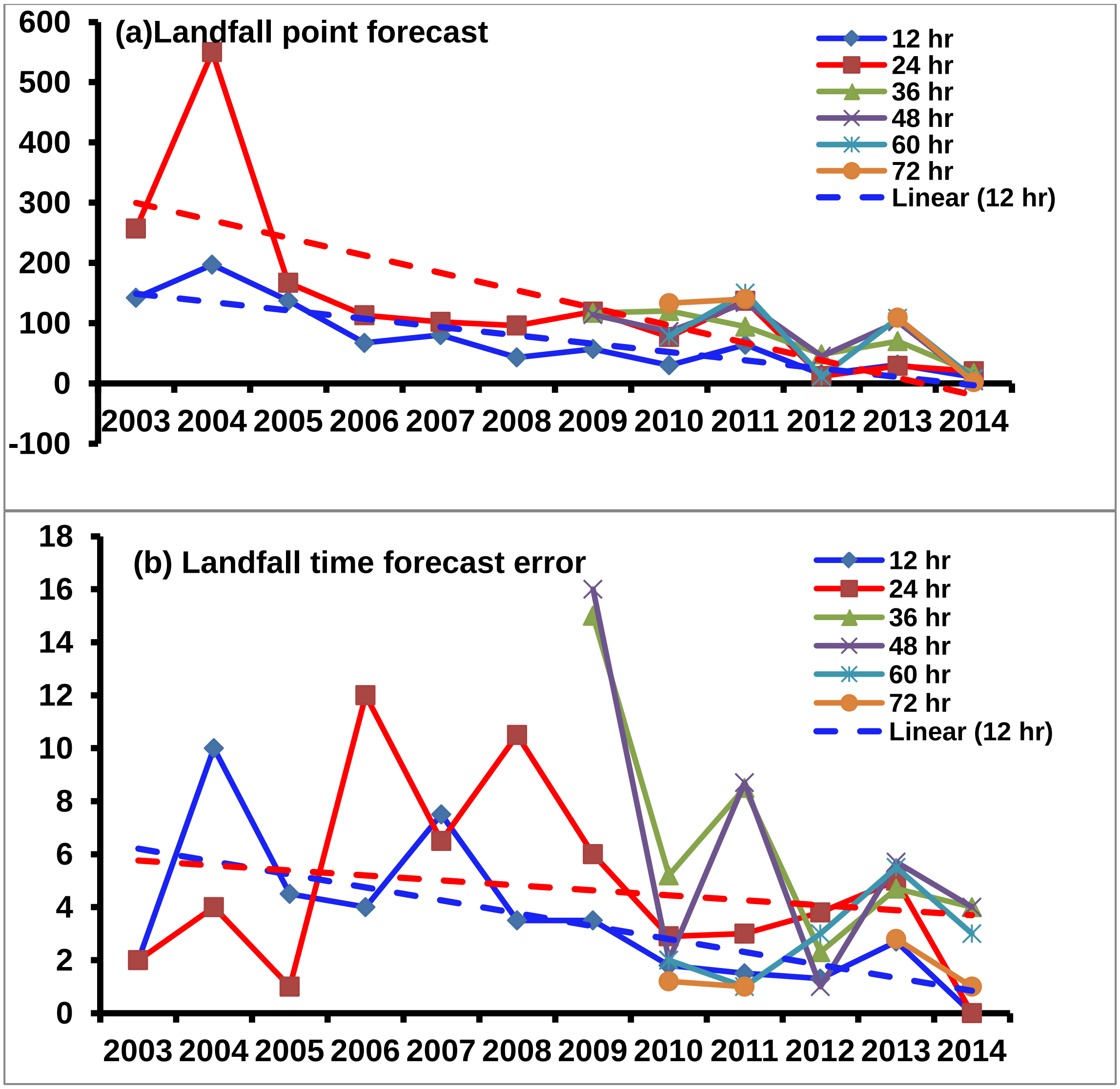

Fig4.5(a-b). Landfall point and time forecast errors of cyclones over north Indian Ocean during 2003-14

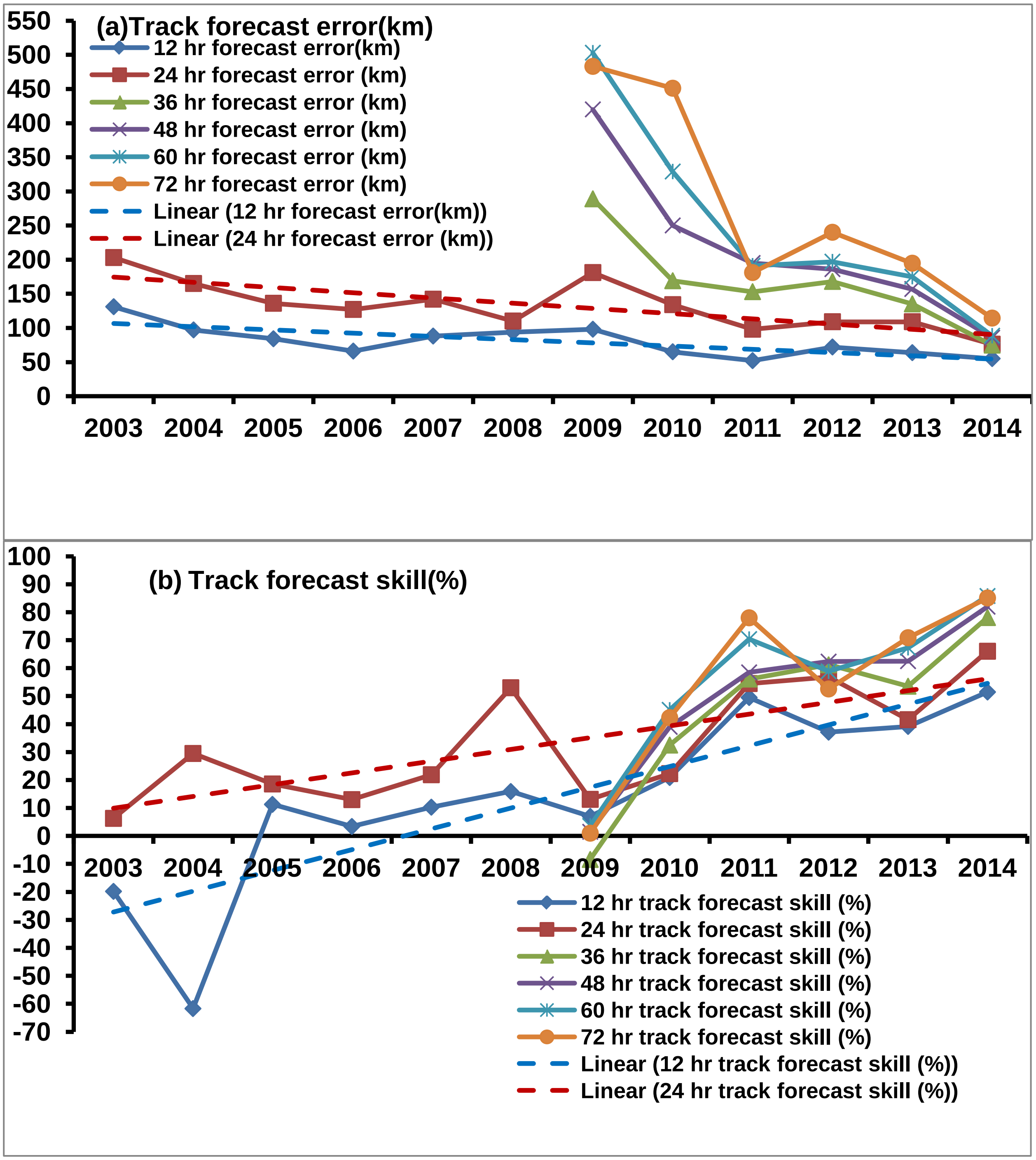

Fig.4.6. (a).Annual average track forecast error(km) (b). skill (%) of cyclones over the north Indian Ocean

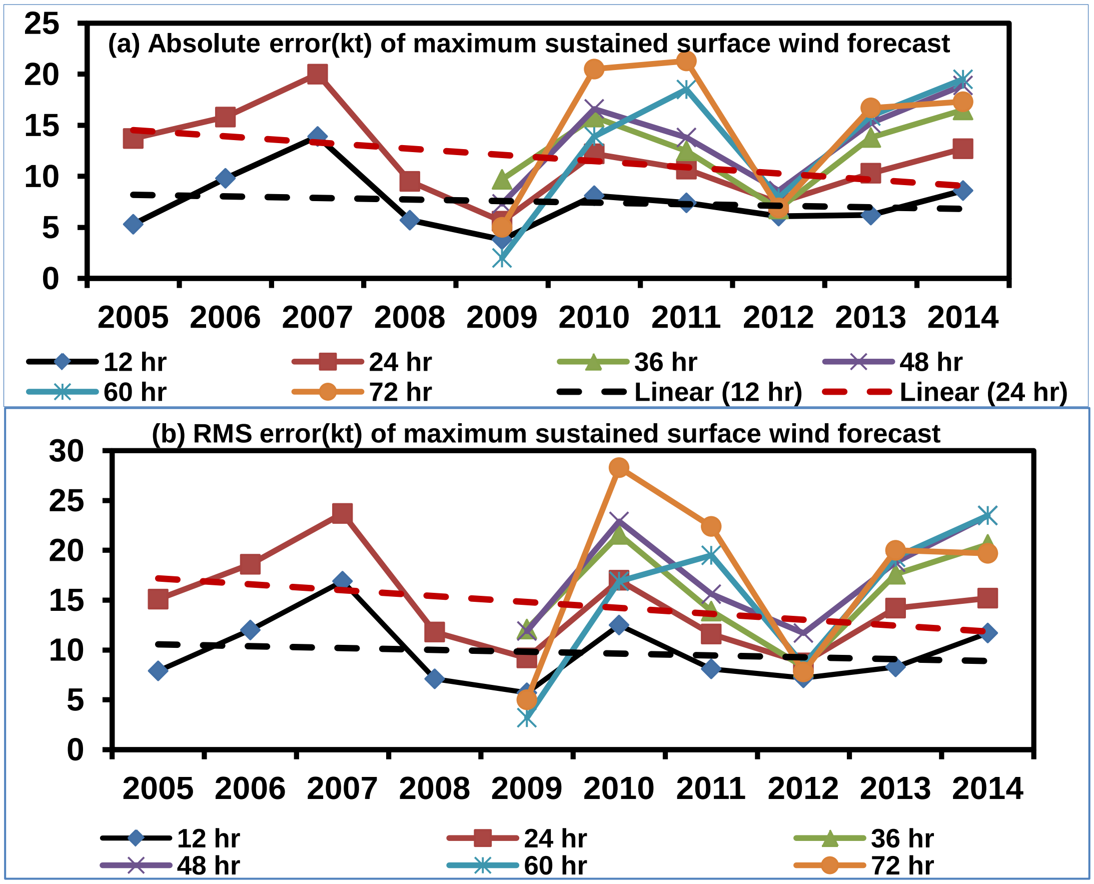

Fig.4.7. Annual average (a) absolute error (knots) and (b) root mean square error (knots) in intensity forecast of cyclones over the north Indian Ocean

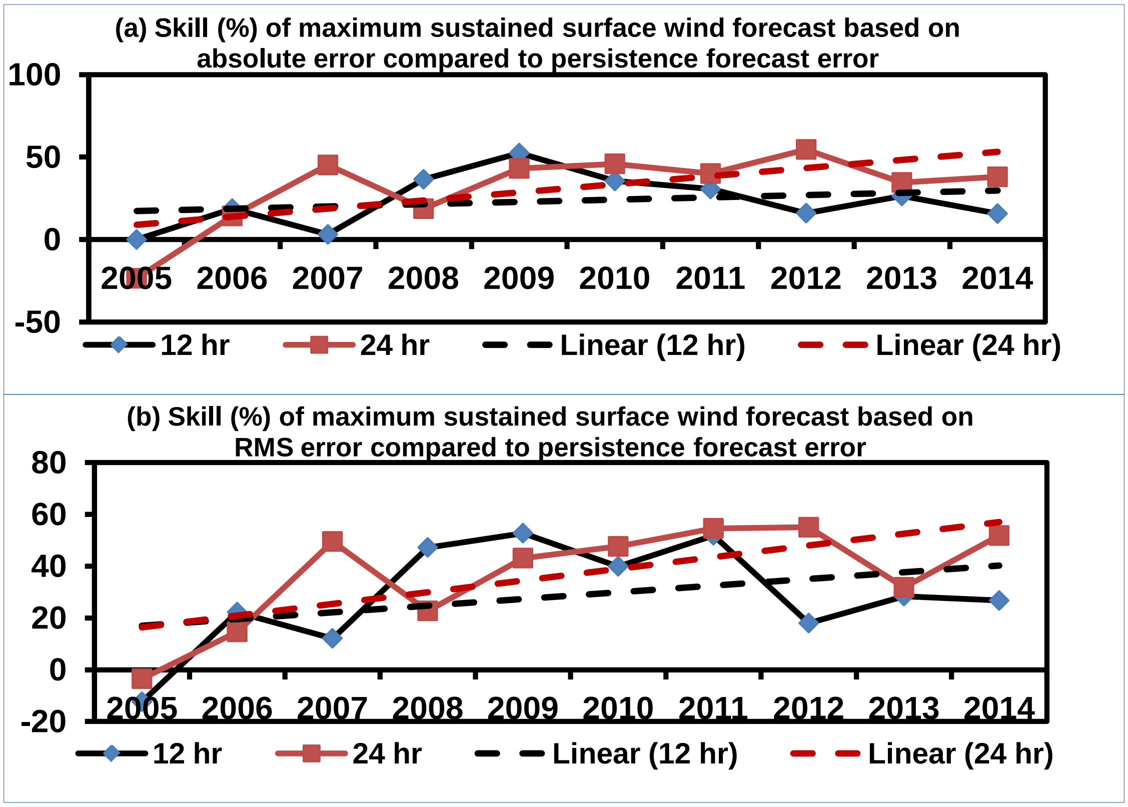

Fig.4.8. Annual average (a) absolute error (knots) and (b) root mean square error (knots) in intensity forecast of cyclones over the north Indian Ocean

The ravaged Visakhapatnam Airport

The Visakhapatnam beach-front was eroded

Gushing waves, whiplashes and splashes

The Visakhapatnam beach-front was eroded by surge and waves

The collapsed telephone tower

Overturned a college bus and up-rooted an electric pole at Visakhapatnam

DAMAGE DUE TO VSCS 'HUDHUD'(07-14 OCT. 2014)