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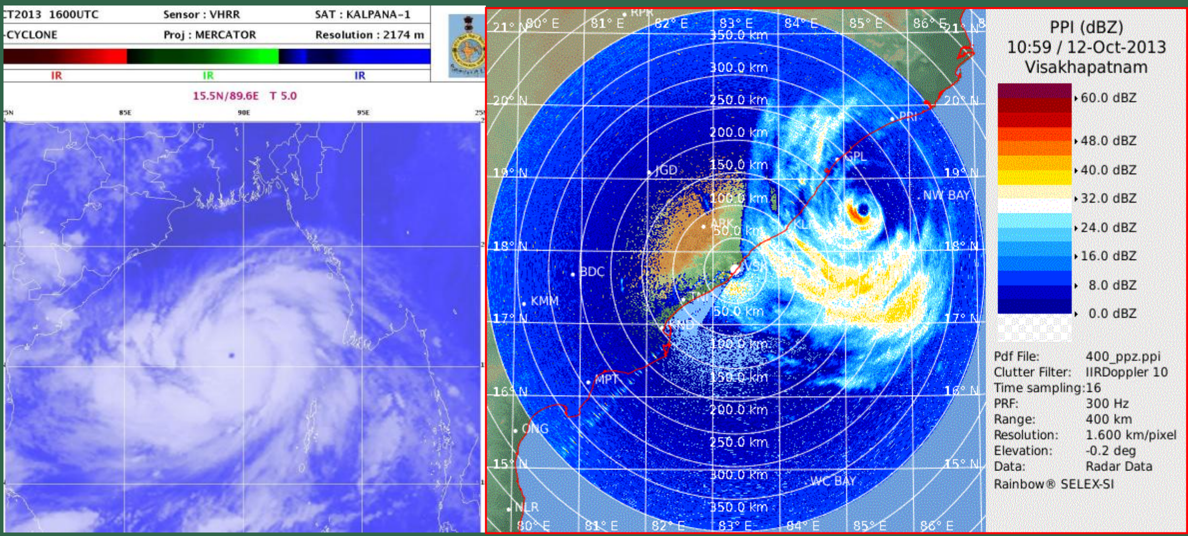
REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2013



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

RSMC-TROPICAL CYCLONES, NEW DELHI

MAY 2014

WMO

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 2013. 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 CENTRE – 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.

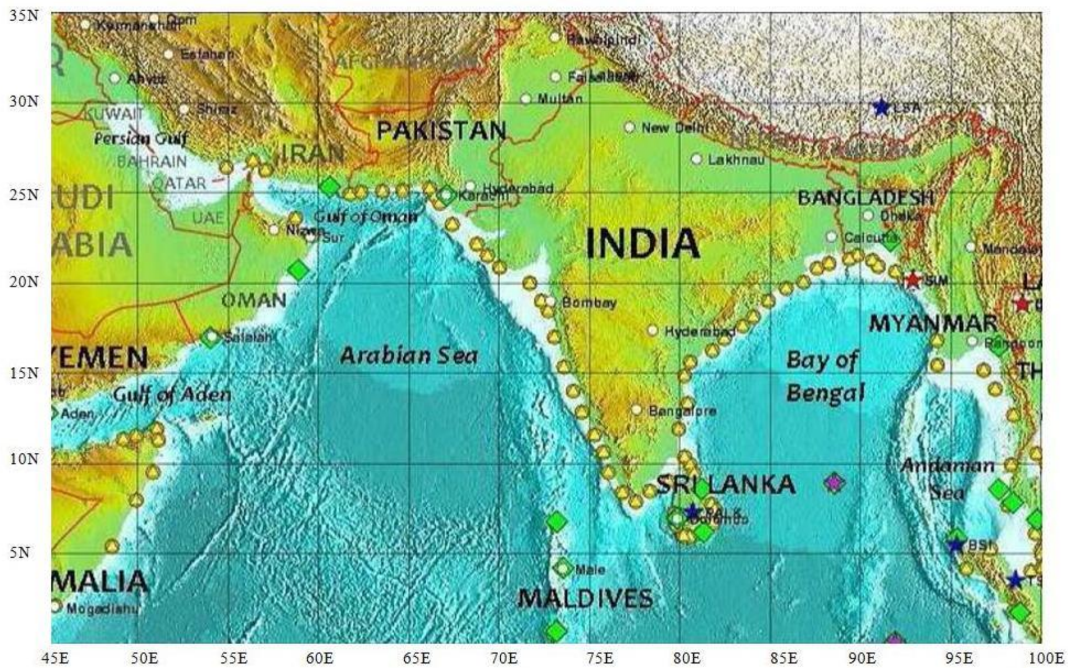


Fig. 1.1 Area of responsibility of RSMC- Tropical Cyclone, New Delhi

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 is continuing the naming of Tropical Cyclones formed over North Indian Ocean since October 2004. 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 countrywise in each column. The names are used sequentially columnwise. 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, 35 names have been utilized till the end of year 2013.

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. A number of Automated Weather Stations (AWS) are also in operation along the coast and provide surface observations on hourly basis which are utilized in cyclone monitoring and forecasting. The surface observatory network of IMD is shown in fig 1.2

Fig.1.2. The surface Observatory Network of IMD

1.3.2. Upper Air Observatories

There are at present 62 Pilot Balloon Observatories, 37 Radiosonde/ Radio wind observatories and 02 Radio sonde Observatory. 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.

1.3.3. Cyclone Detection Radars

There are 11 S-band radars for Cyclone detection located at Kolkata, Chennai, Visakhapatnam, Machilipatnam, Sriharikota, Paradip, Karaikal, Kochi, Goa, Mumbai and Bhuj. Out of these 11 stations, 6 stations (except Kolkata, Chennai, Visakhapatnam, Machilipatnam, Sriharikota) are using conventional S-band radars. Four numbers of S-band Doppler Weather Radars (Meteor 1500 S) imported from M/s Gematronik, Germany were installed, commissioned and made operational at Chennai, Kolkata, Machilipatnam and Visakhapatnam respectively with effect from 22.02.2002., 29.01.2003, 08.12.2004 and 27.07.2006 respectively. One indigenous Doppler Weather Radar developed by Indian Space Research Organization (ISRO) under IMD-ISRO collaboration has also been installed and made operational at SHAR Centre, Sriharikota (Andhra Pradesh) with effect from 9 April, 2004. As the radars at Goa, Mumbai, Paradip, Karaikal, Bhuj and Kochi has become old/obsolete, these radars are under the process of replacement.

IMD is modernizing its observational network in the phased manner. In the first phase, 12 numbers Doppler Weather Radar have been procured from M/s Beijing Metstar Co. Ltd. China. Out of these, 3 DWRs meant for Goa, Karaikal and Paradip could not be installed at coastal site due to some unavoidable reasons and these are planned for re-location at inland stations. 2 S-band DWRs procured from M/s BEL, Bangalore have been installed at Mumbai & Bhuj. Four DWRs meant for Kochi, Goa, Karaikal and Paradip are under process of installation.

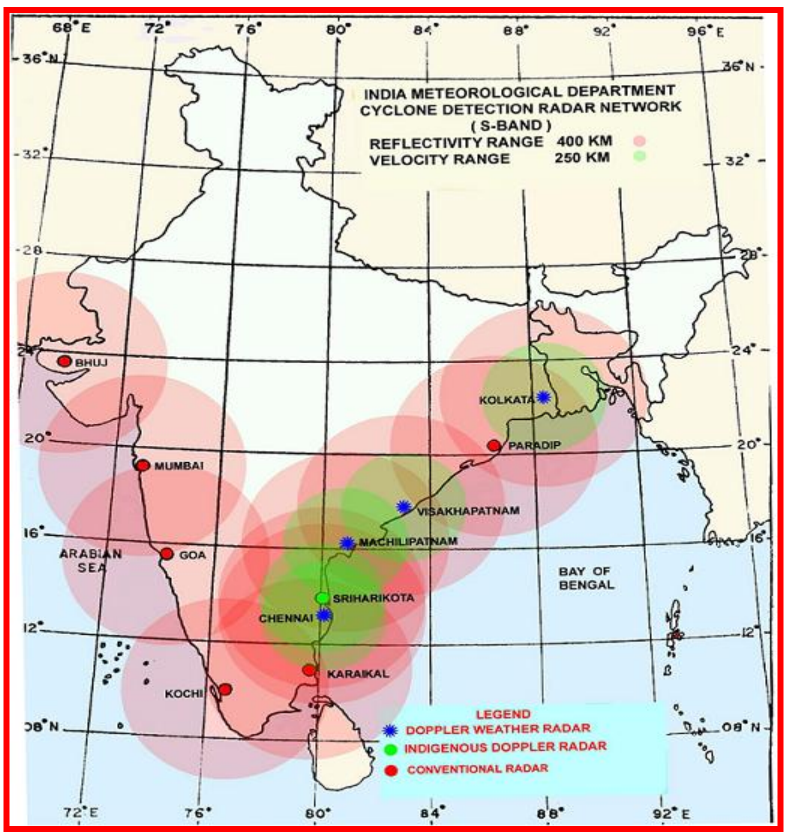


Fig. 1.3. S-Band Cyclone Detection Radar Network

DWRs Provide vital informations on radial velocity and spectral width in addition to reflectivity. Reflectivity estimates obtained from these radars are more accurate in comparison to those from conventional radars as the DWRs have capability for correcting the values for clutters, bright band etc. Surface Rainfall Intensity (second level product derived from reflectivity) and other hydrological products like Precipitation Accumulation (PAC), Vertical Integrated Liquid (VIL) are very important for issuing warnings for heavy rain, flash flood and hail. The algorithms for generation of these products employ some adaptable parameters which depend on Drop Size Distribution (DSD) present in the precipitation (DSD is different for different season, geographical location and type of precipitation).

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 pay load 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 Centre (NSDC), New Delhi. Indian 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 0.25^0X0.25^0 resolution
2. Quantitative Precipitation Estimation (QPE) at $1^0/1^0$ resolution
3. Sea Surface Temperature (SST) at $1^0/1^0$ resolution
4. Cloud Motion Vector (CMV)
5. Water Vapor 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 widely 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/INSAT-3A/INSAT-3D data products, imageries and satellite bulletins are archived. The automatic script is being used to keep and update the images/products on the website for 1 month. These are available to all users.

On 23rd Sept 09, polar orbiting satellite OCEANSAT–II has been launched by Indian Space Research Organisation (ISRO) which carries 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 are used regularly for locating the centre and intensity of the tropical systems in the formative stage.

Space Application Centre (SAC), ISRO Ahmedabad has developed a technique to predict the formation of tropical cyclones over north Indian Ocean (Bay of Bengal & Arabian Sea) before 24-96 hrs lead time based on OCEANSAT-II Scatterometer wind. Satellite Division of IMD has acquired the software and validating the technique before making it operational.

On 12th October, 2011 another Polar orbiting satellite MEGHA TROPIQUES has been launched which covers the area 20º N to 20º S. MEGHA TROPIQUES has three payloads:

1. MADRAS: a microwave imager aimed mainly at studying precipitation and clouds properties,
2. SAPHIR: a 6 channels microwave radiometer for the retrieval of water vapour vertical profiles and horizontal distribution,
3. SCARAB: a radiometer devoted to the measurement of outgoing radiative fluxes at the top of the atmosphere.

The basic principles of the MEGHA-TROPIQUES mission are to provide simultaneous measurements of several elements of the atmospheric water cycle, water vapour, clouds, condensed water in clouds, precipitation and evaporation, measure the corresponding radiative budget at the top of the atmosphere, ensure high temporal sampling in order to characterise the life cycle of the convective system and to obtain significant statistics. However the MADRAS component is not serviceable at present.

1.3.4.2. Digital Meteorological Data Dissemination:

IMD transmits processed imagery, meteorological data and facsimile weather charts to field forecasting offices distributed over the country using the Digital Meteorological Data Dissemination (DMDD) facility, through INSAT in broadcast mode. The bulletins providing description of the cloud organization and coverage are also sent as advisory to forecasting offices every synoptic hour. When cyclones are detected in satellite imagery, these bulletins are sent every hour. Such advisories are also transmitted to the neighbouring countries.

Processed satellite imagery, analyzed weather charts and conventional synoptic data are up-linked to the satellite in C-band. Satellite broadcasts these data to DMDD receiving stations in S-band. DMDD receiving stations analyze weather imagery and other data to generate required forecast. There are 37 no. of DMDD stations installed in India. Three DMDD receiving stations are also operating in neighbouring SAARC countries at Sri Lanka, Nepal and Maldives. These stations are receiving direct broadcast of cloud imagery, weather facsimile charts and meteorological data on an operational basis. The frequency of transmission from ground to satellite (uplink) is 5886 MHz and that of downlink is 2586 MHz.

1.3.4.3 Future Plan

1. There is a plan to develop state of art Satellite Data Centre.
2. 25 numbers of GNSS stations network will be installed all over India by mid 2014.
3. 4 nos. of DMDD systems to be installed in Afghanistan, Bhutan, Bangladesh & Myanmar.
4. It has been planned to procure software for better monitoring & warning of severe weather events.
5. Planning for automization of Advanced Dvorak Technique and 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.1.4.

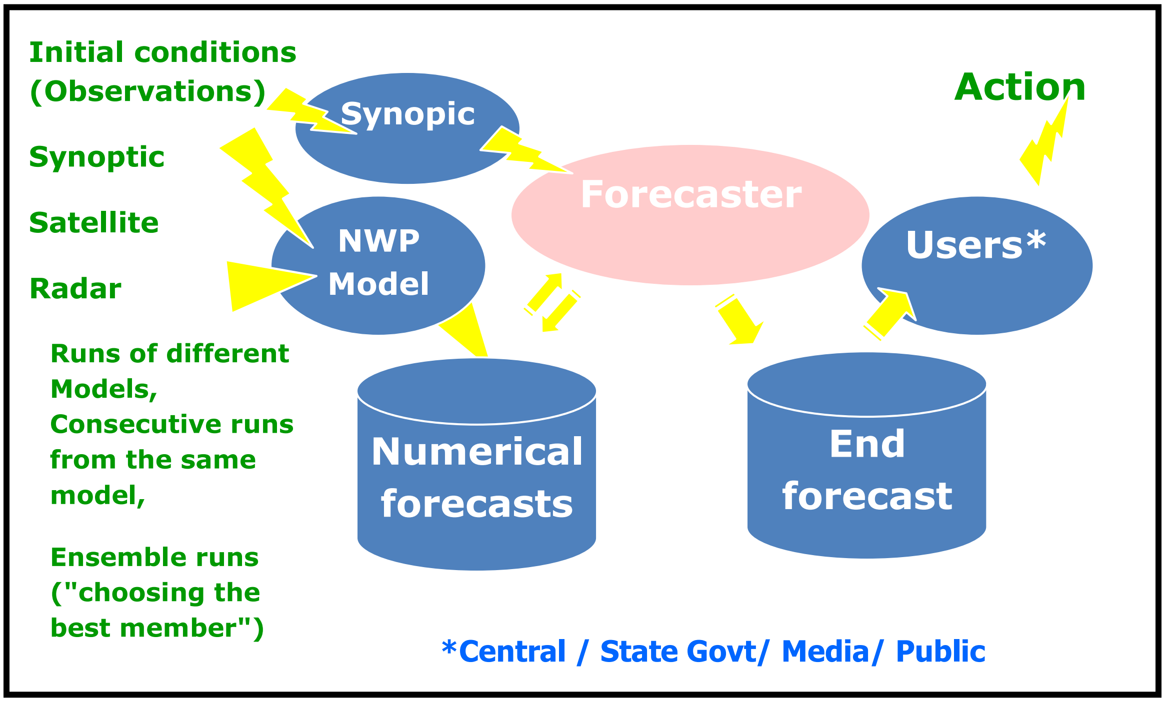


Fig.1.4. Strategy adopted for cyclone analysis and forecasting

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 upto 120 hrs
- Depiction of uncertainty in track forecast

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 centres

- ❖ Dynamical and statistical Model products from various national and international centres.
- ❖ Data, analysis and forecast products from various national and international centres 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 like Oceansat-2, ASCAT & WINDSAT 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 WVWV 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 centre 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 2013

1.5.1. Global Forecast System

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

1.5.2. NCMRWF Model

This model which is adopted from UK Meteorological office (UKMO) is also run National Centre for Medium Range Weather Forecasting (NCMRWF). It is run once a day based on 0000 UTC. The real time inputs are available in NCMRWF website. This model has a spatial resolution of around 25 km

1.5.3. Regional Forecast System

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

1.5.3.1. 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. 25º S 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 centres, very high resolution mesoscale models (WRF at 3 km resolution) are also operational with their respective regional setup/configurations.

1.5.3.2. Quasi-Lagrangian Model (QLM)

The QLM, a multilevel fine-mesh primitive equation model with a horizontal resolution of 40 km and 16 sigma levels in the vertical, is being used for tropical cyclone track prediction in IMD. The integration domain consists of 111x111 grid points centred over the initial position of the cyclone. The model includes parameterization of basic physical and dynamical processes associated with the development and movement of a tropical cyclone. The two special attributes of the QLM are: (i) merging of an idealized vortex into the initial analysis to represent a storm in the QLM initial state and (ii) imposition of a steering current over the vortex area with the use of a dipole. The initial fields and lateral boundary conditions are taken from the IMD GFS T574L64. The model is run twice a day based on 00 UTC and 12 UTC initial conditions to provide 6 hourly track forecasts valid up to 72 hours. The track forecast products are disseminated as a World Weather Watch (WWW) activity of RSMC, New Delhi.

1.5.3.3. Hurricane WRF Model (HWRF)

Recently under Indo-US joint collaborative program, IMD adapted Hurricane-WRF model for Tropical Cyclone track and intensity forecast for North Indian Ocean (NIO) region for its operational requirements. The basic version of the model HWRFV (3.2+) which was operational at EMC, NCEP, USA was ported on IMD IBM P-6/575 machine with nested domain of 27 km and 9 km horizontal resolution and 42 vertical levels with outer domain covering the area of 800x800 and inner domain 60x60 with centre of the system adjusted to the centre of the observed cyclonic storm. The outer domain covers most of the NIO including the Arabian Sea and Bay of Bengal and the inner domain mainly covers 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.

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

1.5.4. NWP based Objective Cyclone Prediction System (CPS)

The method comprises of five forecast components, namely (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) Predicting decaying intensity after the landfall.

1.5.4.1 Genesis Potential Parameter (GPP)

A cyclone genesis parameter, termed the genesis potential parameter (GPP), for the NIO is developed (Kotal et al, 2009). The parameter is defined as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability, and the inverse of vertical wind shear. The parameter is operationally used for distinction between non-developing and developing systems at their early development stages. The composite GPP value is found to be around three to five times greater for developing systems than for non-developing systems. The analysis of the parameter at early development stage of a cyclonic storm 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.imd.gov.in/section/nhac/dynamic/Analysis.htm). Higher value of the GPP over a region indicates higher potential of genesis over the region. Region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis. The analysis of the parameter and its effectiveness during cyclonic disturbances in 2012 affirm its usefulness as a predictive signal (4-5 days in advance) for cyclogenesis over the NIO.

1.5.4.2. Multi-model ensemble (MME) technique

The multi model ensemble (MME) technique (Kotal and Roy Bhowmik, 2011) is based on a statistical linear regression approach. The predictors selected for the ensemble technique are forecasts latitude and longitude positions at 12-hour interval up to 72-hour of five operational NWP models. In the MME method, forecast latitude and longitude position of the member models are linearly regressed against the observed (track) latitude and longitude position for each forecast time at 12-hours intervals for the forecast up to 120 hours. 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,….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. IMD also makes use of NWP products prepared by some other operational NWP Centres like GFS (NCEP), JMA (Japan Meteorological Agency), UKMO etc. A collective bias correction is applied in the MME by applying multiple linear regression based minimization principle for the member models WRF(ARW), GFS(IMD), GFS(NCEP), UKMO and JMA. All these NWP products are routinely made available in real time on the IMD web site (www.imd.gov.in.)

1.5.4.3. Statistical Dynamical model for Cyclone Intensity Prediction (SCIP)

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

1.5.4.4.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 by 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.

1.5.4.5. Decay of Intensity after the landfall

Tropical cyclones 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.

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

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

1.5.6. NCMRWF Global Ensemble Forecast System (GEFS)

At NCMRWF the GEFS configuration consists of four cycles corresponding to 00Z, 06Z, 12Z 18Z and 10-day forecasts are made using the 00Z initial condition.A T190L28 control that is started with T574L64 analysis and run out to 10 days.20 perturbed forecasts each run out to 10 days at T190L28 horizontal and vertical resolution. The initial perturbations are generated using Ensemble Transform with Rescaling (ETR) method. (See Wei et al., 2007; Initial perturbations based on the ensemble transform (ET) technique in the NCEP global operational forecast system; Tellus). In GEFS, ensemble mean & spread, strike probability as well as probabilistic forecast of precipitation and wind are generated.

The ensemble spread is a measure of the difference between the members and is represented by the standard deviation *with respect to the ensemble mean (EM)*. On average, small (*high*) spread indicates a high (*low*) forecast accuracy. The ensemble spread is flow-dependent and varies for different parameters. It usually increases with the forecast range, but there can be cases when the spread is larger at shorter forecast ranges than at longer. This might happen when the first days are characterized by strong synoptic systems with complex structures but are followed by large-scale "fair weather" high pressure systems.

The probability that 24-hour precipitation amounts over a 2.5x2.5 lat-lon grid box will exceed certain threshold values is calculated. The forecast probability is estimated directly from the 20-member global ensemble. At each grid point the number of ensemble members having a 24-hour precipitation amount within a specified range (e.g. 1-2cm, 2-5cm etc) is counted (M) and the probability is expressed as 100*(M/20).

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. The Special Tropical Weather Outlooks are issued at 0600 & 1500 UTC based on 0300 & 1200 UTC observations respectively when a tropical depression formover 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 upto 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 http://www.imd.gov.in. RSMC, New Delhi can also be contacted through e-mail or cwdhq2008@gmail.com) for any real time information on cyclonic disturbances over NIO.

1.6.2. 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 upto 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: http://www.imd.gov.in . RSMC, New Delhi can also be contacted through e-mail or cwdhq2008@gmail.com) for any real time information on cyclonic disturbances over NIO.

1.6.3. Global Maritime Distress Safety System (GMDSS)

Under Global Maritime Distress 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 located at Mumbai and Chennai.

1.6.4. 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 (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 and AFTN channels to designated International Airports of the region prescribed by ICAO. It is also being sent in graphics format through GTS and ftp to ADRR, Hong Kong (WMO's Aviation Disaster Risk Reduction) in coded form.

1.6.5. 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, Print and electronic media. It is also posted on cyclone page of IMD website.

1.6.6. Wind forecast for different quadrants

The forecast of radius of maximum 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. It is also given to NWP centres like IIT, Delhi and NCMRWF, INCOIS Hyderabad and panel member countries in coded form for their use in creating the synthetic vortex in NWP models and running storm surge and coastal inundation model.

1.6.7. Cone of uncertainty forecast

The Cone of uncertainity (COU) represents the probable position of a CD/ TC's circulation centre, 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 20, 40, 60, 80, 115, 135, 165, 185, 205, 235, 265 and 285 nautical miles for 06, 12, 18, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hr forecasts respectively. The radii of the circles are based on the past standard errors of forecast by IMD upto 24 hrs and of Quasi-Lagrangian Model of IMD for remaining forecast times.

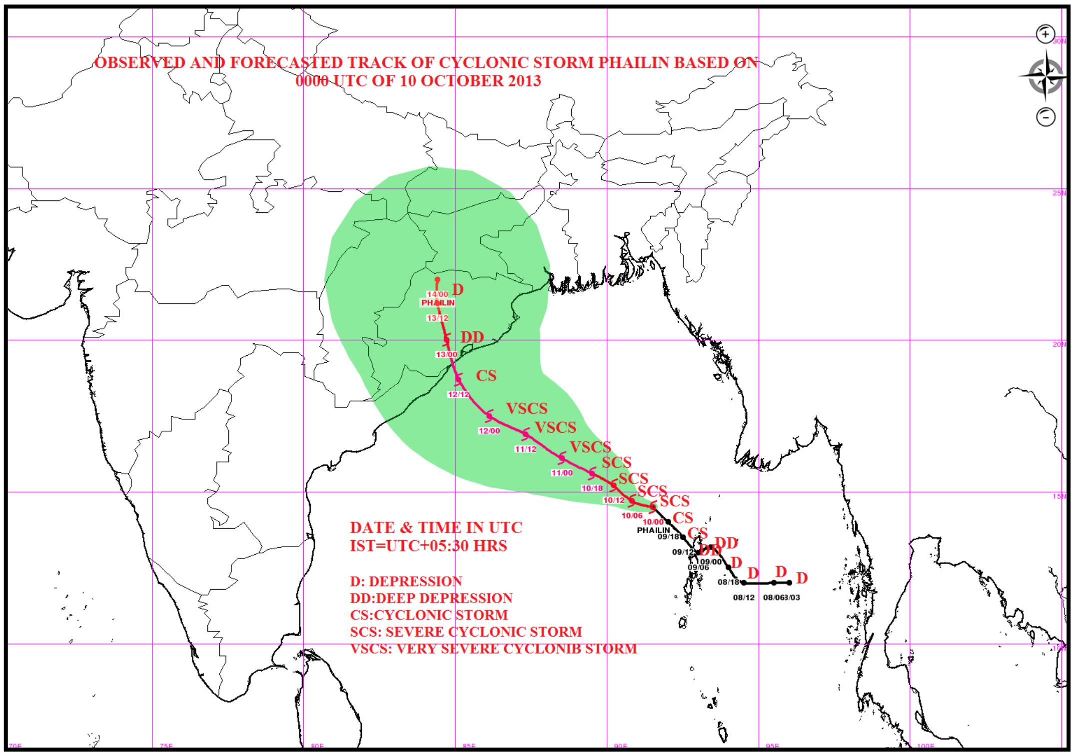


Fig.1.5. A typical example of observed and forecast track of depression which later on became the VSCS PHAILIN

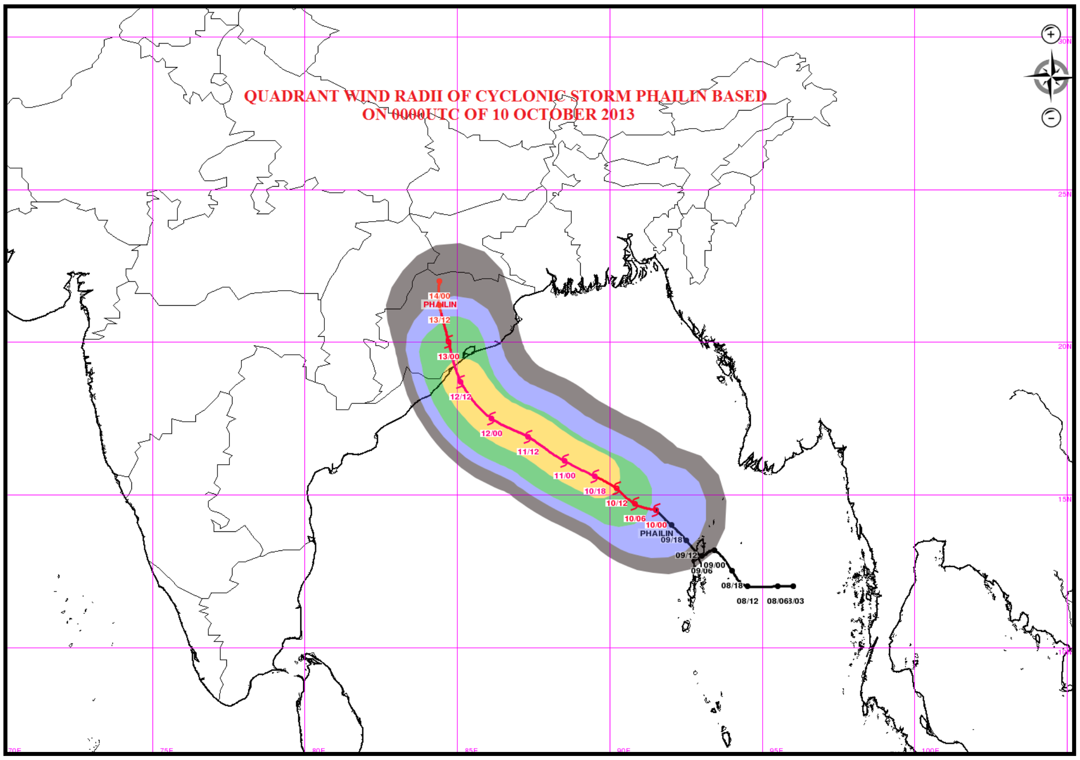


Fig.1.6. A typical graphical presentation of cyclone wind forecast during cyclone, VSCS PHAILIN

1.7. Cyclone Warning Dissemination

Cyclone warnings are disseminated to various users through telephone, fax, e-mail SMS, GTS, All India Radio, Television and other print & electronic media. These warnings/advisories are also put in the website (www.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 Centres/ Regional Meteorological Centres. 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. 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. There are 352 Cyclone Warning Dissemination System (CWDS) stations along the Indian coast; out of these 101 digital CWDS are located along Andhra coast. The IMD's Area Cyclone Warning Centres (ACWCs) at Chennai, Mumbai & Kolkata and Cyclone Warning Centre (CWCs) at

Bhubaneswar, Visakhapatnam & Ahmedabad are responsible for originating and disseminating the cyclone warnings through CWDS. The bulletins are generated and transmitted every hour in three languages viz English, Hindi and regional language. The cyclone warning bulletin is up-linked to the INSAT in C band. For this service, the frequency of transmission from ground to satellite (uplink) is 5859.225 MHz and downlink is at 2559.225 MHz. The warning is selective and will be received only by the affected or likely to be affected stations. The service is unique in the world and helps the public in general and the administration, in particular, during the cyclone season. It is a very useful system and has saved millions of lives and enormous amount of property from the fury of cyclones. The digital CWDS have shown good results and working satisfactorily. Recently a direct to home (DTH) service is being attempted for dissemination of cyclone bulletin in coastal areas.

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- 13 Dec. 2013, several national institutions participated for joint observational, communicational & NWP activities, like during 2008-2012. However there was improved observational campaign with the observation from Buoys, Oceansat-II and microwave satellites. There was intense observation period for 31 days during the field phase 2013 in association with the systems over Bay of Bengal. 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. Considering the predicted cyclogenesis of Madi in December, the FDP was extended upto 13 Dec 2013.

1.9. Modernised Forecast and Warning System of IMD

India Meteorological Department has completed phase-I of an extensive modernisation programme **(2008-12)** with the following objectives and expected outcomes. The phase II of the programme will be taken up in 12th five year plan continuing from 2013.

Objectives

- Induction of advanced technology for observational systems with induction of AWS, DWR etc.
- Digital data communication and data base integration
- Assimilation of non-conventional data into NWP systems
- Improved data dissemination and better public access
- Induction of more objective forecasting system
- Improvement in public weather services (PWS) and early warning system

CHAPTER-II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2013.

During the year 2013, 10 cyclonic disturbances developed over NIO including one deep depression over Arabian Sea, one land depression and 8 cyclonic disturbances over Bay of Bengal. Out of 8 disturbances in Bay of Bengal, 3 intensified into Very Severe Cyclonic Storm (VSCS), one each into a Severe Cyclonic Storm (SCS) & Cyclonic Storm (CS), and three upto depressions. Considering season-wise distribution, out of 10 disturbances, 2 developed during pre-monsoon, 2 during monsoon and 6 during post-monsoon season. The track of cyclonic disturbances formed over the NIO during the year are shown in Fig. 2.1

Salient features of cyclonic disturbances during 2013 are given below.

i. There were five cyclones over the Bay of Bengal and no cyclone over the Arabian Sea against the long period average of 5.5 per year over the entire NIO with ratio of 4:1 over Bay of Bengal and Arabian Sea.
ii. Five cyclones developed over the Bay of Bengal for the first time after 1987. Considering NIO as a whole, five cyclones occurred in 2010.
iii. Four severe cyclonic storms developed over Bay of Bengal for the first time since 1982. Considering NIO as a whole, four such severe cyclonic storms occurred in 2010.
iv. Three very severe cyclonic storms occurred over NIO for the first time since 1999.
v. Post-monsoon season (Oct.-Dec.)was very active, especially over the Bay of Bengal with the formation of three very severe cyclonic storms and one severe cyclonic storm. Four such severe cyclonic storm during post-monsoon season occurred over Bay of Bengal in the year 1922 & 1966 based on the data of 1891-2012 and three very severe cyclonic storm occurred in the year 1967,1971, 1977 & 1981 during the period 1965-2012.
vi. Though there were five cyclones, only one cyclone (Phailin) crossed coast as very severe cyclonic storm and other two (Viyaru and Helen) as cyclonic storms. Other two cyclones (Lehar and Madi) crossed the coast as depressions. However, cyclone Lehar crossed Andaman and Nocobar Islands as a severe cyclonic storm. It was the first severe cyclonic storm that crossed Andaman and Nicobar Islands since November 1989.
vii. While track of Lehar was straight moving, tracks of all other cyclones were recurving in nature. While Phailin recurved after landfall, cyclone Viyaru recurved northeastwards over the sea, cyclone Helen recurved west-southwestwards just before landfall and cyclone Madi recurved southwestwards over the sea. Comparing the tracks, the track of Madi was most unique in nature and had a rare analogue with past records.
viii. The total life period of cyclonic disturbances during 2013, was maximum (42.6 days) as compared to previous years (1990-2012)
ix. The annual cyclone energy over the NIO, has also been maximum in 2013 as compared to previous years (1990-2012).

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

(a) Cyclonic Storm 'Viyaru' (10-16 May 2013)

A cyclonic storm, Viyaru crossed Bangladesh coast near lat.22.8^{0}N and long. 91.4^{0}E, about 30 km south of Feni around 0800 UTC 16th May 2013 with a sustained maximum wind speed of about 85-95 kmph. The salient features of this storm are as follows.

(i) The genesis of the disturbance took place in a lower latitude, near 5°N. It recurved northeastwards after initial northwestward movement.
(ii) It was one of the longest track over NIO in recent period after the very severe cyclonic storm, Phet over the Arabian Sea (31 May-07 June, 2010)
(iii) The cyclonic storm moved very fast (about 40-50 km per hour on the day of landfall, i.e. on 16th May 2013. Such type of fast movement of the cyclonic storm is very rare.
(iv) Due to the faster movement, the adverse weather due to the cyclonic storm was relatively less.

(b) Very Severe Cyclonic Storm (VSCS) PHAILIN over the Bay of Bengal (08-14 October 2013)

A Very Severe Cyclonic Storm (VSCS) PHAILIN over Bay of Bengal moved northwestwards and crossed Odisha & adjoining north Andhra Pradesh coast near Gopalpur (Odisha) around 1700 UTC of 12th October 2013 with a sustained maximum surface wind speed of 215 kmph. The salient features of this storm are as follows.

i. VSCS Phailin was the most intense land falling cyclone after Odisha Super Cyclone of 29th October 1999.
ii. At the time of landfall on 12th Oct, maximum sustained surface wind speed in association with the cyclone was about 115 knots (215 kmph) and estimated central pressure was 940 hPa with pressure drop of 66 hPa at the centre compared to surroundings
iii. There was rapid intensification of the system from 10th Oct. morning to 11th October morning leading to an increase in wind speed from 45 knots to 115 knots.
iv. It caused very heavy to extremely heavy rainfall over Odisha leading to floods, and strong gale wind leading to large scale structural damage and storm surge leading to coastal inundation over Odisha.
v. Maximum rainfall occurred over northeast sector of the system centre at the time of landfall. Maximum 24 hr cumulative rainfall of 38 cm has been reported over Banki in Cuttack district of Odisha.
vi. Based on post-cyclone survey report, maximum storm surge of 2-2.5 meters above the astronomical tide has been estimated in the low lying areas of Ganjam district of Odisha in association with the cyclone and the in-land inundation of saline water extended upto about one kilometer from the coast.

(c) Severe Cyclonic Storm 'Helen' over Bay of Bengal (19-23 Nov 2013)

The Severe cyclonic storm Helen over westcentral Bay of Bengal moved initially westwards and then west-southwestwards and crossed Andhra Pradesh coast close to south of Machilipatnam (near lat. 16.1°N and long. 81.2°E) between 0800-0900 UTC of 22nd Nov. 2013 as a cyclonic storm with a wind speed of 80-90 kmph gusting to 100 kmph.The salient features of this storm are as follows.

(i) It changed its direction of movement from west-northwest and moved west-southwestward 12 hrs before landfall
(ii) It weakened slightly before landfall and rapidly after the landfall and hence caused less rainfall over coastal Andhra Pradesh.
(iii) Under its influence rainfall at most places with isolated heavy to very heavy rainfall occurred over coastal Andhra Pradesh.

(d) Very Severe Cyclonic Storm VSCS 'Lehar' (23-28 Nov. 2013)

The very severe cyclonic storm, Lehar developed over south Andaman Sea from a remnant cyclonic circulation from South China Sea on 23rd. While moving northwestward it further intensified into a severe cyclonic storm and crossed Andaman & Nicobar Island near Port Blair around 0100 UTC of 25th Nov. 2013 with a wind speed of about 110-120 kmph. It caused extremely heavy rainfall and coastal inundation leading to uprooting of trees, damage to structures and flooding of low lying areas.

On 25th it emerged into southeast Bay of Bengal and moved west-northwestward, intensified into a very severe cyclonic storm in the early hours of 26th Nov. near southeast Bay of Bengal. It maintained its very severe cyclonic storm intensity with a maximum wind speed reaching upto 140-150 gusting to 165 kmph till noon of 27th Nov. It then came under the influence of colder Sea, high vertical wind shear and entrainment of dry & cold air into the cyclone field. As a result, it rapidly weakened into a deep depression by early morning of 28th (i.e. within 18 hours). It crossed Andhra Pradesh coast close to south of Machilipatnam around 0830 UTC of 28th Nov. 2013. The salient features of this system are given below.

(i) It was the first severe cyclonic storm to cross Andaman and Nicobar Islands after November, 1989.
(ii) It had second landfall near Machillipatnam as a depression.
(iii) It rapidly weakened over the sea from the stage of very severe cyclonic storm to depression in 18 hrs.
(iv) It did not cause any significantly heavy rainfall over Andhra Pradesh

(e) Very Severe Cyclonic Storm VSCS 'Madi' (06-13 December 2013)

A depression formed over southwest Bay of Bengal in the morning of 6th December and became deep depression in the same midnight. It moved very slowly northward and intensified into a cyclonic storm, 'Madi' in the morning of 7th December. It continued to move slowly and intensified into a severe cyclonic storm in the afternoon of 7th Dec. and into a very severe cyclonic storm in the forenoon of 8th December 2013.

However due to entrainment of cold air, colder sea and increase in vertical wind shear, the very severe cyclonic storm weakened into severe cyclonic storm in the evening of 9th Dec. Due to weakening, the system moved southwestward after reaching the latitude of 15.7°N under the influence of lower and middle tropospheric steering ridge. It further weakened into cyclonic storm in the early hours 11th Dec., into deep depression in the morning of 11th, depression in night of 11th. It crossed Tamil Nadu coast near Vedaranniyam around 1330 UTC of 12th Dec., emerged into Palk strait around 1500 UTC and again crossed Tamil Nadu coast near Tondi around 1700 UTC. It then emerged into southeast Arabian Sea as a well marked low pressure area in the early morning of 13th Oct. 2013. The salient features of this system are given below.

(i) It has a unique track with near northerly movement till 15.7°N and then it recurved southwestwards to Tamil Nadu coast.
(ii) It moved very slowly during its northward journey and speed peaked up gradually after the recurvature to southwest.
(iii) The system had temporary intensification also during its weakening phase.

The statistics of the cyclonic disturbances formed during 2013 are given in Table 2.1. The characteristic features of these disturbances are given in Table 2.2.The intraseasonal variation in frequency of genesis, intensification and life period of the disturbances is shown in Table 2.3.

Table 2.1: Cyclonic disturbances formed over north Indian Ocean and adjoining land areas during 2013

1.	Cyclonic storm Viyaru over the Bay of Bengal (10-16 May 2013)
2.	Depression over the Bay of Bengal (29-31 May 2013)
3.	Depression over the Bay of Bengal (30 July-01 Aug. 2013)
4.	Land Depression (20-23 Aug.2013)
5.	Very Severe cyclonic storm Phailin over the Bay of Bengal (08-14 Oct. 2013)
6.	Deep Depression over Arabian Sea (08-11 Nov.2013)
7.	Depression over the Bay of Bengal 13-17 Nov.2013
8.	Severe cyclonic storm Helenover the Bay of Bengal (19-23 Nov.2013)
9.	Very Severe cyclonic storm over the Bay of Bengal Lehar (23-28 Nov2013)
10.	Very Severe cyclonic storm over the Bay of Bengal Madi (06-13 Dec.2013)

Table 2.2 Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2013

Cyclonic storm/Depression	Date, Time& Place of genesis (Lat.N/long E)	Date, Time(UTC) Place (Lat./Long.) of Landfall	Estimated lowest central pressure, Time& Date (UTC)& Lat°N/long°E	Estimated Maximum wind speed (kt), Date & Time	Max T. No. Attained
Cyclonic Storm Viyaru over the Bay of Bengal(10-16 May 2013)	10 May 2013 at 0900 UTC over southeast the Bay of Bengal near	Crossed Bangladesh coast near lat. 22.8^{0}N and long. 91.4^{0}E, about 30 km south of Feni	0990 hPa at 0600 UTC of 15 May 2013 near 17.0/87.5	45 knots at 0600 UTC of 15 May 2013	T -3.0

	05.0/92.0	around 0800UTC of 16 May 2013			
Depression over the Bay of Bengal(29-31 May)	0300 UTC of 29May 2013 over north the Bay of Bengal near lat. 21.0^{0}N and 89.5^{0}E,	crossed West Bengal coast near lat. 21.8^{0}N and long. 88.7^{0}E, about 30 km south of Canning (West Bengal) between 0800-0900 UTC of 29 May2013	0990 hPa at 0300 UTC of 30 May2013 near 22.3/87.5	25 Knot at 0300 UTC of 29May 2013	T-1.5
Depression over the Bay of Bengal(30 July-01 August)	30 July2013 at 0300 UTC over the Bay of Bengal near 21.0/88.0	crossed north Odisha and adjoining West Bengal coast between Balasore and Digha around 0700 UTC of 30 July 2013	0990 hPa at 0300 UTC of 30 July 2013 near 21.0/88.0	25 Knot at 0300 UTC of 30 July 2013	T-1.5
Depression over Gangetic West Bengal during 20 – 23 August, 2013	20 August-2013 at 0000 UTC over Gangetic West Bengal near 22.0/87.5	-	0990 hPa at 0000 UTC of 20 August 2013 near 22.0/87.5	25 Knot at 0300 UTCof 20 August 2013 near22.0/87.5	-
Very Severe Cyclonic Storm 'Phailin' over the the Bay of Bengal during 08-14 October, 2013	08 October2013 at 0300UTC near 12.0/96.0	Crossed Andaman & Nicobar near Maya Bandar between 0700-0800 UTC of 9 October as DD and later the VSCS crossed Odisha & adjoining north Andhra Pradesh coast near Gopalpur around 1700 UTC near 19.2^{0}N and 84.9^{0}E	0940hPa at 0300UTC of 11.October 2013 near 16.0/88.5	115 knot at 0300 UTC of 11.October 2013 near 16.0/88.5	T-6.0
Deep Depression over Arabian Sea during 08-11 Nov.2013	8 November, 2013 at 0600 UTC near 8.0/56/5	Crossed Somalia coast near 8.2/50.1 between 2300 UTC of 10 Nov. and 0000 UTC of 11 Nov., 2013	1002 hPa at 0000 UTC of 9 November, 2013 near 8.0/53.0	30 knot at 0000 UTC of 9 November, 2013 near 8.0/53.0	T-2.0
Depression over the Bay of Bengal during 13 – 17 November, 2013	13 Nov 2013 at 0000UTC near 11.5/86.5	Crossed Tamil Nadu coast near Nagapattinam on 0730 UTC of	1003 hPa at 1200UTC of 13 Nov.2013 near 11.5/86.0	25 knot at 0000UTC of 13 Nov.2013 near 11.5/86.5	T-1.5

		16 Nov. 2013 near 11.0/79.5			
Severe Cyclonic Storm ‘Helen’ over the the Bay of Bengal during 19-23 November, 2013	19 Nov.2013 0000 UTC near 14.5/86.5	Crossed Andhra Pradesh coast close to south of Machilliptnam near 16.1^0N/81.2^0E between 0800-0900UTC	0990hPa 0600 UTC 21 Nov.2013 near 15.9/83.3	55 knot at0600 UTC 21 Nov.2013 near 15.9/83.3	T-3.5
Very Severe Cyclonic Storm ‘Lehar’ over the Bay of Bengal during 23-28 November, 2013	23 Nov. 2013 1200UTC near 8.5/96.5	Crossed Andaman & Nicobar island south of Port Blair 0100 UTC of 25 November and later Andhra Pradesh close to north of Machilipatnam near 15.9^0N/81.1^0 E around 0830 UTC of 27 Nov., 2013 as a depression	0980hPa at 1800 UTC of 26 Nov.2013 near 13.1/88.0	75 knot at1800 UTC of 26 Nov.2013 near 13.1/88.0	T-4.0
Very Severe Cyclonic Storm ‘Madi’ over the the Bay of Bengal during 06-13 Dec 2013	06 Dec.2013 at 0300UTC of 12 December, 2013 near 10.0/84.0	Crossed Tamil Nadu coast near Vedaranyam around 1330 UTC and emerged into Palk straight and again crossed Tamil Nadu coast near Tondi around 1700 UTC of 12 Dec.2013	0986 hPa at 0600 UTC of 8 Dec. 2013 near 12.3/84.7	65 knot 0600 UTC of 8 Dec. 2013 near 12.3/84.7	T-4.0

Table 2.3: Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2013

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

S. N.	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) Life time of cyclonic disturbances during 2013 at different stages of intensity

S.No.	Type	Life Time in (Days)
1	D	17.37
2.	DD	6.25
3.	CS	8.25
4.	SCS	4.62
5.	VSCS	6.12
6.	SuCS	0
	Total Life Time in(Days)	42.6

C) Frequency 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
No of Disturbances	10	6	5	5	4	3	1	1

D) Basin-wise distribution of cyclonic distribution

Basin	Number of cyclonic disturbances
Bay of Bengal	8
Arabian Sea	1
Land depression	1

Table 2.4. Cyclonic disturbances formed over the NIO and land areas of India during 1997-2013

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**

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

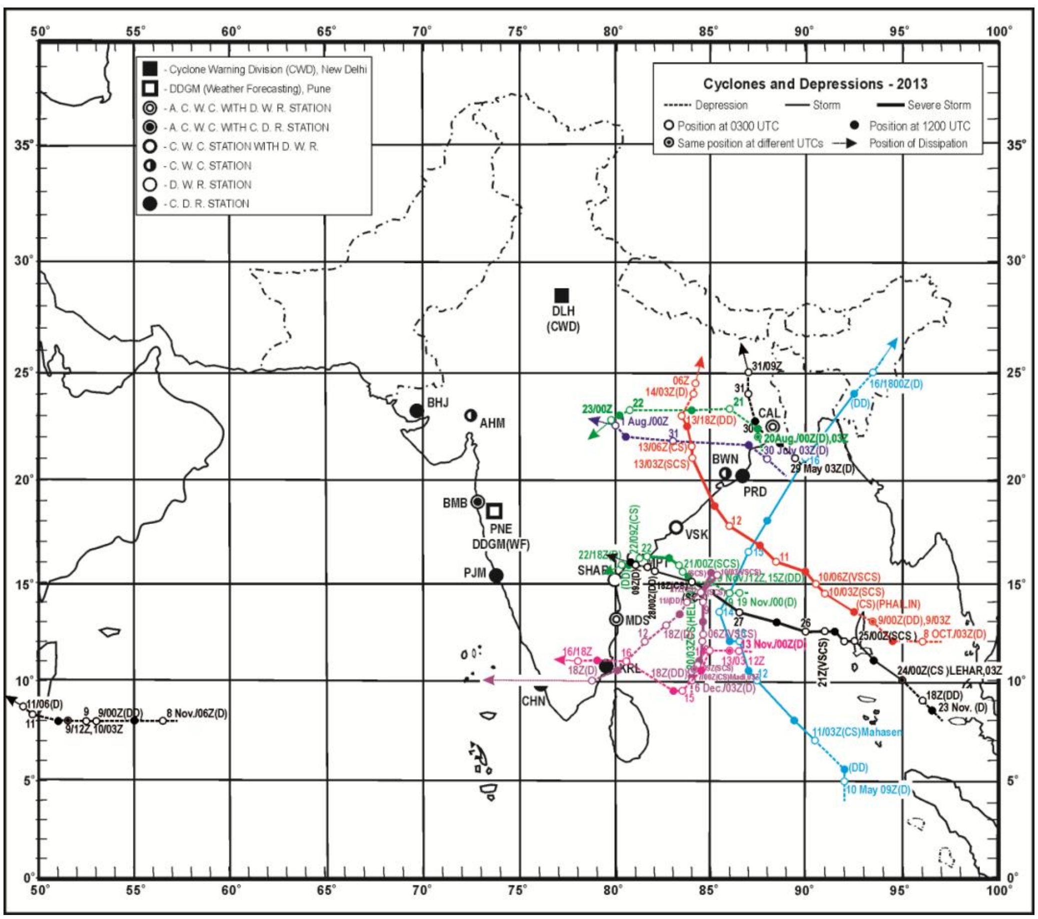


Fig. 2.1 Tracks of the cyclonic disturbances formed over the north Indian Ocean during the year, 2013

2.1 Cyclonic Storm, Viyaru over Bay of Bengal (10 - 16 May, 2013)

2.1.1 Introduction

A cyclonic storm, Viyaru crossed Bangladesh coast near lat.22.8^{0}N and long. 91.4^{0}E, about 30 km south of Feni around 1330 hrs IST of 16th May 2013 with a sustained maximum wind speed of about 80-90 kmph. The salient features of this storm are as follows.

(i) The genesis of the disturbance took place in a lower latitude, near 5 degree North.
(ii) It recurved northeastward after initial northwestward movement.
(iii) It was one of the longest track over NIO in recent period after the very severe cyclonic storm, Phet over the Arabian Sea (31 May-07 June, 2010)
(iv) The cyclonic storm moved very fast (about 40-50 km per hour) on the day of landfall, i.e. on 16th May 2013. Such type of fast movement of the cyclonic storm is very rare.
(v) Due to the faster movement, the adverse weather due to the cyclonic storm was relatively less.

2.1.2 Brief life history

A depression formed over southeast Bay of Bengal at 0900 UTC 10th May 2013 near latitude 5.0^{0}N and longitude 92.0^{0}E. It moved northwestwards and intensified into a deep depression in the evening of the same day. Continuing its northwestward movement, it further intensified into a cyclonic storm, Viyaru in the morning of 11th May 2013. Under the influence of the anticyclonic circulation lying to the east, the cyclonic storm changed its direction of movement initially from northwesterly to northerly and then to north-northeasterly on 13th and 14th May respectively. On 15th May, it further came under the influence of the mid-latitude westerly trough running roughly along 77^{0}E, which further helped in enhancing the north-northeastward movement of the cyclonic storm. As this trough came closer on 16th, the north-northeastward speed of the cyclonic storm significantly increased, becoming about 40-50 kmph. The cyclonic storm crossed Bangladesh coast near lat. 22.8^{0}N and long. 91.4^{0}E, about 30 km south of Feni around 0800 UTC of 16th May 2013 with a sustained maximum surface wind speed of about 85-90 kmph. After the landfall, it continued to move north-northeastwards and weakened gradually due to interaction with land surface. It weakened into a deep depression over Mizoram in the evening and into a depression over Manipur around mid-night of 16th. It further weakened into a well marked low pressure area over Nagaland in the early morning and moved away towards Myanmar as a low pressure area in the morning of 17th.

The track of the system is shown in Fig. 2.1. It was a recurving track with north-northeastward recurvature. Climatologically, most of the cyclones generating over the southeast Bay of Bengal recurve towards Bangladesh-Myanmar coast in the month of May. The best track parameters of cyclonic storm, Viyaru are shown in Table 2.1.1. The typical satellite and radar imageries are shown in Fig.2.1.1.

Table 2.1.1 Best track positions and other parameters of the Cyclone 'Viyaru' over the Bay of Bengal during 10-16 May, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
10-05-2013	0900	5.0/92.0	1.5	1004	25	3	D
	1200	5.5/92.0	2.0	1002	30	5	DD
	1800	6.0/91.5	2.0	1000	30	5	DD
11-05-2013	0000	6.5/91.0	2.0	998	30	6	DD
	0300	7.0/90.5	2.5	996	35	8	CS
	0600	7.0/90.5	2.5	996	35	8	CS
	0900	7.5/90.0	2.5	996	35	8	CS
	1200	8.0/89.5	2.5	994	40	8	CS
	1500	8.5/89.0	2.5	994	40	8	CS
	1800	9.0/89.0	2.5	994	40	8	CS
	2100	9.5/88.5	2.5	994	40	8	CS
12-05-2013	0000	10.0/88.0	2.5	994	40	8	CS
	0300	10.0/87.5	2.5	994	40	8	CS
	0600	10.0/87.5	2.5	994	40	8	CS
	0900	10.5/87.0	2.5	994	40	8	CS
	1200	10.5/87.0	2.5	994	40	8	CS
	1500	10.5/86.5	2.5	994	40	8	CS
	1800	11.0/86.5	2.5	994	40	8	CS
	2100	11.0/86.5	2.5	994	40	8	CS
13-05-2013	0000	11.5/86.5	2.5	994	40	8	CS
	0300	12.0/86.5	2.5	994	40	8	CS
	0600	12.0/86.5	2.5	994	40	8	CS
	0900	12.0/86.0	2.5	994	40	8	CS
	1200	12.0/86.0	2.5	994	40	8	CS
	1500	12.5/86.0	2.5	994	40	8	CS
	1800	12.5/85.5	2.5	994	40	8	CS
	2100	13.0/85.5	2.5	994	40	8	CS
14-05-2013	0000	13.5/85.5	2.5	994	40	8	CS
	0300	13.5/85.5	2.5	994	40	8	CS
	0600	14.0/85.5	2.5	994	40	8	CS
	0900	14.0/85.5	2.5	994	40	8	CS
	1200	14.5/86.0	2.5	994	40	8	CS
	1500	14.5/86.0	2.5	994	40	8	CS
	1800	15.0/86.5	2.5	994	40	8	CS
	2100	15.5/86.5	2.5	994	40	8	CS
15-05-2013	0000	16.0/87.0	2.5	994	40	8	CS
	0300	16.5/87.0	2.5	992	40	8	CS
	0600	17.0/87.5	3.0	990	45	10	CS

	0900	17.5/87.5	3.0	990	45	10	CS
	1200	18.0/88.0	3.0	990	45	10	CS
	1500	18.5/88.5	3.0	990	45	10	CS
	1800	19.0/88.5	3.0	990	45	10	CS
	2100	19.5/89.0	3.0	990	45	10	CS
16-05-2013	0000	20.0/89.5	3.0	990	45	10	CS
	0300	21.0/90.0	3.0	990	45	10	CS
	0600	22.5/91.0	3.0	990	45	10	CS
	Crossed Bangladesh coast between Chittagong and Feni, near latitude 22.8ºN and longitude 91.4ºE (about 30 km south of Feni), around 0800 UTC.						
	0900	23.5/92.0	-	994	40	8	CS
	1200	24.0/92.5	-	996	30	6	DD
	1800	25.0/93.5	-	998	25	4	D
17-05-2013	0000	Weakened into a well marked low pressure area over Nagaland					

D: Depression, DD: Deep Depression, CS: Cyclonic storm

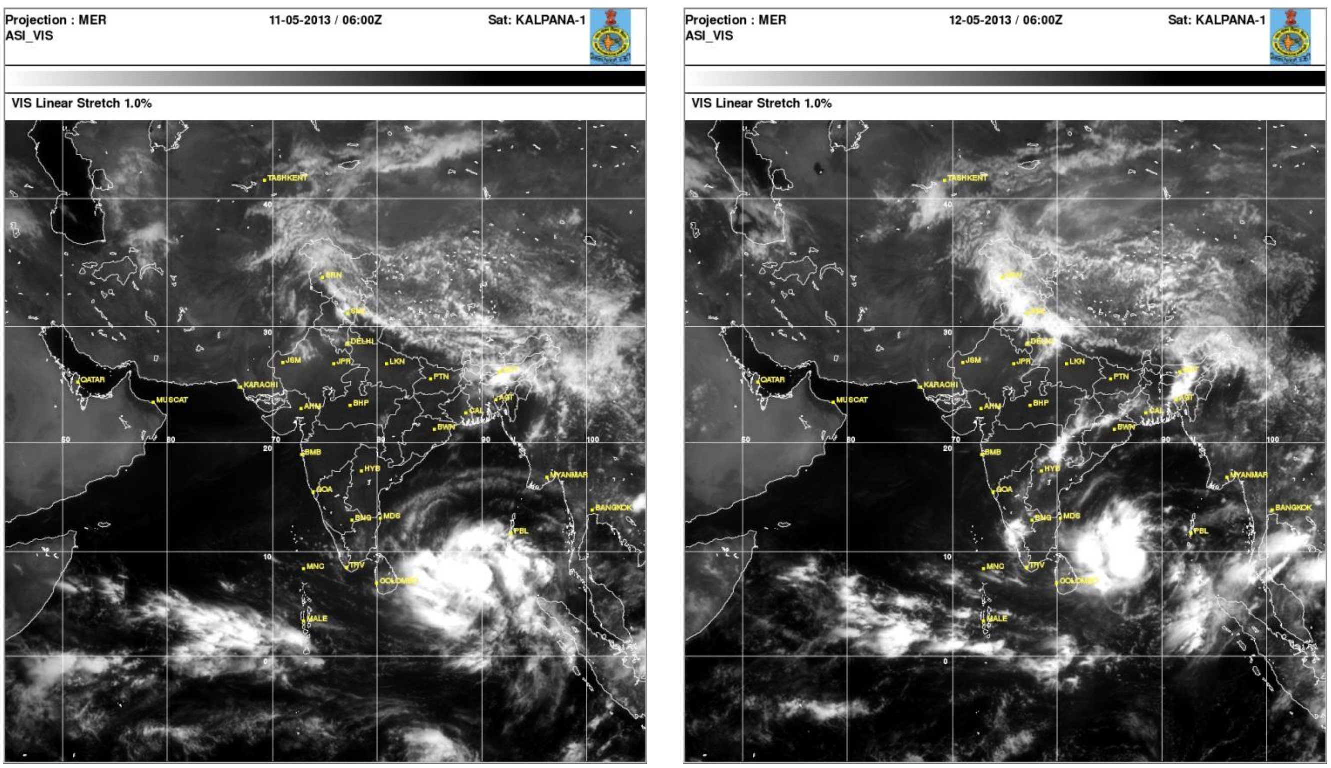


Fig. 2.1.1 Typical Kalpana-1 Satellite imageries of cyclonic storm VIYARU at 0600 UTC of 11-12 May, 2013.

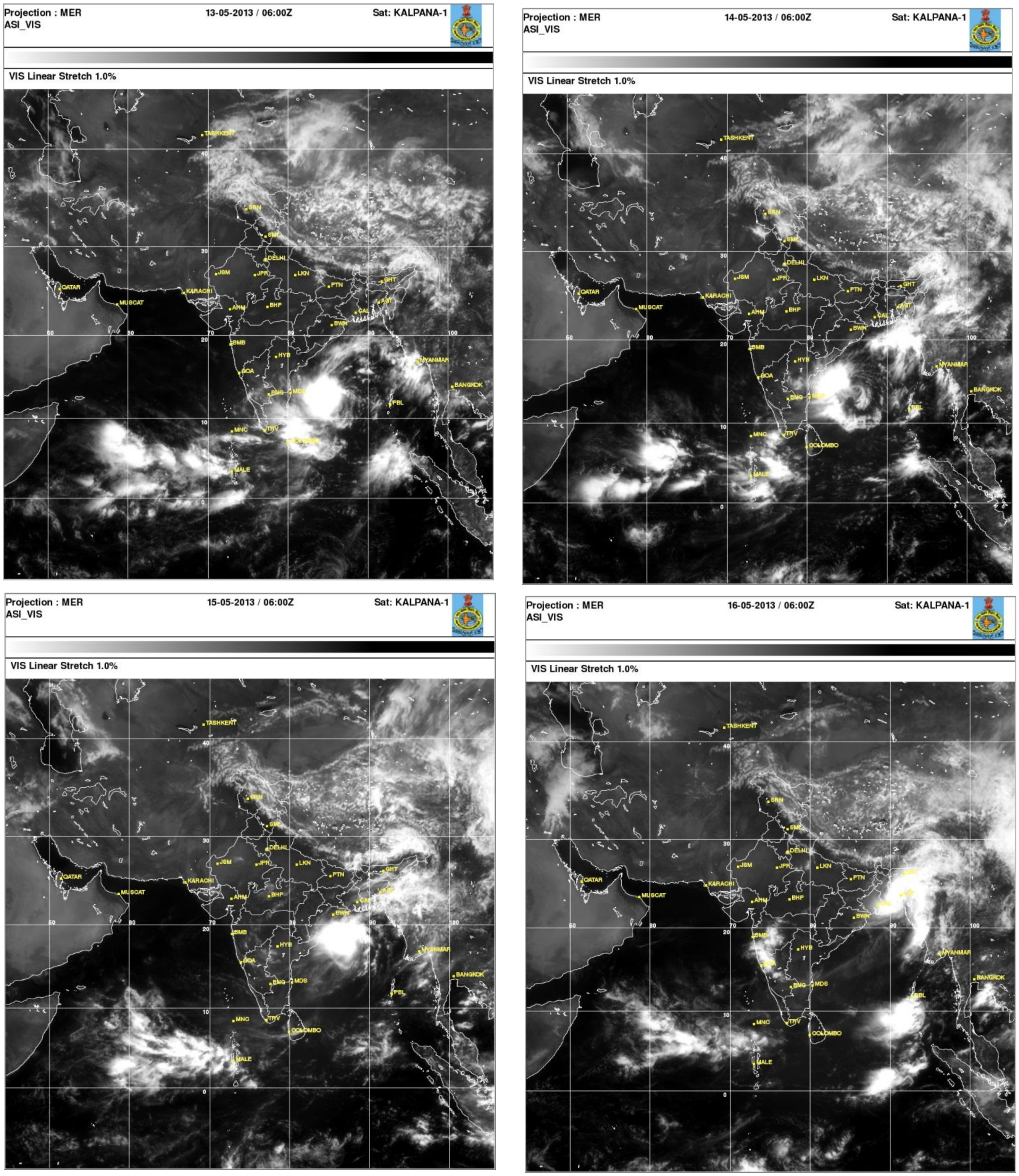


Fig.2.1.1(contd.) Typical Kalpana-1 Satellite imageries of cyclonic storm VIYARU at 0600 UTC of 13-16 May,. 2013.

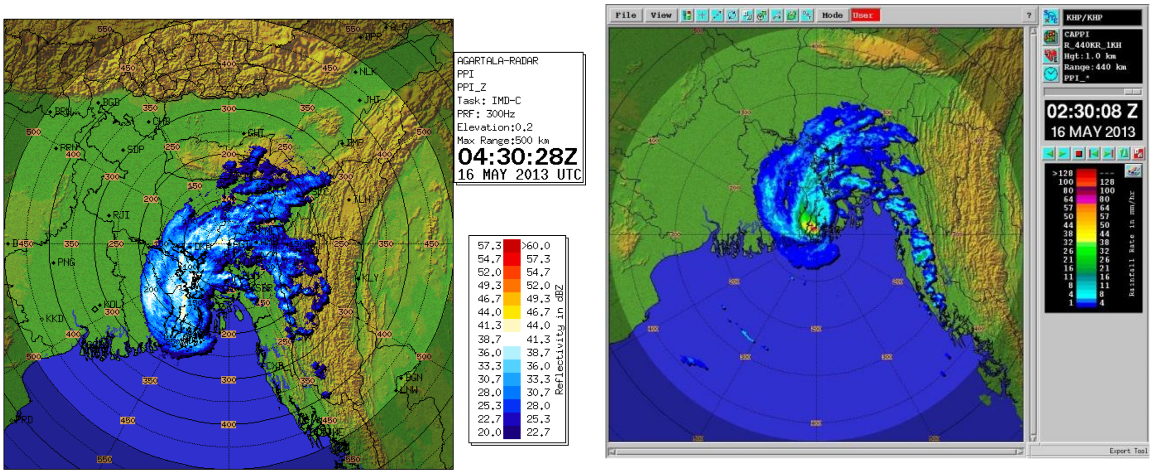


Fig.2.1.2 Typical DWR imageries of Agartala & Khepupara (Bangladesh) in forenoon of 16 May, 2013

2.1.3 Dynamic features

To illustrate the dynamical features, the MSLP, wind at 10m 850 hpa, 500 hpa and 200 hpa are shown in fig.2.1.3 based on 0000 UTC analysis of IMD GFS model during 10-16 May 2013

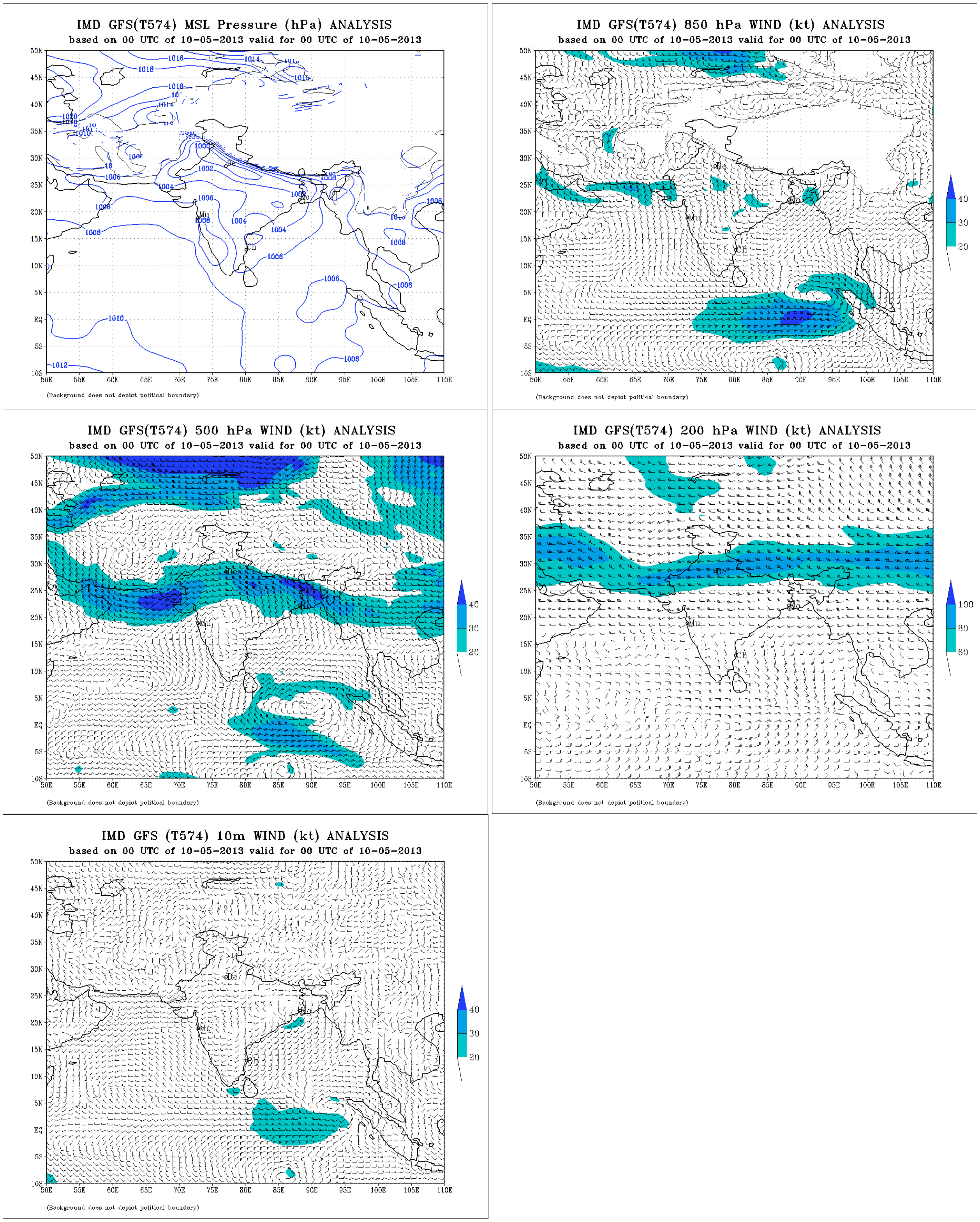


Fig.2.1.3(a). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m, 850,500 & 200 hPa based on 0000 UTC of 10th May, 2013

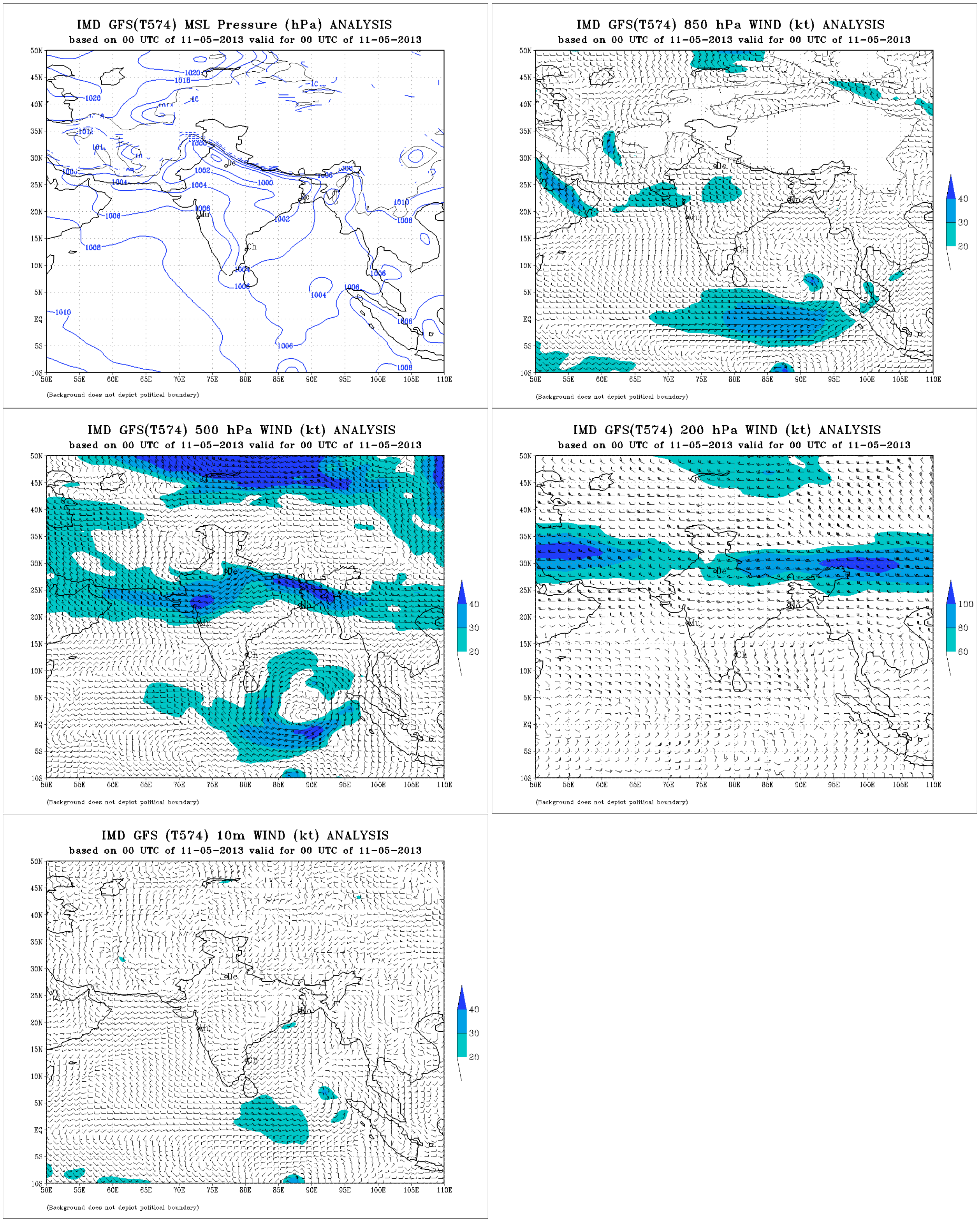


Fig.2.1.3(b). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 11th May, 2013

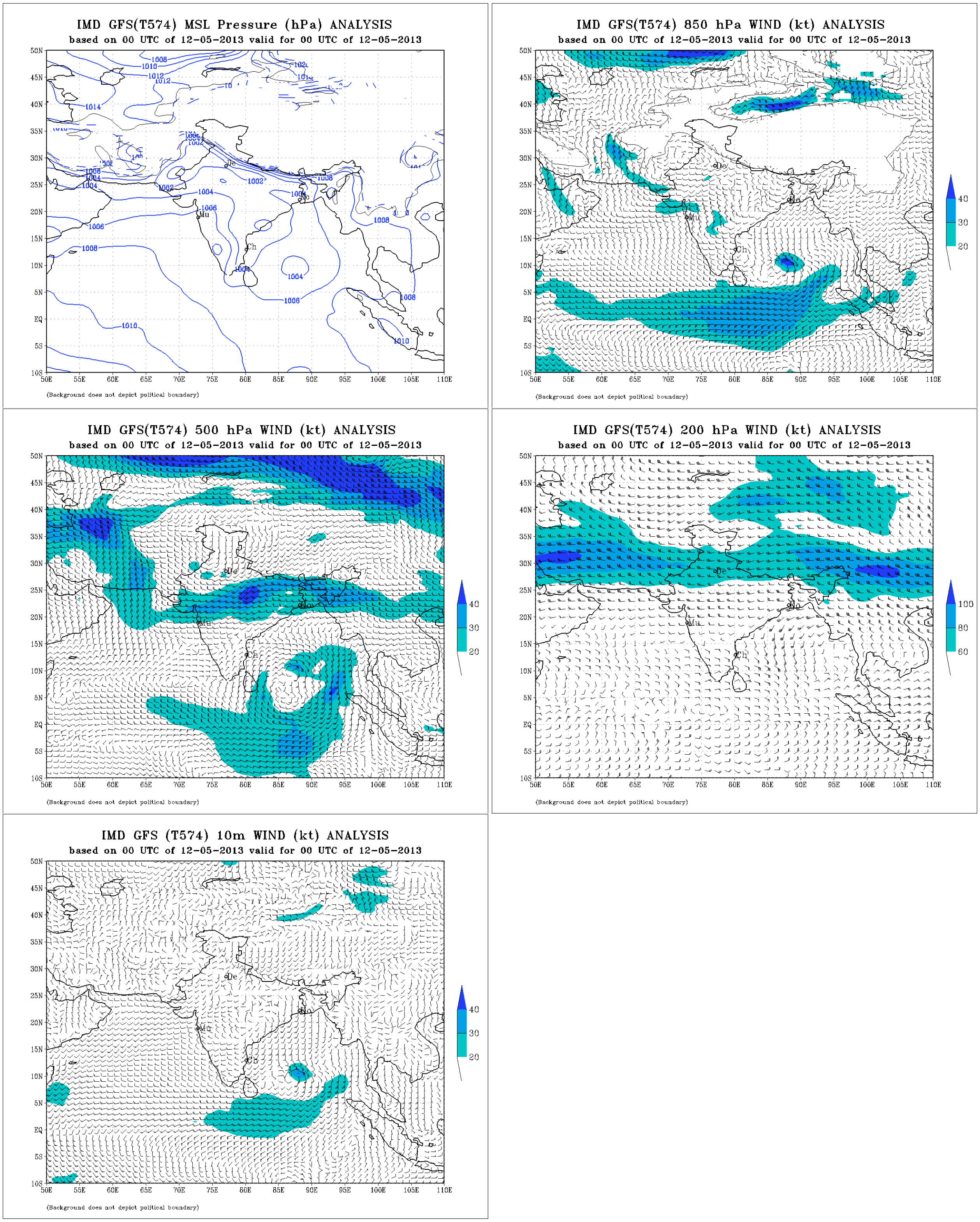


Fig.2.1.3(c). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of12th May, 2013

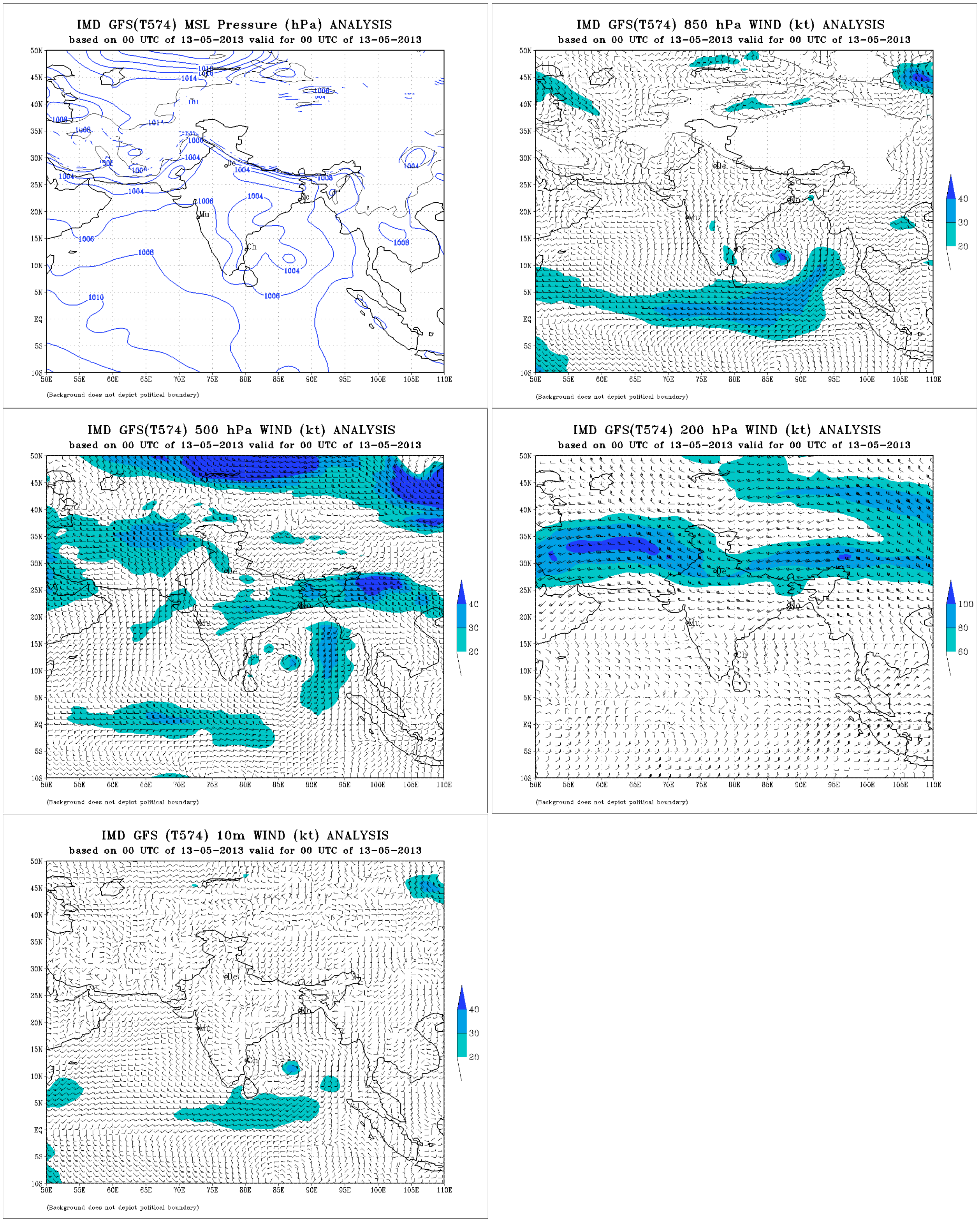


Fig.2.1.3(d). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m, 850,500 & 200 hPa based on 0000 UTC of 13th May, 2013

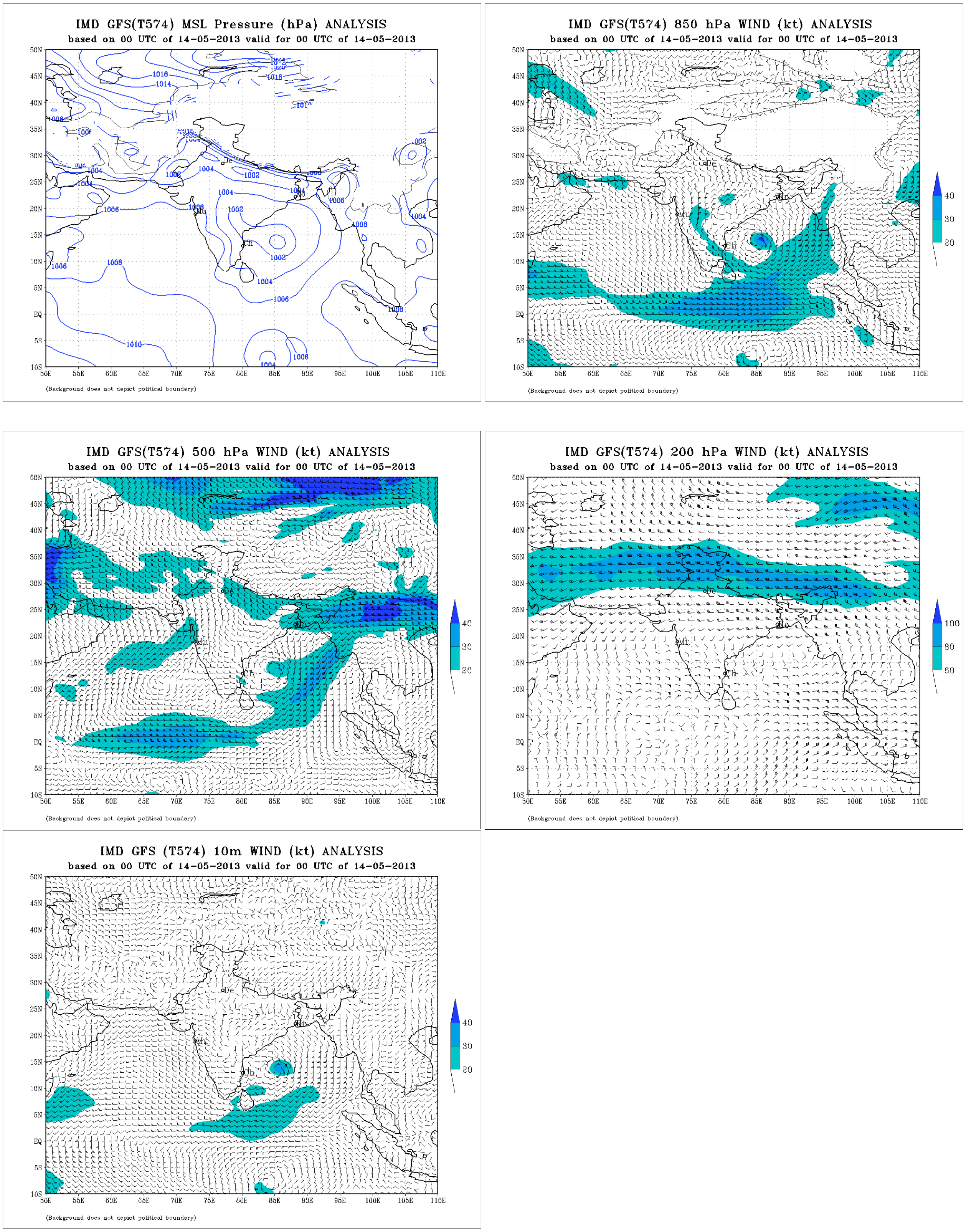


Fig.2.1.3(e). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 14th May, 2013

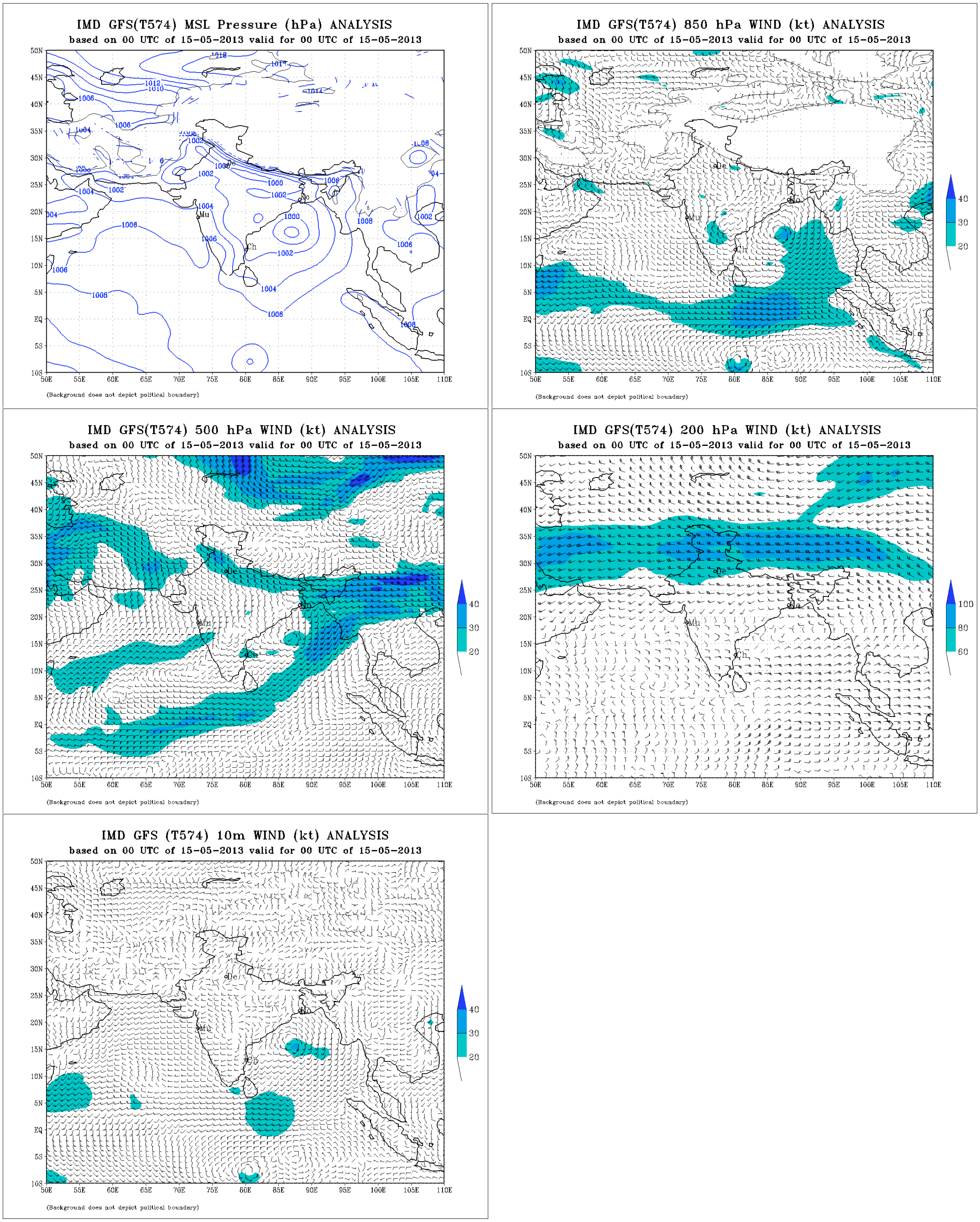


Fig.2.1.3(f). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 15th May, 2013

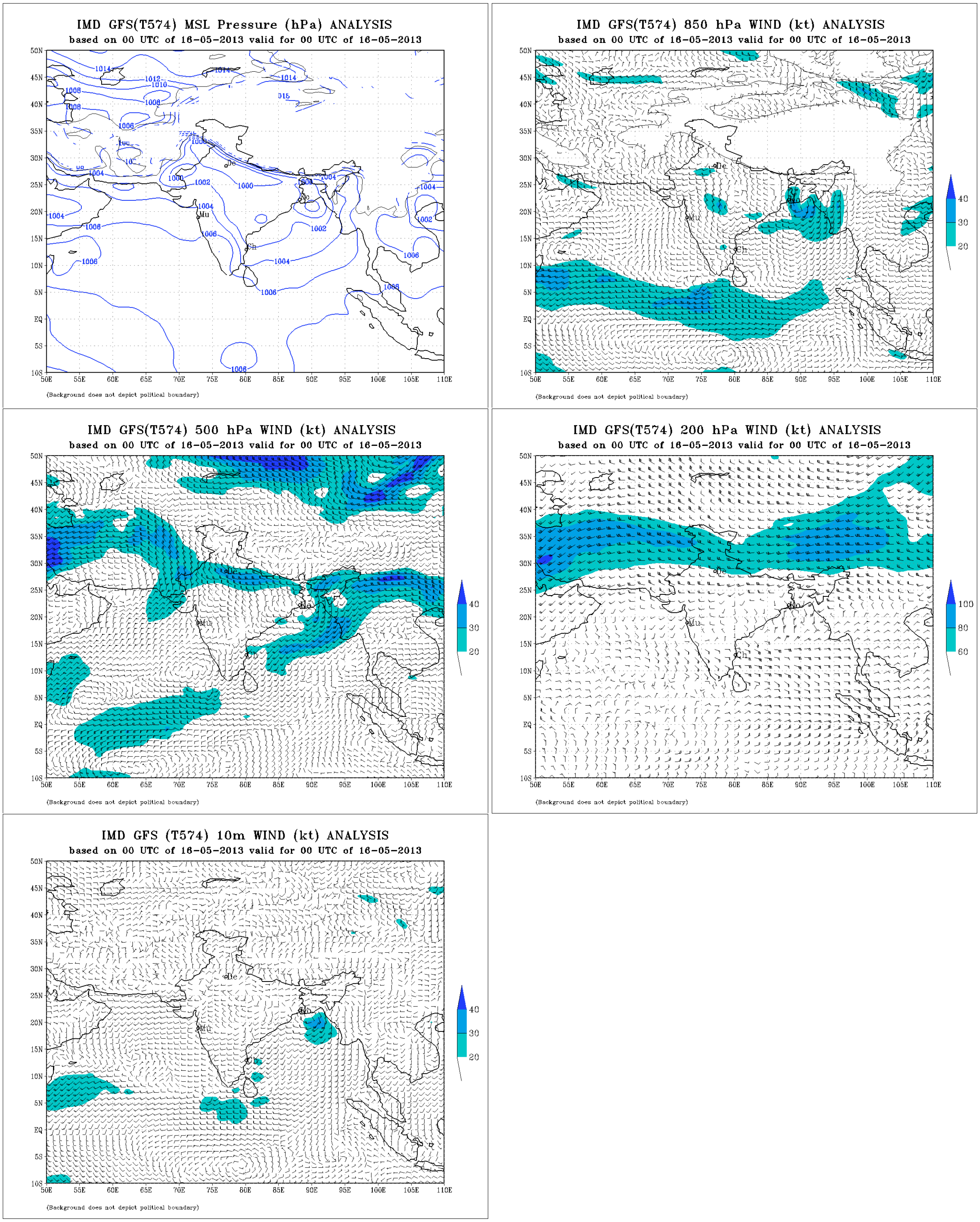


Fig.2.1.3(g). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 16th May, 2013

2.1.4 Realized Weather at the time of landfall

Surface Wind: Maximum surface wind of 92 kmph has been reported over Patuakhali, Bangladesh during the time of landfall of Cyclonic Storm, VIYARU against the forecast wind speed of 75-85 kmph gusting to 95 kmph. Surface wind of 35-45 kmph prevailed over Mizoram, Manipur and Tripura against forecast of 55-65 kmph.

Rainfall: Widespread rainfall with isolated heavy to very heavy falls occurred over Bangladesh. Fairly widespread rainfall with isolated heavy rainfall also occurred over Mizoram, Manipur and Tripura.

Storm surge: A storm surge of height of about 1 metre has been reported in section of media in Bangladesh coast.

2.1.5. Damage

Bangladesh:

At least 17 people died in Bangladesh. Also many livestock were killed. Around 49 thousand houses were totally destroyed and around 49 thousand were damaged. 10 thousand trees were uprooted which caused travel disruption. Standing crop over vast area was destroyed. Crops over 128,000 hectares in patuakhali district only,half of which was sweet potato crop were affected. Around 1,285,508 people were affected by this cyclone in Bangladesh.

Myanmar:

In Myanmar 8 people died during evacuation of 100 people travelling in a boat. In other incidents also around 200 people drowned.

2.2. Depression over the Bay of Bengal (29-31 May, 2013)

2.2.1 Introduction:

A depression formed over north Bay of Bengal on 29th May, 2013. Moving north-northwestwards, it crossed West Bengal coast near lat. 21.8^{0}N and long. 88.7^{0}E, about 30 km south of Canning in the evening of 29th May. It caused heavy to very heavy rainfall at a few places over West Bengal, north Odisha, Jharkhand and Bihar and isolated heavy rainfall over Assam and Meghalaya. The salient feature of this depression are given below:

(i) The track of the depression was unique, as it initially moved north-northwestwards before landfall, then moved slowly for next 24 hrs over Gangetic West Bengal and then moved nearly northwards upto Bihar.

(ii) Due to its slow westward movement over Gangetic West Bengal, it caused very good rainfall activity in southwest sector including Gangetic West Bengal and Odisha.

2.2.2 Brief history:

Under the influence of southerly surge, the low level convergence and relative vorticity increased over the central Bay of Bengal in the beginning of the last week of May 2013. It led to the development of an upper air cyclonic circulation over west central Bay of Bengal on 27th May, 2013. A low level cyclonic circulation (LLCC) was also observed by Satellite Division of IMD by 27th May 2013. It was declared as a vortex (T1.0) in the evening of 27th. The upper air cyclonic circulation over westcentral Bay of Bengal concentrated into a low pressure area on 28th over westcentral and adjoining northwest Bay of Bengal.

Under the favourable conditions like warmer Sea surface temperature (about 30^{0}C), lower level convergence and relative vorticity, the low pressure area further concentrated into a depression at 0300 UTC of 29th over north Bay of Bengal near lat. 21.0^{0}N and 89.5^{0}E, about 200 km southeast of Kolkata. The upper tropospheric ridge ran along 23^{0}N and provided poleward outflow in association with anticyclonic circulation lying to the northeast of system centre. The vertical wind shear was moderate to high. The Madden Julian oscillation (MJO) index lay over phase 1 with negligible amplitude. Further the depression lay close to the coast and there was incursion of dry and warm northwesterly wind from northwest India in middle level. Hence though factors were favourable for genesis of depression but they were not favourable for further intensification. However, as the depression was lying close to the south of ridge, it moved north-northwestwards and crossed West Bengal coast near lat. 21.8^{0}N and long. 88.7^{0}E, about 30 km south of Canning (West Bengal) during 1330-1430 UTC of 29th. After the landfall, as the depression lay to the south of ridge and the ridge became stronger, there was slow westerly movement of the system during 29th night to noon of 30th May. However on 31st a trough in upper tropospheric westerlies ran along 80^{0}E to the north of 20^{0}N and an anticyclonic circulation with centre near Long. 77^{0}E and Lat. 20^{0}N lay over central India. Under the influence of these two systems, the depression moved nearly northward on 31st. As it moved northward, due to moisture cut off and interaction with land surface and unfavourable northwesterly winds entering into depression field in middle level and upper troposphere, the depression weakened into a well marked low pressure area at 1200 UTC of 31st May, 2013 over Bihar and adjoining Jharkhand. It lay as a low pressure area over north Chhattisgarh and neighbourhood in the morning of 1st June and became less marked in the same forenoon. The best track parameters are shown in Table 2.2.1. The track of the depression over the Bay of Bengal (29-31 May) is shown in Fig. 2.1 and typical satellite imageries are shown in Fig.2.2.1 respectively.

Table 2.2.1 Best track positions and other parameters of Depression over the Bay of Bengal during 29-31 May, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
29-05-2013	0300	21.0/89.5	1.5	996	25	4	D
	0600	21.3/89.3	1.5	996	25	4	D
	0900	21.5/89.0	1.5	996	25	4	D
	1200	21.7/88.8	1.5	994	25	4	D
	The system crossed West Bengal coast near lat. 21.8 and Long. 88.7 between 1330-1430 UTC						
	1500	22.0/88.7	-	994	20	4	D
	1800	22.1/88.4	-	994	20	4	D
30-05-2013	0000	22.2/87.8	-	994	20	4	D
	0300	22.3/87.5	-	990	20	4	D
	0600	22.3/87.5	-	990	20	4	D
	1200	22.7/87.3	-	990	20	4	D
	1800	22.8/87.2					
31-05-2013	0000	23.5/87.1	-	990	20	4	D
	0300	24.0/87.0	-	990	20	4	D
	0600	24.5/87.0	-	994	20	3	D
	0900	25.0/87.0	-	996	20	3	D
	1200	The system weakened into a well marked low pressure area over Bihar & adjoining Jharkhand					

2.2.3 Realised Weather:

Chief amounts of 24 hrs. rainfall (7 cm or more) ending at 0300 UTC of 30thMay-1st June, 2013 are given below.

<u>30.5.2013</u>:
Gangetic West Bengal: Contai-26, Sagar Islands-17, Kalaikunda-12, Jhargram-9, Digha, Kharagpore -8, Midnapore, Haldia-7,

Sub-Himalayan West Bengal and Sikkim: Gazolwdoba-13, Sevoke-11, Nagrakata-8, Bagrakote, Champasari, Damthang, Darjeeling, Murti -7 each.

Odisha:Rajghat-12, Jamsholaghat, Dharmanagar-11 each, Bangiriposhi, Rairangpur, Baripada, Jaleswar, Samakhunta-9 each, Soro, Basudevpur, Pattamundai, Chandbali-8 each, Chandanpur, Jaipur, Chandipore, Tihidi, Udala, Govindpur, Batanati, Nilagiri and Paradip-7 each

Assam: Karimganj-9, Udalguri-9, Beki-Mathanguri-8.

Meghalaya : Cherrapunjee (Rama Krishna Mission)-10 Cherrapunji(AWS)-9

<u>31.05. 2013</u>:
Gangetic West Bengal: Purulia-14, Midnapore-13, Kalaikunda-12, Kharagpur & Bankura -8 each,

Sub-Himalayan West Bengal and Sikkim: Darjeeling-17, Sevok-10, Champasari & Damthang-7 each.

Odisha: Tiring-14, Rairangpur-12, Bangiriposhi-9, Jhorigam & Chandihandi-8

Jharkhand: Jamsedpur(Airport)-13, Jamsedpur-11 and Ranchi-12, Mohanpur-7

Bihar: Saraiya-17, Motihari-12, Jamoi-10, Gaya, Patna, Chhapra, Islampur, Hisua, Vaishali and Muzaffarpur -9 each, Marhura and Chakia -8 each, Sono-7

<u>1.6. 2013</u>:
ASSAM & MEGHALAYA:
Dhekiajuli – 7

BIHAR:
Jamui-12, Purnea and Katihar North -9 each

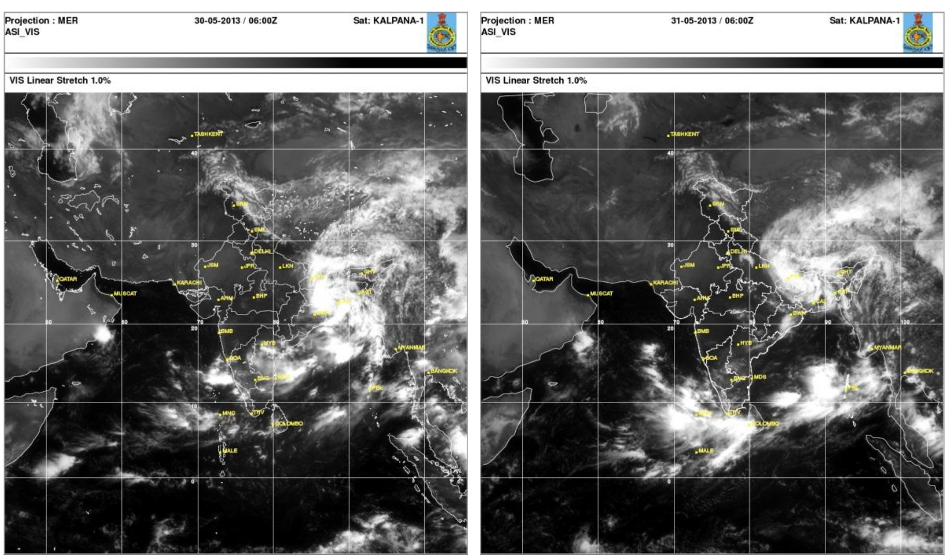


Fig.2.2.1 **Typical Kalpana-1 Satellite imageries of depression at 0600 UTC of 30-31 May, 2013.**

2.3 Depression over the Bay of Bengal (30th July- 01st August 2013)

2.3.1 Introduction:

A depression formed over northwest Bay of Bengal on 30th July, 2013 Moving westnorthwestwards, it crossed north Odisha and adjoining West Bengal coast between Balasore and Digha around 0700 UTC of 30th July 2013. It caused heavy to very heavy rainfall over, Odisha, Chattisgarh, Madhya Pradesh and Maharashtra. The salient features of depression are given below:

(i) The depression initially moved northwestward before landfall and then it moved westwards up to east Madhya Pradesh.
(ii) Due to its slow westward movement over east Madhya Pradesh and adjoining Chhattisgarh, it caused very good rainfall activity over the region.

The depression was monitored with satellite, meteorological buoys, coastal, observations and DWR Kolkata & Nagpur. The half hourly INSAT/ Kalpana imageries & scattrometer wind and every 10 minutes DWR imageries and products were used for monitoring of depression. However the genesis of depression could not be detected through the satellite as any T number could not be assigned. Previous studies also indicate that Dvorak technique has the limitation in detecting the monsoon depression as these are highly sheared system. Hence the intensity of the depression was mainly monitored through synoptic observations from coastal stations and buoys over the sea.

2.3.2 Genesis

Monsoon trough was very active during 3rd and 4th week of July 2013 leading formation of low pressure systems over the north Bay of Bengal one after the other. The eighth low pressure area of the monsoon season, 2013 formed over northwest Bay of Bengal off Odisha and West Bengal coasts on 29th July 2013. The pressure gradient over the Bay of Bengal was very high during this period as the pressure difference between Kolkata and Port Blair was about 10 hPa. As a result of this strong pressure gradient and associated low pressure area over northwest Bay of Bengal, the southerly surge over the region increased on 29th July 2013 and further on 30th July 2013. The low level convergence and relative vorticity increased over the northwest Bay of Bengal from 29th to 30th July 2013. The sea surface temperature over north Bay of Bengal was also warmer (> 30°C). The Madden Julian Oscillation (MJO) index lay in phase 4 during 29th July to 4th August, 2013. However, its amplitude was less than 1 on all the days except on 1st August when it was slightly above 1. Past studies indicate that phase – 4 is favourable for genesis of depression as it helps in enhancing the convection. Under these conditions the low pressure area further concentrated into a depression at 0300 UTC of 30th July, 2013 nea Lat. 21.0°N/Long. 88.0°E. The best track of the depression is shown in fig.2.1. The typical satellite and radar inageries are shown in fig.2.3.1 to 2.3.3

Table 2.3.1 Best track positions and other parameters of Depression over the Bay of Bengal during 30th July-01st August, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
30.07.2013	0300	21.0/88.0	1.5	0990	25	3	D
	0600	21.5/87.5	1.5	0990	25	3	D
	The system crossed north Odisha and adjoining West Bengal coast between Balasore and Digha around 0700 UTC						
	1200	21.7/87.0	-	0990	25	3	D
	1800	21.7/85.5	-	0992	20	3	D
31.07.2013	0000	21.8/84.0	-	0992	20	3	D
	0300	21.8/83.0	-	0992	20	3	D
	0600	21.8/82.5	-	0992	20	3	D
	1200	22.0/80.5	-	0992	20	3	D
01.08.2013	0000	22.5/80.0	-	0992	20	3	D
	0300	The system weakened into a well marked low pressure area over southeast Madhya Pradesh and adjoining Chhattisgarh and Vidarbha.					

2.3.3 Intensification and movement

As the depression lay close to the coast it interacted with land surface. Further the depression moved fast towards the land and crossed coast within 04 hours. The MJO was not favourable for intensification of the depression as its amplitude was less. As a result, it could not intensify further. The depression moved westwards and crossed north Odisha and adjoining West Bengal coast between Balasore and Digha around 0700 UTC of 30th July 2013. The system moved west-northwestwards and weakened gradually into a well marked low pressure area over southeast Madhya Pradesh and adjoining Chhattisgarh and Vidarbha at 0300 UTC of 1st August, 2013.

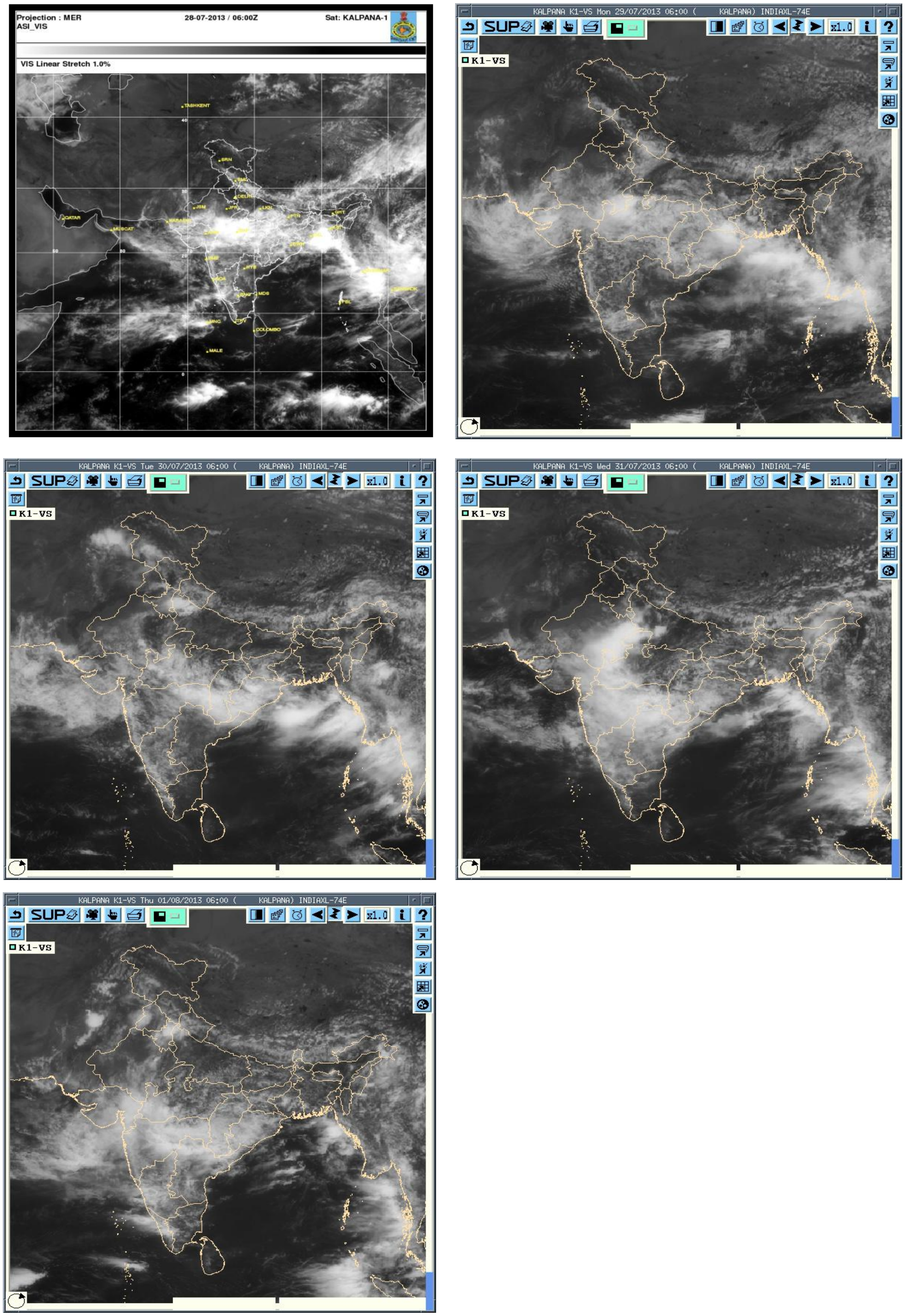


Fig.2.3.1 Typical Kalpana-1 Satellite imageries of depression at 0600 UTC of 28th July to 01st August 2013

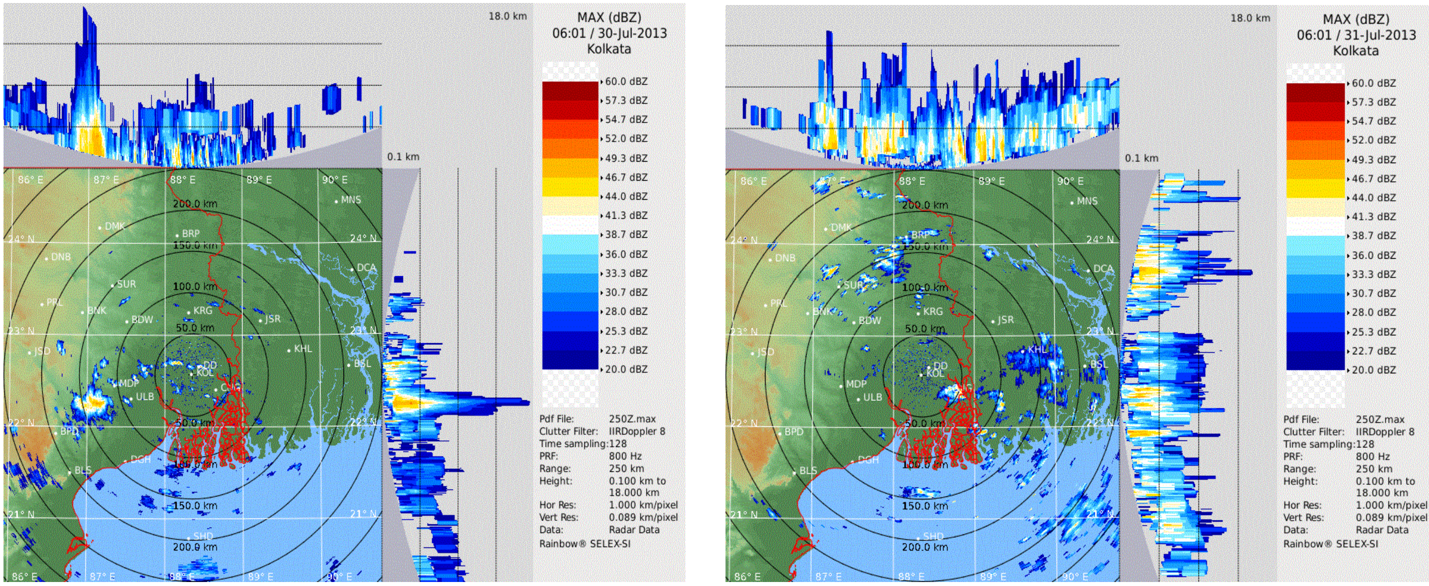


Fig.2.3.2 DWR, Kolkata imageries (maximum reflectivity) of Kolkata at 0600 UTC of 30th& 31st July 2013

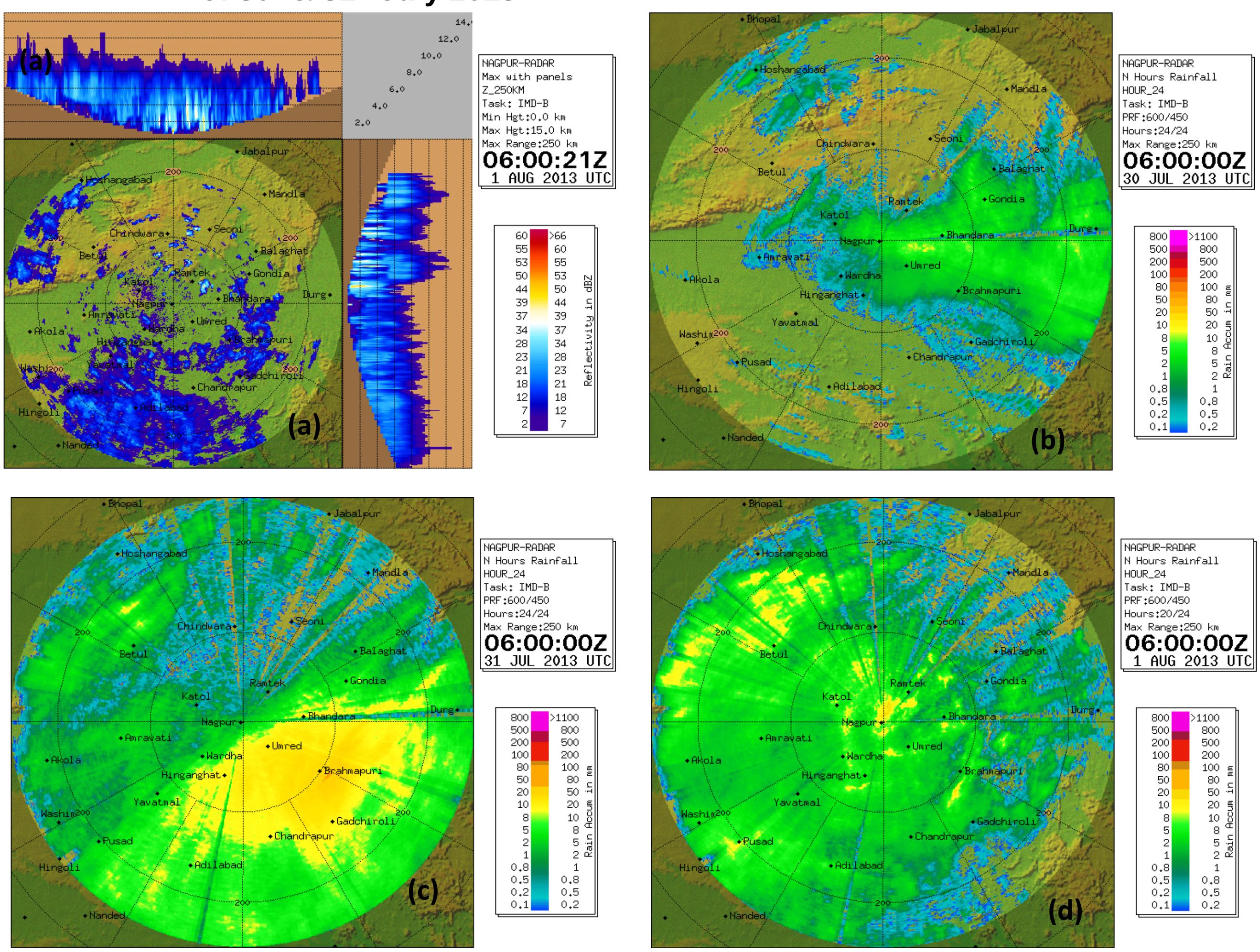


Fig.2.3.3 DWR, Nagpur imageries (a) maximum reflectivity at 0600 UTC of 1st Aug. 2013 and (b-d) 24 hr cumulative rainfall recorded at 0600 UTC of 30th& 31st July and 1st Aug. 2013.

2.3.4 Realised Weather:

Chief amounts of 24 hrs. rainfall (7 cm or more) ending at 0300 UTC of 31st July -1st August, 2013 are given below:

31.7.2013:

Jharkhand: Arki -7

Odisha: Komna -19, Khariar -17, Jujumura (ARG) - 6, Padampur, Bijepur, Raighar (ARG), Titlagarh-13 each, Kesinga ARG)- 12, Boden (ARG), Chandahandi (ARG) -11each, Patnagarh, Turekela,Sinapali (ARG), Sonepur -10 each, Batagaon, Pallahara, Junagarh - 9 each, Khaprakhol (ARG), Ullunda (ARG), Banaigarh (AWS), Paikma, Belgaon, Dunguripalli, Madanpur, Rampur, Nawapara, Khairama, Jhorigam (ARG)-8 each, Sohela, Laikera, Atabira (ARG), Boudhgarh, Birmaharajpur (ARG), Rajkishorenagar, Batli (ARG), Ambabhona, Tarva (ARG), Loisingha (ARG), Saintala (ARG), Kirmira (ARG), Kolabira (ARG) -7 each.

Chhittisgarh: Ambagarh Chowki-17, Bemetara -16, Simga, Dongargaon- 15 each, Dhamtari-14, Raipur, Bijapur, Arang, Rajnandgaon-13 each, Dongargarh, Dondilohara-12 each, Balod-11, Gariabund-10, Rajim, Saraipali, Raipur(AP) -9 each, Deobhog,Sarangarh-8 each, Durg-7.

Vidarbha: Bramhapuri, Desaiganj, Mulchera-19 each, Kurkheda, Armori, Arjuni, Morgaon, Deori-18 each, Korchi -17, Nagbhir, Lakhandur-16 each, Pauni -15, Sakoli, Bhiwapur, Maregaon -14 each, Gadchiroli, Sadakarjuni, Saoli, Sindewahi-13 each, Chimur, Lakhani, Mul, Dhanora – 11each, Salekasa, Chamorshi-10 each, Etapalli, Chandrapur, Umrer, Bhandara, Bhamragad-9 each, Kuhi, Zarizamni, Hinganghat, Chikhalda – 8 each, Korpana, Goregaon, Mauda, Ralegaon, Tirora -7 each

01.08.2013

Odisha: Saintala (ARG) -7,

Chhattisgarh: Sukma-7,

Vidarbha: Armori-22, Desaiganj -21, Dharni -17, Kurkheda, Saoli, adchiroli – 14 each , Katol, Mahagaon, Wani – 13 each, Arjuni Morgaon -12, Narkheda, Kamptee, Zarizamni, Umerkhed, Arni, Etapalli, Perseoni -11 each, Ballarpur, Chamorshi, Nagpur Aerodrome, Kalmeshwar, Sironcha, Saoner-10 each, Korpana, Lakhani, Joiti, Yeotmal, Rajura, Mul, Mangrulpir, Warora, Pandherikawara, Amraoti-9 each, Ahiri, Ner, Pombhurna, Digras, Maregaon, Manora, Chandrapur, Washim, Selu, Morsi, Bramhapuri - 8 each, Risod, Paratwada, Akola, Anjangaon, Karanjalad, Patur, Nandgaonkazi, Ramtek, Darwha, Bhadravati, Ghatanji, Gondpipri, Chandur Rlwy, Amgaon, Murtajapur, Bhiwapur, Hinganghat - 7 each.

East Madhya Pradesh: Sausar -10

West Madhya Pradesh: Chicholi– 28, Pachmarhi-25, Betul- 21, Khandwa -20, Khaknar-19, Shajapur -17, Sarangpur, Khirkiya-15, Bhainsdehi - 14, Harda, Nusrulgunj – 13, Susner- 12, Tarana-11, Nepanagar, Pandhana -10 each, Atner,Tonkhurd, Barwaha – 9 each, Harsud, Karera, Kannod – 8 each, Datia, Bhikangaon, Khategaon, Ashta, Kolaras, Multai, Maheshwar, Sonkatch – 7 each,

Telengana: Perur, Sirpur- 13, Venkatapuram, Eturnagaram, Adilabad(A), Adilabad- 12 each, Utnoor, Mulug- 11 each, Parkal-10, Kaleswaram – 9, Asifabad, Nirmal – 8

Madhya Maharashtra: Mahabaleshwar-25, Gaganbawada-10, Igatpuri, Chandgad, Ajra, Peint – 7 each,

Marathawada: Kinwat – 8, Bhokar, Kallamnuri, Sengaon, Hingoli – 7 each.

East Rajasthan:Dholpur Tehsil, Neemkathana – 10, Tizara -9, Atru – 8, Shahabad – 7

Gujarat ragion: Valsad, Daman – 7 each,

Kokan & Goa: Poladpur, Jawhar- 11 each, Khed- 10, Mokheda -9, Valpoi, Sanguem, Mandangad, Chiplun, Talasari, Dodamarg -7each.

02.08.2013
West Madhya Pradesh: Badnagar, Ratlam – 11 each, Mhow, Nalchha, Petlawad - 10 each, Sardarpur, Dewas - 9 each, Thandla, Kasarwad, Jhabua - 8 each, Badnawar, Khachrod – 7 each.

Vidarbha: Lakhani, Deori – 11 each, Mahagaon – 10, Sakoli, Sadakarjuni, Washim – 9 each, Digras, Arni, Malegaon – 8 each, Joiti, Manora – 7 each.

Madhya Maharashtra: Mahabaleshwar – 17, Gaganbawada – 14, Shahuwadi – 7

Konkan & Goa: Talasari – 23, Mahad- 19, Dahanu – 17, Bhira – 15, Vikramgad, Roha – 14 each, Matheran, Jawhar – 13 each, Dapoli Agri, Khalapur, Chiplun – 10 each, Mumbai, Tala, Mangaon, Guhagarh, Panvel Agri, Khed, Mokheda - 9 each, Poladpur, Mandangad, Tbia, Uran – 8 each, Harnai, Karjat Agri, Sangameshwar Devrukh, Sudhagad Pali, Mumbai (Colaba), Mhasla, Pen – 7 each.

Gujarat Region: Madhbun – 19, Umergam – 15, Idar, Silvassa – 14, Dahod, Sankheda – 13, Daman, Pardi – 12 each, Surat City – 11, Rajpipala, Vapi – 10 each, Bodeli, Chhota Udepur, Kaprada, Limkheda, Tilakwada - 9 each, Bhiloda, Nanipalson – 8 each, Choryasi, Halol, Jalalpor, Jetpur Pavi, Morva Hadaf, Nandod, Naswadi, Navsari, Vijapur – 7 each.

East Rajasthan: Vallabhnagar – 9, Dungarpur Tehsil, Kanva – 7

West Rajasthan: Pali, Rohat – 9 each, Marwar Junction – 7

03.08.2013

West Madhya Pradesh: Raisen – 7

Madhya Maharashtra: Mahabaleshwar, Ajra – 9 each, Gaganbawada – 8.
Konkan & Goa: Sangameshwar Devrukh – 12, Talasari - 9
Gujarat Region: Tilakwada (ARG) -22, Tilakwada – 21, Nandod – 20, Rantij, Rajpipala– 17 each, Kamrej– 16, Dahegam –15, Gandhinagar, Umergam – 14 each, Dholka, Viramgam(ARG),Talod, Kathalal – 13 each, Ghandinagar (AWS) – 12, Olpad, Kalol (G), Himatanagar – 11 each, Dholka (ARG), Songadh – 10 each, Vyara, Valod, Padra - 9 each, Surat, Navsari, Sankheda, Sinor, Sanand, Bhabhar, Surat(AWS), Umerpada, Kaprada – 8 each, Mahuva, Mangrol, Mahudha, Karjan, Kalol (ARG), Thasra, Bardoli (ARG), ChoryasiAbad City, Wav, Jalalpor, Palsana, Dascroi, Khambhat, Bavla – 7 each.

Saurashtra & Kutch : Amreli – 14, Jamnagar – 13, Liliya (ARG) -12, Gariadhar, Lilia – 11 each, Palitana, Lathi – 10 each, Lodhika, Jafrabad, Jafrabad (ARG) – 9 each, Una, Talaja, Botad, Kodinar – 8 each, Lodhika (ARG), Gondal, Lalpur – 7 each.

West Rajasthan: Sanchore, Raniwada – 8 each.

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

2.4 Land Depression (20th August – 23rd August, 2013)

2.4.1 Introduction

A land depression formed over Gangetic West Bengal and adjoining areas of north Odisha, Jharkhand and north Bay of Bengal on 20th August, 2013 morning about 100 km southeast of Jamshedpur and 100 km south of Bankura. It moved westward upto central part of south Madhya Pradesh during 20th August – 22nd August, 2013 and weakened on 23rd morning. It caused heavy to very heavy rainfall over north Odisha, Gangetic West Bengal, Jharkhand, Chhattisgarh and Madhya Pradesh. The salient features of this depression are given below:

- (i) Though it was a land depression, it originated from a low pressure area over the northwest Bay of Bengal.
- (ii) It activated the southwest monsoon condition over the country.
- (iii) It moved slowly initially for about 24hours and then moved westward upto east Madhya Pradesh and then westsouthwestwards upto central part of south Madhya Pradesh.

2.4.2 Genesis

During second week of August, the eastern end of the monsoon trough lay significantly to the south of its normal position passing through south Chhattisgarh and south Odisha to southeast Bay of Bengal across westcentral Bay of Bengal. An upper air cyclonic circulation lay over westcentral Bay of Bengal, off coastal Andhra Pradesh extending between 3.1 km and 5.8 km above mean sea level on 11th August. It persisted over the same area and extended upto mid-tropospheric level on 13th August. It moved northward and lay over westcentral Bay, off north coastal Andhra Pradesh and adjoining south Odisha coast on 14th and persisted there on 15th. Under its influence, a low pressure area formed over west central and adjoining northwest Bay of Bengal off north coastal Andhra Pradesh and south coastal Odisha on 16th with associated cyclonic circulation extending upto mid-tropospheric level. It further moved northward and lay over northwest Bay of Bengal on 17th and over northwest Bay of Bengal and adjoining areas of Gangetic West Bengal on 18th. It lay as a well-marked low pressure area over northwest Bay of Bengal and adjoining areas of north Odisha and Gangetic West Bengal on 19th. It concentrated into a depression at 0000 UTC of 20th and lay centered over Gangetic West Bengal and adjoining areas of north Odisha, northwest Bay of Bengal and Jharkhand near latitude 22.0°N and longitude 87.5°E, about 50 km north-northeast of Digha (West Bengal).

Table 2.4.1 Best track positions and other parameters of Depression over Gangetic West Bengal during 20th August – 23rd August, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at theCentre (hPa)	Grade
20.08.2013	0000	22.0/87.5	-	0990	25	3	D
	0300	22.0/87.5	-	0990	25	3	D

	0600	22.0/87.5	-	0990	25	3	D
	1200	22.3/87.5	-	0990	25	3	D
	1800	22.5/87.5	-	0990	25	3	D
21.08.2013	0000	23.3/87.0	-	0990	20	3	D
	0300	23.3/86.0	-	0992	20	3	D
	0600	23.2/85.7	-	0992	20	3	D
	1200	23.2/84.0	-	0991	20	3	D
	1800	23.2/82.2	-	0994	20	3	D
22.08.2013	0000	23.2/82.0	-	0994	20	3	D
	0300	23.2/80.7	-	0994	20	3	D
	0600	23.2/80.3	-	0996	20	3	D
	1200	23.0/80.1	-	0998	20	3	D
23.08.2013	0000	22.8/79.8	-	0998	20	3	D
23.08.2013	0300	Weakened into a well marked low pressure area over central part of south Madhya Pradesh and adjoining Vidarbha.					

2.4.3 Intensification and movement:

The depression initially moved north-northwestwards upto 0000 UTC of 21st August across Gangetic West Bengal. It then moved nearly westwards till the morning of 22nd August and moved west-southwestwards thereafter upto central part of south Madhya Pradesh. It weakened into a well-marked low pressure area over central part of south Madhya Pradesh and adjoining Vidarbha at 0300 UTC by 23rd August and into a low pressure area over the same region in 23rd evening. It became less marked on 24th August, 2013.

The track of the depression is shown in Fig.2.1. The best track parameters are shown in table 2.4.1. Typical satellite and Radar imageries are shown in Fig.2.4.1 and Fig.2.4.2 respectively.

The 24 hours accumulated precipitation received by DWR Kolkata indicates most intense rainfall in the southwest sector of the depression covering southern part of Gangetic West Bengal and north Odisha on 20th and 21st August. Similar imageries from DWR, Nagpur indicates an east-ward oriented precipitation to the north of Nagpur on 20th& 21st August. It spread to the south on 22nd& 23rd August. However, most intense rainfall occurred to the northwest of Nagpur covering southwest Madhya Pradesh.

2.4.4 Dynamical features:

The IMD GFS analyses at 0000UTC of 20 -23 August, 2013 are shown in Fig. 2.4.3(a-d). It indicates that the genesis of the system could be well captured by the model on 20th as it showed a low pressure area over Gangetic West Bengal and neighborhood.

The model could not detect the intensity. It also showed slow northwestward movement till 21st August and then westward movement and west-southwestward movement upto 79°E till 23rd August. Considering the prediction by the model it could predict the track reasonably. But the intensity of the system was under predicted. Initial north-northwestward movement of the depression was mainly due to the steering southerly to south-southeasterly wind at 200 hPa level in association with anti-cyclonic circulation over Mizoram and neighborhood. After that it moved westward till 22nd and then west-southwestwards with the steering wind at 200 hPa level as shown in Fig.2.4.3(a-d).

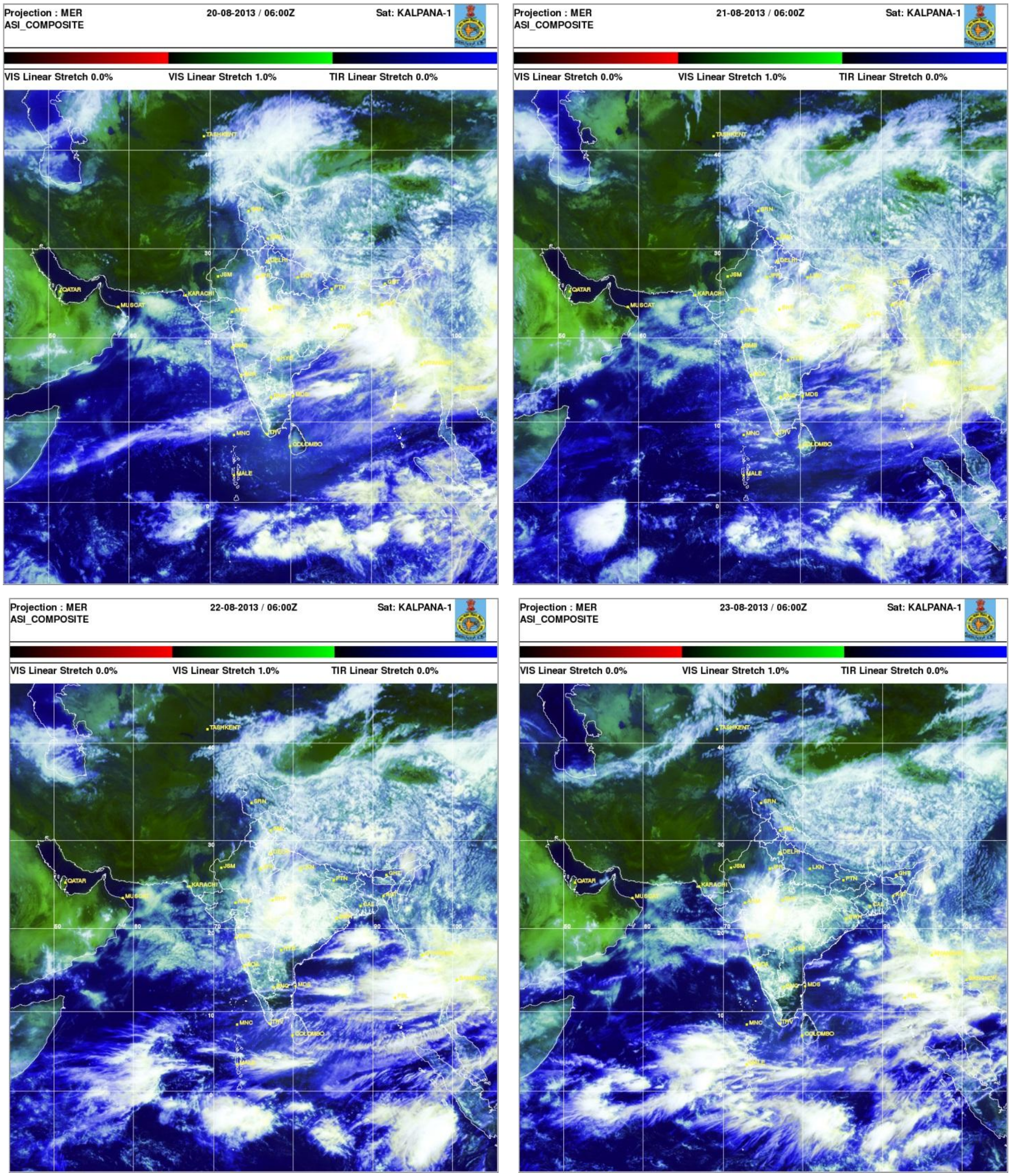


Fig 2.4.1. Typical Kalpana-1 Satellite imageries of depression at 0600 UTC of 20th August to 23rd August, 2013

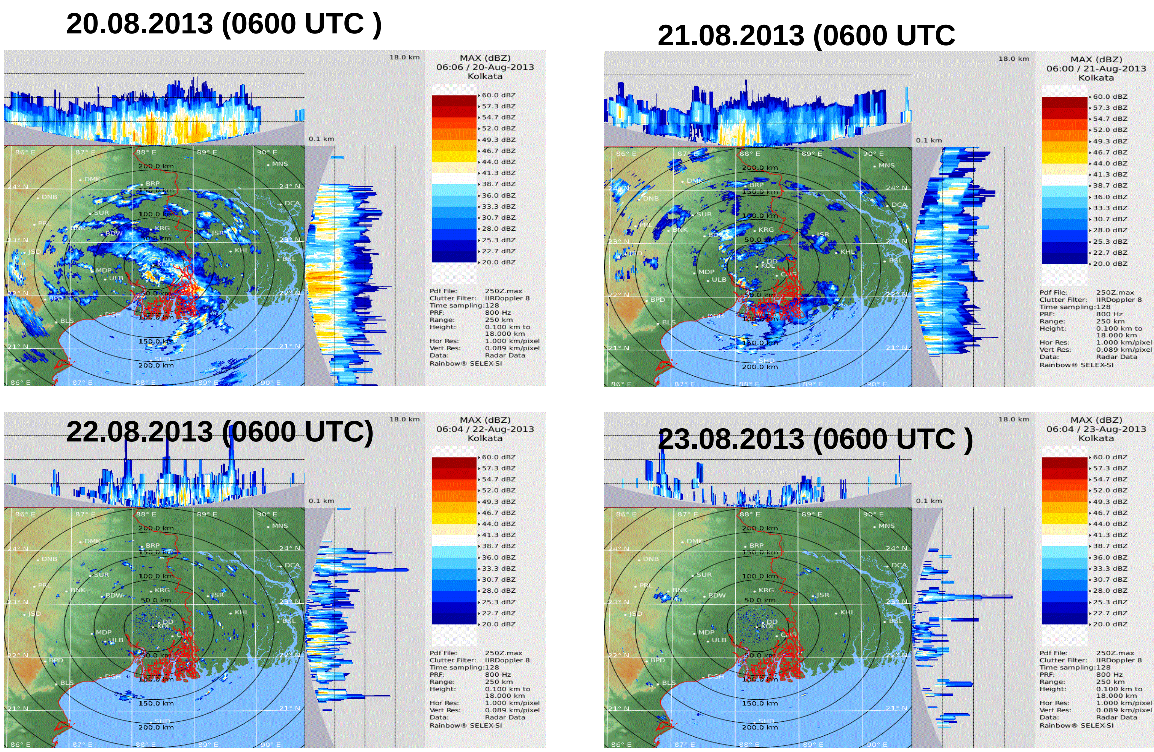


Fig.2.4.2 (a). Reflectivity imageries (Max Z) of DWR Kolkata at 0600 UTC of 20- 23 August, 2013

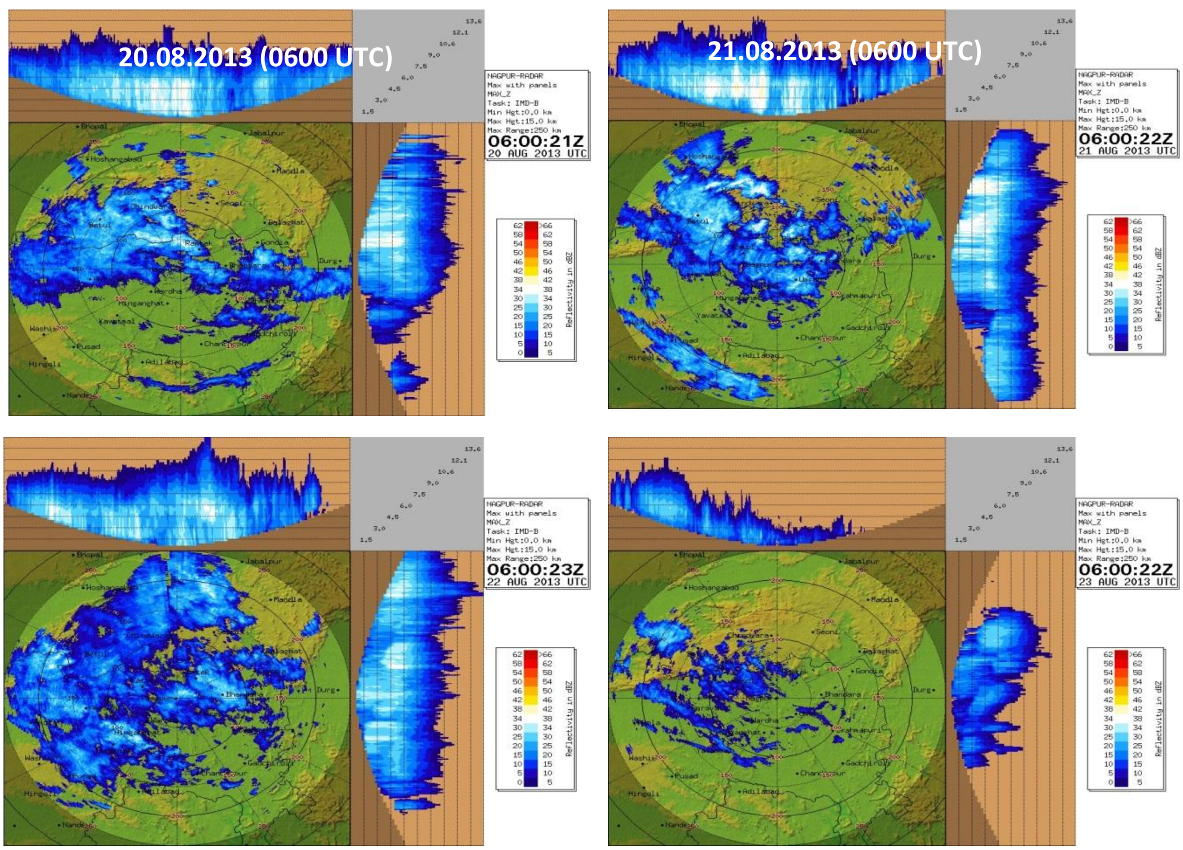


Fig.2.4.2 (b).Reflectivity imageriesof DWR Nagpur at 0600 UTC of 20– 23 August, 2013

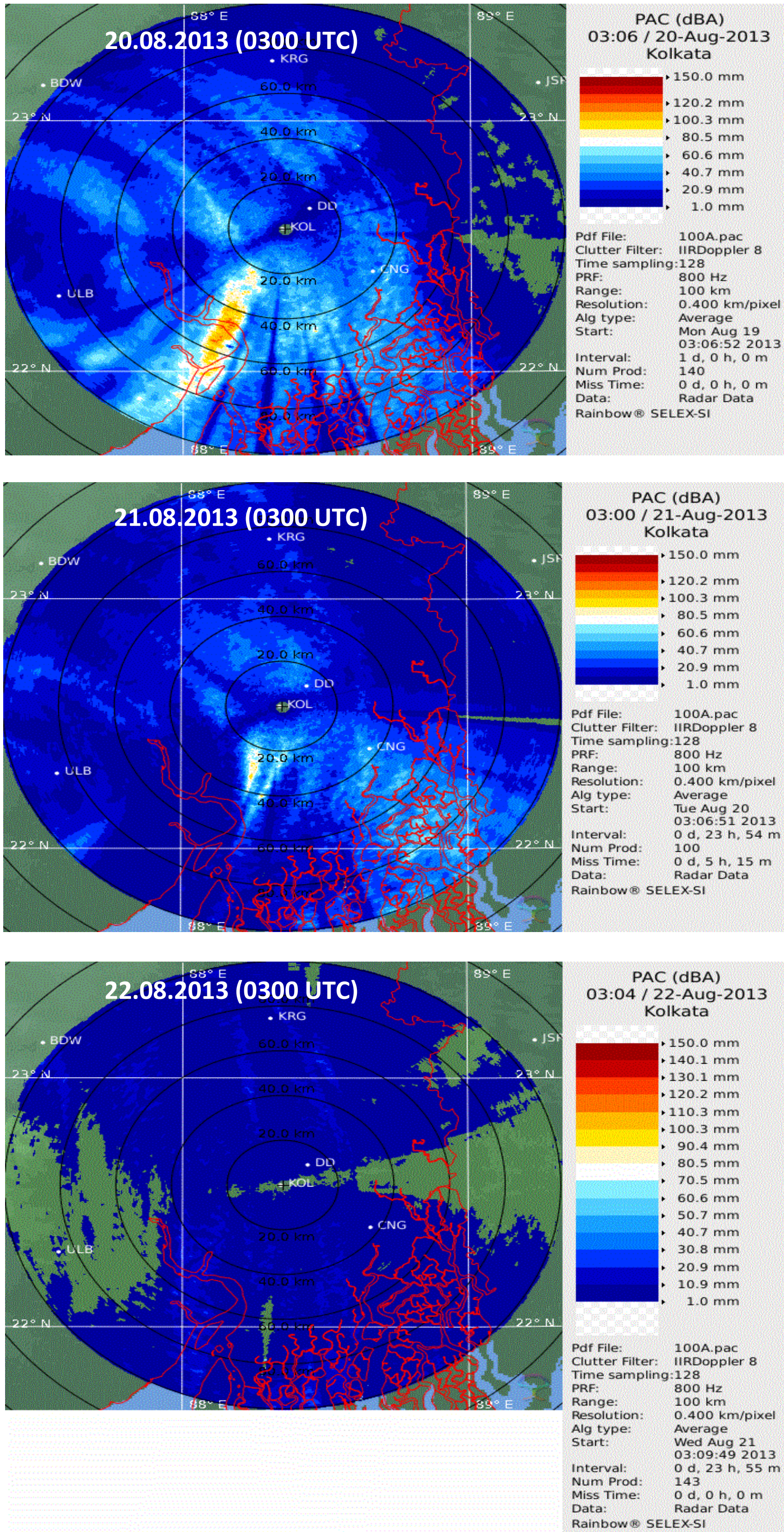


Fig.2.4.2 (c). Cumulative Rainfall imageriesof DWR Kolkata at 0300 UTC of 20– 22 August, 2013

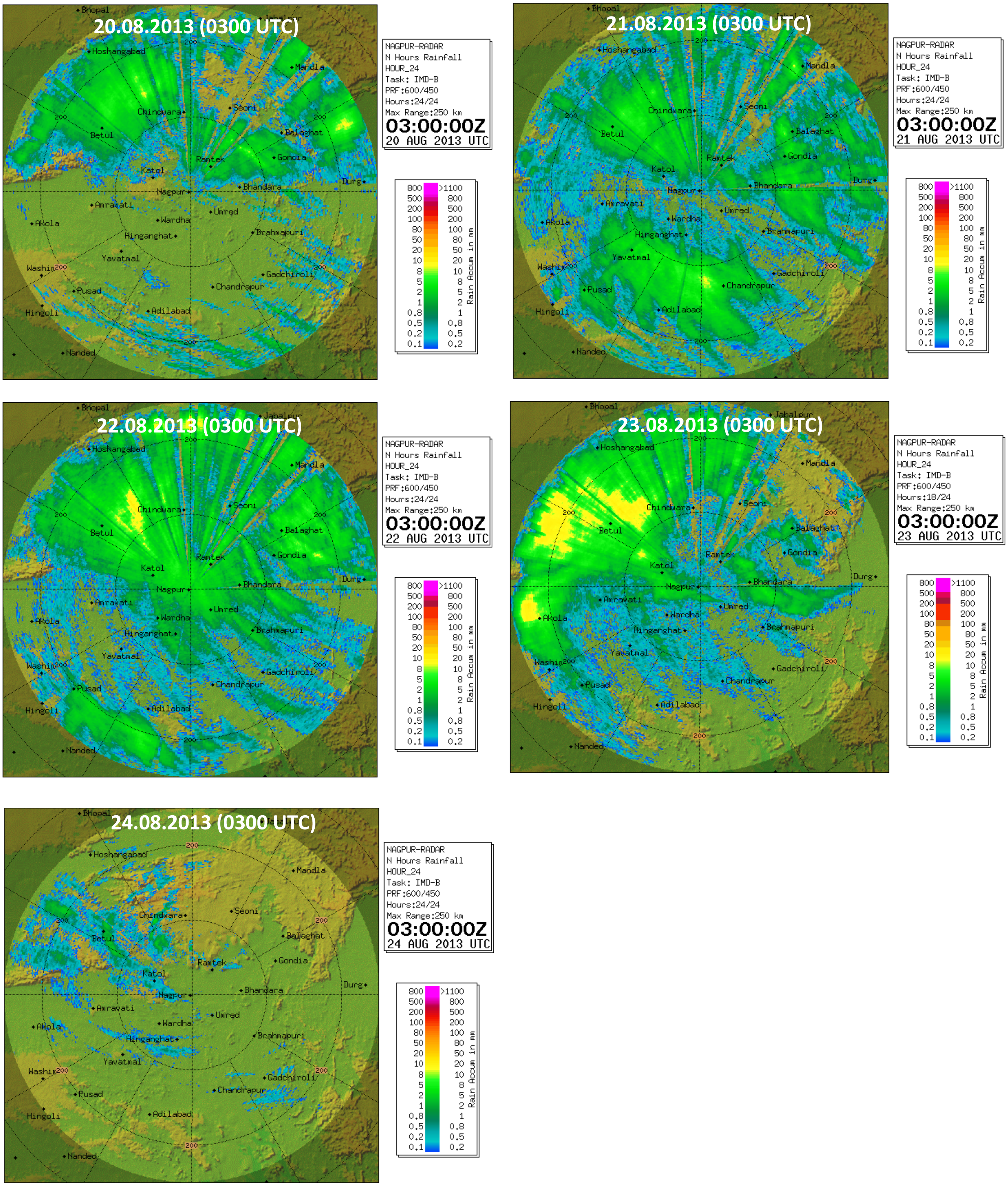


Fig.2.4.2 (d). Cumulative Rainfall imageriesof DWR Nagpur at 0300 UTC of 20– 24 August, 2013

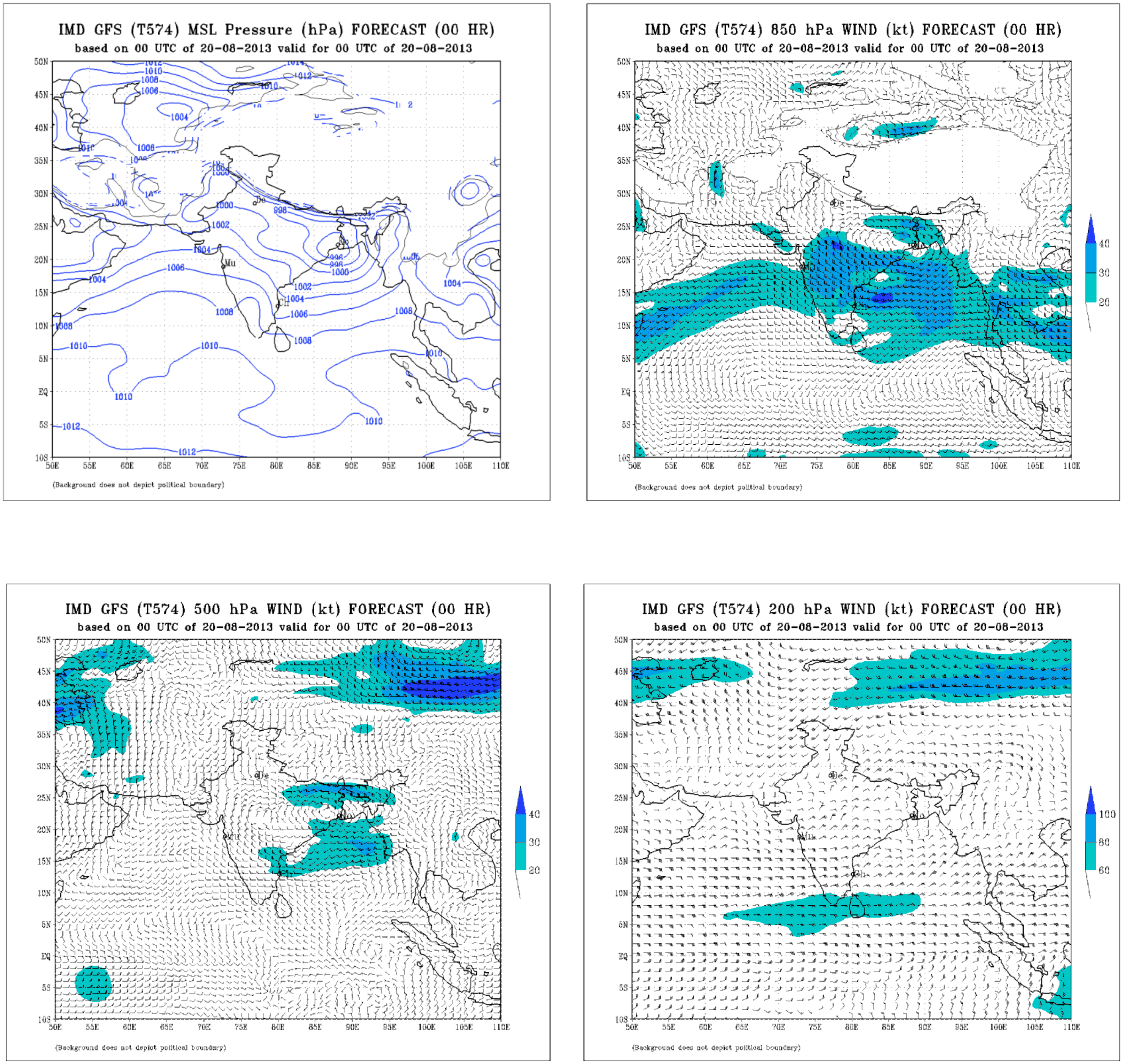


Fig.2.4.3 (a). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 850,500 & 200 hPa based on 0000 UTC of 20th August, 2013

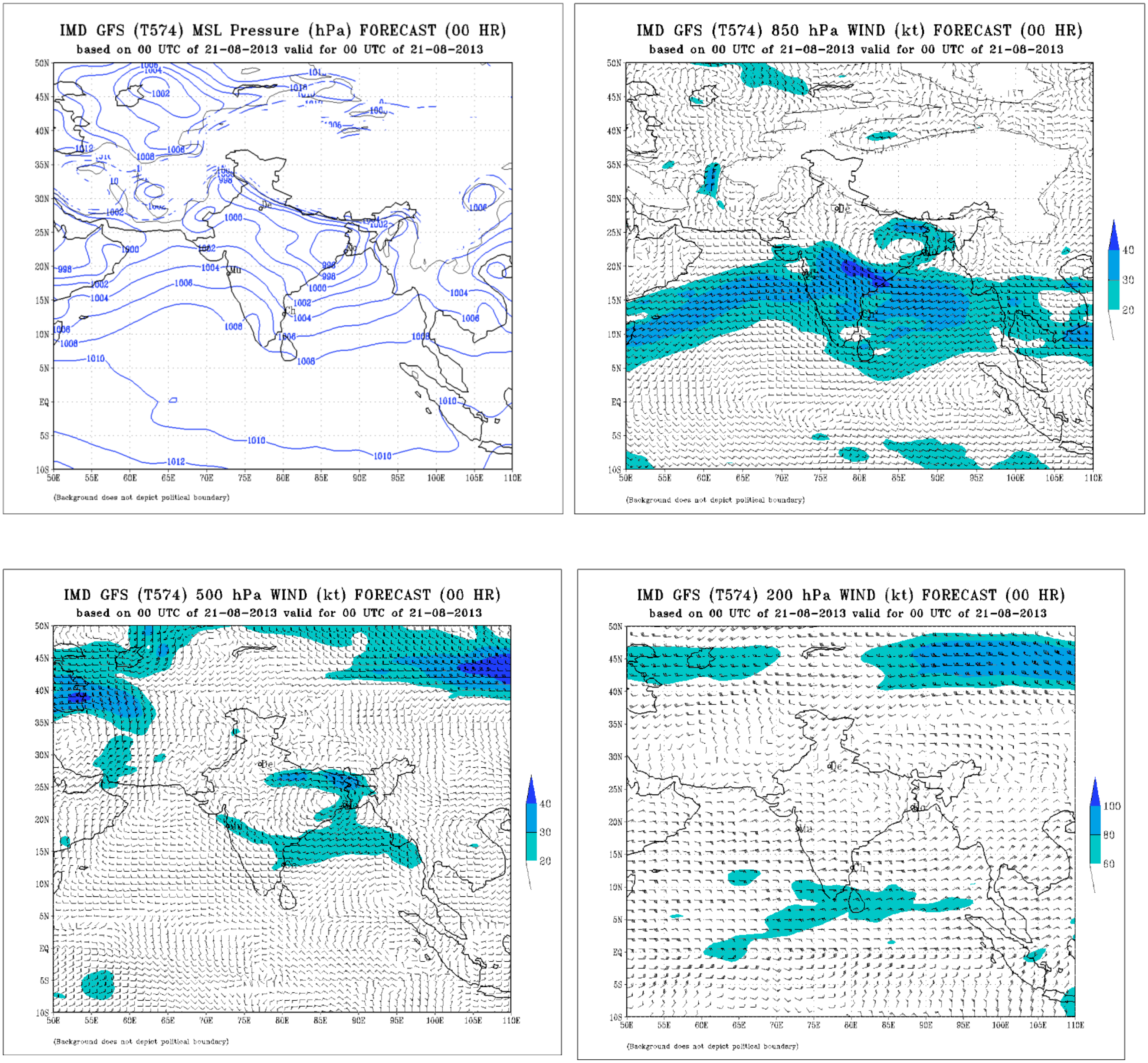


Fig.2.4.3(b). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 850,500 & 200 hPa based on 0000 UTC of 21st August, 2013

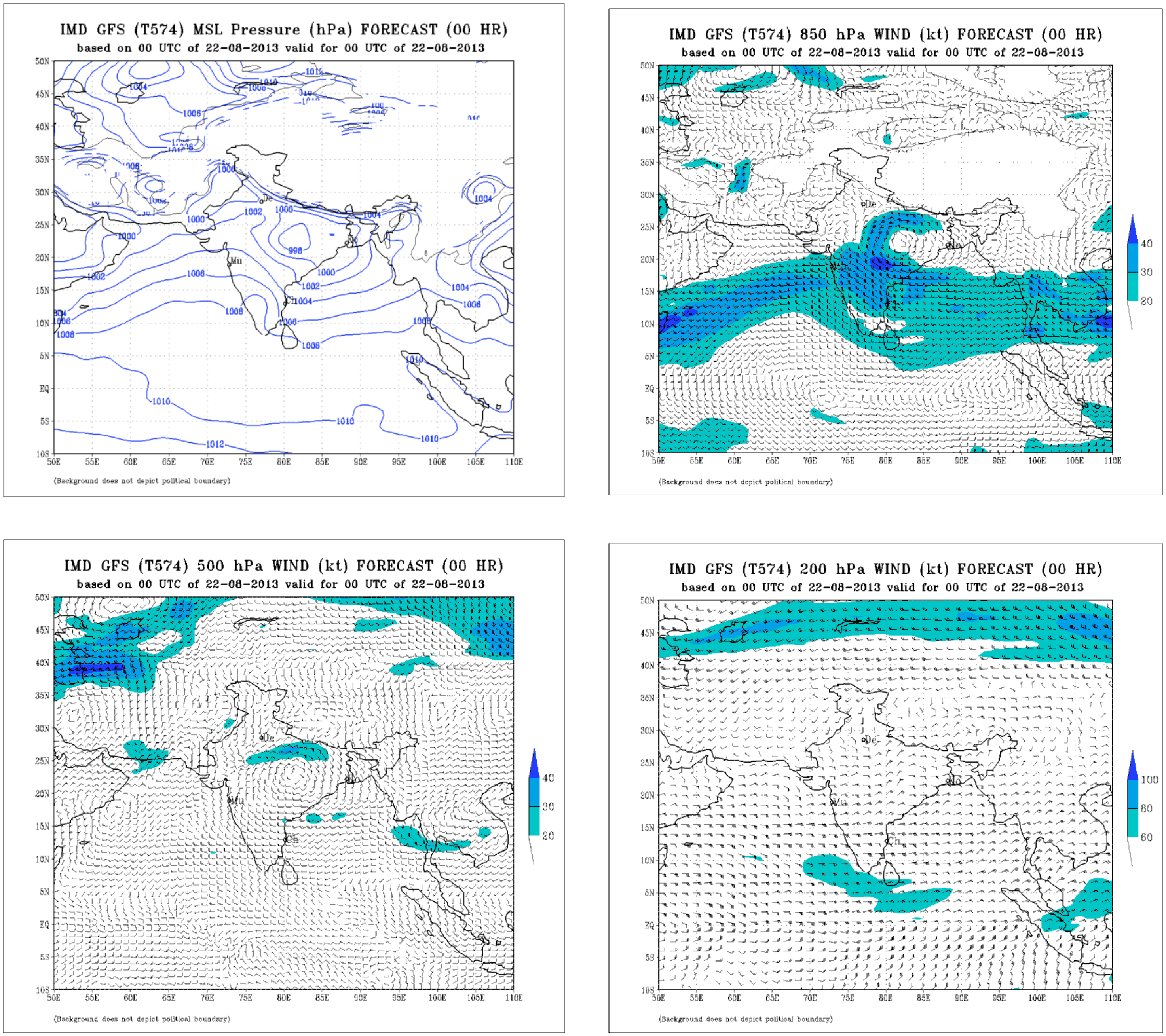


Fig.2.4.3(c). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 850,500 & 200 hPa based on 0000 UTC of 22nd August, 2013

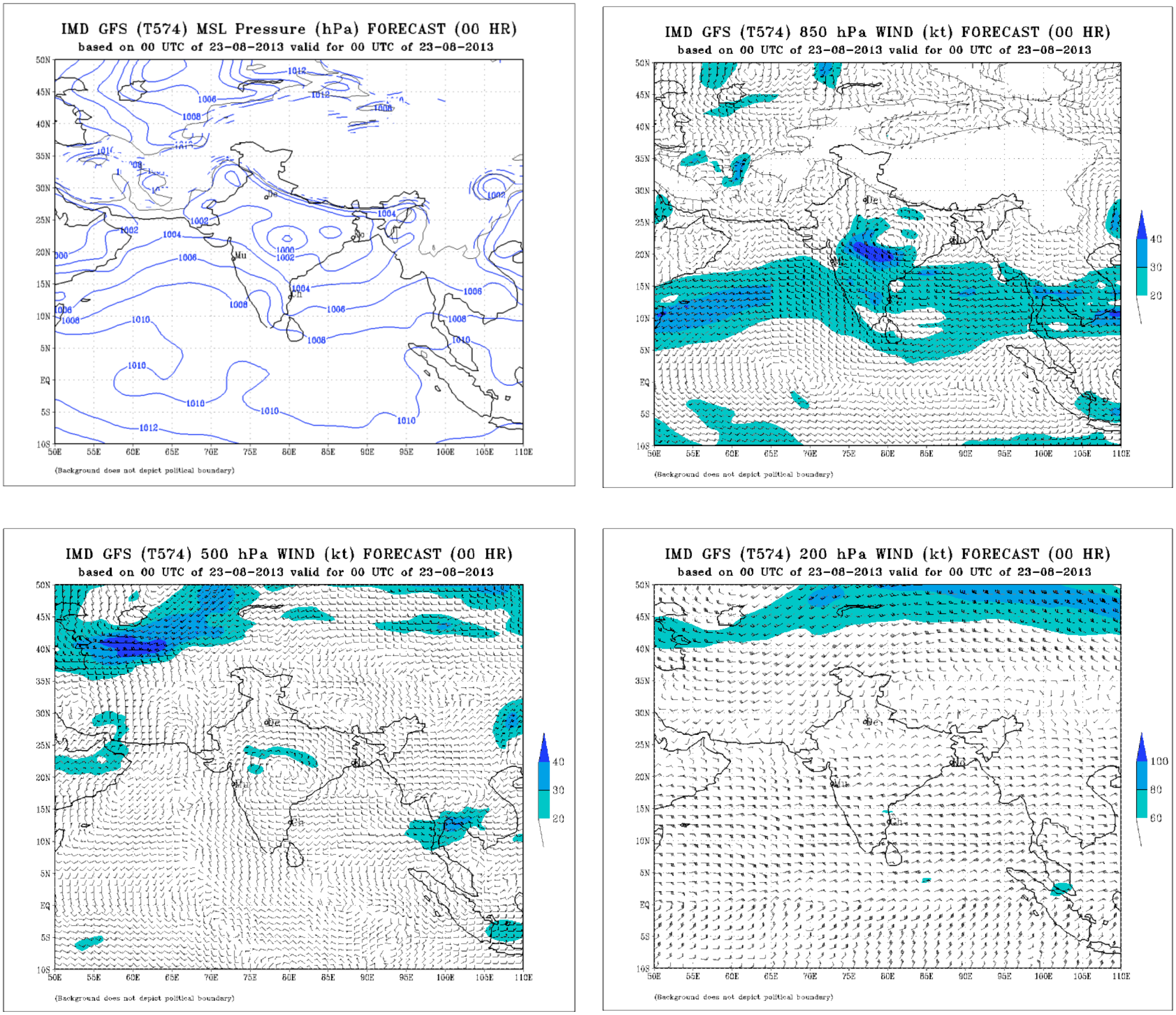


Fig.2.4.3 (d) IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 850,500 & 200 hPa based on 0000 UTC of 23 August, 2013

2.4.6. Realised Weather:

Chief amounts of 24 hrs. rainfall (7 cm or more) ending at 0300 UTC of 20th August – 25th August, 2013 are given below:

20.08.2013:

Odisha: Deogarh- 22;Batagaon-20, Chandanpur- 13, Rengali-12, Danagadi-ARG, Rairangpur,Baripada -11each, Jaleswar,Pallahara, Reamal and Jamsolaghat-10each,Keonjhargarh,KNuagaon ARG,Bangiriposi and Ghatagaon-9 each, Samakhunta

AWS,Sundargarh,Tensa,Kuchinda, Joda ARG Komna,Soro and Nawana- 8 each,Nawapara,Bhograi,Joshipur,Tiring,Korei ARG,Udala,Baliguda,Rajghat and Kesinga ARG - 7 each.
Gangetic West Bengal: Durgachack,Diamond Harbour -17 each,Jagatballarpur-15, Canning-11, Contai-10, Harinkhola, Baruipur Agro-AWS,Kolkata (Alipore),Sagar_Island AWS- 9 each, Tamluk AWS- 8, Kalyani, Kalaikunda- 7each.

21.08.2013:
Gangetic West Bengal: Tusuma -19; Purihansa -12, Barrackpur, Shekhampore ARG and Canning- 9 each, Baruipur Agro-AWS and Dum Dum- 8 each, Simula, Kotshila ARG, Jagatballavpur Arg, Mohanpur and Suri -7 each.
Odisha: Baripada- 16, Rairangpur- 15, Jaleswar and Rajghat- 13 each, Nawana -12, Betanati ARG- 10, Jamsolaghat, Bangiriposi, Samakhunta AWS, Joshipur and Tensa- 9 each, Kaptipada ARG, Chandanpur and Udala- 8 each, Sundargarh, Balimundali, Paradeep, Nilgiri, Deogarh and Balasore- 7 each.
West Madhya Pradesh: Pachmarhi- 12, Sujalpur- 8, Betul and Agar- 7 each.
East Madhya Pradesh: Damoh- 16, Garhakota- 8, Hatta, Kaneli and Sagar- 7 each.
Chattishgarh: Manendragarh- 13.
Jharkhand: Messonjori -7.

22.08.2013:
Jharkhand: Papunki-13, Dumri-11, Bagodar-10, Barkisuriya-9, Topchanchi-8, Japla-7
Chhattisgarh: Manendragarh-12
East Madhya Pradesh: Damoh-19, Garhakota-14, Rehli-13, Ghansore-12, Maihar-11, Jabalpur-New—9, Kaneli, Deori, Narsinghpur, Sausar, Lakhnadon, Hatta and Gotegaon-7 each.
West Madhya Pradesh: Neemuch-15, Pachmarhi-13, Multai-9, Chicholi, Betul and Bhainsdehi-8 each, Ambah, Agar and Morena-7each.
Vidarbha: Chikhaldhara 7.

23.08.13
West Madhya Pradesh : Pachmarhi-25, Betul -23, Chicholi -22, Multai-21, Bhainsdehi -18, Khategaon, Budhni,Raisen-13 each, Nusrulgunj, Bhopal -12 each, Hoshangbad-11, Atner,Ichhawar,Vidisha-10 each, Ganjbasoda, Khaknar, Sehore, Ashta – 9 each, Kannod, Tonkhurd, Khandwa-8 each, Harsud, Narsingarh, Biaora, Shujalpur, Kurwai-7each.
East Madhya Pradesh: Gadarwara, Seoni-12 each, Lakhnadon-10, Narsinghpur-9, Sohagpur, Khurai, Panna-8 each, Chindwara, Ghansore-7 each.
Vidarbha: Chikhalda-15, Narkheda-9, Warud-7.
Chhattisgarh: Manendragarh-11

24/08/13
East Rajasthan : Khushalgarh-10, Shergarh- 9, Sallopat, Badesar-8 each, Bagidora, Arthuna, Sajjangarh, Danpur-7 each.
West Madhya Pradesh: Gautampura-19, Depalpur-17, Dewas-16, Badnagar, Dhar-15 each, Bagli, Indore, Tonkhurd, Mhow- 14 each, Nalchha, Sonkatch-13 each, Ujjain, Kasarwad, Maheshwar, Barwaha-11 each, Badnawar, Jhabua, Petlawad, Mahidpur-10 each, Khaknar, Thikri, Sardarpur, Sarangpur, Thandla, Susner-9 each, Khandwa,

Bhikangaon, Khachrod, Shujalpur, Manawar-8 each, Gandhwani, Bhabhra, Ashta, Agar, Tarana, Kannod, Khargone, Shajapur-7 each.
Gujarat Region: Godhra, Dahod, Fatepura, Kalol-7each.
Vidarbha: Chikhalda-7,

25.08.2013
East Rajasthan :Dug-9,
Gujarat Region : Sankheda-10, Dahod, Jambughoda, Kalol-7 each.

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

2.5 Very Severe Cyclonic Storm (VSCS) Phailin over the Bay of Bengal(08-14 October 2013)

2.5.1 Introduction

A Very Severe Cyclonic Storm (VSCS) Phailin over Bay of Bengal moved northwestwards and crossed Odisha & adjoining north Andhra Pradesh coast near Gopalpur (Odisha) around 1700 UTC of 12th October 2013 with a sustained maximum surface wind speed of 215 kmph.

The salient features of this storm are as follows.

i. VSCS Phailin is the most intense landfalling cyclone over NIO after Odisha Super Cyclone of 29th October 1999.
ii. There was rapid intensification of the system from 10th Oct. morning to 11th October morning leading to an increase in wind speed from 45 knots to 115 knots.
iii. At the time of landfall on 12th Oct, maximum sustained surface wind speed in association with the cyclone was about 115 knots (215 kmph) and estimated central pressure was 940 hPa with pressure drop of 66 hPa at the centre compared to surroundings.
iv. It caused very heavy to extremely heavy rainfall over Odisha leading to floods, and strong gale wind leading to large scale structural damage and storm surge leading to coastal inundation over Odisha.
v. Maximum rainfall occurred over northeast sector of the system centre at the time of landfall. Maximum 24 hr cumulative rainfall of 38 cm has been reported over Banki in Cuttack district of Odisha.
vi. Based on post-cyclone survey report, maximum storm surge of 2-2.5 meters above the astronomical tide has been estimated in the low lying areas of Ganjam district of Odisha in association with the cyclone and the in-land inundation of saline water extended upto about one kilometer from the coast.

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.

2.5.2 Genesis

The VSCS Phailin originated from a remnant cyclonic circulation from the South China Sea. The cyclonic circulation lay as a low pressure area over Tenasserim coast on 6th October 2013. It lay over north Andaman Sea as a well marked low pressure area on 7th October.

On 8th October, scatterometry data indicated the cyclonic circulation over the region and associated wind speed to be about 25-30 knots. The wind speed was relatively higher in southern sector in association with cross equatorial flow. According to satellite observation, intense to very intense convection was seen over Andaman Sea and adjoining area between lat 8.5^{0}N to 14.5^{0}N and east of long 88.5^{0}E to Tenasserim coast at 0000 UTC of 8th October. The associated convection increased gradually with respect to height and organisation during 7th to 8th October. The lowest cloud top temperature (CTT) was about -70^{0}C. The convective cloud clusters came closer and merged with each other during the period ending at 0000 UTC of 8th October. According to Dvorak's intensity scale, the intensity of the system was T 1.5. The system showed shear pattern with convection shifted to the west of low level circulation centre. Considering all these, the well marked low pressure area was upgraded as a depression over the north Andaman Sea at 0000 UTC of 8th with its centre near latitude 12.0^0N and longitude 96.0^0E. Maximum sustained surface wind speed was estimated to be about 25 knots gusting to 35 knots around the system centre.

2.5.3 Intensification and movement

The upper tropospheric ridge at 200 hPa level ran along 21^0N in the morning of 8th October and was providing poleward out flow in association with the anticyclonic circulation over central India and another 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 past 24 hrs ending at 0000 UTC of 8th October. The sea surface temperature based on satellite and available buoys and ships observation was about $28\text{-}29^0$C and ocean thermal energy was about 60-80 KJ/cm^2. The sea height anomaly was about 5-10 metre. The vertical wind shear of horizontal wind decreased and 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 northwestwards and intensified into a deep depression at 0000 UTC of 9th Oct. near 13.0^0N and 93.5^0E. Moving west-northwestwards, it crossed Andaman Islands near Mayabandar at 0900 UTC of 9th Oct. It moved slowly over east central Bay of Bengal and intensified into a Cyclonic Storm (CS), PHAILIN at 1200 UTC of 9th Oct. Most of the NWP models suggested west-northwestward to northwestward movement during next 72 hrs towards north Andhra Pradesh and Odisha coast. The NWP guidance including IMD's dynamical statistical model also suggested intensification of the system into a severe cyclonic storm.

Tracking over an area of high sea surface temperatures and Ocean thermal energy and especially low vertical wind shear (5-10 knots), rapid intensification ensued from 10th Oct. morning. Moving westwards, the CS intensified further into an SCS at 0300 UTC and further into VSCS at 0600 UTC of 10th Oct. over east central Bay of Bengal. The system intensified further and attained its maximum intensity of 115 knots in the morning of 11th October. Thus there was a rapid intensification of the system by about 70 knots during morning of 10th to morning of 11th October. The VSCS continued to move northwestwards at a speed of about 15 kmph and crossed Andhra Pradesh & Odisha coast near Gopalpur around 1700 UTC of 12th Oct. 2013. However, northerly component of the movement increased gradually, about 12 hrs before landfall. It continued to move north-northwestwards after the landfall for some time and then northward and finally north-northeastwards upto southwest Bihar. The system weakened gradually into an SCS at 0830 hrs IST of 13th Oct. and into a CS over south Odisha at 0600 UTC of same day. It further weakened into a deep depression over north Chhattisgarh and adjoining Odisha & Jharkhand at 1200 UTC of 13th Oct and into a depression at 0300 UTC of 14th Oct over southwest Bihar. It weakened into a well marked low pressure area at 0900 UTC of 14th over southwest Bihar and neighbourhood. The observed track of the system is shown in fig.2.1. The best track parameters are shown in Table 2.5.1.

Table 2.5.1 Best track positions and other parameters of the Very Severe Cyclonic Storm 'Phailin' over the Bay of Bengal during 08-14 October, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
08-10-2013	0300	12.0/96.0	1.5	1004	25	3	D
	0600	12.0/95.5	1.5	1004	25	3	D
	1200	12.0/94.5	1.5	1003	25	4	D
	1800	12.5/94.0	1.5	1003	25	4	D
09-10-2013	0000	13.0/93.5	2.0	1002	30	5	DD
	0300	13.0/93.5	2.0	1001	30	5	DD
	0600	13.0/93.0	2.0	1000	30	6	DD
	0900	13.5/92.5	2.0	1000	30	6	DD
	1200	13.5/92.5	2.5	999	35	7	CS
	1500	13.6/92.5	2.5	999	35	7	CS
	1800	14.0/92.0	2.5	998	40	8	CS
	2100	14.0/92.0	2.5	998	40	8	CS
10-10-2013	0000	14.5/91.5	3.0	996	45	10	CS
	0300	14.5/91.0	3.5	990	55	15	SCS
	0600	15.0/90.5	4.0	984	65	22	VSCS
	0900	15.0/90.5	4.0	982	70	24	VSCS
	1200	15.5/90.0	4.5	976	75	30	VSCS
	1500	15.5/90.0	5.0	966	90	40	VSCS
	1800	15.5/89.5	5.0	960	95	46	VSCS
	2100	15.5/89.0	5.5	954	100	52	VSCS
11-10-2013	0000	16.0/88.5	5.5	946	110	60	VSCS
	0300	16.0/88.5	6.0	940	115	66	VSCS
	0600	16.2/88.3	6.0	940	115	66	VSCS
	0900	16.5/88.0	6.0	940	115	66	VSCS
	1200	16.8/87.7	6.0	940	115	66	VSCS
	1500	16.9/87.2	6.0	940	115	66	VSCS
	1800	17.0/87.0	6.0	940	115	66	VSCS
	2100	17.1/86.8	6.0	940	115	66	VSCS
12-10-2013	0000	17.5/86.5	6.0	940	115	66	VSCS
	0300	17.8/86.0	6.0	940	115	66	VSCS
	0600	18.1/85.7	6.0	940	115	66	VSCS
	0900	18.6/85.4	6.0	940	115	66	VSCS
	1200	18.7/85.2	6.0	940	115	66	VSCS
	1500	19.1/85.2	6.0	940	115	66	VSCS
	The VSCS crossed Odisha & adjoining north Andhra Pradesh coast near Gopalpur around 1700 UTC (landfall point : 19.2^{0}N and 84.9^{0}E)						
	1800	19.5/84.8	-	956	100	50	VSCS
	2100	20.0/84.5	-	966	90	40	VSCS
13-10-2013	0000	20.5/84.5	-	976	75	30	VSCS

	0300	21.0/84.0	-	990	55	15	SCS
	0600	21.5/84.0	-	996	40	10	CS
	0900	21.8/83.8	-	998	35	8	CS
	1200	22.5/83.8	-	998	35	8	CS
	1800	23.0/83.5	-	1002	30	6	DD
14-10-2013	0000	23.5/84.0	-	1002	30	6	DD
	0300	24.0.84.1	-	1004	25	3	D
	0600	24.5/84.2		1005	25	3	D
	0900	Weakened into a well marked low pressure area over southwest Bihar and neighbourhood					

2.5.4 Monitoring of VSCS, Phailin

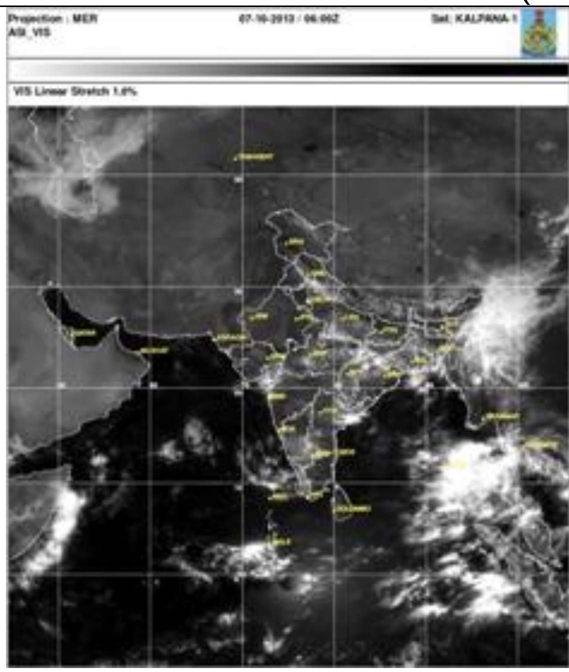
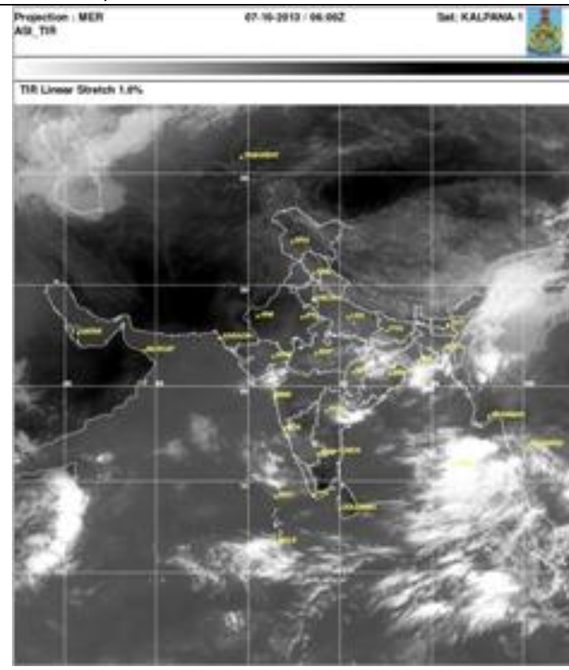
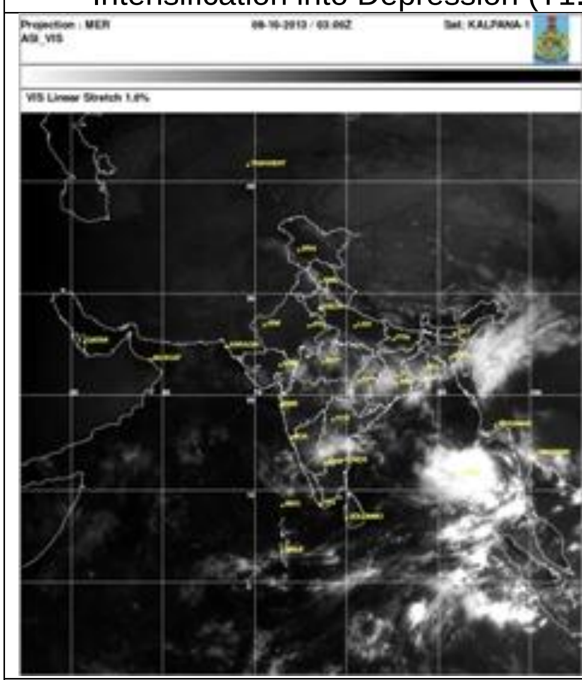
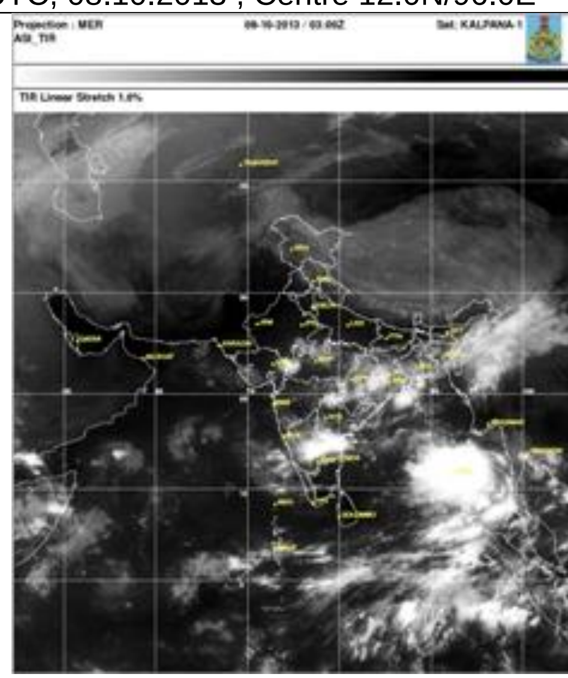
The VSCS Phailin was monitored & predicted continuously since its inception by the India Meteorological Department. The forecast of its genesis on 8th, its track, intensity, point & time of landfall, as well as associated adverse weather like heavy rain, gale wind & storm surge were predicted exceedingly 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. On 12th October, when the system lay within radar range, the DWR at Visakhapatnam was utilized and continuous monitoring by this radar started from 0100 UTC of 12th when the system was at about 310 km east-southeast of Visakhapatnam coast and continued till 1800 UTC of that date. In addition, the observations from satellite and coastal observations from conventional observatories and 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 Phailin.

2.5.5 Characteristic features of PHAILIN

2.5.5.1 Features observed through satellite

A low level circulation developed over Andaman Sea on 06 October 2013 at 2100UTC. It intensified into a vortex with intensity T1.0 and centre near 12.0°N/98.5°E at 0600 UTC of 7th October. The pattern was of shear type at this stage. Initially it moved in westerly direction. The system intensified again at 0300 UTC of 8th October with centre near 12.0°N/96.0°E and intensity T1.5. Moving in the west-northwesterly direction, it intensified with intensity of T2.0 and centre near 12.5°N/94.0°E at 2100 UTC on the same day. The intensity became T 2.5 at 1000 UTC of 9th October with centre near 13.5°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 very rapidly then to T3.5 within 5 hours. The eye was visible at this time but ragged. Intensification to T4.0 occurred at 0600UTC of 10th October as the spiral bands were more organized and centre at this time was 15.1°N/90.6°E, eye temperature was -42 deg C and diameter of the eye was 12 km (Table 2.5.2). Very rapid intensification occurred after this upto T6.0 at 0300 UTC of 11th October 2013, because of continuous organization of eye and spiral bands. System continued to move northwestwards till landfall near 19.26°N/84.82°E (near Gopalpur, Odisha) at 1600 UTC of 12th October 2013. Typical satellite imageries of the system are shown in fig.2.5.1 (a-f)

<table>
<tr><td colspan="2">Satellite (Kalpana-1) imageries at different stages of the VSCS (Phailin)</td></tr>
<tr><td colspan="2">Formation of well marked Low (T1.0), 0600 UTC, 07.10.2013 Centre 12.0N/98.5E</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Visible imagery</td><td>IR Imagery</td></tr>
<tr><td colspan="2">Intensification into Depression (T1.5),0300 UTC, 08.10.2013 , Centre 12.0N/96.0E</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Visible imagery</td><td>IR Imagery</td></tr>
<tr><td colspan="2">Fig.2.5.1 (a) Typical satellite imageries in different stages in cyclone, Phailin</td></tr>
</table>

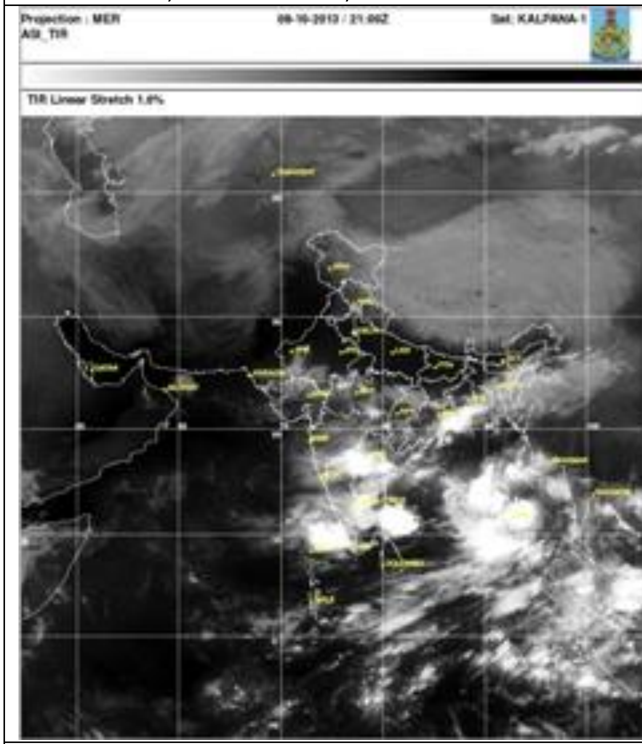
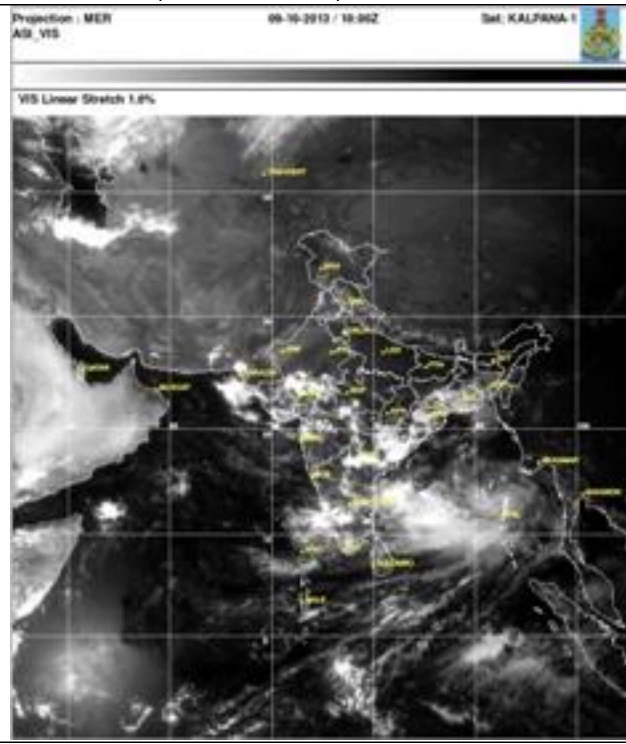
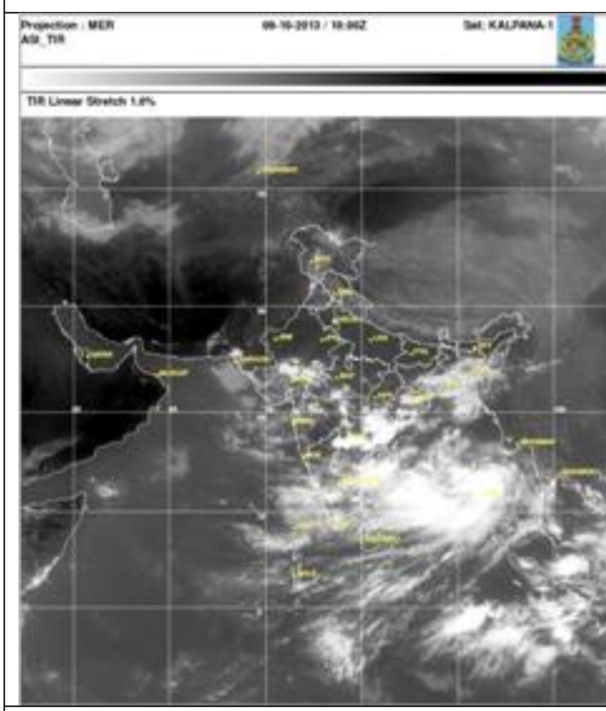
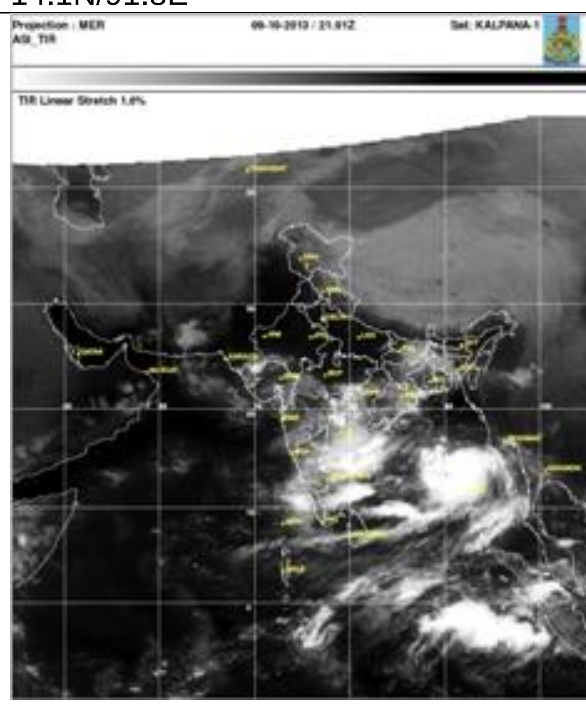
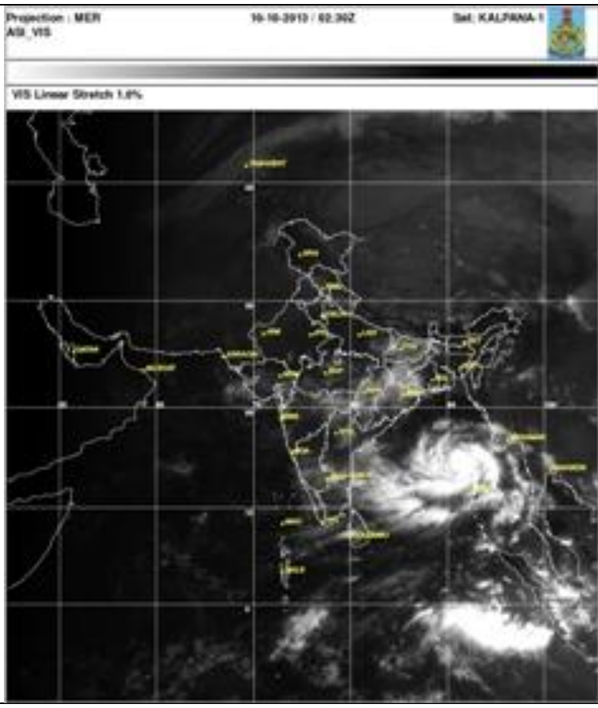
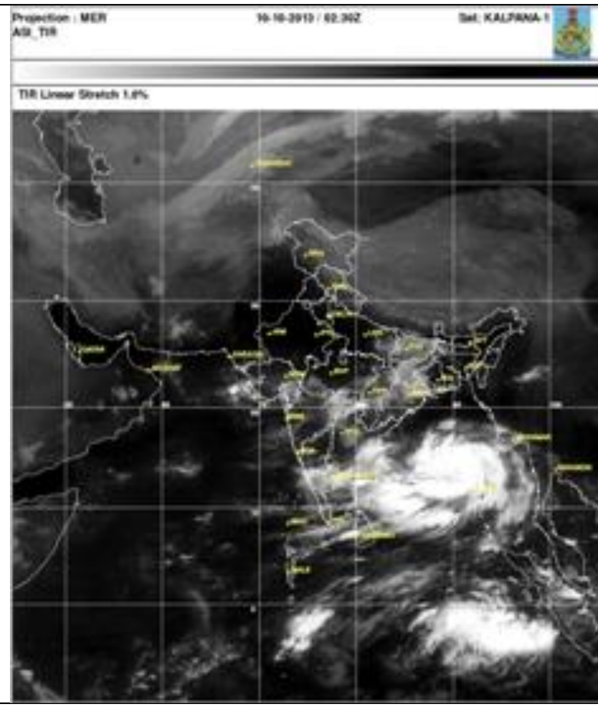
Intensification into Deep Depression (T2.0) 2100 UTC, 08.10.2013, Centre 12.5N/94.0E	Formation of tropical cyclone (Phailin), T2.5, 1000 UTC, 09.10.2013, Centre 13.5N/92.5E
	
IR Imagery	Visible imagery
Formation of tropical cyclone (Phailin), T2.5, 1000 UTC, 09.10.2013, Centre 13.5N/92.5E	Further intensification of the tropical cyclone (T3.0), 2100 UTC, 09.10.2013, Centre 14.1N/91.8E
	
IR Imagery	IR Imagery

Fig.2.5.1 (b) Typical satellite imageries in different stages in cyclone, Phailin

Intensification into Severe Cyclonic Storm (T3.5), 0230 UTC 10.10.2013, Centre 14.7N/91.1E

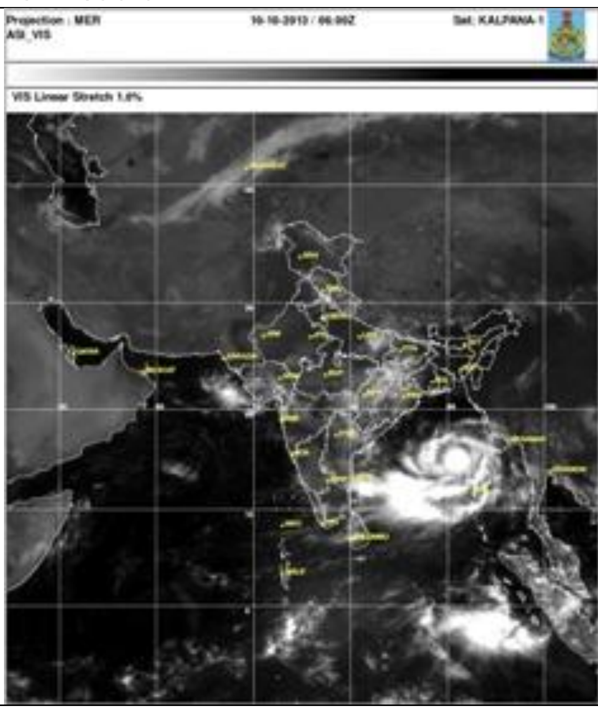


Visible imagery



IR Imagery

Intensification in Very Severe Cyclonic Storm (T4.0). 0600 UTC, 10.10.2013, Centre 15.1N/90.6E

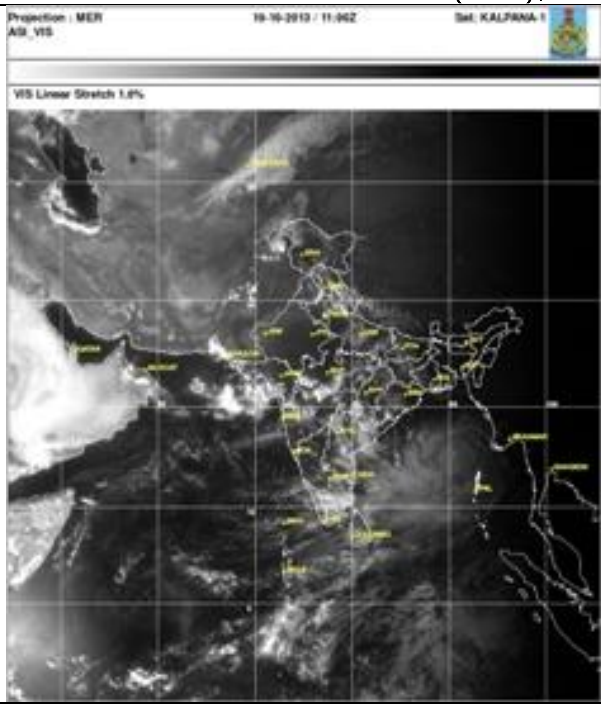


Visible imagery

IR Imagery

Fig.2.5.1 (c) Typical satellite imageries in different stages in cyclone, Phailin

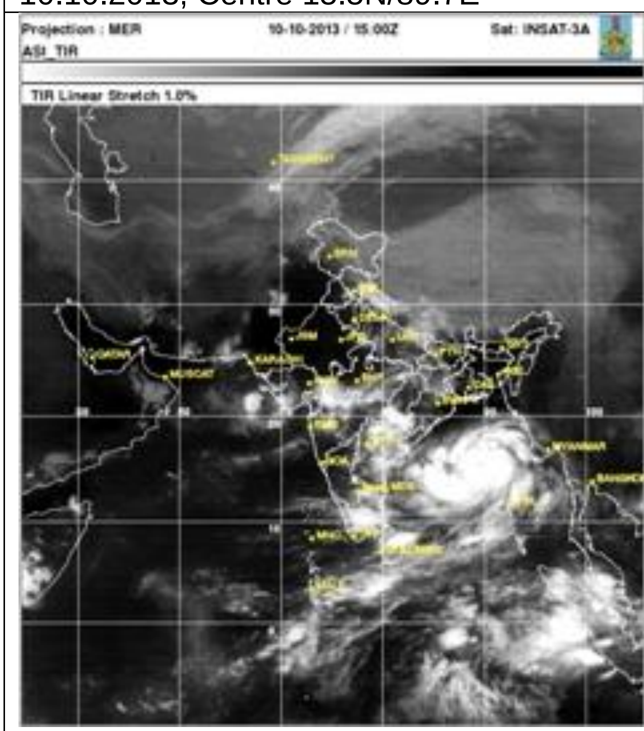
Further Intensification (T4.5), 1100 UTC, 10.10.2013, Centre 15.3N/90.2E



Visible imagery

IR Imagery

Further Intensification (T5.0), 1500 UTC, 10.10.2013, Centre 15.5N/89.7E



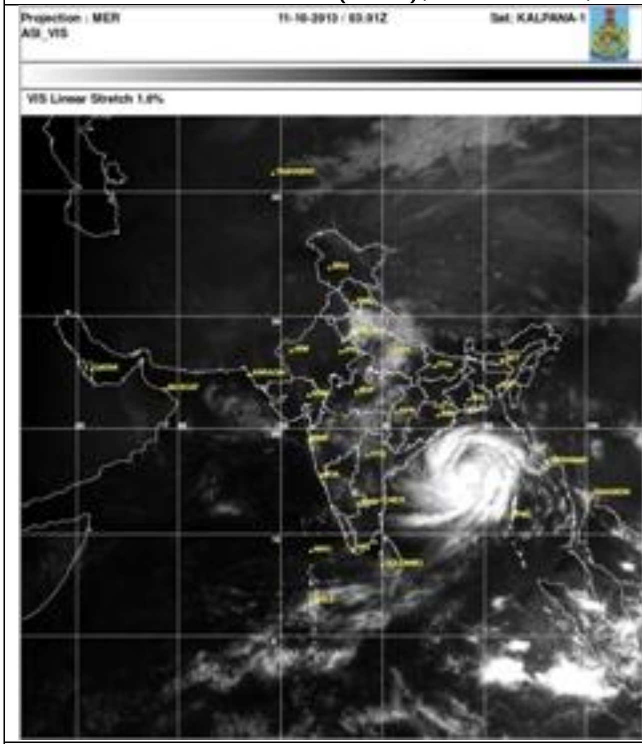
IR Imagery (INSAT-3A)

Further Intensification (T5.5), 2100 UTC, 10.10.2013, Centre 15.6N/89.2E

IR Imagery

Fig.2.5.1(d) Typical satellite imageries in different stages in cyclone, Phailin

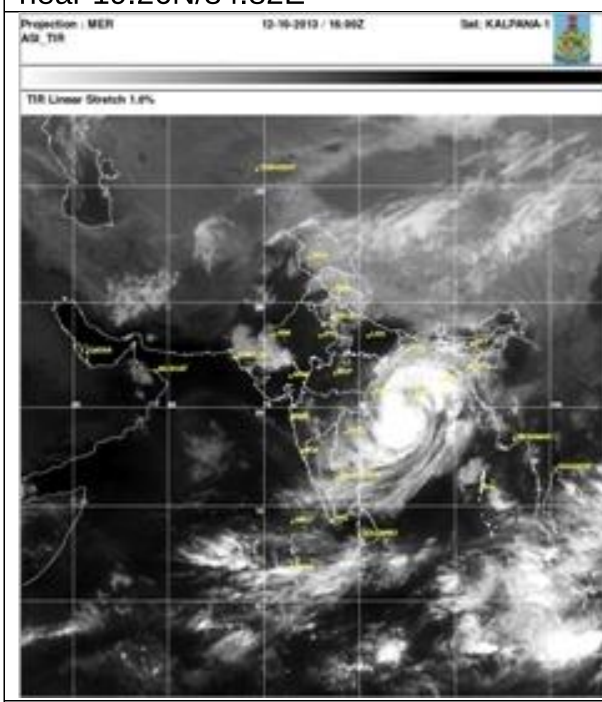
Further Intensification (T6.0), 0300 UTC, 11.10.2013, Centre 16.0N/88.5E



Visible imagery

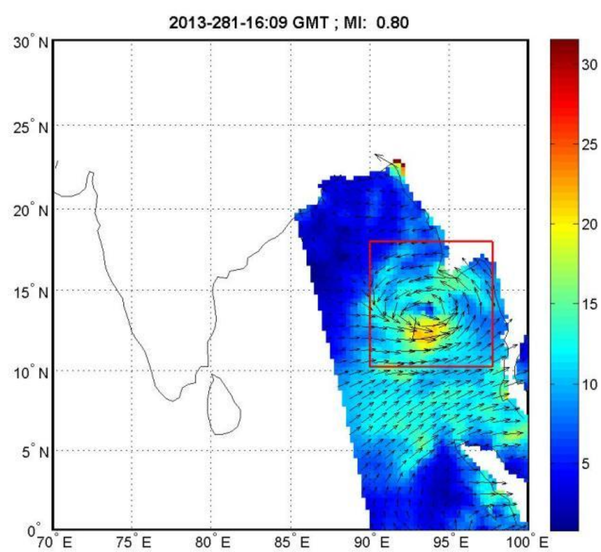
IR Imagery

Landfall of the cyclone 1600UTC, 12.10.2013 near 19.26N/84.82E



IR Imagery

Cyclogenesis predicted formation of Tropical cyclone



1609 UTC, 08.10.2013

Fig.2.5.1(e) Typical satellite imageries in different stages in cyclone, Phailin

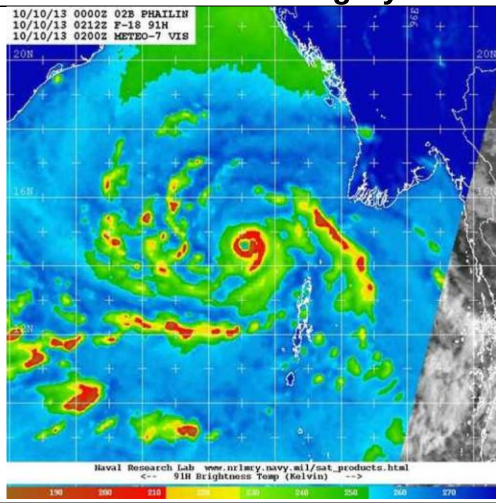
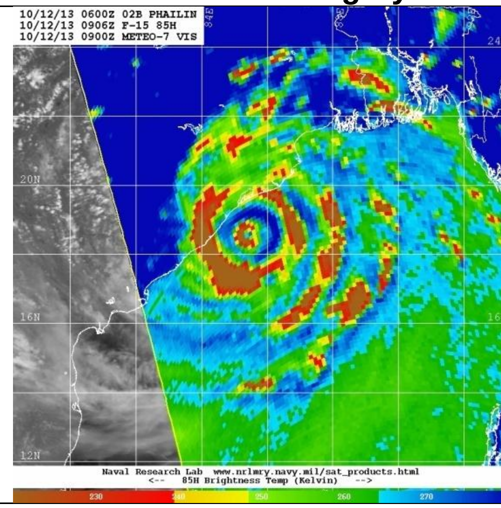
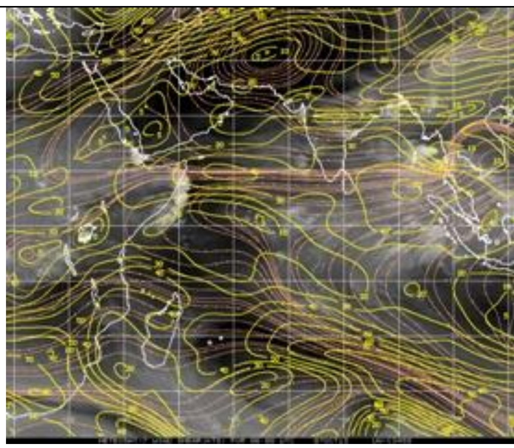
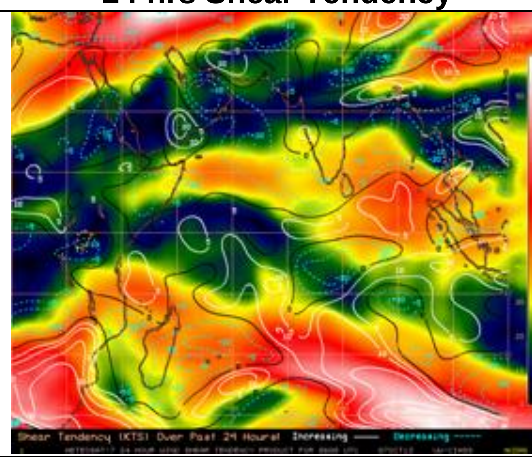
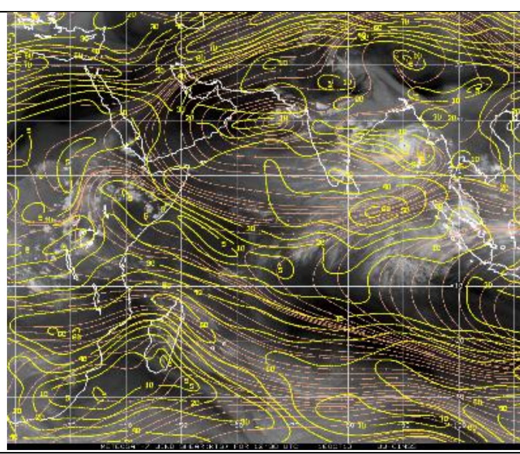
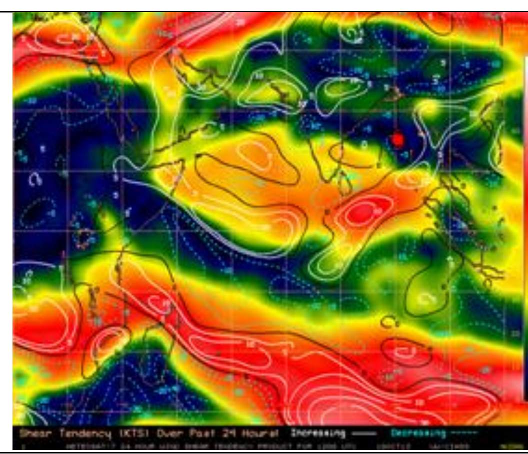
Microwave imagery	Microwave imagery
	
0212 UTC , 10.10.2013	0906 UTC, 12.10.2013
Wind Shear	**24 hrs Shear Tendency**
	
0600 UTC, 07.10.2013	0600 UITC, 07.10.2013
	
1200 UTC, 10.10.2013	1200 UTC, 10.10.2013

Fig.2.5.1(f). Typical microwave imageries, wind shear and shear tendency on 10 October 2013

As the buoys were away from the track of the system, satellite observations played a vital role in tracking of the system. After the landfall also Satellite Application Unit of Satellite Meteorology Division provided centre and expected intensity for better monitoring of the system. Monitoring of the system was mainly done by using half hourly Kalpana-1 imageries but 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.

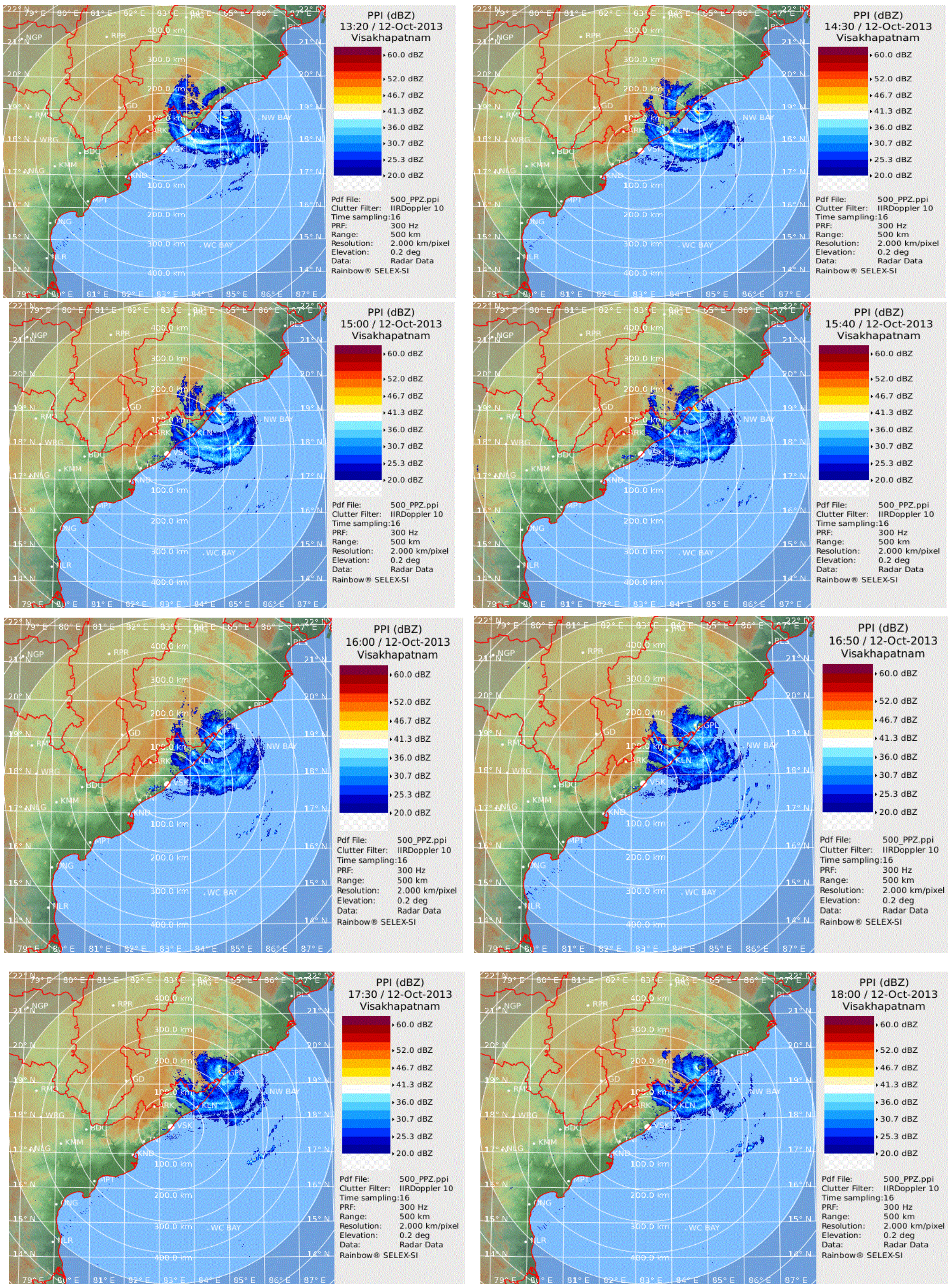


Fig. 2.5.2 : Visakhapatnam RADAR imageries based on 1320,1430, 1500, 1540 UTC, 1600 , 1650, 1730, 1800 UTC of 12th October 2013

Table 2.5.2. Position Of Cyclone Phailin based on Satellite

DATE	TIME	LAT	LONG	INTENSITY	CTT	Eye Temp	Diametre of eye
	(UTC)	(N)	(E)	T	(- Deg C)	(- deg C)	
08.10.2013	0300	12.0	96.0	1.5	82		
	0600	12.0	95.5	1.5	69		
	1200	12.0	94.5	1.5	68		
	1700	12.0	94.0	1.5	63		
09.10.2013	0000	12.9	93.5	2.0	73		
	0600	13.2	93.0	2.0	76		
	1130	13.5	92.5	2.5	78		
	1900	14.0	92.0	2.5	NA		
10.10.2013	0000	14.4	91.3	3.0	79		
	0600	15.1	90.6	4.0	79	42	12 km
	1200	15.3	90.0	4.5	80	14	15-20 Km
	1730	15.5	89.4	5.0	81	3	15-20 Km
11.10.2013	0000	15.7	88.7	5.5	83	6	15-20 Km
	0600	16.2	88.3	6.0	80	37	15-20 Km
	1200	16.7	87.5	6.0	82	27	15-20 Km

2.5.2. Features observed through Radar

The initial cloud echoes were observed at 2100UTC of 11th October, 2013 in Special 400 PPI Scan. The Eye appeared first at 0000UTC of 12th. The first radar based bulletin was issued by Doppler Weather Radar (DWR) station, Visakhapatnam at 0100UTC and bulletins continued at 30 minutes interval till the VSCS PHAILIN crossed Odisha coast near Gopalpur. The bulletins were issued based on maximum reflectivity (Max. Z) product with effect from 0730 UTC of 12th October. The Maximum wind speed of 60mps at 4Kms height was reported at 1410 UTC (Table 2.5.3). A few DWR imageries are shown in Fig.2.5.2. The eye was visible during 0120 UTC to 1755 UTC of 12 October 2013. The eye diameter gradually decreased and was about 15-20 km at the time of landfall.

Table2.5.3 Position of Cyclone Phailin based on DWR, Visakhapatnam

SN	Date and time (UTC)	Lat deg N	Long deg E	Range kms	Azimuth deg	Radial wind speed(mps)/eye dia (km)	Shape of eye/ confidence
1	12.10.13 0120z	17.647	86.258	309	91.5	-/NA	Almost closed eye/fair
2	12.10.13 0220z	17.794	86.094	291	88.4	-/NA	Almost closed eye/Good
3	12.10.13 0320z	17.868	85.950	277	86.7	-/NA	Almost closed eye/Good
4	12.10.13	17.912	85.899	270	85.6	-/36.5KM	Almost closed

	0350z						eye/Good
5	12.10.13 0420z	17.927	85.838	265	85.2	-/33.0KM	Almost closed eye/Good
6	12.10.13 0450z	17.971	85.778	258	84.0	-/32.0KM	Almost closed eye/Good
7	12.10.13 0520z	17.971	85.748	255	83.9	-/27.2KM	Almost closed eye/Good
8	12.10.13 0600z	18.058	85.734	255	81.7	40/30.0KM	Almost closed eye/Good
9	12.10.13 0640z	18.145	85.720	255	79.5	40/30.0KM	Almost closed eye/Good
10	12.10.13 0800z	18.420	85.587	248	72.0	40/NA	Almost closed eye/Good
11	12.10.13 0950z	18.599	85.261	223	64.7	58/24.0KM	Almost closed eye/Good
12	12.10.13 1100z	18.599	85.261	223	64.7	58/26.0KM	Almost closed eye/Good
13	12.10.13 1140z	18.671	85.262	227	62.9	57/27.5KM	Almost closed eye/Good
14	12.10.13 1200z	18.679	85.262	227	62.9	57/26.0KM	Almost closed eye/Good
15	12.10.13 1310z	18.897	85.208	234	56.7	57/24.0KM	Almost closed eye/Good
16	12.10.13 1410z	18.997	85.094	231	52.8	60/18.0KM	Almost closed eye/Good
17	12.10.13 1455z	19.071	85.032	231	50.3	58/18.0KM	Almost closed eye/Good
18	12.10.13 1525z	19.144	85.024	235	48.5	57/20.0KM	Almost closed eye/Good
19	12.10.13 1555z	19.192	84.982	236	46.7	51/20.0KM	Almost closed eye/Good

20	12.10.13 1635z	19.282	84.934	238	44.1	45/16.0KM	Eye over land/ Good
21	12.10.13 1725z	19.415	84.853	243	40.5	42/NA	Eye over land/ Fair
22	12.10.13 1755z	19.454	84.842	48 (from the coast)	-	42/NA	Eye over land/ Fair

2.5.5.3 Estimated Central Pressure and Maximum Wind

The estimated central pressure of the system gradually decreased from genesis stage on 8th October to 10th morning. There was sharp decrease then till 11th morning due to rapid intensification of the system. It became lowest (940 hPa) at 0300 UTC of 11th October and continued so till the landfall (Table 2.5.1). During decay, the rise in central pressure was rather rapid than that in genesis stage. Similar was the variation in estimated maximum wind, as it gradually increased from 8th to 10th morning and then rapidly increased till 11th morning. It reached maximum value of 115 knots at 0300 UTC of 11th and continued so till the landfall.

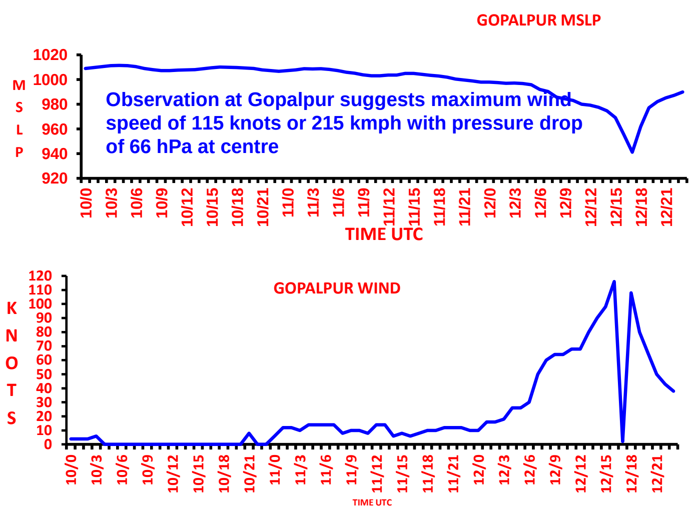
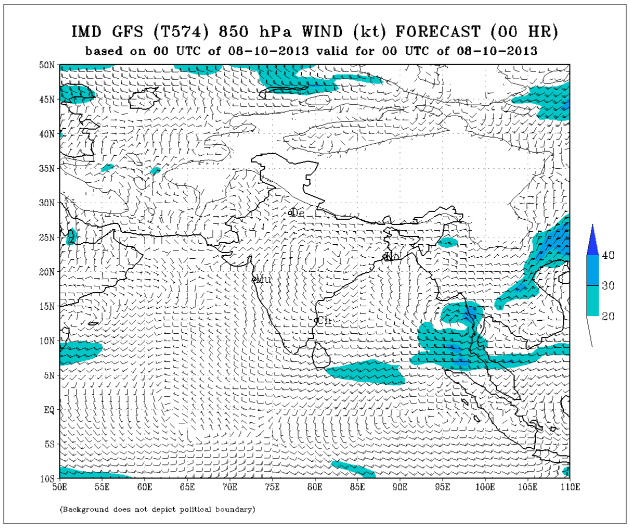


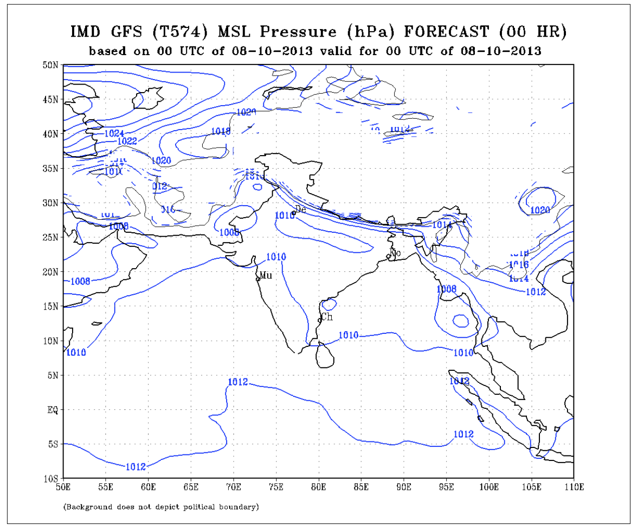
Fig.2.5.3 Variation of mean sea level pressure and wind over Gopalpur during the passage of cyclone

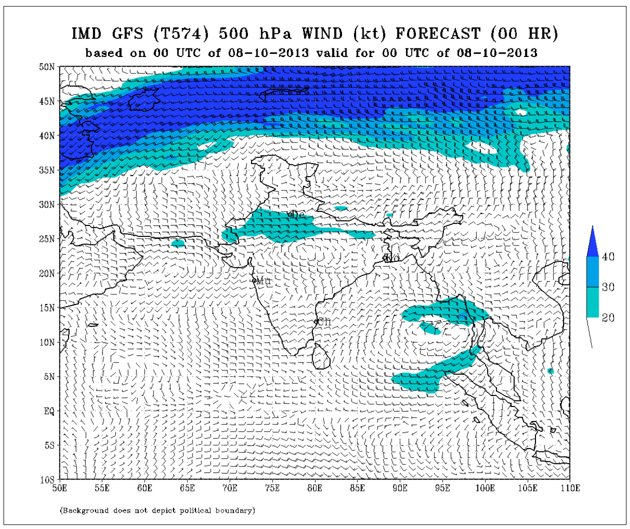
The pressure and wind variation over Gopalpur (point of landfall) are shown in Fig.2.5.3. It is worth mentioning that the eye of the cyclone passed over Gopalpur around 1700 UTC, when it experienced variable wind of about 2 knots for a few minutes followed by strong gale wind due to rear sector of the cyclone lying over the station. The estimated maximum wind speed over Gopalpur was about 115 knots (215 kmph) at the time of landfall.

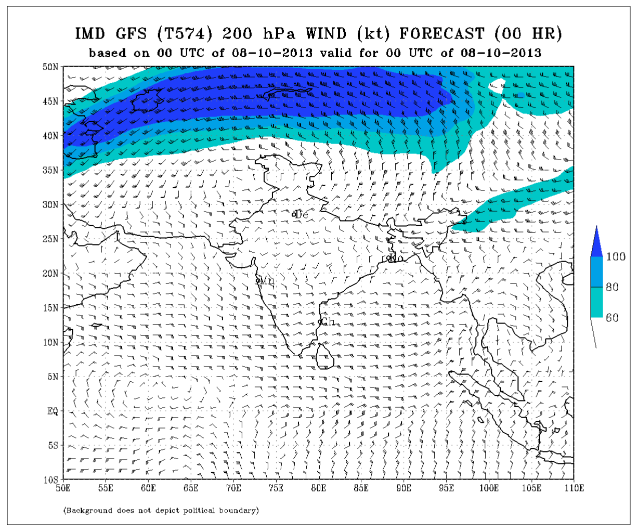
2.5.6. Dynamical features

To illustrate the dynamical features, the MSLP and wind at 10m, 850 hpa, 700 hpa & 200 hpa level based on IMD GFS (T574) model at 0000 UTC of 8-14 Oct., 2014 shown in fig.2.5.4.









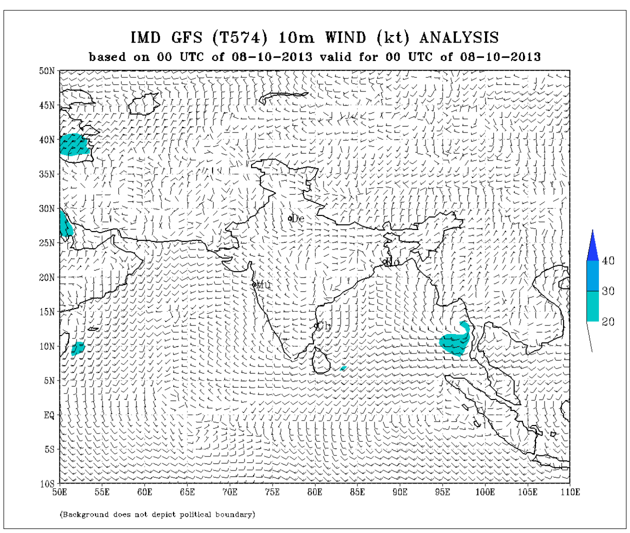


Fig.2.5.4(a). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 8th October, 2013

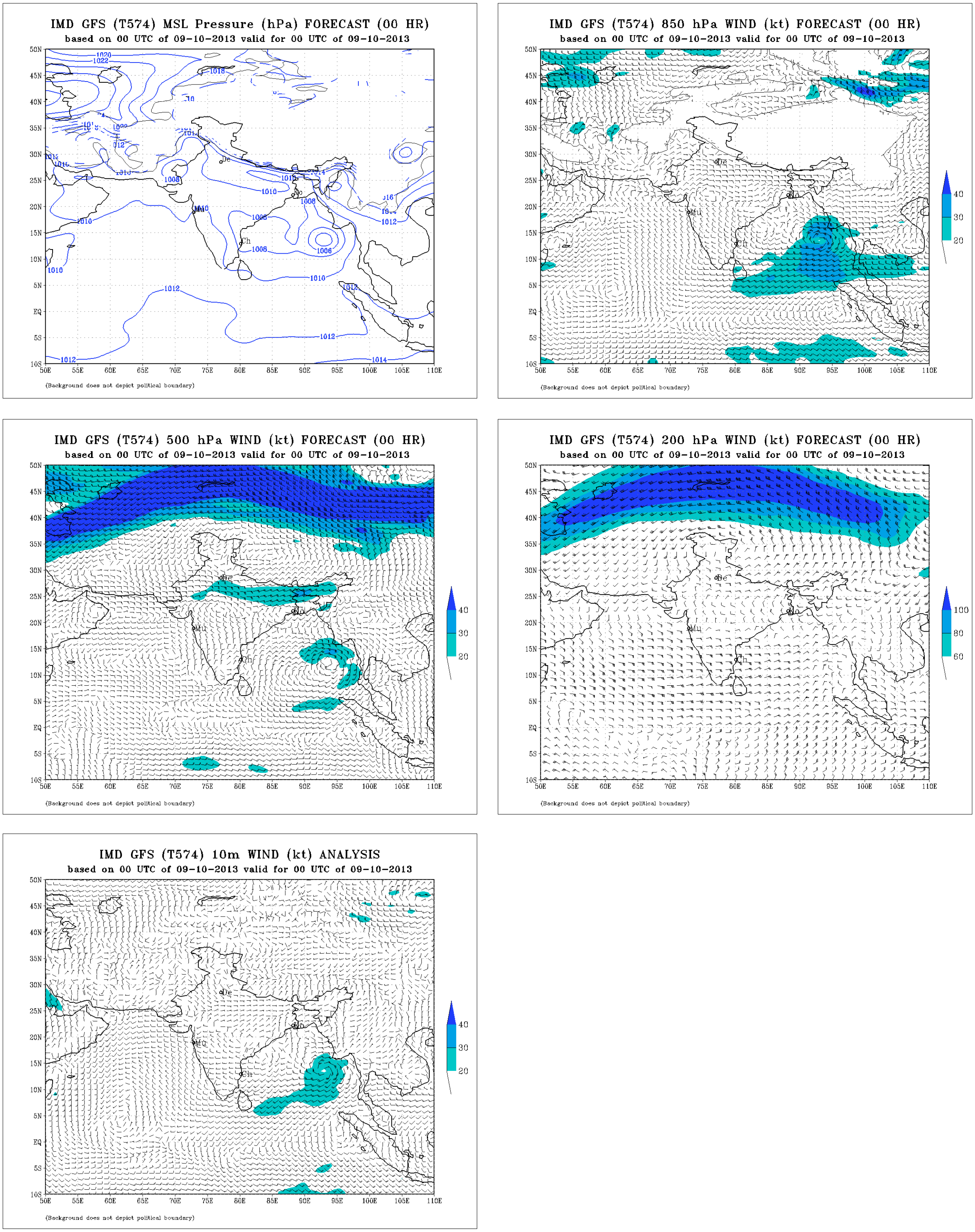


Fig.2.5.4(b). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 9th October, 2013

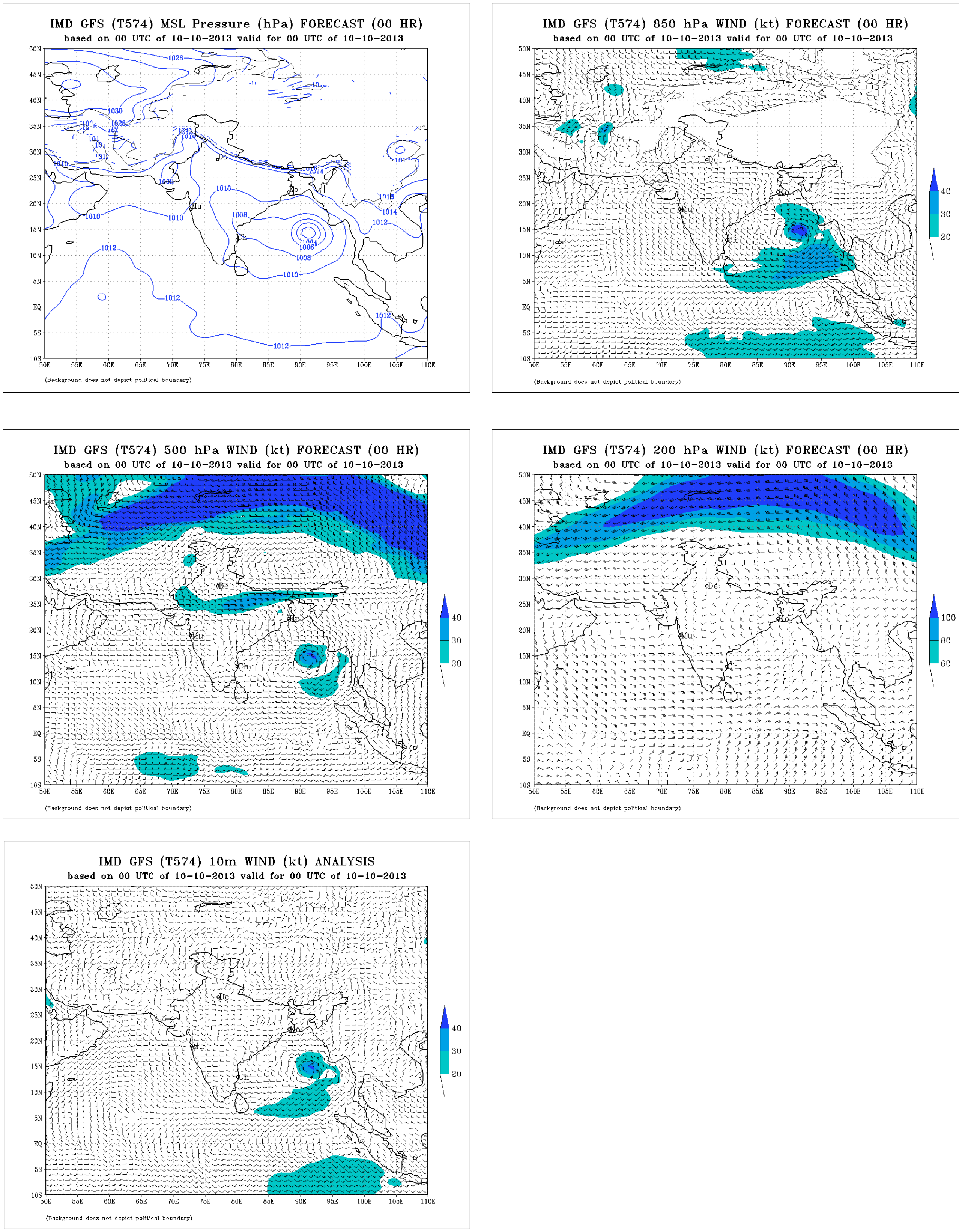


Fig.2.5.4(c) IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 10th October, 2013

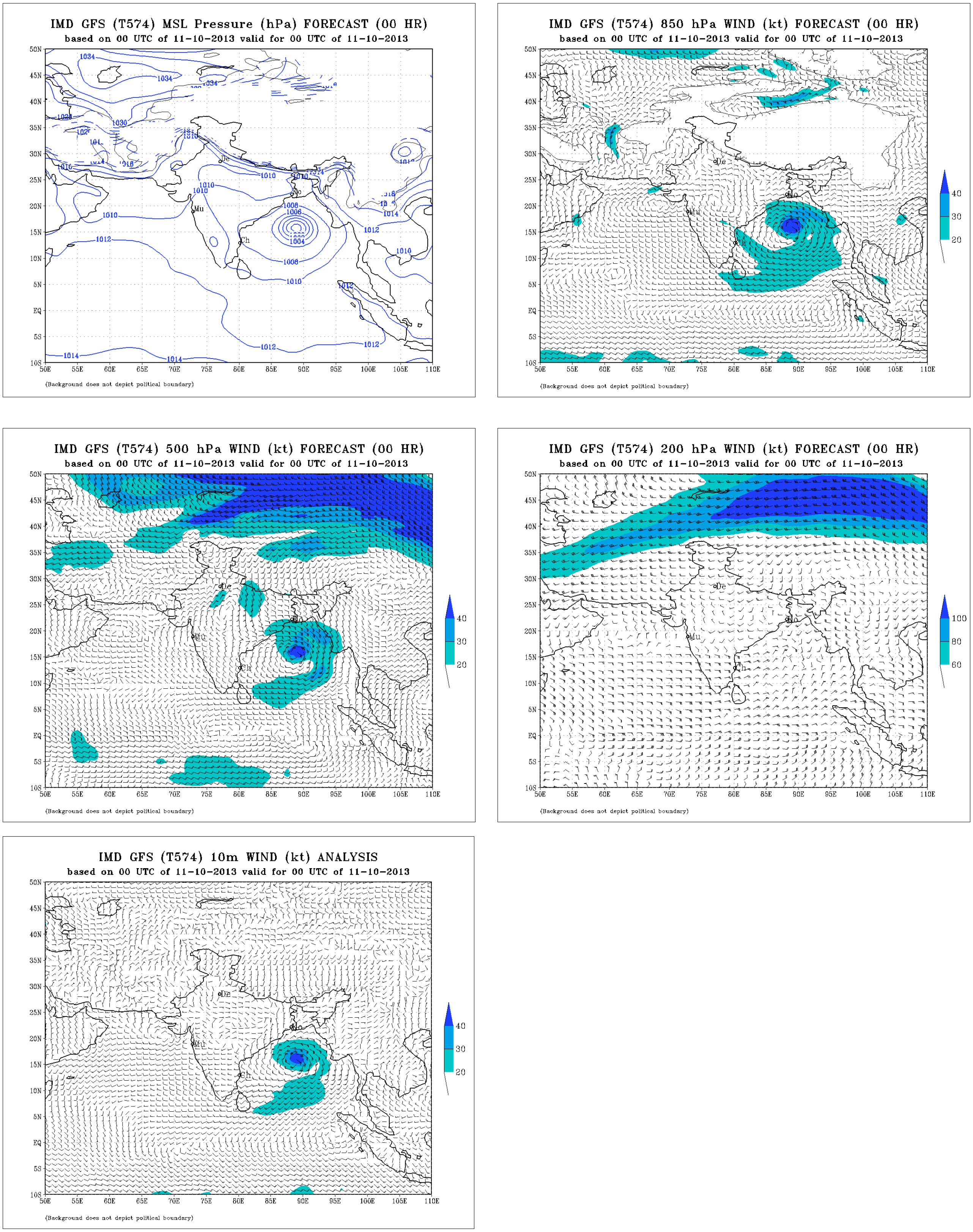


Fig.2.5.4(d). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 11th October, 2013

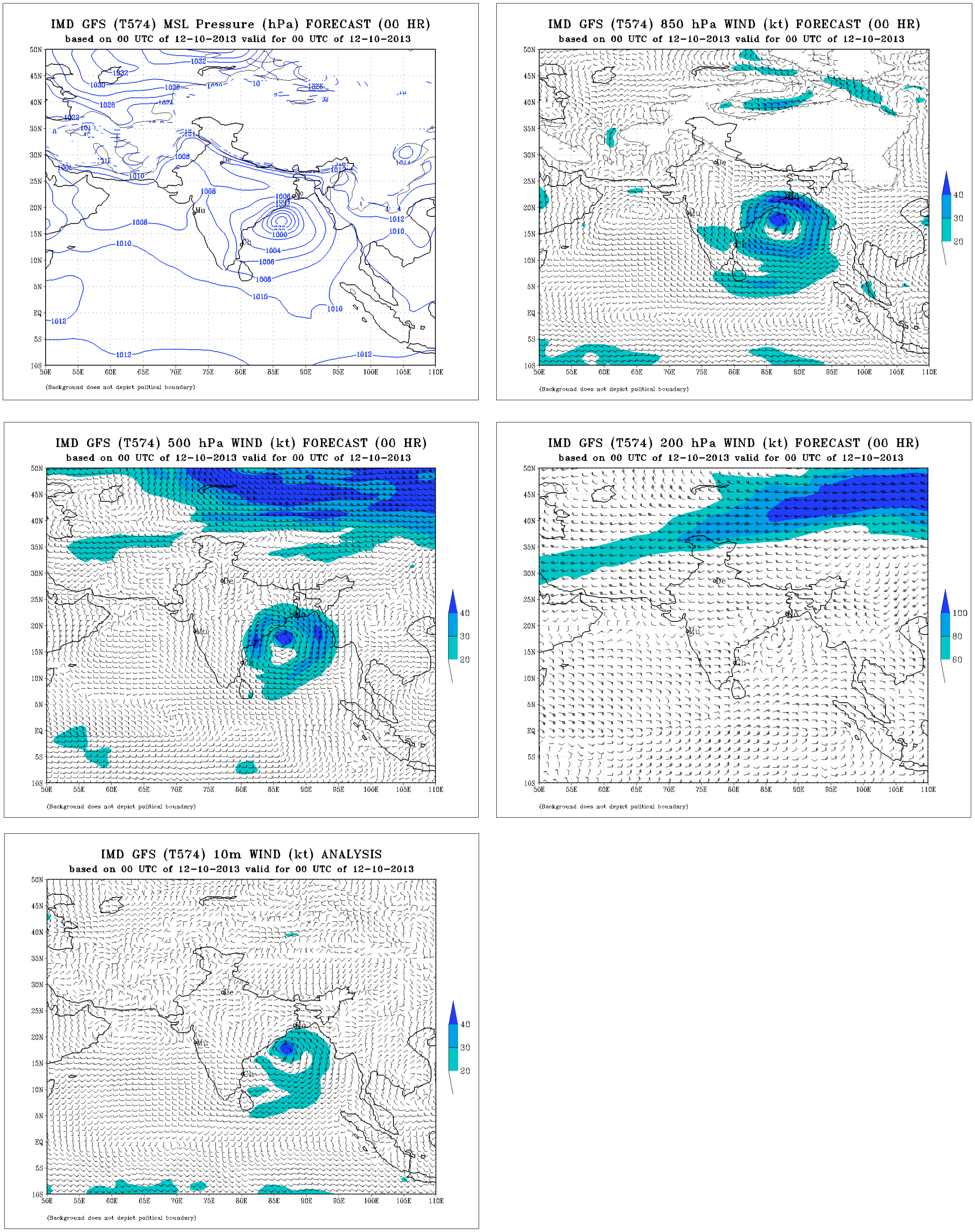


Fig.2.5.4(e). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 12th October, 2013

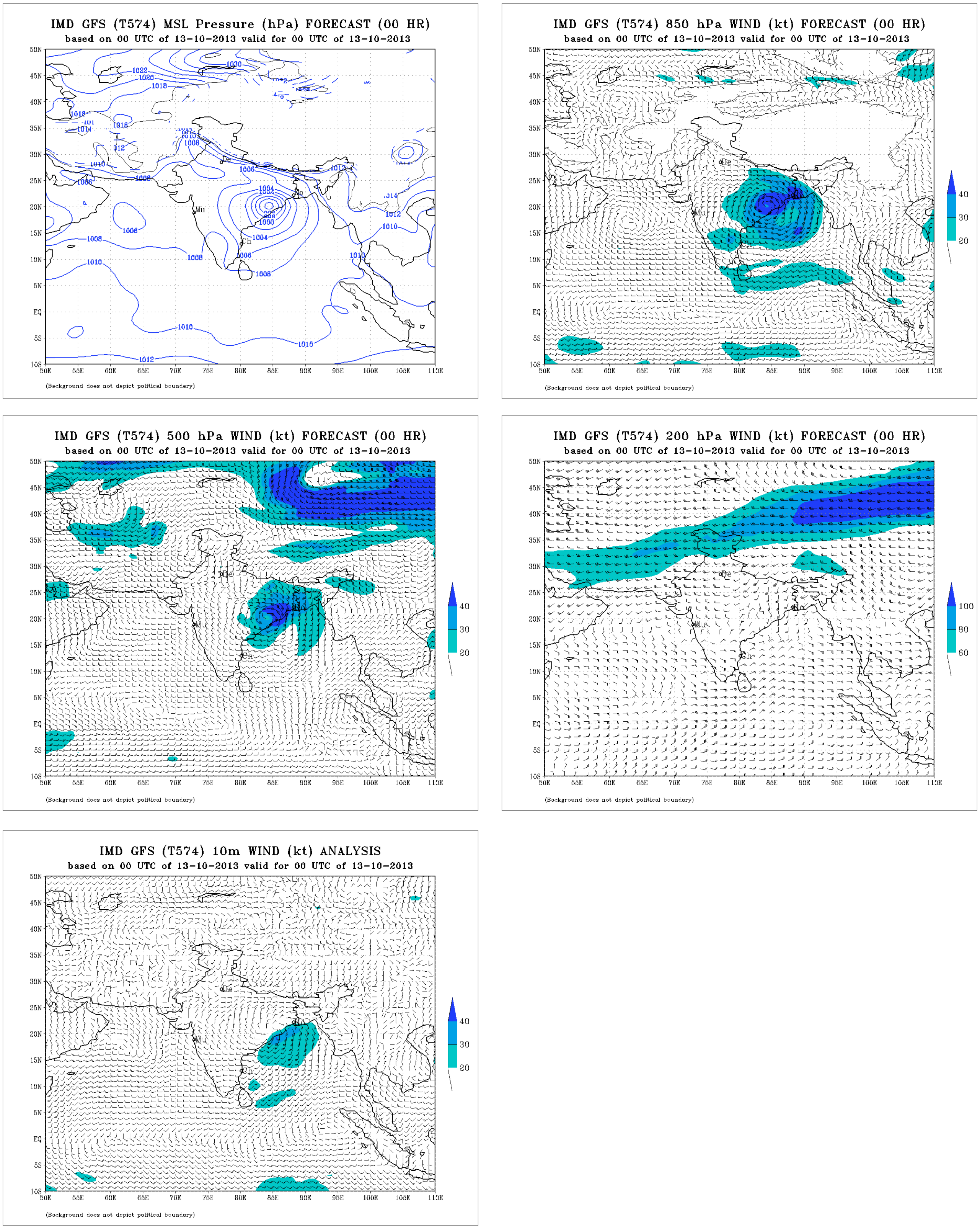


Fig.2.5.4(f). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 13th October, 2013

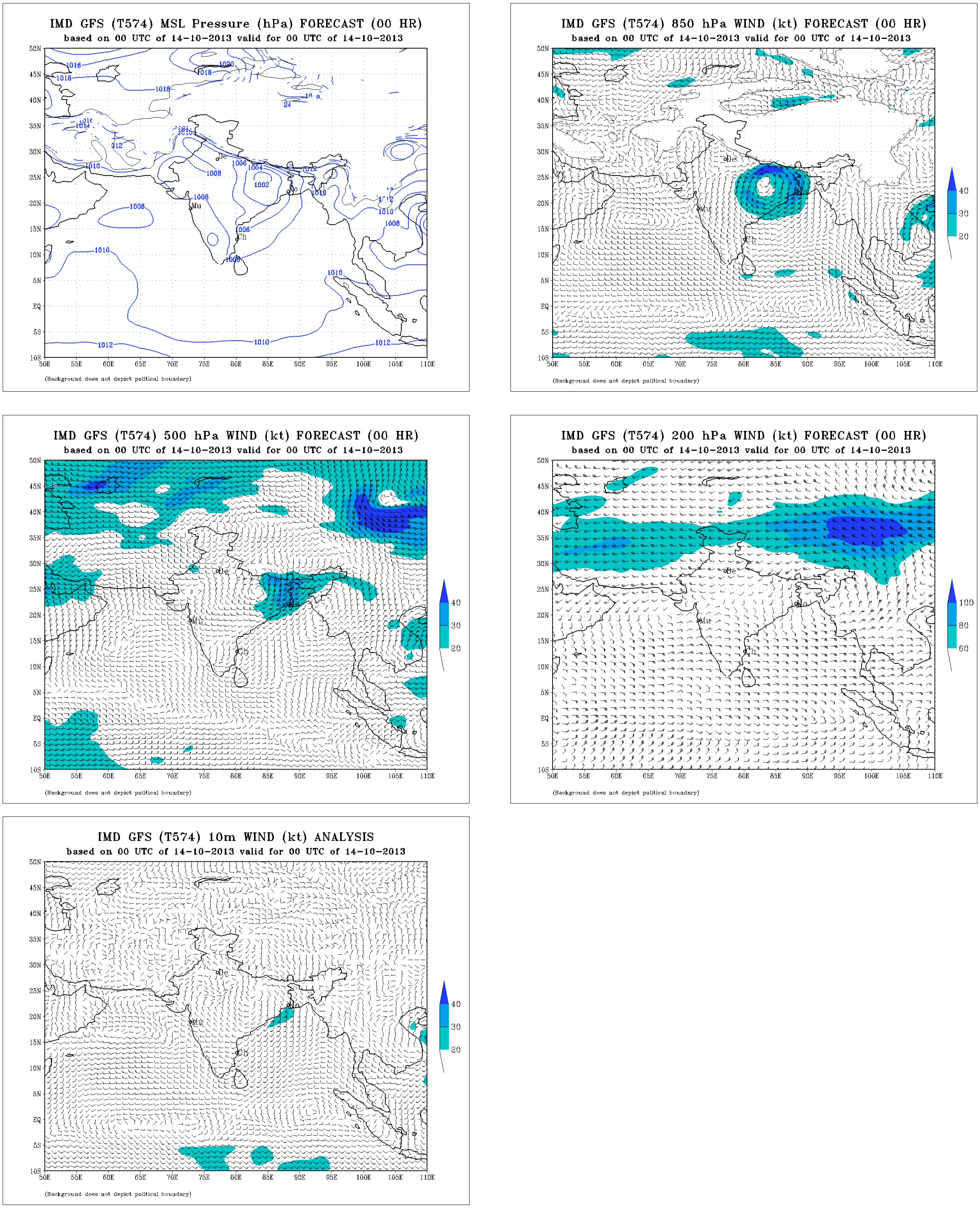


Fig.2.5.4(a). IMD GFS Analysis of Mean Sea Level Pressure (MSLP) and wind at 10m,850,500 & 200 hPa based on 0000 UTC of 14th October, 2013

2.5.7. Realized Weather

2.5.7.1Heavy rainfall due to Phailin

The VSCS, Phailin caused very heavy to extremely heavy rainfall over Andaman & Nicobar Islands, Odisha and isolated heavy to very heavy rainfall over North Coastal Andhra Pradesh (AP), West Bengal, Jharkhand, Bihar, Chhattisgarh and Sikkim. Maximum rainfall occurred over Odisha. The rainfall was higher over north Odisha than over south Odisha (Fig.2.5.5). The rainfall departures over central and northeastern India during the period of 12-14 October 2013 are shown in Fig.2.5.6. It indicates that the rainfall extended upto sub-Himalayan West Bengal and Sikkim.

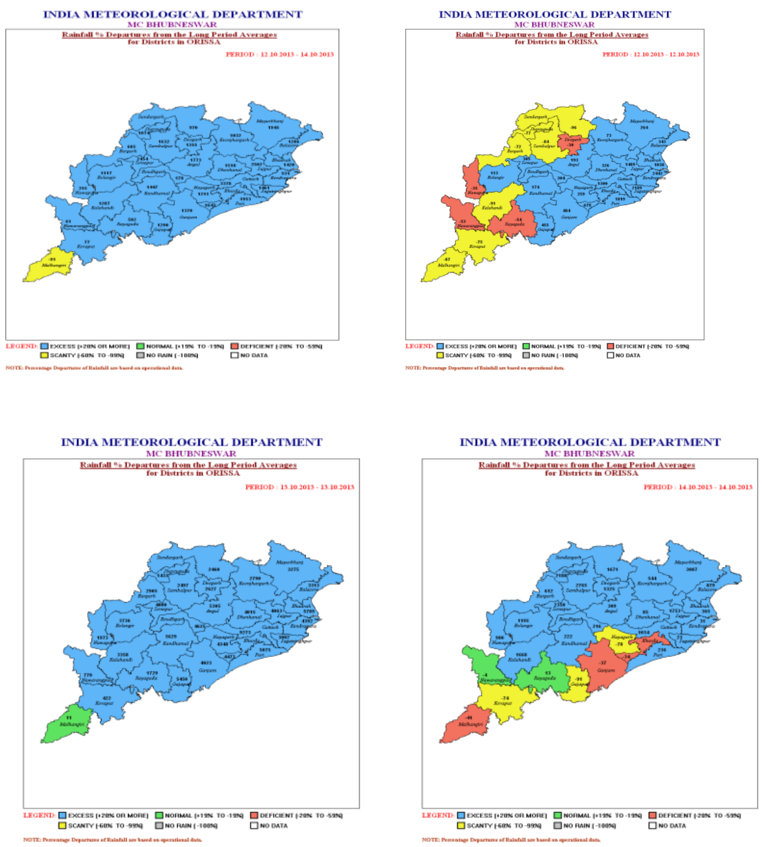


Fig.2.5.5. Rainfall departure over Odisha during 12-14 October 2013

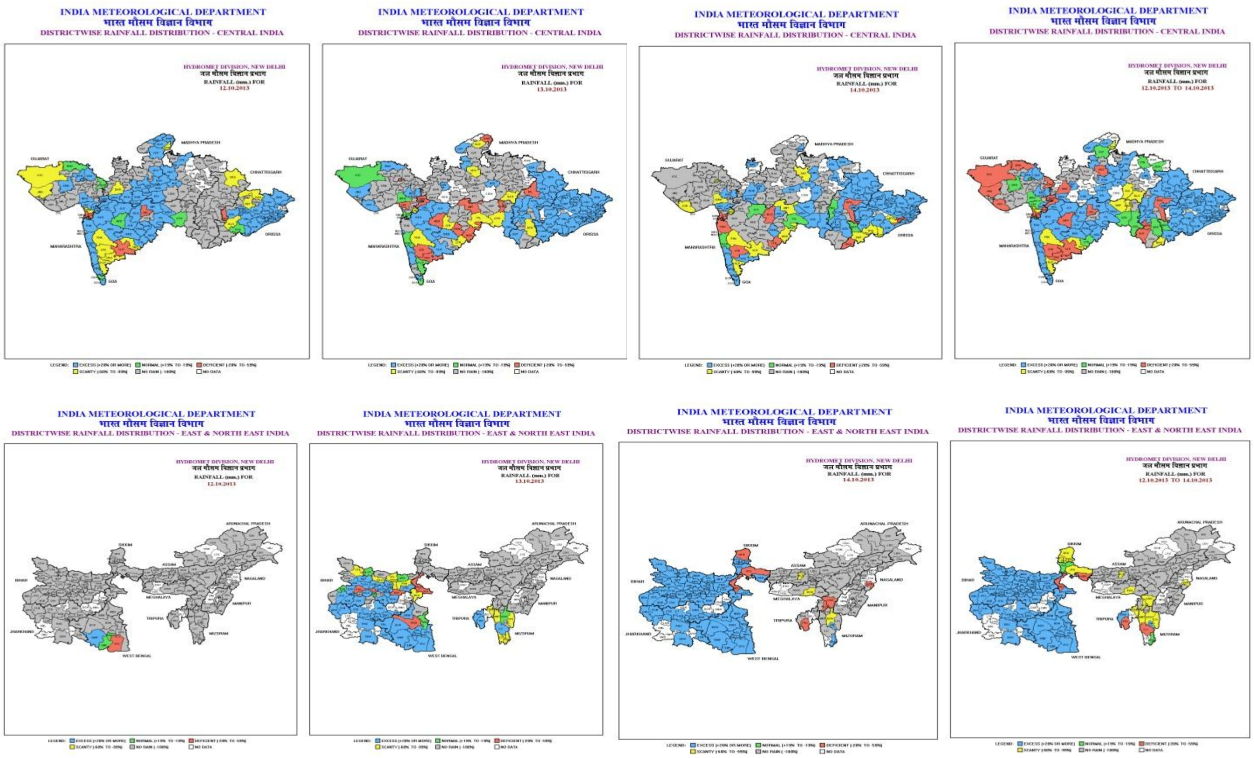


Fig 2.5.6. Rainfall departure over central and northeast India during 12-14 October 2013

The station-wise daily 24 hr cumulative rainfall (7 cm or more) during 8-15 October recorded in districts of different states at 080300 UTC of date are given below. States and districts are highlighted.

08-10-2013

(i) Odisha

Bargarh - Bijepur, Paikmal – 8 each, Ambabhona - 11, **Jharsuguda -** Kolabira (ARG) – 8, **Puri:** Puri - 11

(ii) Chhattisgarh

Janjgir : Champa – 8, **Jashpur:** Jashpurnagar-**7, Korba : K**atghora- 8, **Raigarh: S**arangarh-9

(iii) Jharkhand

Latehar : Balumath – 9,

(iv) Andaman & Nicobar Islands

North & Middle Andaman- Maya bandar – 24, **South Andaman**- Port Blair – 9

(v) Gangetic West Bengal

Hooghly- Harinkhola – 10, **North 24 Parganas-** Barrackpur (IAF) -7,

09-10-2013

(i) Odisha

Kendrapara- Derabis (ARG), Dattamundai-9 each, **Mayurbhanj-** Baripada -9, **Puri -** Satyabadi ARG) -7

(ii) Andaman & Nicobar Islands

North & Middle Andaman - Long Island, Maya Bandar – 34 each
South Andaman - Port Blair -7

10-10-2013
(i) Odisha
Ganjam - Belaguntha (Arg), Jagannath Prasad (ARG)- 9 each, **Keonjhargarh - S**wam-Patna -8, **Sonepur - U**llunda (ARG) -7
(ii) Coastal Andhra Pradesh
Krishna - Vijayawada (A.P).-8,**Vizianagaram**- Srungavarapukota -8, **West Godavari -** Narsapuram- 8
(iii) Andaman & Nicobar Islands
A & N Island - Iaf Carnicobar – 8, Car Nicobar - 10,
North & Middle Andaman - Maya Bandar - 16

11-10-2013
(i) Telangana
Adilabad- Chinnoor – 7, **Karimnagar-** Kaleswaram - 7

12-10-2013
(ii) Odisha
Balasore -Soro -7, **Bhadrak** - Akhuapada – 8, **Jagatsinghpur** - Jagatsinghpur (AWS), Kujanga (AWS)-9 each, J**ajpur**-Korei (AWS)-8, **Puri-** Puri -7, Brahmagiri (AWS)-8,

13-10-2013
(i) Odisha
Angul - Banarpal (ARG), Chendipada-8 each, Rajghat-9, Kaniha (ARG)-9, Angul, Athmalik -11 each, Talcher- 12, Pallahara, Tikarpara-17 each, **Balasore -**Balasore-11, Nh5 Gobindpur-13, Jaipur-26, **Bargarh -** Bijepur-7, Chandbali-12, Akhuapada-14, **Cuttack -** Niali (ARG), Mahanga (ARG), Tigiria (ARG)-9 each, Cuttack, Salepur (ARG), Nischintakoili (ARG)-11each, Athgarh- 12, Naraj-13, Narsinghpur-14, Mundali-25, Banki (ARG)-38, **Deogarh -**Reamal-9, **Dhenkanal -**Altuma (CWC)-7,Hindol-23, **Gajapati -** Nuagada Arg, R.Udaigiri-19 each,Mohana-20, **Ganjam -** Rambha (AWS)-14, Purushottampur-18, (Gopalpur reported rainfall till 0900 UTC of 12th Oct. and cumulative rainfall was about 09 cm till 1330 IST and after that reading could not be taken due to damage of raingauge by cyclone.)**Jagatsinghpur-** Raghunathpur (ARG)-7, Balikuda (ARG), Paradeep Cwr-.8 each, Jagatsinghpur (AWS) , Tirtol (ARG)-9 each**,** Alipingal- 10, **Jajpur-** Jajpur-7, Sukinda, Binjharpur Arg-9 each, Jenapur- 10, Bari (ARG) -12, Chandikhol (ARG) - 15, Danagadi (ARG) , Korei (ARG) -19 each,
Kalahandi - Madanpur Rampur-11, Lanjigarh-12, Narla (ARG) -13, **Kandhamal -** Kotagarh- 8, G Udayagiri (AWS), Tikabali- 13 each, Phulbani, K Nuagaon (ARG) -14 each, Raikia (ARG) -15 , Phiringia Arg-16, Daringibadi-17, Baliguda-9, **Kendrapara –** Rajkanika- 9, Derabis (ARG), Kendrapara- 11 each, Pattamundai-15, **Keonjhargarh -** Harichandanpur (ARG)-7, Champua-9, Swam-Patna, Telkoi-10 each, Anandpur-11, Jhumpura, Ghatagaon-14 each, Keonjhargarh-15, Daitari-16, , Joda (ARG)-19, **Khurda -** Barmul-13, Bhubaneswar (Aero), Bolagarh (ARG), Balipatna (ARG)-17 each, Banpur-20, **Mayurbhanj** - Jamsolaghat-11,Thakurmunda-13, Baripada, Rairangpur-14 each, Tiring, Betanati (ARG), Udala- 15 each, Samakhunta(AWS)-17, Bangiriposi-21, Balimundali-31, **District: Nayagarh -** Gania (ARG) - 12, Daspalla- 14, Khandapara-17,

Nayagarh- 18, Odagaon Arg -21, Ranpur- 30 **Puri -** Puri-12, Nimpara - 15, **Rayagada -** Muniguda (ARG) - 8, **District: Sambalpur -** Batagaon, Jujumura (ARG), Airakhol-11each.

(ii) Coastal Andhra Pradesh
Srikakulam- Mandasa, Palasa -10 each, Sompeta – 11, Itchapuram -20,
Jharkhand
Bokaro - Tenughat – 7, **Dhanbad-** Papunki – 7, **Giridih-** Dumri- 9, **Pakur -** Hiranpur - 7
Ranchi - Ranchi Aero – 7, **West Singbhum -** Chaibasa - 20
(iii) Gangetic West Bengal
Purulia- Phulberia – 7,

14-10-2013
(i) Odisha
Balasore-Jaipur-9, **Cuttack-** Salepur Arg-9, **Jajpur-**Chandikhol Arg-9, Korei Arg-16
Mayurbhanj - Balimundali, Thakurmunda- 9 each, Bangiriposi, Baripada-11 each, Jamsolaghat- 14, **Sundargarh-**Tensa-11

(ii) Jharkhand
Bokaro - Bokaro, Tenughat- 15 each, **Dhanbad -** Panchet , Putki -10 each, Papunki - 16, **East Singbhum-**Jamshedpur, Jamshedpur Aero – 10 each, **Giridih -** Maithon -9, Nandadih – 11, Barkisuriya - 16, **Hazaribag-**Barhi – 9, **Jamtara-**Jamtara – 15, **Pakur -** Pakur, Pakuria – 7 each, Maheshpur -8, Hiranpur -9, **Palamu -** Japla -11, Panki- 13
(iii) Bihar
Araria - Forbesganj – 7, Araria - 10, **Arwal-** Kuratha – 10, Kinjar - 11, Arwal - 12, **Aurangabad-**Palmerganj – 9, **Banka-**Banka – 13, **Begusarai-** Sahebpur Kanal – 13, Kodawanpur/C.Bii -22, **Bhagalpur-** Sabour – 9 Bhagalpur-11, Colgaon - 12, **Bhojpur-** Koilwar – 9, **Darbhanga-** Kamtaul- 10, Hayaghat- 14, **Gaya -** Gaya Aero -15,Bodh Gaya- 17, **Jahanabad –** Makhdumpur-8, Jahanabad -9, **Jamui -** Sono-9, Jamui-12, Garhi-13, Jhajha - 14, **Katihar -** KatiharNorth, Manihari- 10 each,K**hagaria-** Khagadia-10, Baltara -12, **Madhepura-**Murliganj-10, Udai Kishanganj-15 **Madhubani-** Jhanjharpur-10, **Monghyr -** Monghyr-13, **Muzaffarpur -** Sahebganj , Saraiya – 8 each, Rewaghat, Minapur-9 each, Benibad, Muzaffarpur-11each, **Nalanda-**Bihar Shrif-9, Ekangersarai -12, **Nawada-**Hisua, Nawada-7 each, Rajauli- 9, **Patna-**Patna Aerodrome-8, Sripalpur-9, **Purnea-** Purnea – 11, **Rohtas-** Dehri – 9, **Saharsa-**Sirmari B. Pur – 10, **Samastipur-** Samastipur-11,Rosera-14, Hasanpur - 16, **Saran-**Chapra-11, **Sheikhpura-**Barbigha-8, **Sitamarhi-**Belsand-9, **Siwan-**Siswan-8, **Supaul-** Bhimnagar, Nirmali-8 each, Basua-10, **Vaishali-**Vaishali-9,
(iv) Sub-Himalayan West Bengal and Sikkim (SHWB & SIKKIM)
Malda-Ratua Arg 7
(v) Gangetic West Bengal
Bankura- Bankura- 10, Bankura(Cwc) - 10Kansabati Dam – 7, **Burdwan-** Asansol(Cwc) – 12, **Hooghly-** Bagati – 9, **Kolkata-** Alipore – 8, **North 24 Parganas -** Barrackpur(Iaf) – 8, **Purulia-** Phulberia - 9, Kharidwar - 13, Simula , Tusuma -15 each, Purihansa - 18, **West Midnapore-** D.P.Ghat – 9

15-10-2013

Bihar: Katihar/North-24, Kursela-24, Purnea-23, Madhipura-17, Murliganj-16, Barahara-15, Chargharia-15, Udai Kishanganj-14, Bhagalpur-14, Colgaon-12, Araria-11, Manihari-11, Sabour-11, Chanpatia-10, Phulparas-8, Koilwar-7, Ramnagar-7, Taibpur-7, Jainagar-7, Basua-7,

Sub-Himalayan West Bengal & Sikkim: Gangarampur (ARG)-22, Darjeeling-18, Bagrakote-16, Champasari-13, Murti-13, Kalimpong-13, Pedong-13, Malda-13, Siliguri (ARG)-13, Jalpaiguri-12, Dinhata (ARG)-12, Gajoldoba-12, Namchi (AWS)-12, Domohani-11, Gangtok-11, Sevoke-11, Soreng (ARG)-11, Bagdogra Iaf-10, Damthang-10, Khanitar-9, Neora-9, Mekhliganj (ARG)-9, Mathabhanga-9, Singla Bazar-9, Tadong-8, Chepan-8, Nagarkata-8, Gyalsing (AWS)-8, Cooch Behar-7, Pundibari (AWS)-7,

Gangetic West Bengal: Narayanpur-7,

Odisha: Astaranga (ARG)-9,

2.5.7.2 Gale Wind

Maximum wind of 115 knots (215 kmph) has been estimated to have occurred over the region near landfall based on the observations from the DWR, Visakhapatnam and the observations from Gopalpur and Puri in Odisha.

2.5.7.3 Storm Surge

According to survey report, maximum storm surge of 2-2.5 meters above the astronomical tide has been reported in the coastal areas of Ganjam district. The coastal inundation has been reported maximum upto 500 metre to one km in the low lying areas of Ganjam district.

2.5.8. Damage due to Cyclone 'Phailin'

The VSCS, PHAILIN mainly affected Odisha and coastal Andhra Pradesh. Details of the damage are given below.

2.5.8.1. Odisha

Districts Affected: Angul Balasore, Bhadrak, Bolangir, Cuttak, Ganjapati, Ganjam, Jagatsinghpur, Jajpur, Kamdhamal, Kendrapara, Keonjhar, Khurda, Koraput, Mayurbhanj, Nayagarh, Puri

Block Affected (Nos.)	: 151
GPs Affected(Nos.)	: 2015
Village Affected(Nos.)	: 18117
ULB Affected (Nos.)	: 43
Population Affected (Nos.) due to flood & cyclone	: 12396065
Human Casualty due to cyclone	: 21
Human Casualty due to flood	: 17
Crop area affected (hect)	: 668268
Person evacuated due to cyclone	: 983642
Person evacuated due to flood	: 171083
Cattle evacuated	: 31062
House damaged	: 419052

2.5.8.2. Coastal Andhra Pradesh

Districts affected	: Srikakulam, Vizainagaram, Visakhapatnam
Village affected	: 294
Human death	: 01
Persons evacuated	: 134,426
Paddy crop inundated	: 6192 Ha

2.6. Deep Depression over Arabian Sea (08 -11 November, 2013)

2.6.1 Introduction

A depression formed over the southwest Arabian Sea in association with an active intertropical convergence zone on 08 November 2013. It moved westwards and intensified into a deep depression on 09 November 2013 and crossed Somalia coast between 2300 UTC of 10 November and 0000 UTC of 11 November near lat. 8.2^{0}N and 50.0^{0}E. It then moved west-northwestwards and weakened gradually into a depression at 0600 UTC and into a well marked low pressure area over Somalia at 1200 UTC of 11 November 2013.

The salient features of this cyclone are given below.

(i) The deep depression maintained its intensity, though it moved across colder Sea near Somalia coast.

(ii) The low vertical wind shear around the depression centre throughout its life period helped it to maintain the intensity of deep depression at the time of landfall

2.6.2 Monitoring and prediction

The deep 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 used for monitoring of this deep depression. Various numerical weather prediction (NWP) models and dynamical-statistical models including IMD's global and meso-scale models were utilized to predict the genesis, track and intensity of the deep 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.

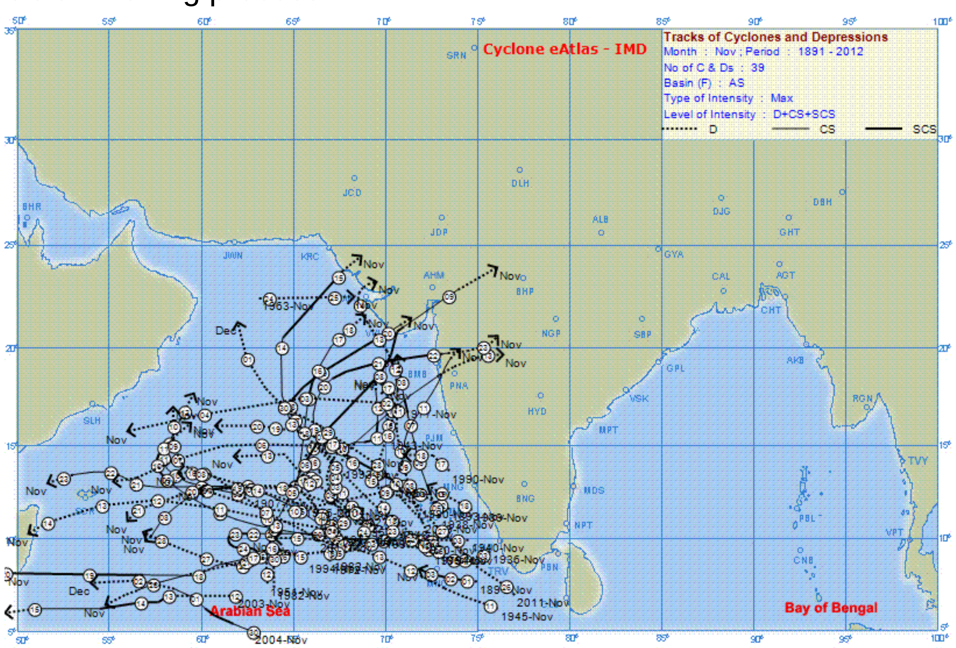


Fig.2.6.1. Tracks of cyclonic disturbances formed over the Arabian Sea during the month of November over the period of 1891-2012.

2.6.2 Climatological characteristics

Considering the data during 1891-2013, there has been no genesis of cyclonic disturbance in the past over the Arabian Sea to the west of 60^0E in the month of November prior to the deep depression during 8-11 November 2013. The cyclonic disturbances formed over the Arabian Sea during November for the period of 1891-2012 are shown in Fig.2.6.1. It indicates that about two third of cyclonic disturbances developing over south Arabian Sea during the month of November moved westwards/west-northwestwards. Considering the landfalling disturbances, Somalia experienced all the disturbances, which could make landfall over Arabia-Africa.

The brief history of the genesis, intensification and movement of this storm are discussed in following sections.

2.6.3 Genesis

Under the influence of an active inter-tropical convergence zone, a low pressure area formed over the southeast Arabian Sea on 08 November 2013. It moved westwards and became well marked over southeast and adjoining southwest Arabian Sea on 07 November. Continuing to move westwards, it concentrated into a depression at 0600 UTC of 08 November 2013 and lay centred over southwest Arabian Sea near lat. 8.0^0N and long. 56.5^0E, about 680 km east-southeast of Ras Binnah (Somalia).

During the genesis phase, the Madden Julian Oscillation index lay in phase 2 with amplitude approximately one. The phase 2 is favourable for genesis and intensification of the cyclonic disturbances over the Arabian Sea. The sea surface temperature (SST) over the southwest Arabian Sea and adjoining areas was 28-30 degree C. The Ocean heat content (OHC) was 80-100 KJ/cm^2 over the area. The lower level convergence and relative vorticity as well as upper level divergence increased from 07 to 08 November. The upper tropospheric ridge lay along 12^0N and hence provided poleward out flow in association with an anticyclonic circulation located to the northeast of the system centre. The vertical wind shear between 200 and 850 hPa levels was low to moderate (05-15 knots) around the system centre. Considering all these, the environmental parameters were favourable for genesis and intensification of the system.

2.6.4 Intensification and movement

As the depression lay to the south of the upper tropospheric ridge and the steering winds at middle and upper tropospheric levels were easterly the system moved nearly westwards till landfall. It intensified into a deep depression and lay centred at 0000 UTC of 09 November 2013 over southwest Arabian Sea near lat. 8.0^0N and long. 53.0^0E, about 400 km south-southeast of Ras Binnah, Somalia as the favourable environmental conditions as mentioned in the previous section continued on 09 November 2013.

On 09 November, the convection increased in the northwest sector with increase in low level relative vorticity. The low to moderate wind shear continued to prevail over the region. Under these circumstances, the deep depression moved westwards and maintained its intensity as deep depression till landfall, though the system was moving over a relatively colder sea area. On 24 December, as the system came closer to Somalia coast, it experienced further colder sea with Ocean thermal energy of < 40 KJ/cm-2 and sea surface temperature of $26\text{-}28^0$C. The vertical wind shear of horizontal wind however decreased and was low (about 5-10 knots) around the system centre.

The dynamical statistical models of IMD indicated the system to attain the intensity of marginal cyclone and most of the NWP models indicated gradual weakening of the system. The system crossed Somalia coast as a deep depression between 2300 UTC of 10 November and 0000 UTC of 11 November near lat. 8.2^{0}N and 50.1^{0}E. It then moved west-northwestwards to northwestwards and weakened into a depression at 0600 UTC and into a well marked low pressure area over Somalia at 1200 UTC of 11 November 2013.

Table 2.6.1 Best track positions and other parameters of the Deep Depression over the Arabian Sea during 08-11 November, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO	Estimated Central Pressure (hPa)	Estimated Maximum sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
08-11-2013	0600	8.0/56.5	1.5	1006	25	3	D
	1200	8.0/55.0	1.5	1004	25	3	D
	1800	8.0/54.0	1.5	1004	25	3	D
09-11-2013	0000	8.0/53.0	2.0	1002	30	5	DD
	0300	8.0/52.5	2.0	1002	30	5	DD
	0600	8.0/52.5	2.0	1002	30	5	DD
	1200	8.0/51.5	2.0	1002	30	5	DD
	1800	8.0/51.5	2.0	1002	30	5	DD
10-11-2013	0000	8.0/51.5	2.0	1002	30	5	DD
	0300	8.0/51.5	2.0	1002	30	5	DD
	0600	8.0/51.0	2.0	1002	30	5	DD
	1200	8.0/51.0	2.0	1002	30	5	DD
	1800	8.1/50.5	2.0	1002	30	5	DD
	Deep Depression crossed Somalia coast near lat. 8.2°N and long. 50.1^{0}E between 2300 UTC of 10-11-2013 and 0000 UTC of 11-11-2013						
11-11-2013	0000	8.2/50.0	2.0	1002	30	5	DD
	0300	8.4/49.6	2.0	1002	30	5	DD
	0600	8.7/49.3	1.5	1004	25	3	D
	1200	**Weakened into a well marked low pressure area over Somalia**					

The track of the system is shown in Fig.2.1. The best track parameters are shown in Table 2.6.1. The typical infrared and visible satellite imageries of deep depression are shown in Fig.2.6.2 – 2.6.3.

2.6.5 Realised Weather

As estimated by satellite imagery and products, the maximum sustained wind of 30 knots prevailed along and off Somalia coast, when the deep depression crossed this coast. There was no meteorological observations available from Somalia to estimate the actual intensity and adverse weather due to this deep depression.

2.6.6 Damage

According to media report, the deep depression caused heavy damage to the Puntland region of Somalia. Hundreds of houses were damaged and livestocks died. About 140 people died due to heavy rain and flood. In connection with this system

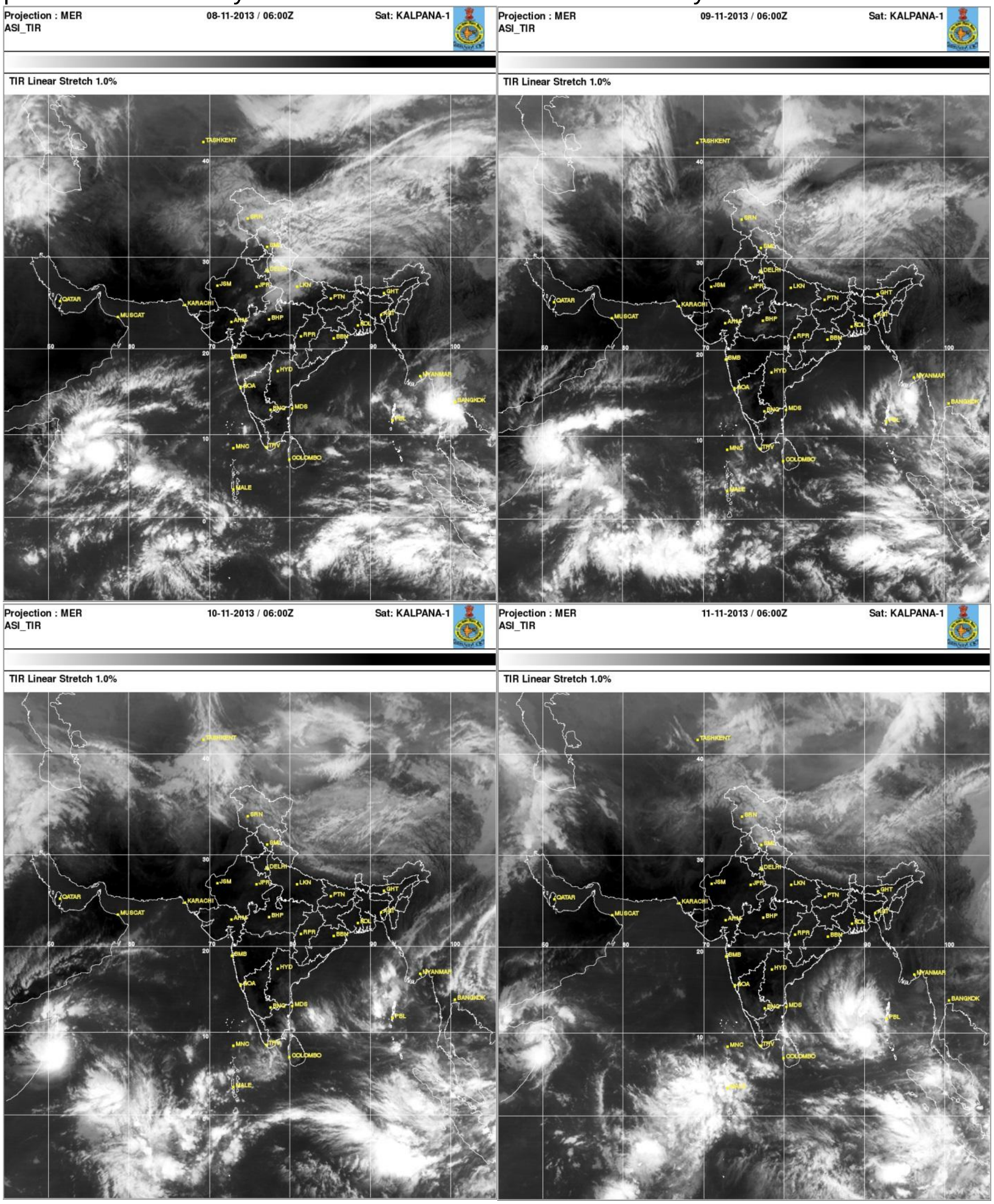


Fig.2.6.2 Kalpana-1 satellite IR imageries of deep depression over the Arabian Sea at 0600 UTC of 8-11 November 2013

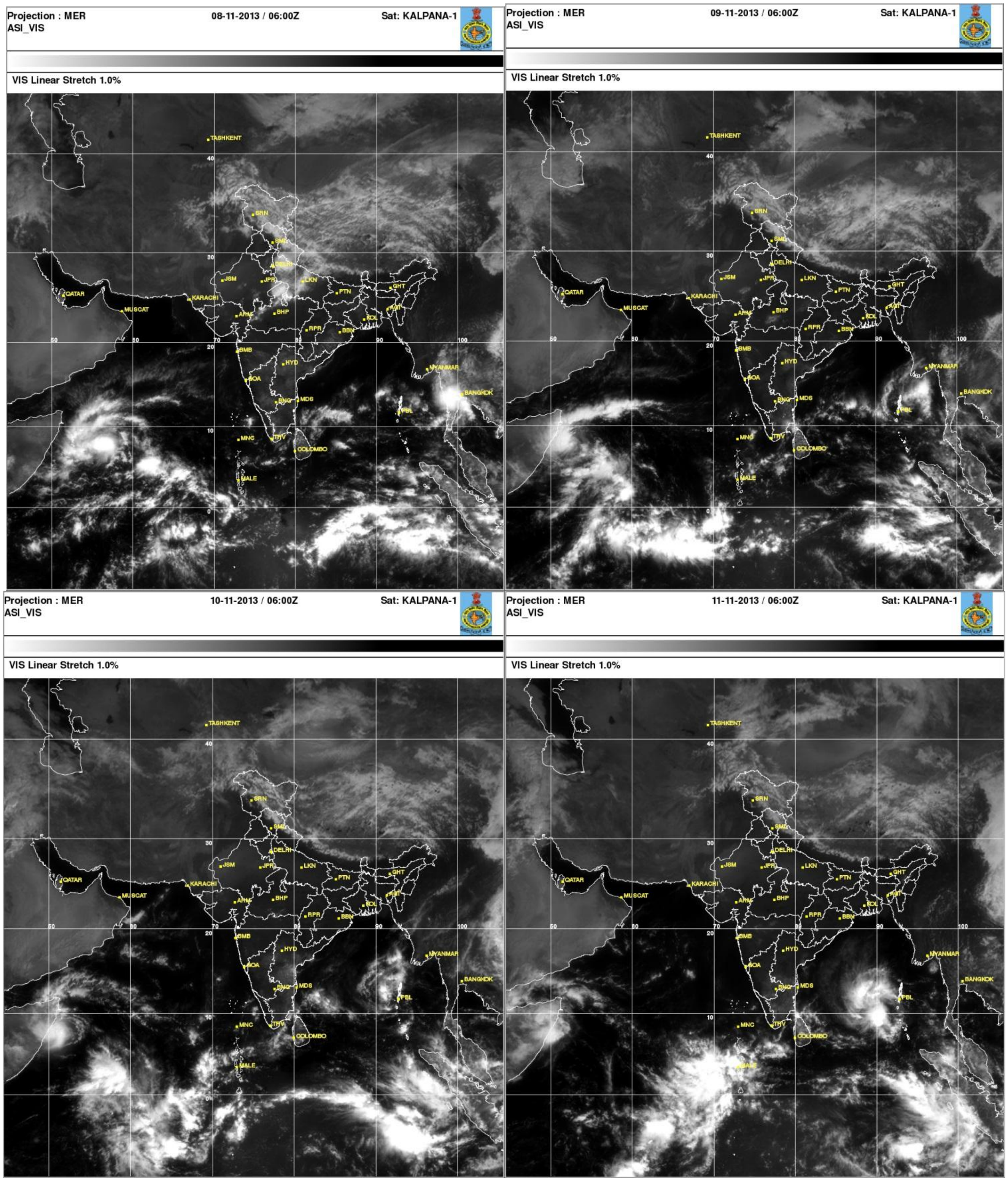


Fig.2.6.3 Kalpana-1 satellite visible imageries of deep depression over the Arabian Sea at 0600 UTC of 8-11 November 2013

2.7 Depression over the Bay of Bengal (13 – 17 November 2013)

2.7.1 Introduction

A depression formed over southwest and adjoining southeast Bay of Bengal on 13th November 2013 near latitude 11.5^{0}N and longitude 86.5^{0}E, about 700 km east-southeast of Chennai. The system crossed Tamil Nadu coast near Nagapattinam around 0730 UTC of 16th November, 2013. It then moved westwards and weakened gradually into a well marked low pressure area over north interior Tamil Nadu at 0000 UTC of 17th November, 2013. The salient features of this depression are given below:

(i) The depression initially moved westward and then it moved southwestwards and after that it moved west-northwestwards up to north interior Tamil Nadu.
(ii) Due to its slow movement over north Tamil Nadu, it caused very good rainfall activity over the region.

2.7.2 Genesis

The remnant of the tropical depression (Wilma) over south China Sea moved over Malay peninsula and emerged as a low pressure area over Andaman Sea & neighbourhood with associated upper air cyclonic circulation extending upto mid-tropospheric levels on 9th November, 2013. It lay over southeast Bay of Bengal and adjoining Andaman & Nicobar Islands on 10th November. It lay as a well marked low pressure area on 11th and persisted over the same region on 12th. It further concentrated into a depression and lay centred at 0300 UTC of 13th near lat. 11.5°N and long. 86.0°E, about 650 km east-southeast of Chennai. The low level convergence and relative vorticity increased over the south Bay of Bengal. The sea surface temperature over southwest Bay of Bengal was also warmer (28-30°C). The ocean thermal energy was about 80-100 KJ/cm^{2}over the region. The Madden Julian Oscillation (MJO) index lay in phase 3 during these periods with amplitude less than 1. Past studies indicate that phase 3 is favourable for genesis of depression as it helps in enhancing the convection. The vertical wind shear was moderate to high (15-25 knots).. Under these conditions the depression formed at 0000 UTC of 13th November near Lat. 11.5°N/Long. 86.5°E. The best track position and other parameters of depression is given in Table 2.7.1 and the track of the depression is given in Fig. 2.1. The typical satellite imageries, DWR Chennai imageries and IMD GFS MSLP and wind at 850, 500 and 200 hPa are shown in Fig. 2.7.1-3 respectively.

Table 2.7.1 Best track positions and other parameters of Depression over the Bay of Bengal during 13 – 17 November, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at theCentre (hPa)	Grade
	0000	11.5/86.5	1.5	1004	25	3	D
	0300	11.5/86.0	1.5	1004	25	3	D
	0600	11.5/86.0	1.5	1004	25	3	D

13.11.2013	1200	11.5/86.0	1.5	1003	25	3	D
	1800	11.5/85.5	1.5	1003	25	3	D
14.11.2013	0000	11.5/85.0	1.5	1003	25	3	D
	0300	11.5/85.0	1.5	1003	25	3	D
	0600	11.5/85.0	1.5	1003	25	3	D
	1200	10.5/84.5	1.5	1003	25	3	D
	1800	10.5/84.5	1.5	1003	25	3	D
15.11.2013	0000	10.0/84.0	1.5	1003	25	3	D
	0300	9.5/83.5	1.5	1003	25	3	D
	0600	9.5/83.5	1.5	1003	25	3	D
	1200	9.5/83.0	1.5	1003	25	3	D
	1800	10.0/82.0	1.5	1003	25	3	D
16.11.2013	0000	10.5/81.5	1.5	1003	25	3	D
	0300	11.0/80.5	1.5	1003	25	3	D
	0600	11.0/80.0	1.5	1003	25	3	D
	Crossed Tamil Nadu coast near Nagapattinam at 0730 UTC of 16.11.2013						
	0900	11.0/79.5	-	1004	25	3	D
	1200	11.0/79.0	-	1004	25	3	D
17.11.2013	0000	Weakened into a well marked low pressure area over north interior Tamil Nadu & neighbourhood.					

2.7.3 Intensification and movement

The depression initially moved westwards upto 0600 UTC of 14th November 2013. After that the system moved southwestwards till 1200 UTC of 15th November, 2013 and then moved west-northwest wards and crossed Tamil Nadu coast near Nagapattanam around 0730 UTC of 16th November, 2013. It weakened into a well-marked low pressure area over north interior Tamil Nadu at 00 UTC of 17th November 2013.

Though most of the NWP models suggested slow intensification upto deep depression stage, the system did not intensify into a deep depression due to increase in vertical wind shear as the system moved towards the coast. The wind shear became high (20-30 knots) in the evening of 14th November. Due to the high wind shear, the convection got sheared gradually. Further the low amplitude of MJO was not supportive for intensification of the system. The Ocean thermal energy was also less over southwest Bay of Bengal near to Sri Lanka and Tamil Nadu. As the system came closer to Tamil Nadu coast, it did not weaken and maintained its intensity of depression due to decrease in vertical wind shear. The wind shear was low to moderate (10-20 knots) at 1200 UTC of 15th Nov 2013. As a result, the system crossed coast as a depression.

The upper tropospheric ridge ran along 13-14° N throughout the life period of the system. Hence the depression lay to the south of the upper tropospheric ridge. The system moved southwestwards on 14th and 15th November, 2013, under the influence of the mid-tropospheric steering ridge. It then started moving west-northwestwards under the influence of the anticyclonic circulation lying to the northeast of the system centre. The convective cloud which was lying to the southwest of the system centre, shifted to the west and northwest indicating west-northwestward movement of the system.

2.7.4 Realised Weather

Chief amounts of 24 hrs. Rainfall (7 cm or more) ending at 0300 UTC from 14th November to 18th November, 2013 are given below:

14 November 2013

TAMILNADU & PUDUCHERRY: Srivaikuntam-7

16 November 2013

TAMILNADU & PUDUCHERRY: Chidambaram AWS-7.

17 November 2013

Coastal Andhra Pradesh: Tada-9, Atmakur-7, Sriharikota-7,

Rayalaseema: Tirumalla-9,

Tamilnadu & Puducherry: Mayiladuthurai-22**,** Tirupattur AP-14, Sathanur Dam-13, Vandavasi-13, Chembarabakkam-13, Chennai AP-12, Tirupattur Town-12, Poonamallee-12, Tiruvallur-11, Maduranthagam-11, Musiri-11, Gingee-11, Harur-11, Tindivanam-10, Upper Anaicut-10, Pondicherry-10, Tiruttani-10, Pullambadi-10, Uthangarai-9, Poondi-9, Pochampalli-9, Mylam AWS-9, Dharmapuri PTO-9, Thiruvalangadu-9, Thogamalai-9, Lalgudi-9, Penucondapuram-9, Panchapatti-8, Chettikulam-8, Venbavur-8, Thuraiyur-8, Thuvakudi Imti-8, Vanur-8, Dharamapuri-8, Anaikaranchatram(Kollid-8, Chennai(N)-8, Samayapuram-8, Tozhudur-8, Barur-8, Tiruvannamalai-8, Anna University-7, Chengam-7, Mayanur-7, Perambalur-7, DGP Office-7, Jayamkondam-7, Thammampatty-7, Thathiengrpet-7, Padalur-7, Virudachalam-7, Tirukoilur-7, Coonoor PTO-7, Pallipattu-7, Grand Anaicut-7, Ulundurpet-7, Alangayam-7, Palacode-7, Sirkali-7, Chidambaram-7, Thiruvidaimaruthur-7, Trangambadi(Or)Tranqueb-7, Uthiramerur-7,

South Interior Karnataka: M M Hills-7.

18 November 2013

Coastal Andhra Pradesh: Kavali-7, Nellore-7, **Kerala**: Vadakkancherry-7, Irinjalakuda-7, **Lakshadweep:**Amini-7.

2.7.5. Damage:

No damage has been reported due this system**.**

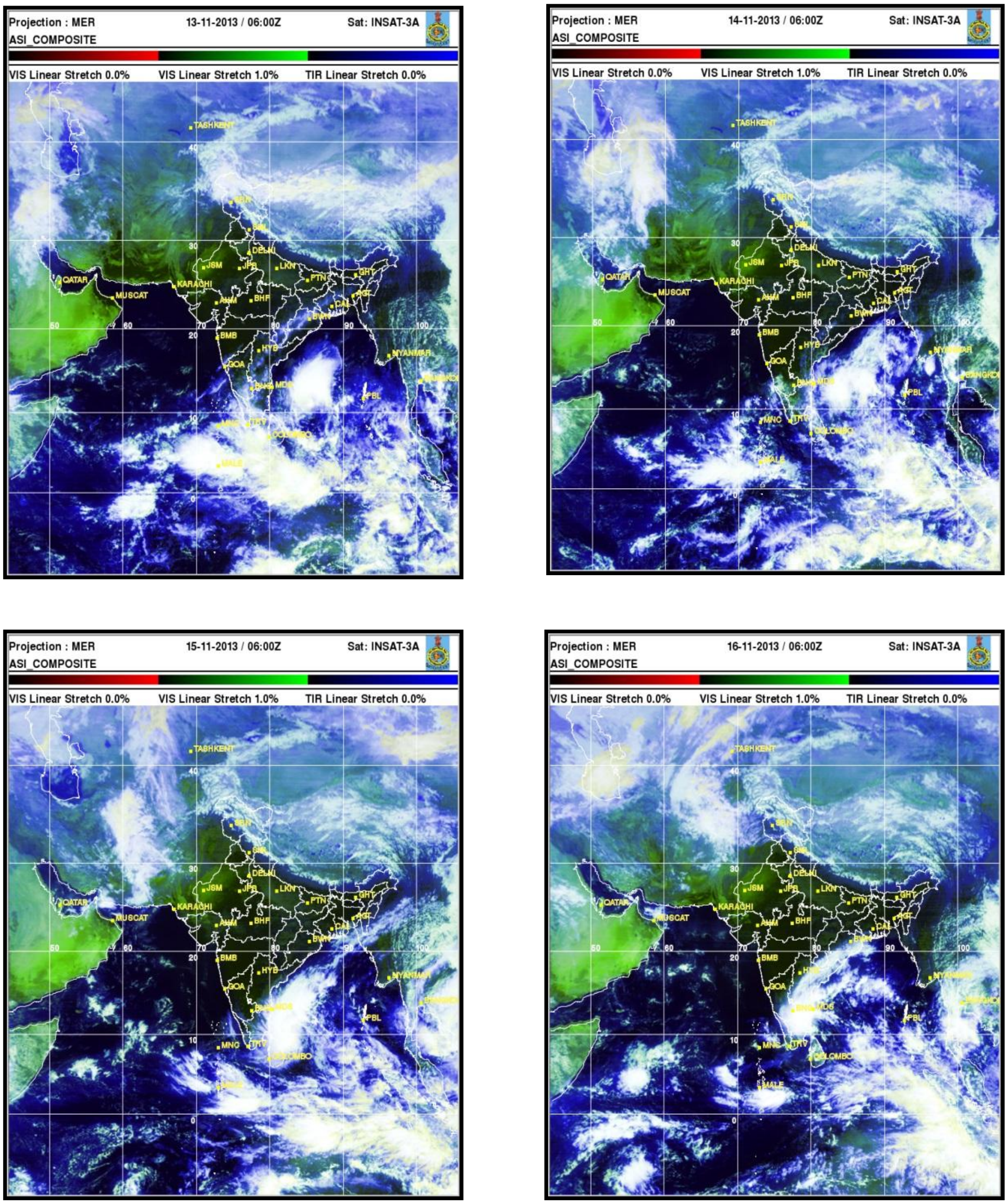


Fig.2.7.1 Typical satellite imageries showing genesis, intensification, movement of the depression (13-16 November 2013)

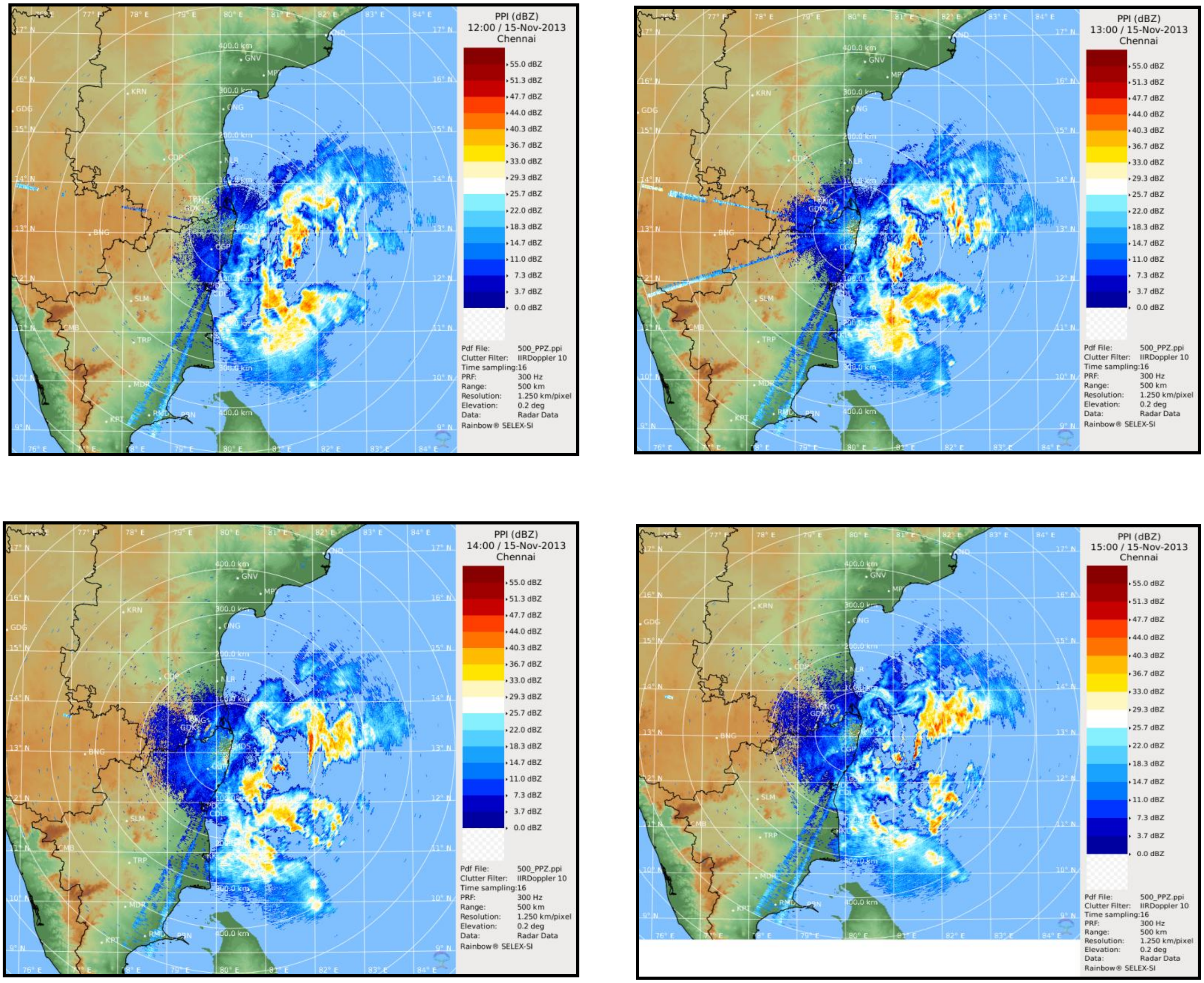


Fig.2.7.2(a) DWR Chennai imageries based on 12,13,14 & 15 UTC of 15th November 2013 during depression over Bay of Bengal.

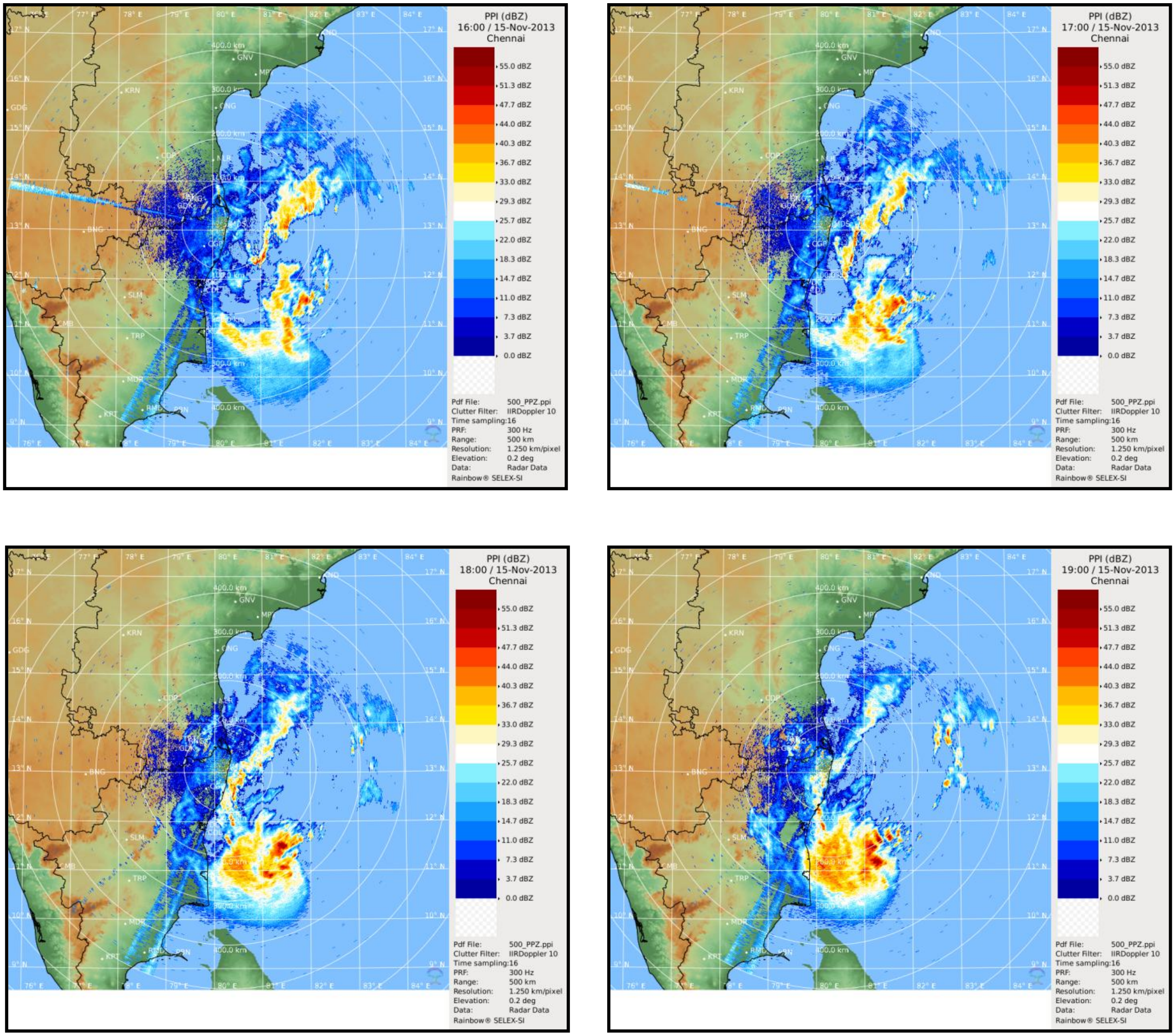


Fig.2.7.2(b) DWR Chennai imageries based on 16,17,18 & 19 UTC of 15 November 2013 during depression over Bay of Bengal.

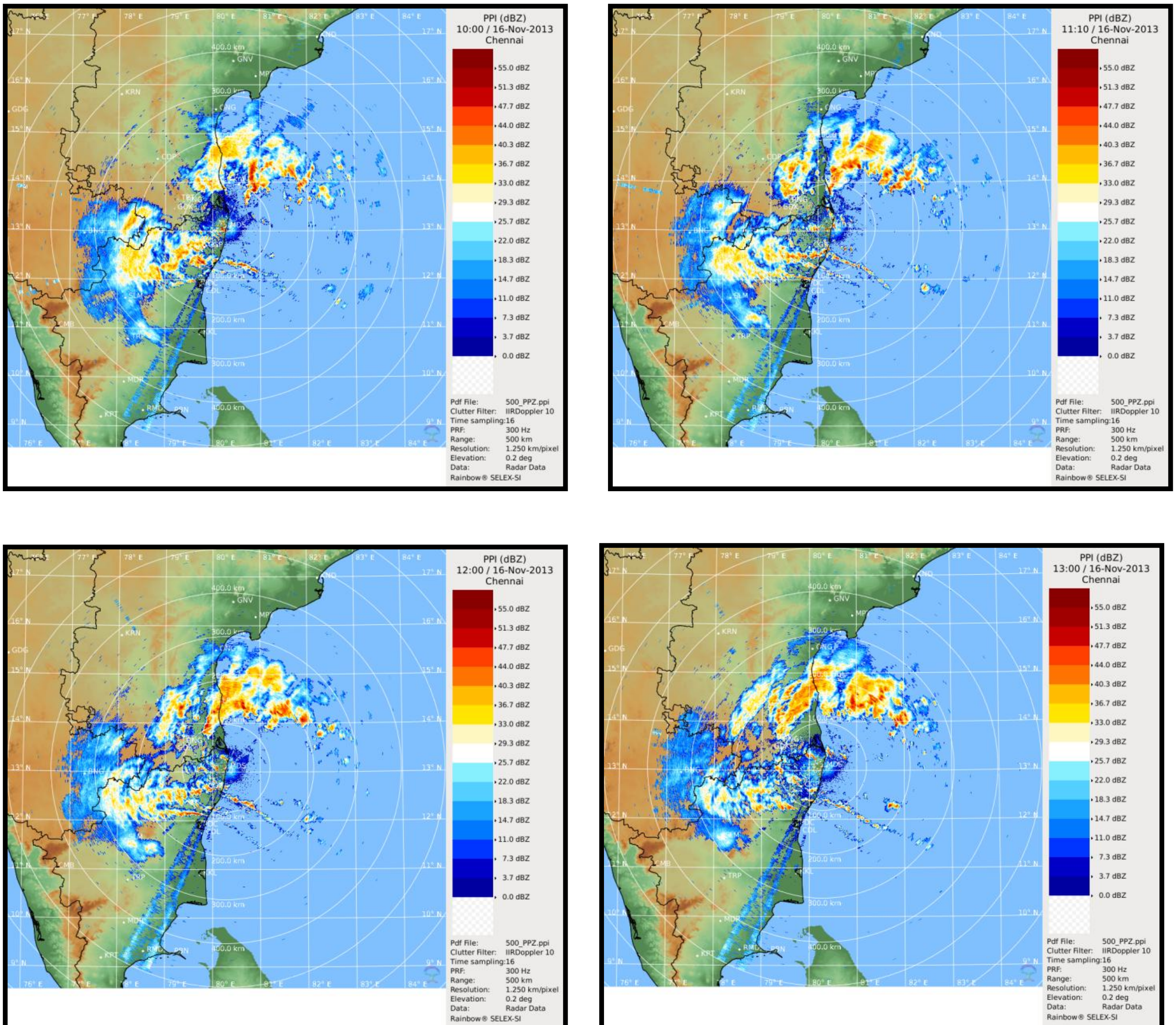


Fig.2.7.2(c) DWR Chennai imageries based on 10,11,12 & 13 UTC of 16th November 2013 during depression over Bay of Bengal.

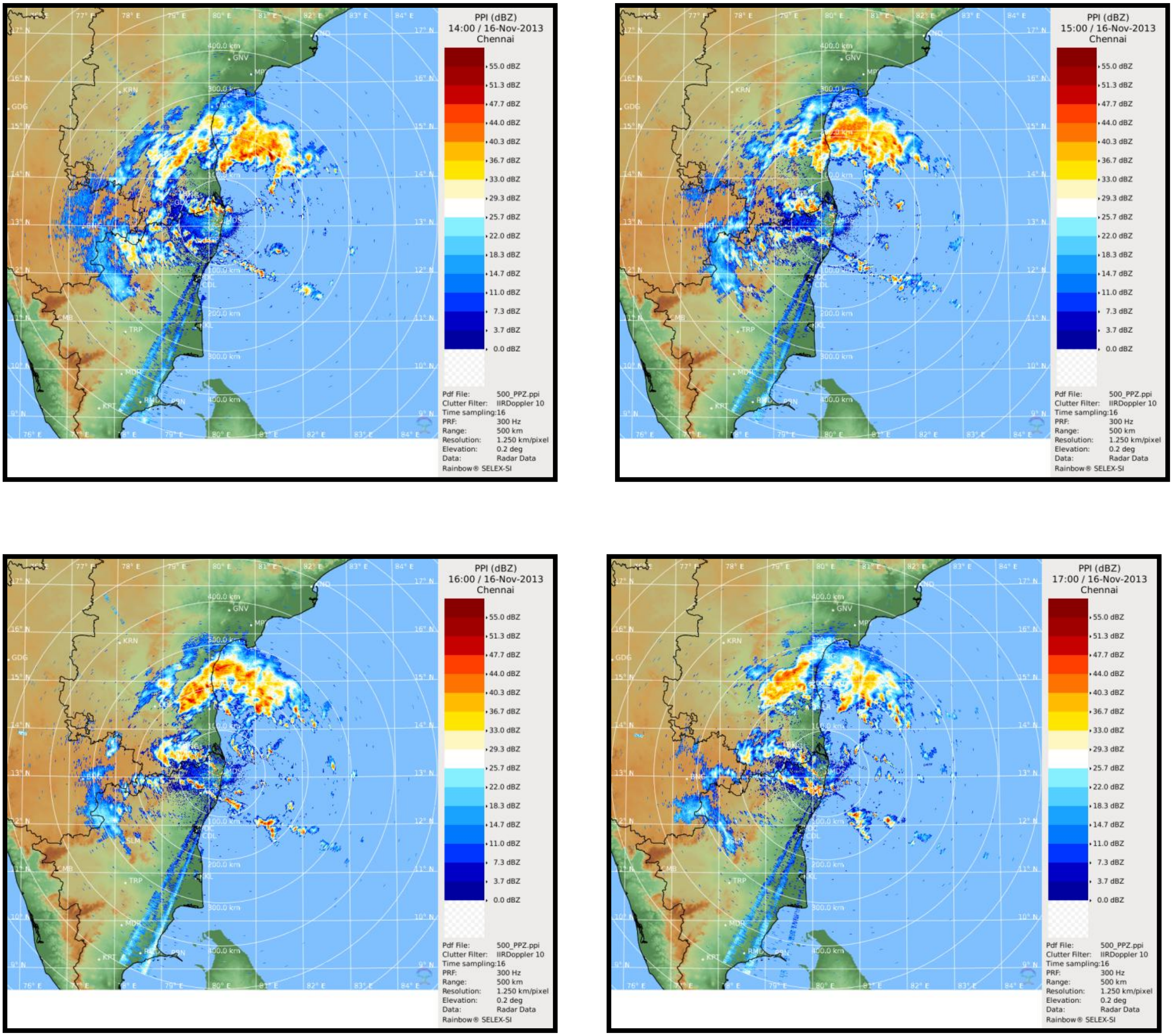


Fig.2.7.2(d) DWR Chennai imageries based on 14,15,16 & 17 UTC of 16th November 2013 during depression over Bay of Bengal.

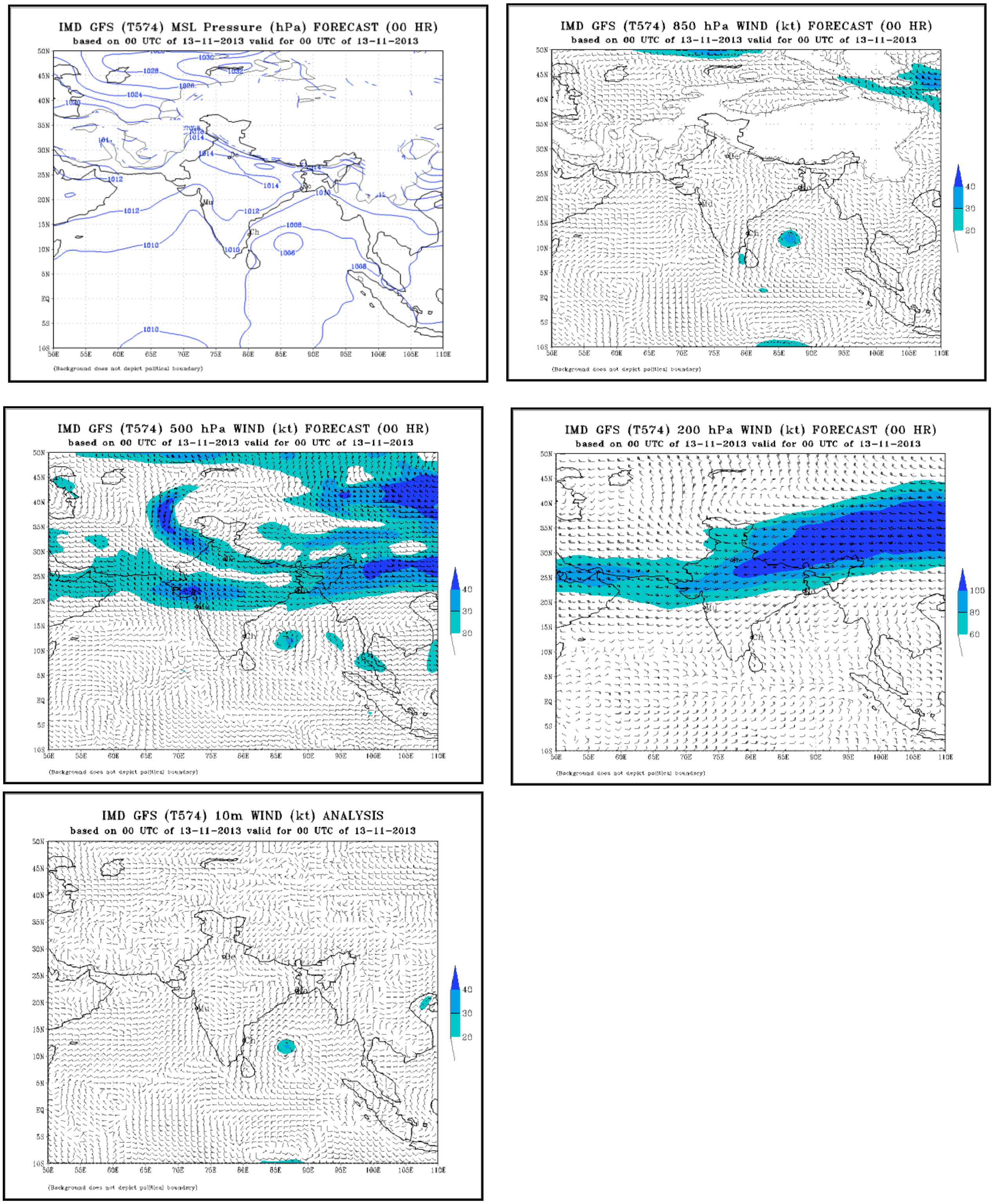


Fig. 2.7.3 (a) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 13th November, 2013.

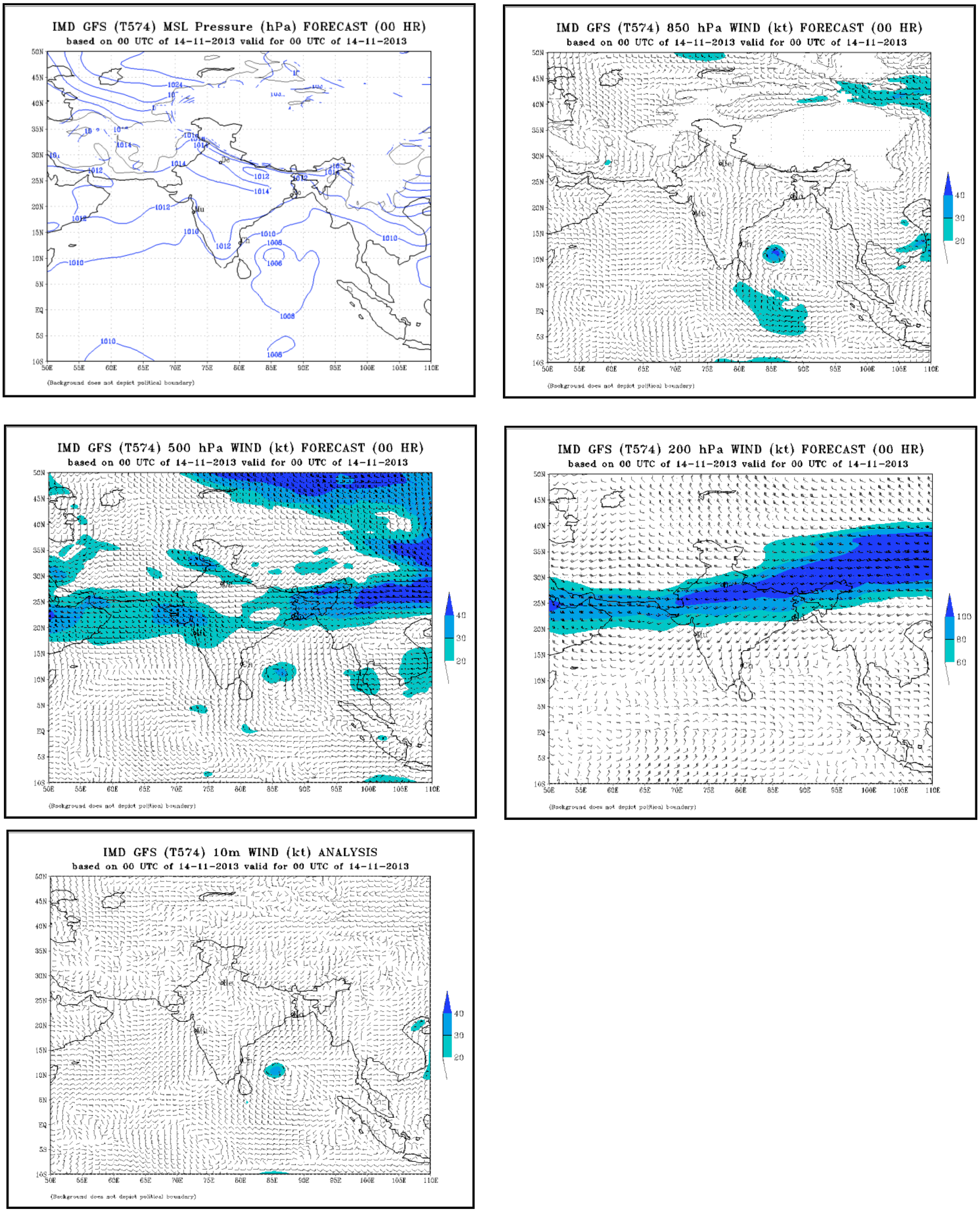


Fig. 2.7.3(b) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 14th November, 2013.

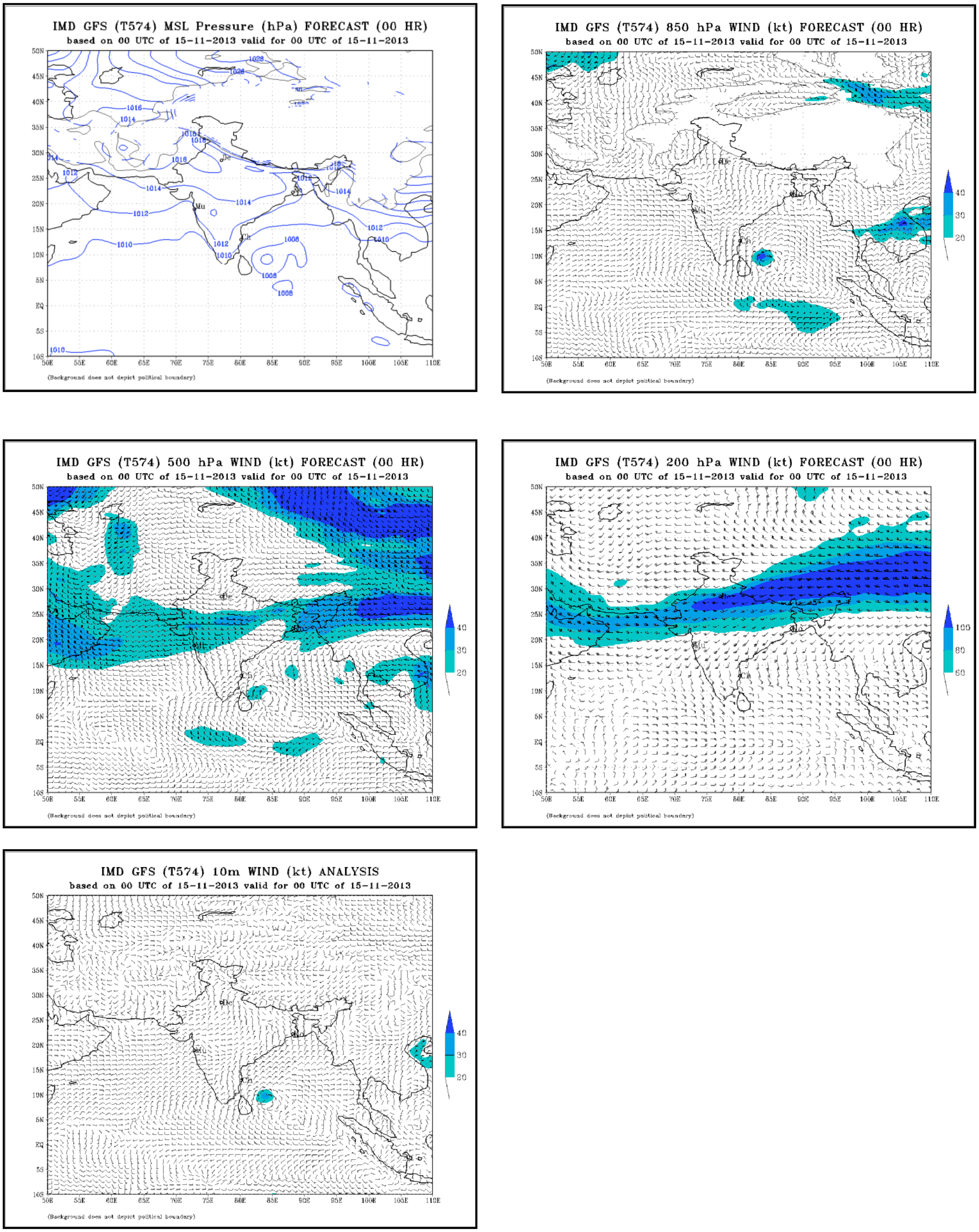


Fig.2.7.3(c) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10meter wind based on 00 UTC of 15th November, 2013.

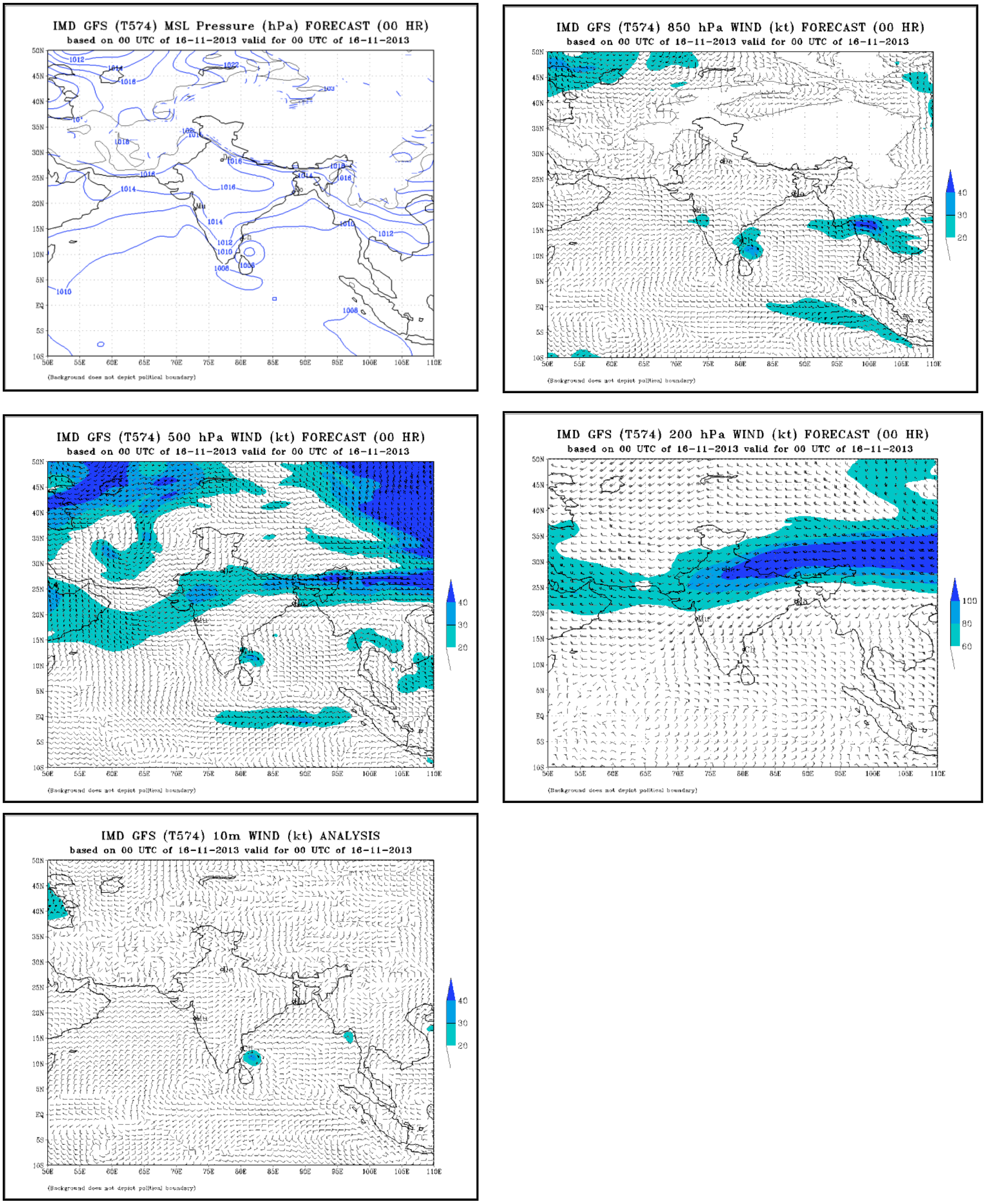


Fig. 2.7.3(d) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 16th November, 2013.

2.8 Severe Cyclonic Storm 'Helen' over Bay of Bengal (19-23 Nov 2013)

2.8.1 Introduction

A severe cyclonic storm Helen crossed Andhra Pradesh coast close to south of Machilipatnam (near lat. 16.1°N and long. 81.2°E) between 0800 and 0900 UTC of 22nd Nov. 2013 as a cyclonic storm with a wind speed of 80-90 kmph gusting to 100 kmph. The salient features of this storm are as follows:

(i) It moved west-southwestward 12 hrs before landfall

(ii) It weakened rapidly after the landfall and hence caused less rainfall over coastal Andhra Pradesh.

Brief life history and other characteristic features of cyclone are described in the following sections.

2.8.2. Monitoring and Prediction

The severe cyclonic storm Helen was monitored & predicted continuously since its inception by the India Meteorological Department. The forecast of its genesis, track, intensity, point & time of landfall, as well as associated adverse weather like heavy rain, gale wind & storm surge was 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 lay within range of DWR, Machilipatnam and Visakhapatnam, it was continuously monitored by the radar in addition to the observations from satellite and coastal observations. Data from conventional observatories and AWS were also 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 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 were utilized to predict the genesis, track, intensity and landfall of the storm. 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.

2.8.3 Genesis

The remnant of the tropical storm (Podul) contributed to the development of a trough over the Bay of Bengal near the Andaman Islands on 16th November. It became organised as a low pressure area over the east central Bay of Bengal on 17th with the active intertropical convergence zone. It became well marked on 18th over the central Bay of Bengal and concentrated into a depression over the west central Bay of Bengal in the early morning of 19th Nov. 2013 with centre near lat. 14.5^{0}N and long. 86.5^{0}E, about 600 km east-southeast of Machillipatnam. The genesis took place due to favourable location of the low pressure system with warmer sea surface temperature (28-29^{0}C), low to moderate vertical wind shear of horizontal winds (10-20 knots), increase in lower level convergence from 18th to 19th November along with upper level divergence. The upper level divergence was provided by the anticyclonic circulation which lay to the northeast of the system centre and associated ridge ran along 16.0^0N. The Madden Julian Oscillation (MJO) index lay in phase 2 with amplitude less than 1.

2.8.4 Intensification and movement

The depression moved west-northwestwards and intensified into a deep depression in the night of 19th Nov. 2013 and further into a cyclonic storm, 'Helen' in the morning of 20th Nov. at about 330 km east-southeast of Machilipatnam. It then moved north-northwestwards till 1200 UTC of 21st and intensified into a severe cyclonic storm in the early morning of 21st Nov. at a distance of 260 km east-southeast of Machilipatnam. On 22nd November, It moved initially westwards and then west-southwestwards and crossed Andhra Pradesh coast close to south of Machilipatnam (near lat. 16.1°N and long. 81.2°E) between 0800 and 0900 UTC of 22nd Nov. 2013 as a cyclonic storm with a wind speed of 80-90 kmph gusting to 100 kmph. It then weakened gradually while moving west-southwestwards across Andhra Pradesh and lay as a low pressure area over coastal Andhra Pradesh and neighborhood in the early morning of 23rd Nov. 2013. As the system moved towards the coast, it experienced decreasing vertical wind shear. The vertical wind shear was low to moderate (5-15 knots) on 20th morning when the system intensified into a cyclonic storm. The low to moderate vertical wind shear continued till 20th leading to further intensification of the system into severe cyclonic storm in the early morning of 21st. Thereafter the vertical wind shear increased gradually becoming moderate on 21st (10-20 knots) and moderate to high (15-25 knots) on 22nd Nov. As a result, the system weakened slightly and crossed coast on 22nd Nov. as a cyclonic storm. Over land surface, it weakened further due to interaction with land surface and cut off in moisture supply.

The system initially moved northwestwards till 20th morning under the influence of the upper tropospheric steering ridge which ran along 16.0^0N in association with the anticyclonic circulation lying to the northeast of the system centre. On 20th Nov. the system came closer to the steering ridge leading to north-northwesterly movement till 1200 UTC of 21st Nov. After that the northerly movement of the system got restricted and started moving nearly westward under the influence of the anticyclonic circulation at middle levels located to the northeast and northwest of the system centre. As the system came closer to the coast the steering anticyclonic circulation over India i.e. to the northwest of the system centre became more dominant leading to west-southwestward movement from 22nd Nov. The track of the system is given in Fig.2.1 and the best track position and other parameters are given in Table 2.8.1. The DWR Machilipatnam radar imagery, typical satellite imagery and IMD GFS MSLP and wind at 850, 500 and 200 hPa are shown in fig.2.8.1-3 respectively. The location of centre of the system as observed by DWR Visakhapatnam is given in Table 2.8.2.

Table 1 Best track positions and other parameters of the Severe Cyclonic Storm 'Helen' over the Bay of Bengal during 19-23 November, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
19-11-2013	0000	14.5/86.5	1.5	1004	25	3	D
	0300	14.5/86.0	1.5	1004	25	3	D
	0600	14.5/85.5	1.5	1004	25	3	D
	1200	15.0/85.0	1.5	1004	25	3	D
	1500	15.0/85.0	2.0	1002	30	5	DD
	1800	15.0/84.5	2.0	1002	30	5	DD
20-11-2013	0000	15.0/84.0	2.0	1002	30	5	DD
	0300	15.0/84.0	2.5	1000	35	8	CS
	0600	15.2/84.0	2.5	1000	40	8	CS
	0900	15.2/84.0	2.5	1000	40	8	CS
	1200	15.3/83.9	3.0	998	45	10	CS
	1500	15.3/83.9	3.0	998	45	10	CS
	1800	15.4/83.7	3.0	996	45	10	CS
	2100	15.5/83.6	3.0	996	45	10	CS
21-11-2013	0000	15.6/83.5	3.0	994	50	15	SCS
	0300	15.8/83.4	3.0	992	50	17	SCS
	0600	15.9/83.3	3.5	990	55	17	SCS
	0900	16.0/83.1	3.5	990	55	17	SCS
	1200	16.1/82.9	3.5	990	55	17	SCS
	1500	16.1/82.7	3.5	990	55	17	SCS
	1800	16.2/82.7	3.5	990	55	17	SCS
	2100	16.2/82.3	3.5	990	55	17	SCS
22-11-2013	0000	16.2/81.9	3.5	990	55	17	SCS
	0300	16.2/81.7	3.5	990	55	17	SCS
	0600	16.2/81.3	3.5	990	55	17	SCS
	The system crossed Andhra Pradesh coast close to south of Machilliptnam near 16.1^{0}N/81.2^{0}E between 0800-0900UTC						
	0900	16.1/81.2	-	1000	40	8	CS
	1200	15.9/80.7	-	1002	30	5	DD
	1800	15.9/80.4	-	1004	25	3	D
23-11-2013	0000	The system weakened into a well marked low pressure area over coastal Andhra Pradesh and neighbourhood.					

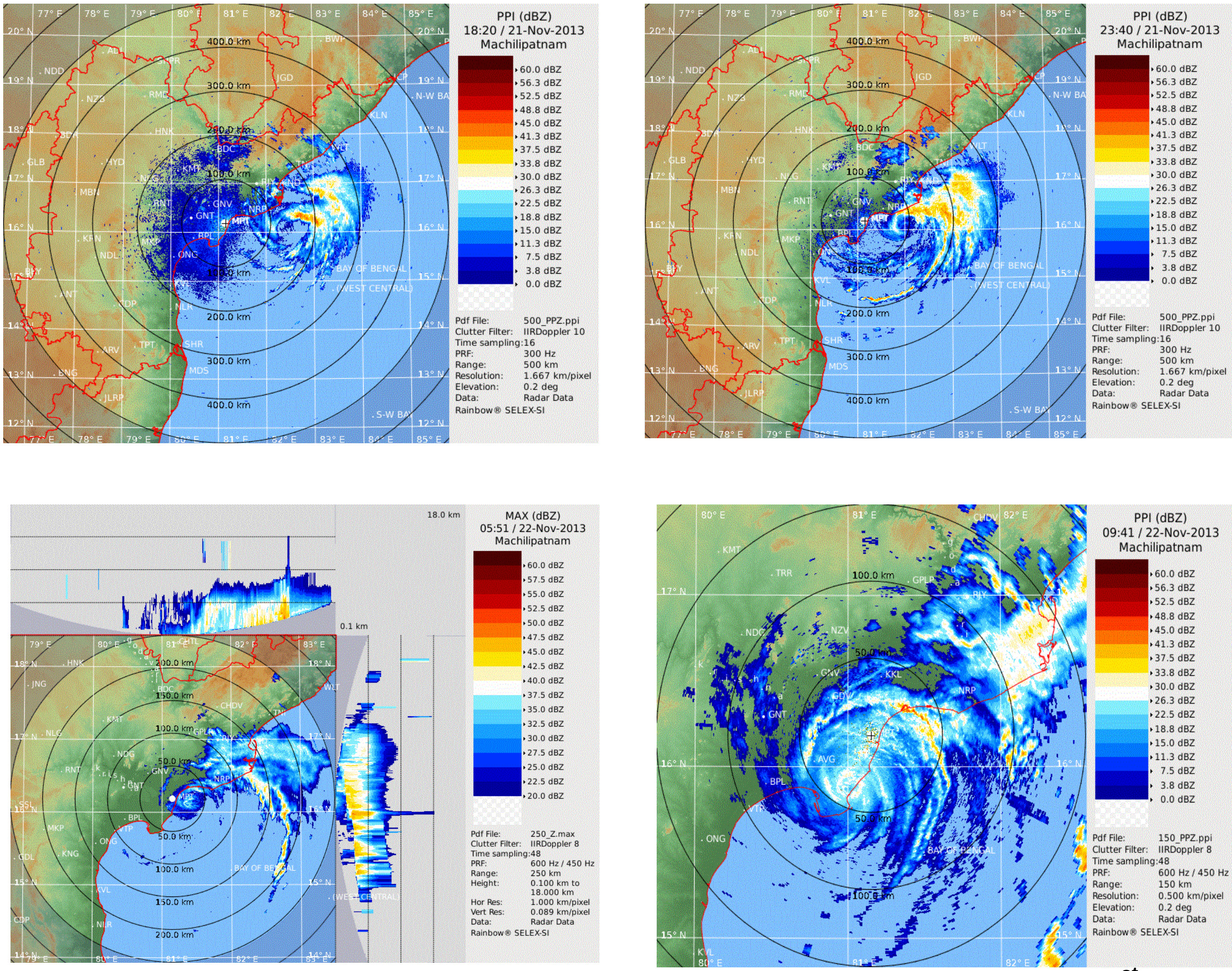


Fig.2.8.1 Typical Radar imageries of DWR Machilipatnam at 1800 UTC of 21st and 00, 06 & 10 UTC of 22nd November 2013.

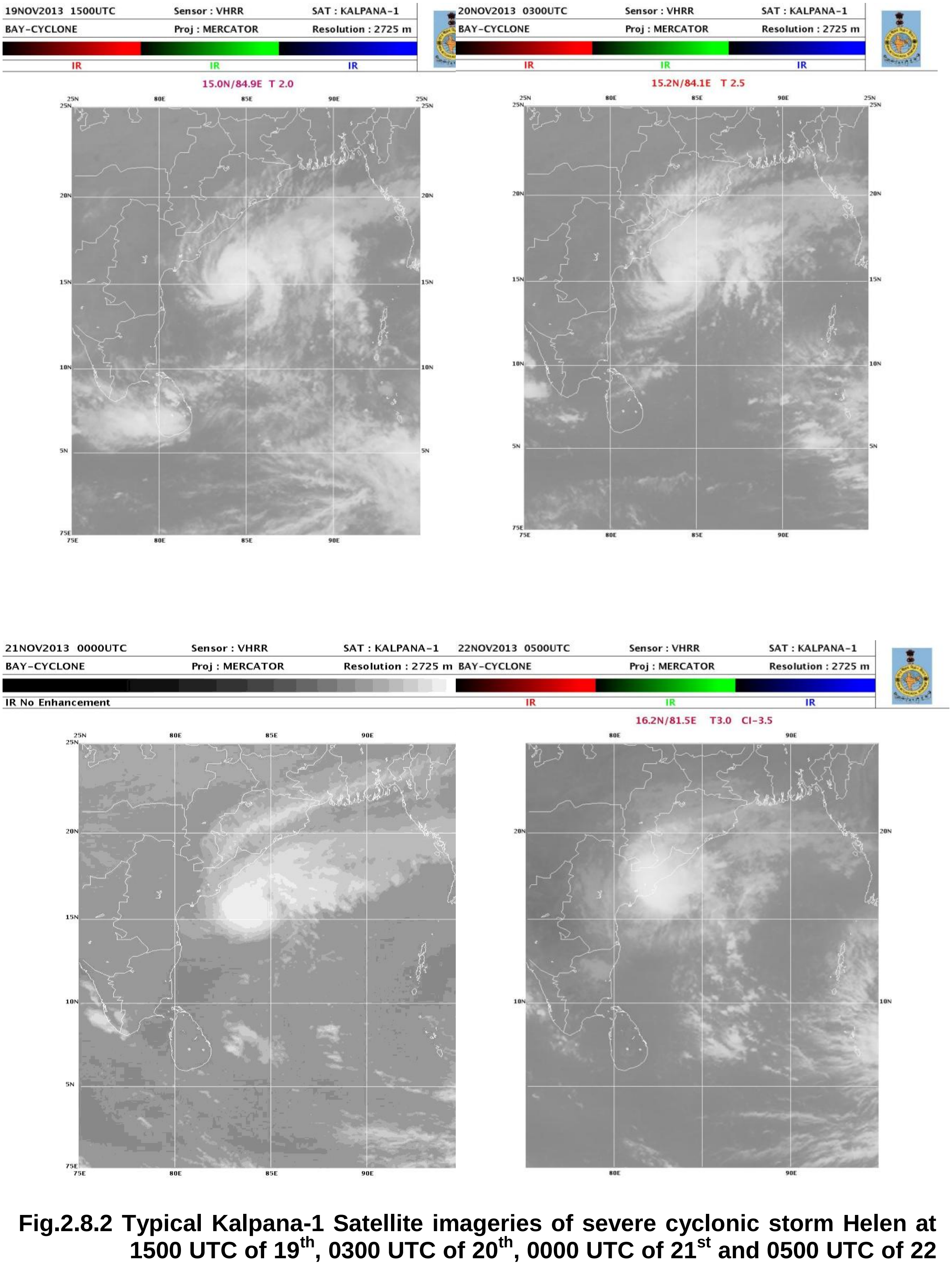


Fig.2.8.2 Typical Kalpana-1 Satellite imageries of severe cyclonic storm Helen at 1500 UTC of 19th, 0300 UTC of 20th, 0000 UTC of 21st and 0500 UTC of 22 November 2013.

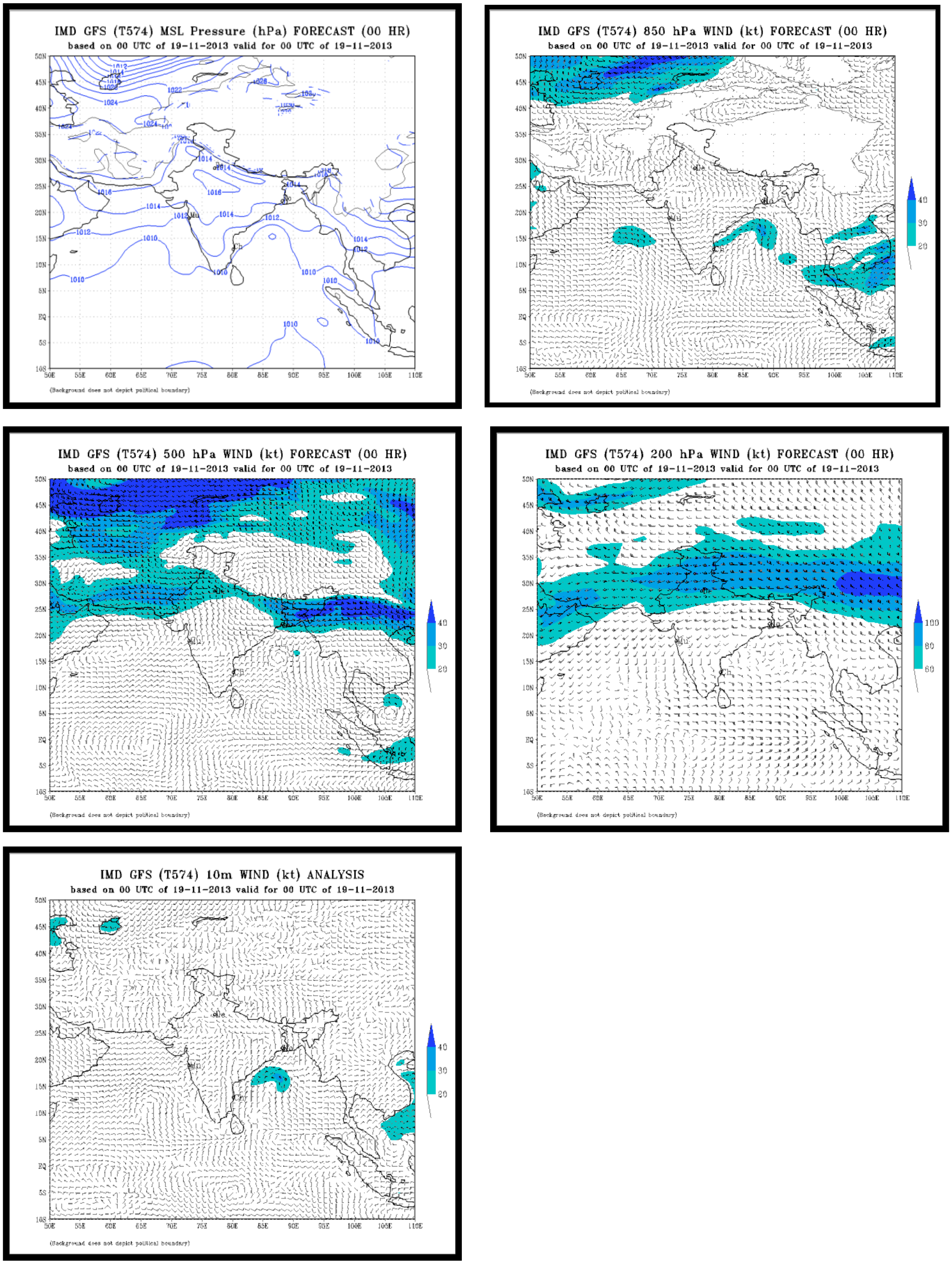


Fig.2.8.3 (a) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 19th November, 2013.

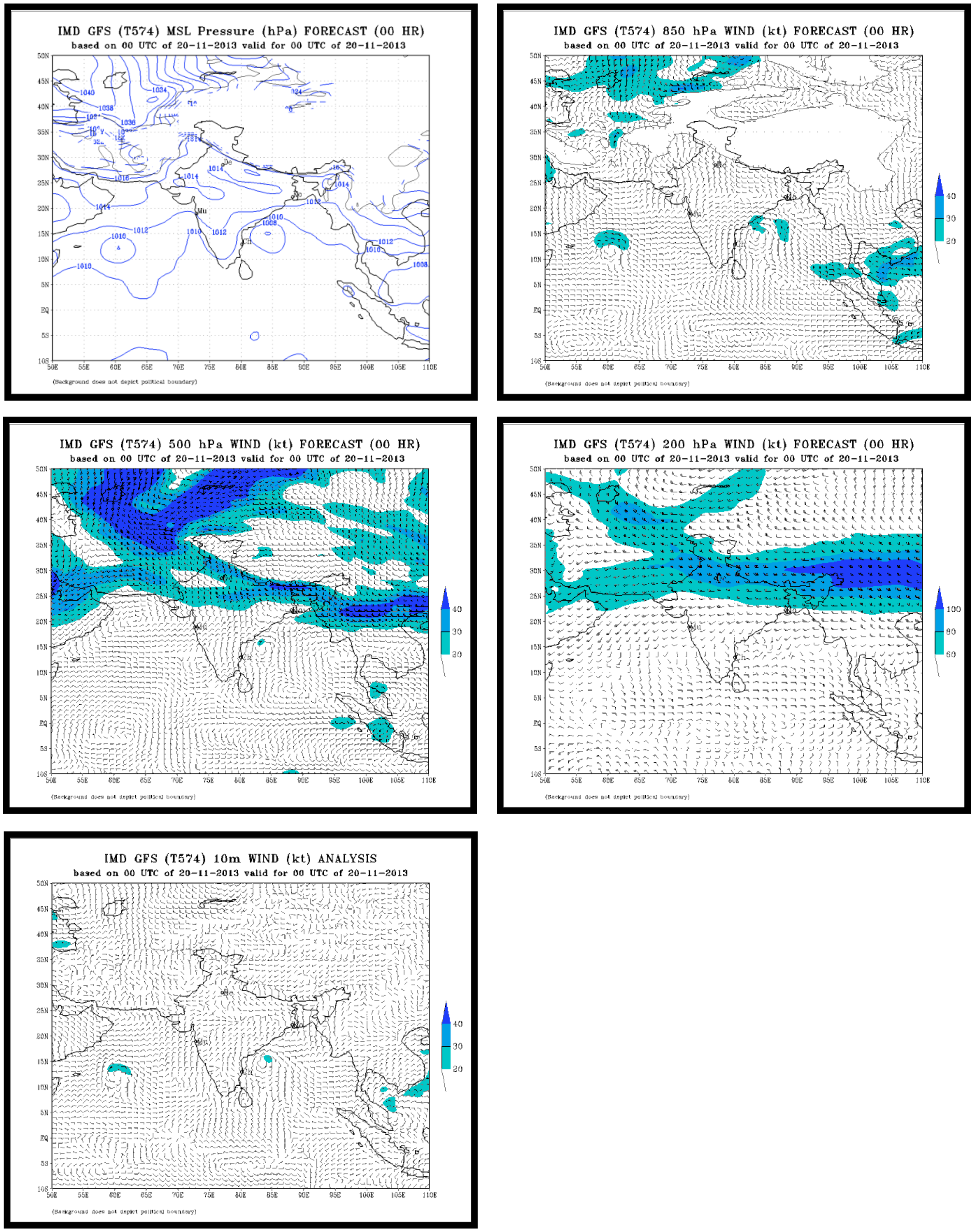


Fig.2.8.3(b) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 20th November, 2013.

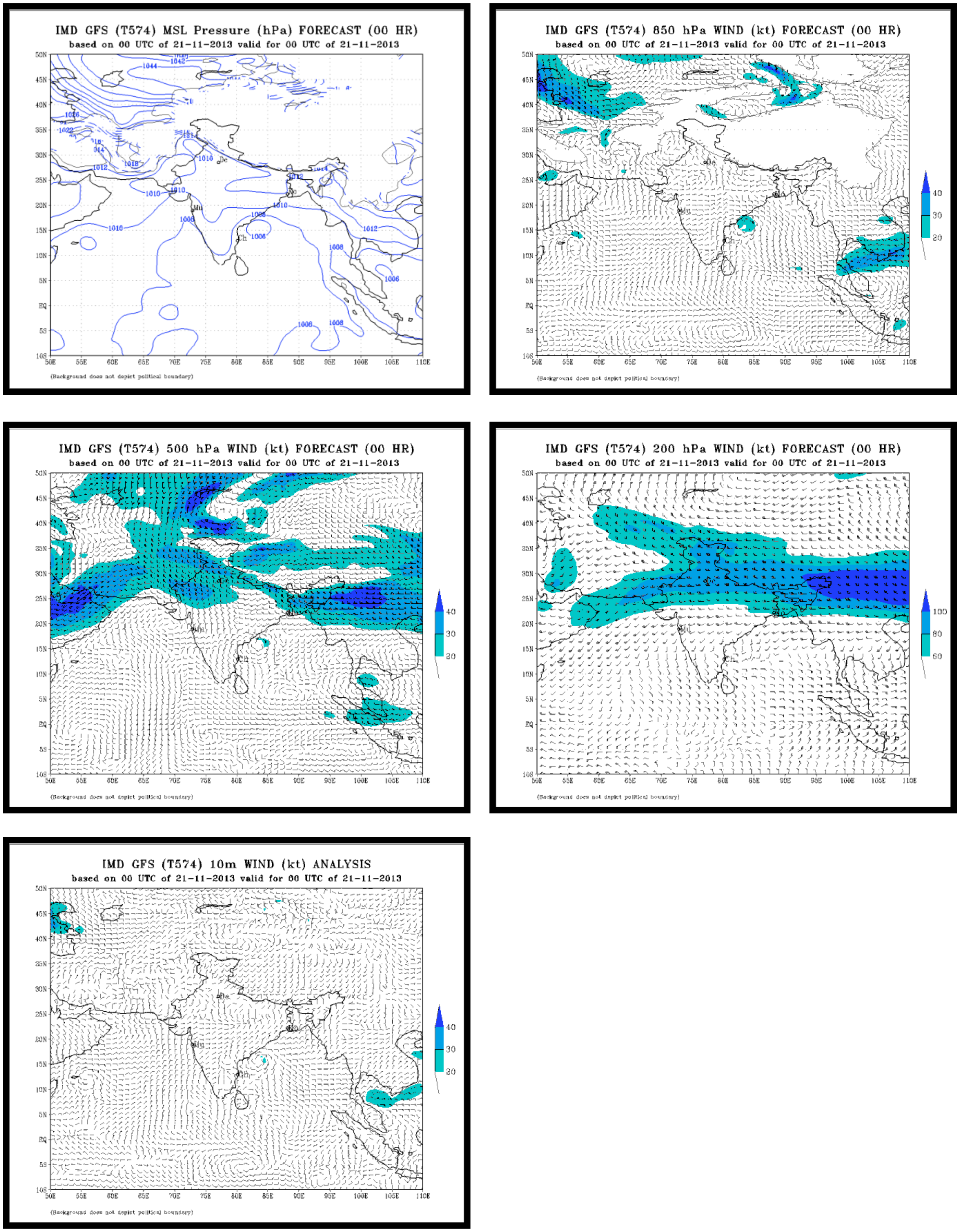


Fig.2.8.3(c) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 21st November, 2013.

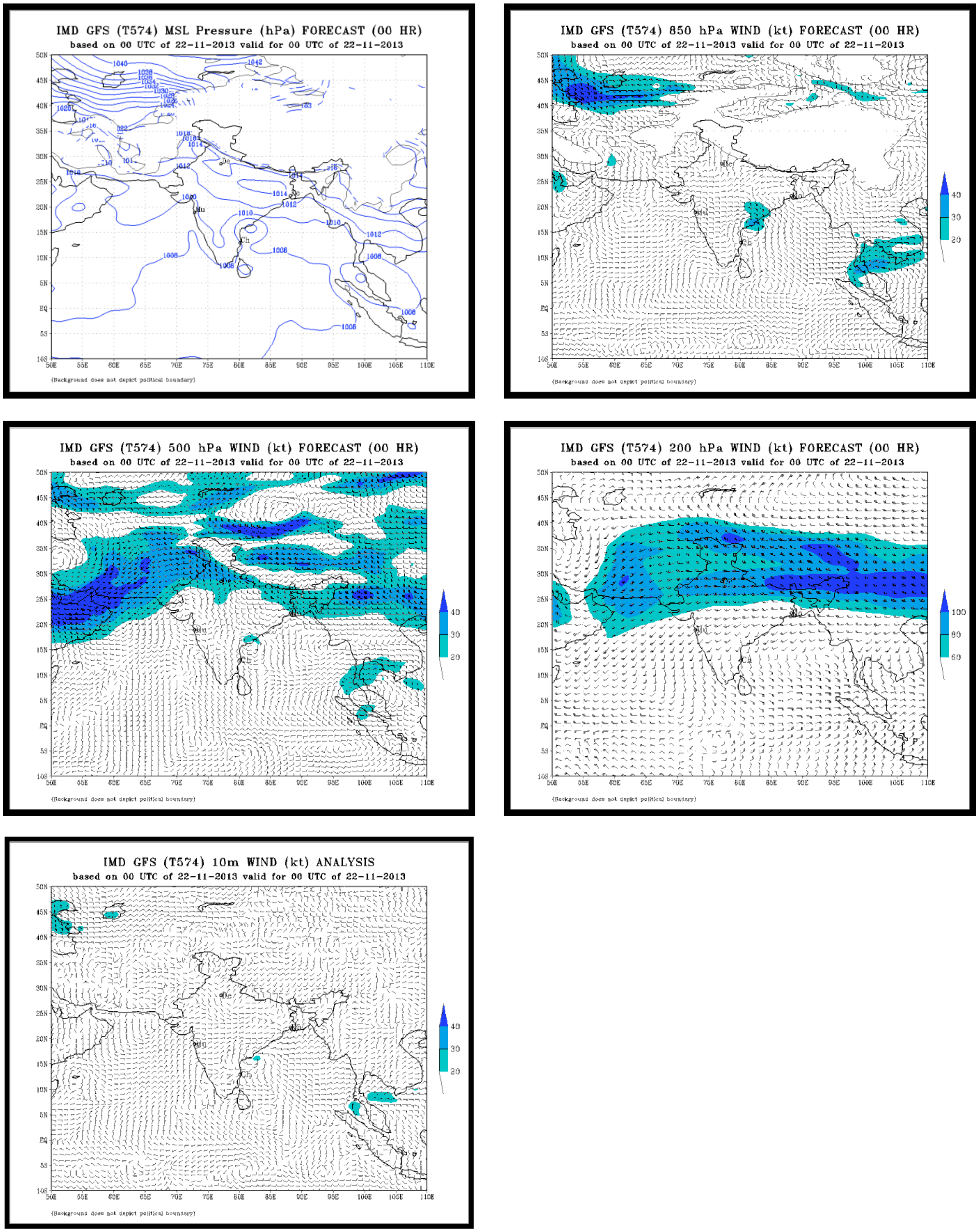


Fig.2.8.3 (d) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 22st November, 2013.

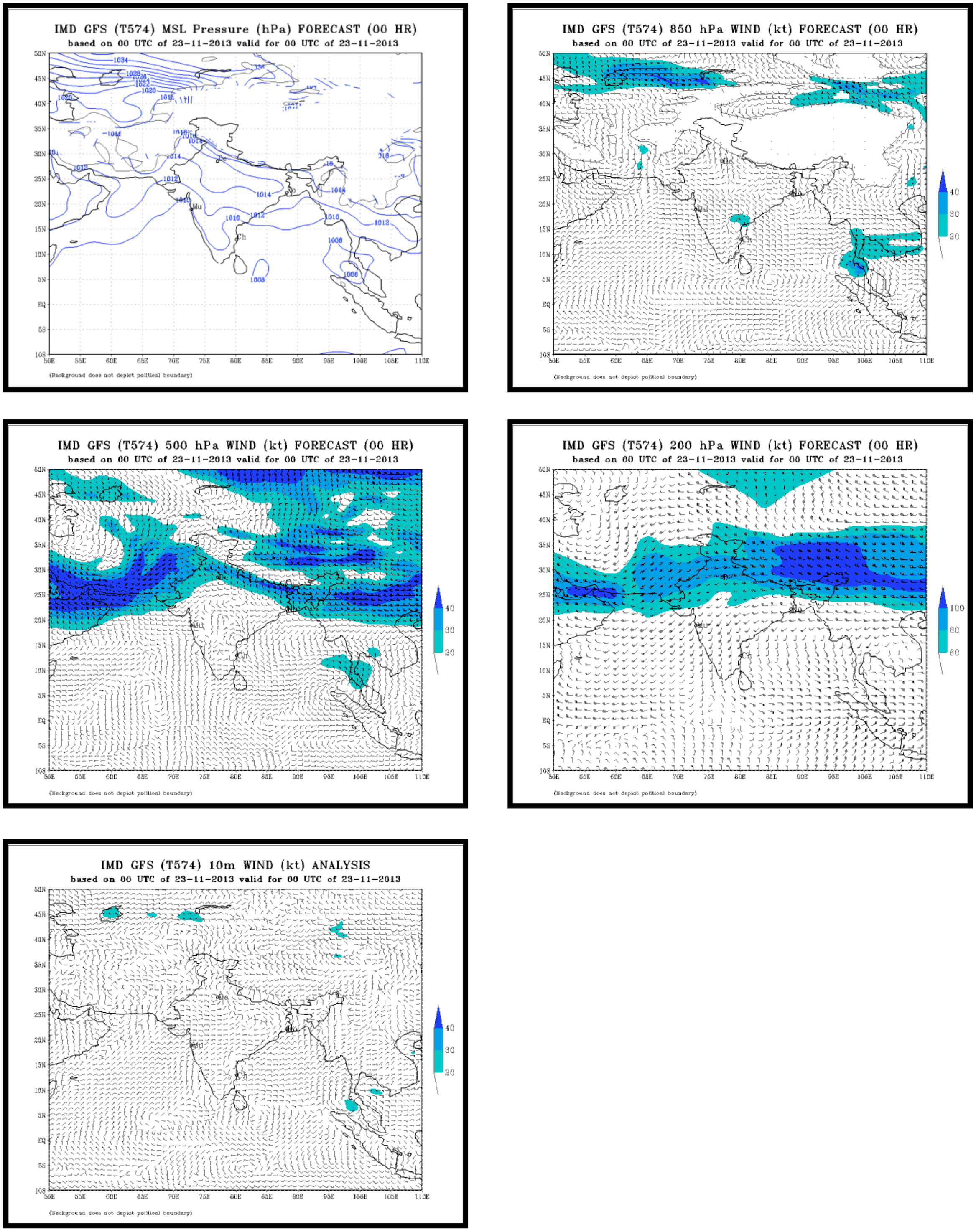


Fig.2.8.3(e) IMD GFS MSLP and winds at 850, 500 & 200 hPa levels analysis and 10 meter wind based on 00 UTC of 23rd November, 2013.

Table 2.8.2. Centre of Cyclone HELEN based on DWR, Visakhapatnam

Date/Time (UTC)	Intensity	Lat/Long N/E
19.11.13/0000	Depression	14.5/86.5
19.11.13/0300	Depression	14.5/86.0
19.11.13/0600	Depression	14.5/85.5
19.11.13/1200	Depression	15.0/85.0
19.11.13/1500	Deep Depression	15.0/85.0
19.11.13/1800	Deep Depression	15.0/84.5
20.11.13/0000	Deep Depression	15.0/84.0
20.11.13/0300	Cyclonic Storm	15.0/84.0
20.11.13/0600	Cyclonic Storm	15.2/84.0
20.11.13/0900	Cyclonic Storm	15.2/84.0
20.11.13/1200	Cyclonic Storm	15.3/83.9
20.11.13/1800	Cyclonic Storm	15.4/83.7
20.11.13/2100	Cyclonic Storm	15.5/83.6
21.11.13/0000	Severe Cyclonic Storm	15.6/83.5
21.11.13/0300	Severe Cyclonic Storm	15.8/83.4
21.11.13/0600	Severe Cyclonic Storm	15.9/83.3
21.11.13/0900	Severe Cyclonic Storm	16.0/83.1
21.11.13/1200	Severe Cyclonic Storm	16.1/82.9
21.11.13/1500	Severe Cyclonic Storm	16.1/82.7
21.11.13/1800	Severe Cyclonic Storm	16.2/82.5
21.11.13/2100	Severe Cyclonic Storm	16.2/82.3
22.11.13/0000	Severe Cyclonic Storm	16.2/81.9
22.11.13/0300	Severe Cyclonic Storm	16.2/81.7
22.11.13/0600	Severe Cyclonic Storm	16.2/81.3
22.11.13/0800-0900	Cyclonic Storm	16.1/81.2
22.11.13/0900	Cyclonic Storm	16.1/81.0
22.11.13/1200	Deep Depression	15.9/80.7
22.11.13/1800	Depression	15.9/80.4

2.8.5 Realized Weather:

a. Surface Wind: Gale wind speed reaching of 80-90 kmph gusting to 100 kmph prevailed along and off Andhra Pradesh coast at the time of land fall.

b. Rainfall: Chief amounts of 24 hrs. Rainfall (7 cm or more) ending at 0300 UTC from 19th November to 23rd November, 2013 are given below:

19 November 2013
Andaman & Nicobar Islands: Maya Bandar-7
Tamilnadu & Puducherry: Sankarapuram-10, Mayiladuthurai-8 Karaikal-7, Kodavasal-7,
Kerala: Piravom-8

20 November 2013 – Nil

21 November 2013
Tamilnadu & Puducherry: Colachel-12, Thuckalay-9, Eraniel-8

22 November 2013
Coastal Andhra Pradesh: Visakhapatnam-11
Tamilnadu & Puducherry: Sivagiri-9
Kerala: Nedumangad-7, Alappuzha-7

23 November 2013

Coastal Andhra Pradesh: Gudivada-13, Vijayawada A.P.-10, Visakhapatnam Ap-10, Masulipatnam-9, Visakhapatnam-7

24 November 2013
Telangana: Narayan Khed-12
Tamilnadu & Puducherry: Watrap-15, Rajapalayam-14, Nanguneri-10, Sivakasi-9, Sivagiri-8, Colachel-8, Uttamapalayam-7, Sankarankoil-7, Coastal Karnataka: Dharmasthala-7
South Interior Karnataka: Bangalore-11, Devanhalli-9, K.R.Nagara-7, Kottigehara-7, Arkalgud-7,
Kerala: Punalur-9, Kurudamannil-9.

2.8.6. Damage Report:
The cyclone, Helen caused considerable damage over coastal Andhra Pradesh, especially over Krishna, west & east Godavari districts. It uprooted trees and electrical poles and damaged crops (paddy, banana & coconut etc). The typical damage photographs are shown in Fig. 2.8.4. Number of human death was 11 due to this system.

Fig.2.8.4. Damage over Machilipatnam and Koduru due to SCS Helen.

2.9. Very Severe Cyclonic Storm VSCS 'Lehar'(23-28 November, 2013)

2.9.1 Introduction

A depression formed over south Andaman Sea on 23rd evening and it intensified into a cyclonic storm, Lehar in the early morning of 24th November 2013 near Latitude 10.0°N and longitude 95.0°E. Moving northwestward, it crossed Andaman & Nicobar Islands near Port Blair around 0000 UTCof 25th November as a severe cyclonic storm. On 25th morning it emerged into southeast Bay of Bengal and moved west-northwestward, intensified into a very severe cyclonic storm in the early hours of 26th Nov. However while moving west-northwestwards over westcentral Bay of Bengal, it rapidly weakened from 27th afternoon and crossed Andhra Pradesh coast close to south of Machilipatnam around 0830 UTC of 28th Nov. 2013 as a depression.

The salient features of this system are given below:

(i) It was the first severe cyclonic storm to cross Andaman and Nicobar Islands after November, 1989.
(ii) It had second landfall near Machilipatnam as a depression.
(iii) It rapidly weakened over the sea from the stage of very severe cyclonic storm to depression in 18 hrs.

Brief life history and other characteristics of the system are described below:

2.9.2 Monitoring and Prediction:

The very severe cyclonic storm, 'LEHAR' was monitored mainly with satellite supported by meteorological buoys, coastal and island observations and Doppler Weather Radar(DWR), Machilipatnam. The half hourly INSAT/KALPANA imageries, hourly coastal observations and every 10 minutes DWR imageries and products were used for monitoring of cyclonic storm.

Various numerical weather prediction (NWP) models and dynamical-statistical models including IMD's global and meso-scale models were utilized to predict the track and intensity of the storm. The Tropical Cyclone Module in the digitized forecasting system of IMD was utilized for analysis and comparison of various NWP models and decision making process. However, there was large divergence in NWP model guidance with respect to genesis and intensification of the system. There was more unanimity in the NWP models with respect to track prediction.

2.9.3 Genesis:

A remnant of tropical depression over south China Sea moved across Malay peninsula and lay as a low pressure area over south Andaman Sea on 21st November, 2013. It became well marked over the same area on 22nd and concentrated into a depression over south Andaman Sea near latitude 08.5°N and longitude 96.5°E about 550 km south-southeast of Port Blair at 1200 UTC of 23rd November, 2013. The genesis was detected with the Ocean Sat-II winds and the observation from the coast of Thailand in addition to satellite imageries. The genesis was associated with upper troposphere ridge which ran along 13° N and provided adequate upper level divergence through Poleward outflow. The lower level convergence and relative vorticity increased over the area from 22nd to 23rd November. The sea surface temperature was 28-29°C and Ocean thermal energy was 60-80 KJ/cm^2. The vertical wind shear of horizontal wind was moderate (10-20 knots). The Madden Julian oscillation (MJO) index lay in

Phase 3 i.e. over east equatorial Indian Ocean. Past studies indicate that the Phase 3 is favorable for genesis of depression.

2.9.3 Intensification and movement:

Due to the favourable atmospheric and Oceanic condition as mentioned above, the depression over south Andaman Sea moved northwestwards, intensified into a deep depression at 1800 UTC of 23rd and further into a cyclonic storm, ‘Lehar’ at 0300 UTC of 24th November and lay centred near latitude 10.0°N and longitude 95.0° E. It further intensified into a severe cyclonic storm, continued to move northwestwards and crossed Andaman & Nicobar Island near Port Blair around 0100 UTC of 25th November, 2013. It then emerged into southeast Bay of Bengal, moved west-northwestwards and intensified into a very severe cyclonic storm at 2100 UTC of 26th November, 2013 over southeast Bay of Bengal near latitude 12.5° N and longitude 91.0°E. It attained the maximum intensity of 75 knots at 1800 UTC of 26th November, 2013 and the same intensity continued till 0300 UTC of 27th November, 2013 when it lay over central Bay of Bengal.

As the westcentral Bay of Bengal was colder with Ocean thermal energy less than 50 KJ/cm^2 and there was entrainment of dry and cold air from central and northern parts of India into the cyclone field and vertical wind shear of horizontal wind increased and became high, the very severe cyclonic storm started to weaken rapidly from the afternoon of 27th November, 2013. It weakened into a severe cyclonic storm at 1200 UTC of 27th November and lay centred near latitude 14.5°N and longitude 85.0°E. It further weakened into a cyclonic storm at 1800 UTC of 27th November, 2013 with centre near latitude 15.0°N and longitude 84.0°E over westcentral Bay of Bengal. It weakened into a deep depression at 0000 UTC of 28th November, 2013 with centre near latitude 15.5°N and longitude 82.0°E. At this time the vertical wind shear was high (about 20 knots). It weakened into a depression and crossed Andhra Pradesh coast near latitude 15.9°N and longitude 81.1°E (close to south of Machilipatnam) around 0830 UTC of 28th November, 2013. It weakened into a well marked low pressure area over coastal Andhra Pradesh and adjoining Telengana at 1800 UTC of 28th November, 2013.

The system moved northwestwards/west-northwestwards as it lay to the south of the upper tropospheric steering ridge which moved northward from its position near latitude 13.0°N on the day of genesis to latitude 17°N on the day of landfall. The best track position and other parameters ofthe Very Severe Cyclonic Storm ‘Lehar’ over the Bay of Bengal is given in Table 2.9.1 and the track of the very severe cyclonic storm ‘Lehar’is given in Fig 2.1.Visakhapatnam & Machilipatnam RADAR imageries, Satellite imageries and IMD GFS MSLP and wind at 850, 500 and 200 hPa levels are shown in Fig. 2.9.1-3 respectively. The position of the cyclone ‘Lehar’ based on DWR, Visakhapatnam is shown in Table 2.9.2.

Table 2.9.1 Best track positions and other parameters of the Very Severe Cyclonic Storm 'Lehar' over the Bay of Bengal during 23-28 November, 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure(hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at theCentre (hPa)	Grade
23-11-2013	1200	8.5/96.5	1.5	1004	25	3	D
	1800	9.0/96.0	2.0	1002	30	5	DD
24-11-2013	0000	10.0/95.0	2.5	999	35	7	CS
	0300	10.0/95.0	2.5	998	40	8	CS
	0600	10.5/94.5	2.5	998	40	8	CS
	0900	10.7/94.0	3.0	996	45	10	CS
	1200	11.0/93.5	3.0	996	45	10	CS
	1500	11.0/93.5	3.0	996	45	10	CS
	1800	11.5/93.0	3.0	996	45	10	CS
	2100	11.5/92.5	3.0	996	45	12	CS
25-11-2013	0000	12.0/92.5	3.5	992	55	15	SCS
	The system crossed Andaman & Nicobar island, south of Port Blair around 0100 UTC						
	0300	12.0/92.0	3.5	988	55	17	SCS
	0600	12.0/91.5	3.5	988	55	17	SCS
	0900	12.0/91.5	3.5	988	60	17	SCS
	1200	12.5/91.5	3.5	988	60	17	SCS
	1500	12.5/91.0	3.5	988	60	17	SCS
	1800	12.5/91.0	3.5	988	55	17	SCS
	2100	12.5/91.0	4.0	984	65	22	VSCS
26-11-2013	0000	12.5/90.5	4.0	982	70	24	VSCS
	0300	12.5/90.0	4.0	982	70	24	VSCS
	0600	12.5/89.5	4.0	982	70	24	VSCS
	0900	13.0/89.0	4.0	982	70	24	VSCS
	1200	13.0/88.5	4.0	982	70	24	VSCS
	1500	13.0/88.5	4.0	982	70	24	VSCS
	1800	13.1/88.0	4.0	980	75	26	VSCS
	2100	13.2/87.5	4.0	980	75	26	VSCS
27-11-2013	0000	13.5/87.0	4.0	980	75	26	VSCS
	0300	13.5/86.5	4.0	980	75	26	VSCS
	0600	14.0/86.0	4.0	982	70	24	VSCS
	0900	14.0/85.5	4.0	984	65	22	VSCS
	1200	14.5/85.0	3.5	988	55	17	SCS
	1500	14.5/84.5	3.5	988	55	17	SCS
	1800	15.0/84.0	3.0	996	45	10	CS
	2100	15.0/83.5	2.5	998	40	8	CS
28-11-2013	0000	15.5/82.0	2.0	1000	30	5	DD
	0300	15.7/81.7	2.0	1000	30	5	DD

	0600	15.7/81.3	2.0	1000	30	5	DD
	The system crossed Andhra Pradesh close to south of Machilipatnam near 15.9^{0}N/81.1^0 E around 0830 UTC						
	0900	15.9/81.0	-	1002	25	4	D
	1200	16.0/80.8	-	1004	20	3	D
	1800	Weakened into a well marked low pressure area over coastal Andhra Pradesh and adjoining Telengana.					

Table 2.9.2. Position of Very Severe Cyclonic Storm 'LEHAR' based on DWR Visakhapatnam

Date	Time(UTC)	Intensity	Lat ^{O}N	Long^{O}E
23.11.13	1200	D	08.5	96.5
	1800	DD	09.0	96.0
	2100	DD	---	---
24.11.13	0000	CS	10.0	95.0
	0300	CS	10.0	95.0
	0600	CS	10.5	94.5
	0900	CS	10.5	94.0
	1200	CS	11.0	93.5
	1800	CS	11.5	93.0
	2100	CS	11.5	92.5
25.11.13	0000	SCS	12.0	92.5
	0300	SCS	12.0	92.0
	0600	SCS	12.0	91.5
	0900	SCS	12.0	91.5
	1200	SCS	12.5	91.0
	1500	SCS	12.5	91 .0
	1800	SCS	12.5	91.0
	2100	VSCS	12.5	91.0.
26.11.13	0000	VSCS	12.5	90.5
	0300	VSCS	12.5	90.0
	0600	VSCS	12.6	89.5
	0900	VSCS	13.0	89.0
	1200	VSCS	13.0	88.5
	1500	VSCS	13.0	88.5
	1800	VSCS	13.0	88.0
	2100	VSCS	13.2	87.5
27.11.13	0000	VSCS	13.5	87.0
	0300	VSCS	13.5	86.5
	0600	VSCS	14.0	86.0
	0900	VSCS	14.0	85.5
	1200	SCS	14.5	85.0
	1500	SCS	14.5	84.5

	1800	CS	15.0	84.0
	2100	CS	15.0	83.5
28.11.13	0000	DD	15.5	82.0
	0300	DD	15.7	81.7
	0600	DD	15.7	81.3
	0900	D	15.9	81.1

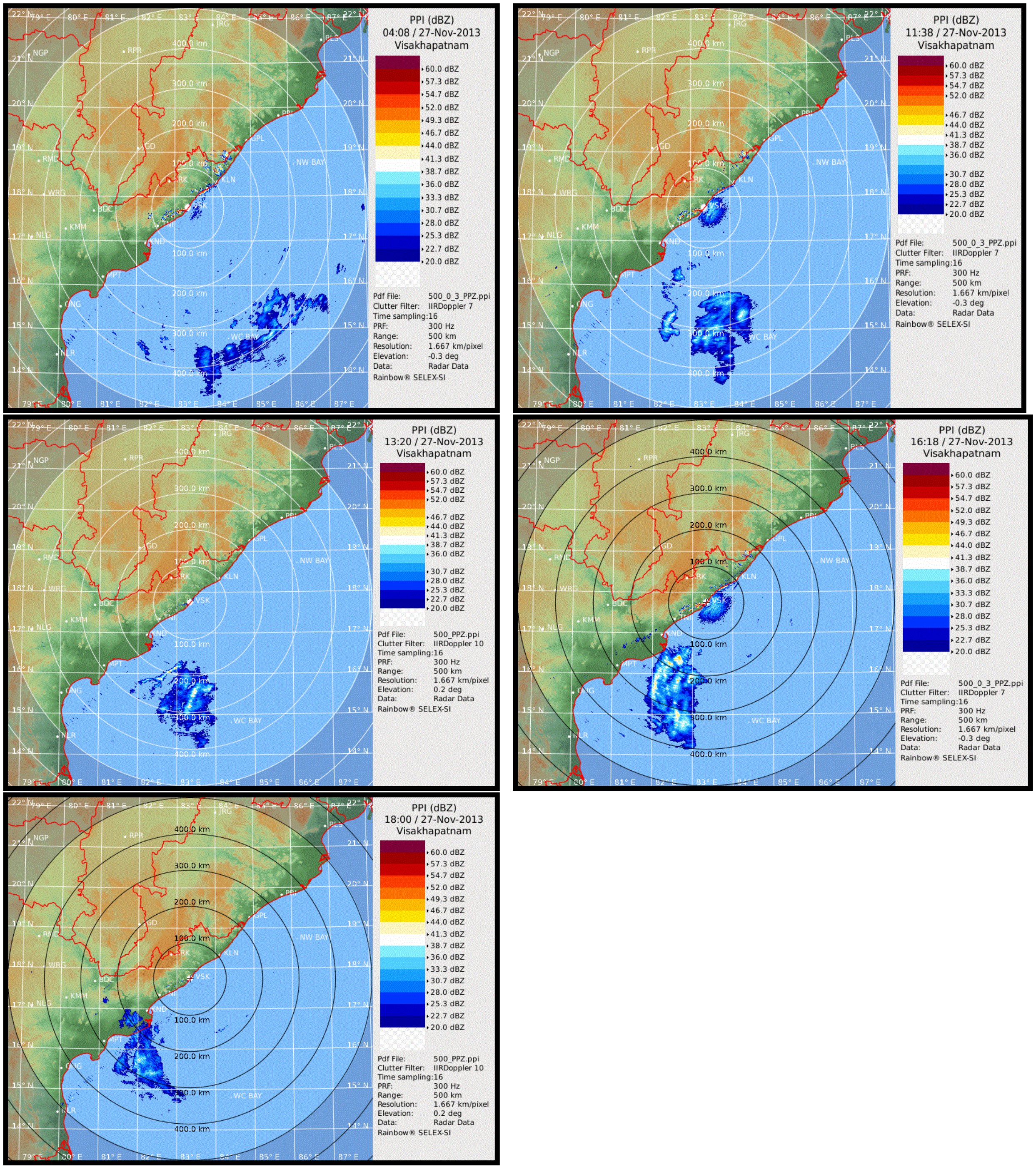


Fig.2.9.1(a) Visakhapatnam RADAR imageries based on 0400,1140,1320,1620 & 1800 UTC of 27th November, 2013

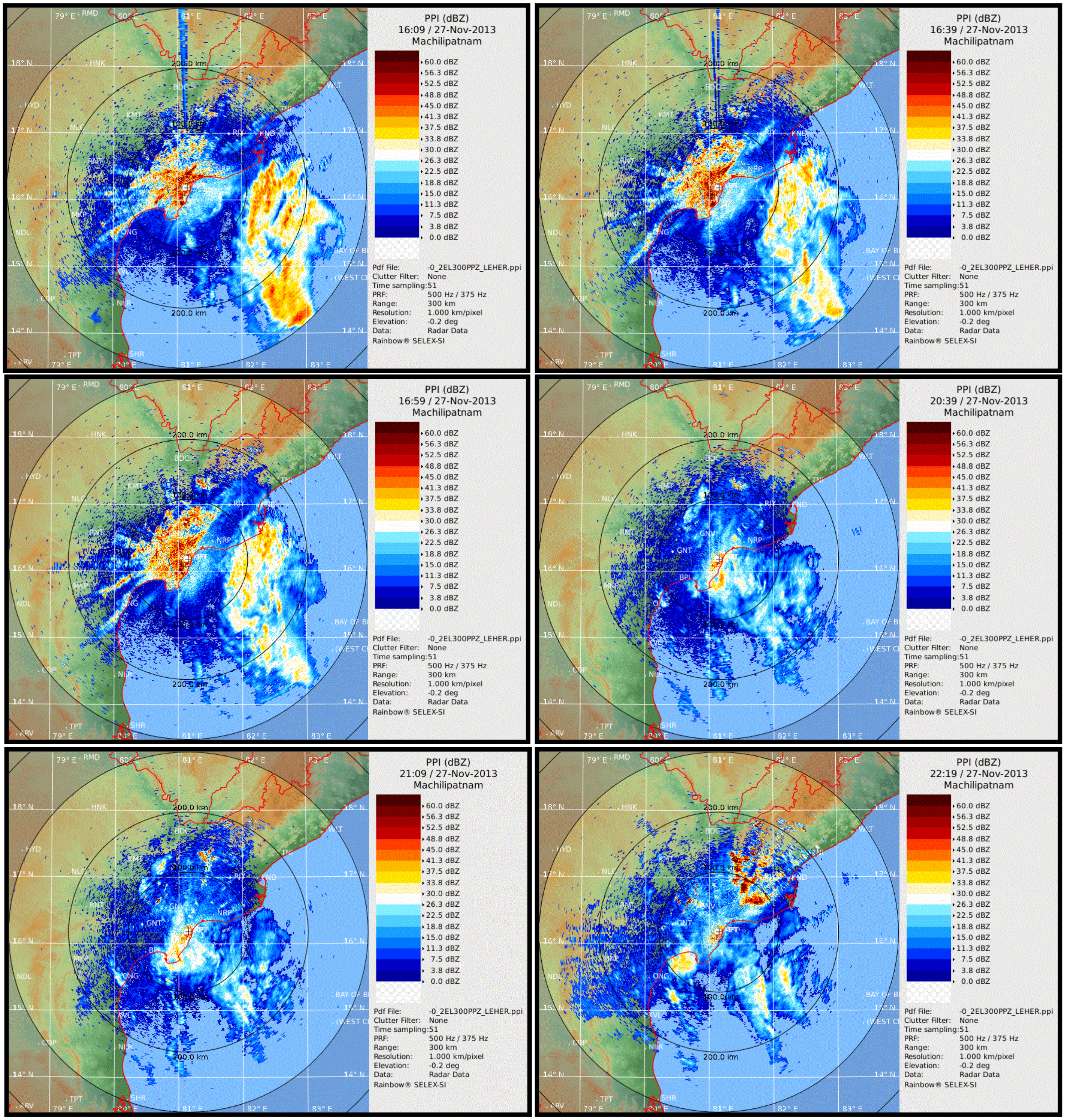


Fig. 2.9.1(b) Machilipatnam RADAR imageries on 27th November, 2013

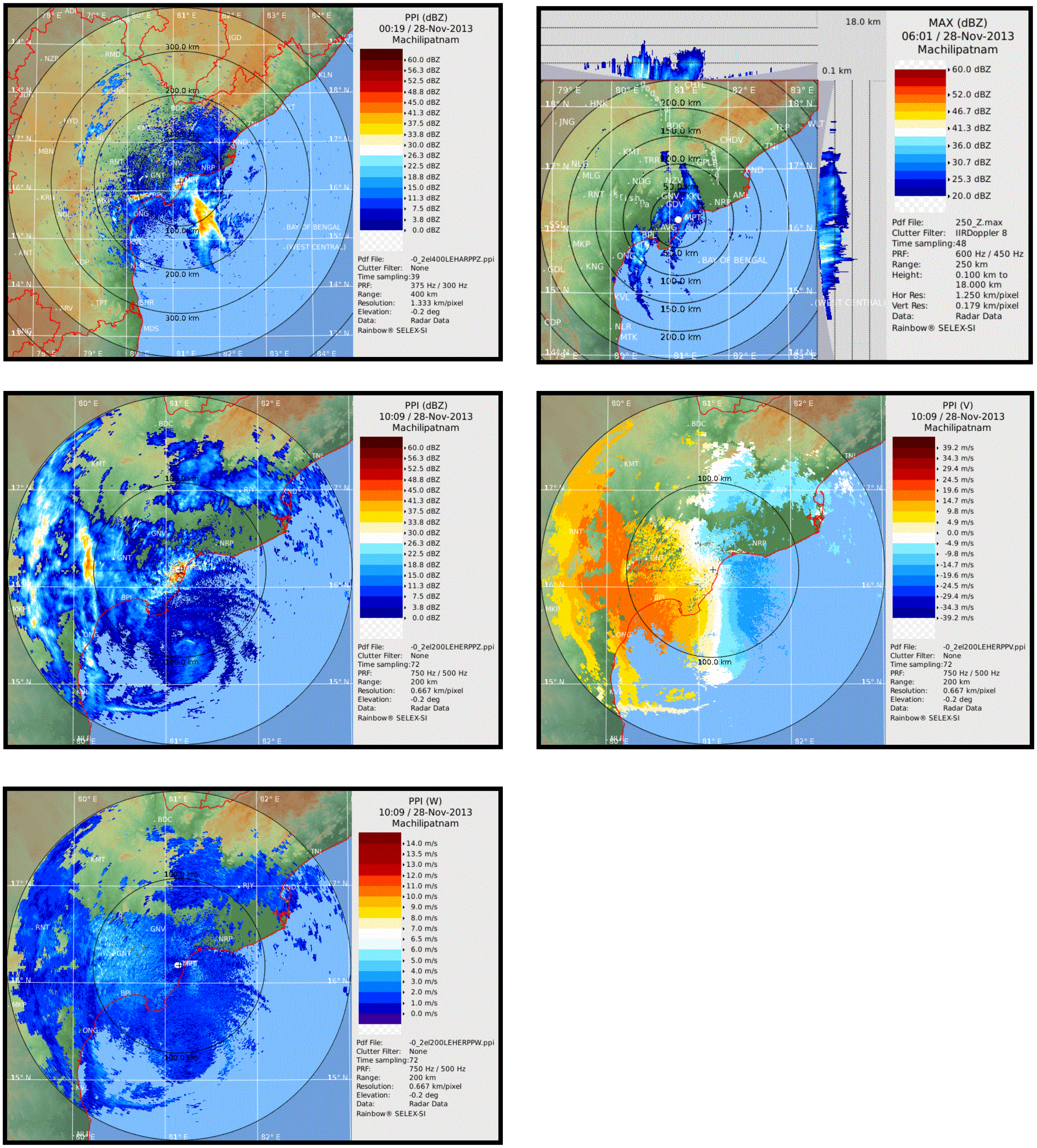


Fig.2.9.1(c) Machilipatnam RADAR imageries on 28th November, 2013

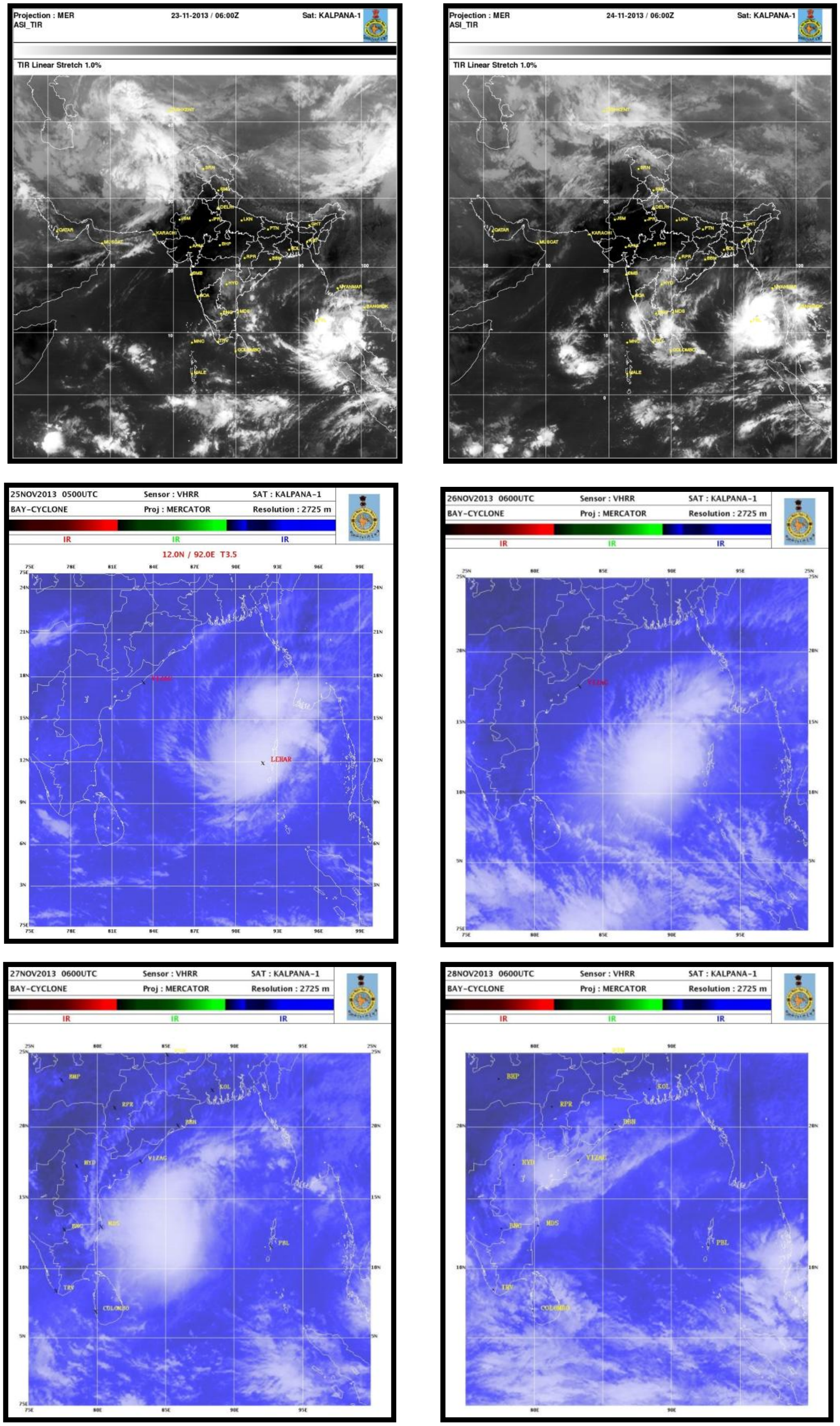


Fig. 2.9.2 Satellite imageries based on 0600 UTC of 23rd, 24th, 26th, 27th and 28th November, 2013

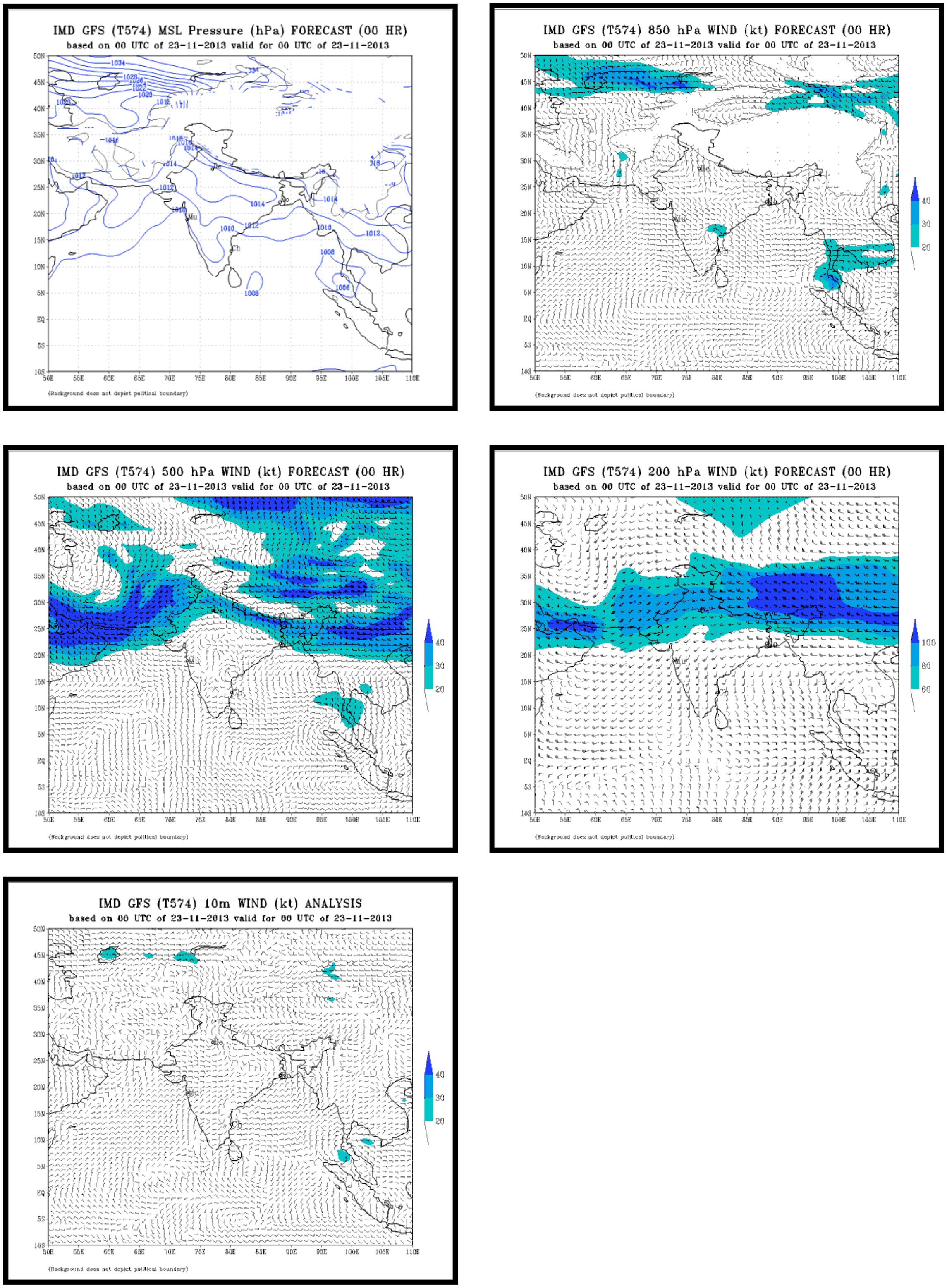


Fig.2.9.3 (a) IMD GFS MSLP and winds at 850, 500 & 200 hpa levels analysis and 10meter wind based on 00 UTC of 23rd November, 2013.

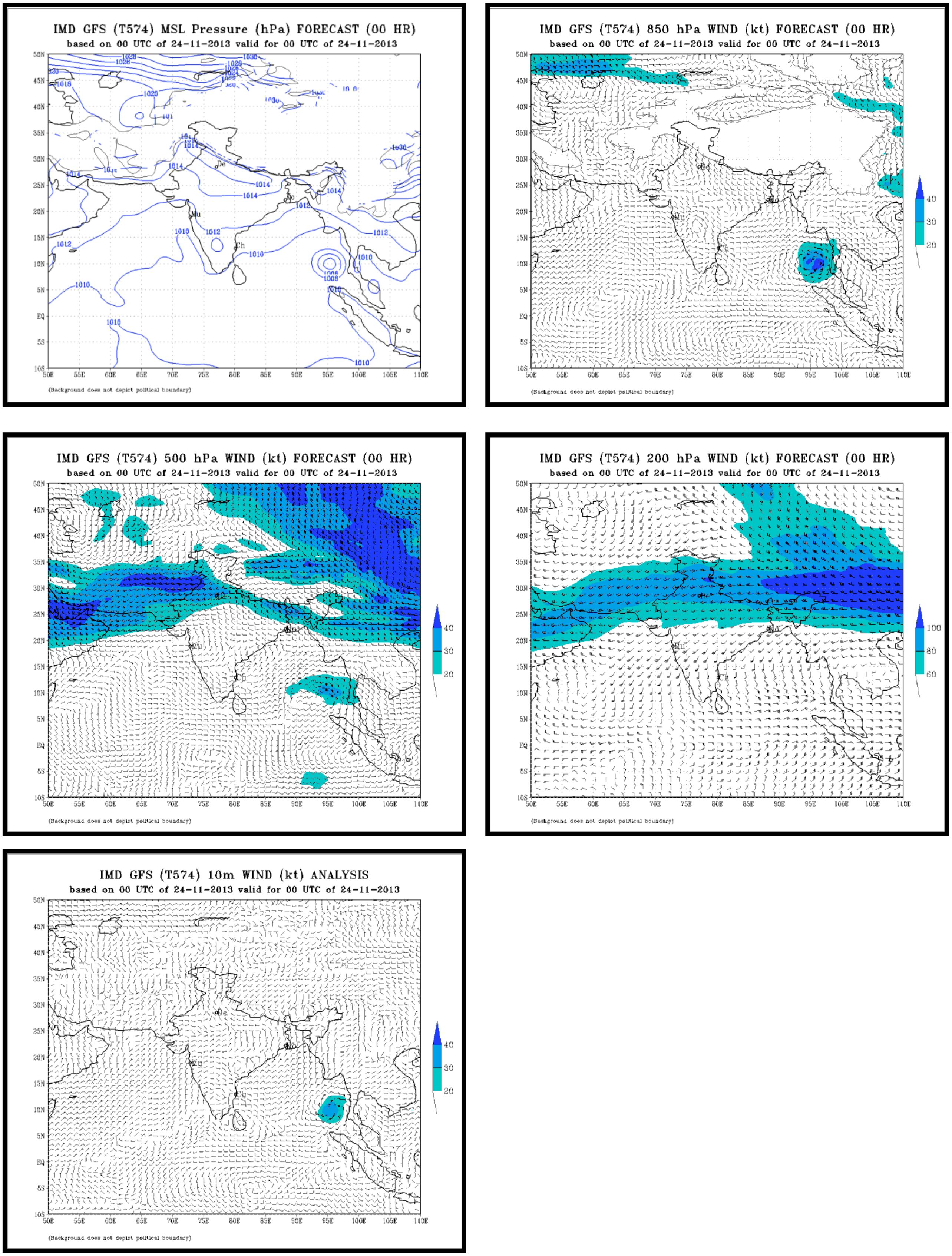


Fig.2.9.3(b) IMD GFS MSLP and winds at 850, 500 & 200 hpa levels analysis and 10meter wind based on 00 UTC of 24th November, 2013.

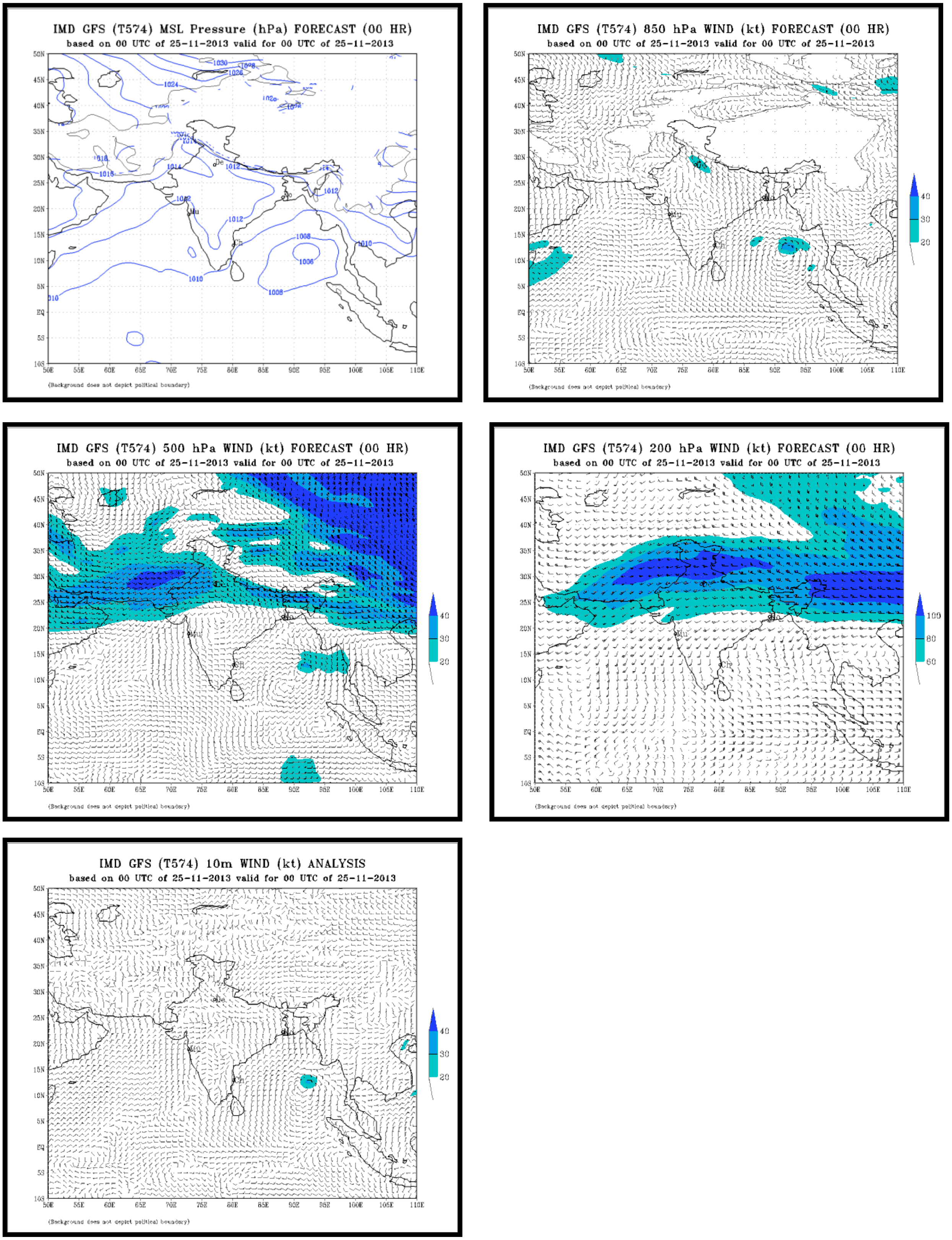


Fig.2.9.3(c) IMD GFS MSLP and winds at 850, 500 & 200 hpa levels analysis and 10meter wind based on 00 UTC of 25th November, 2013.

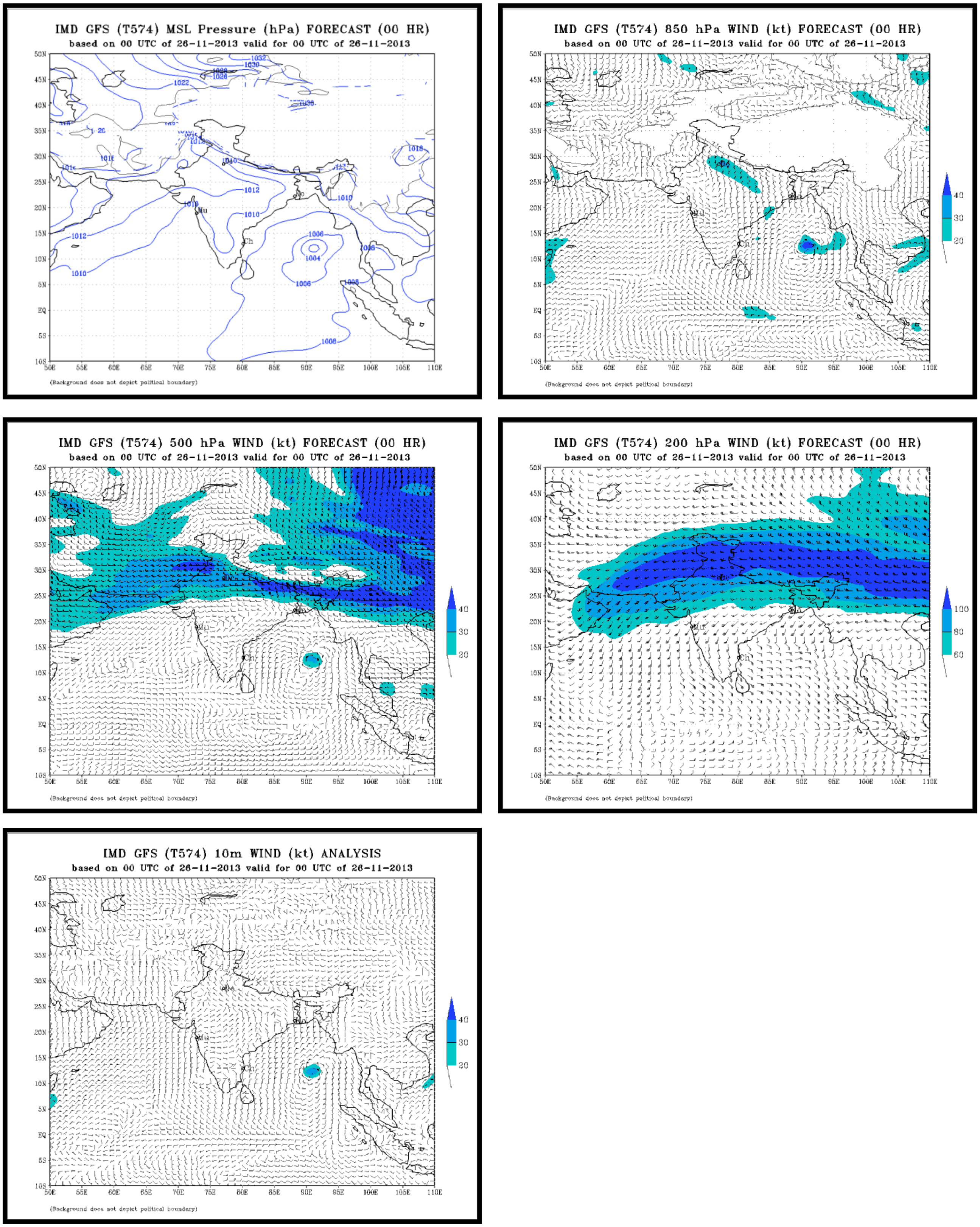


Fig.2.9.3(d) IMD GFS MSLP and winds at 850, 500 & 200 hpa levels analysis and 10meter wind based on 00 UTC of 26th November, 2013.

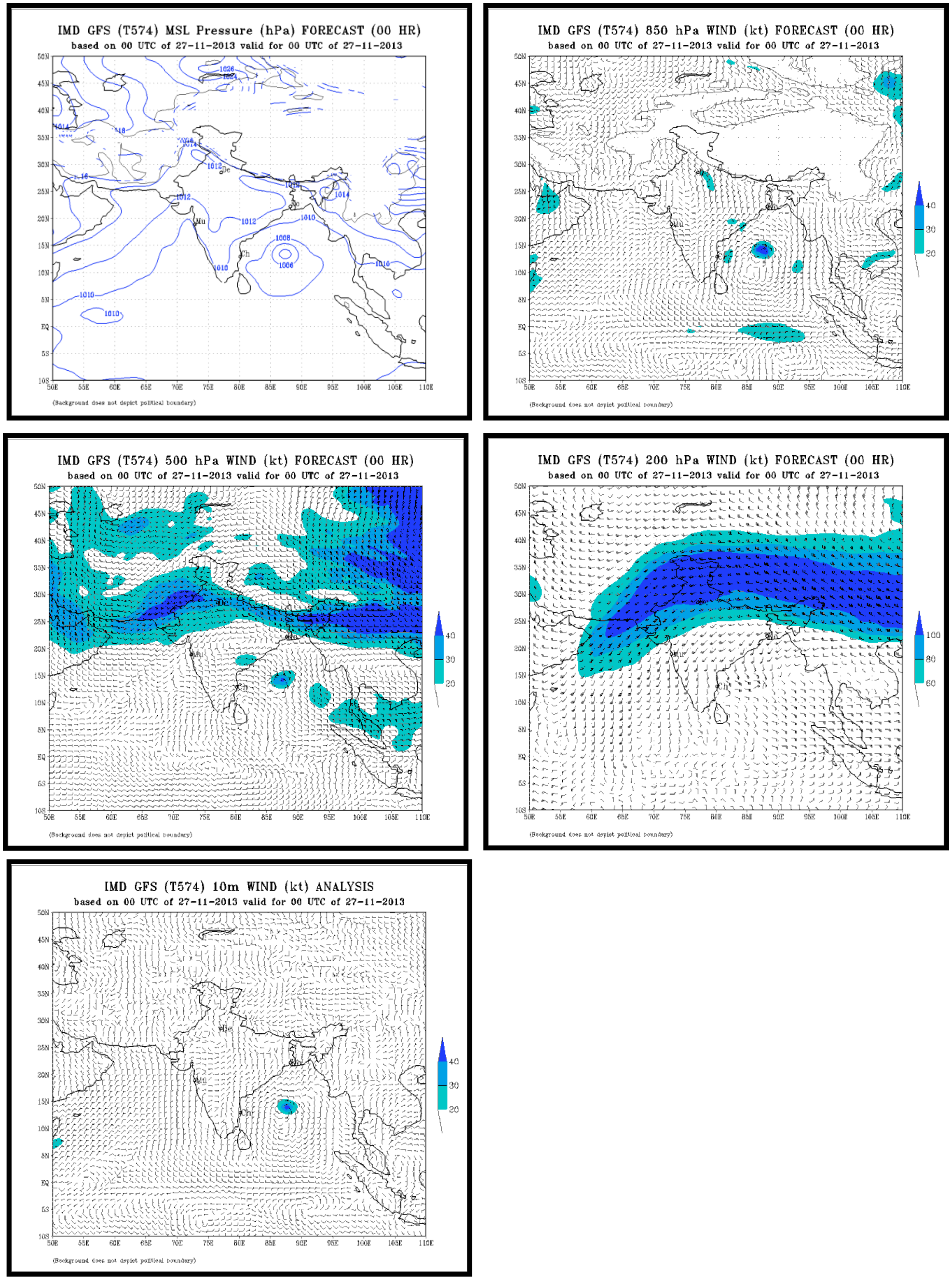


Fig.2.9.3(e) IMD GFS MSLP and winds at 850, 500 & 200 hpa levels analysis and 10meter wind based on 00 UTC of 27th November, 2013.

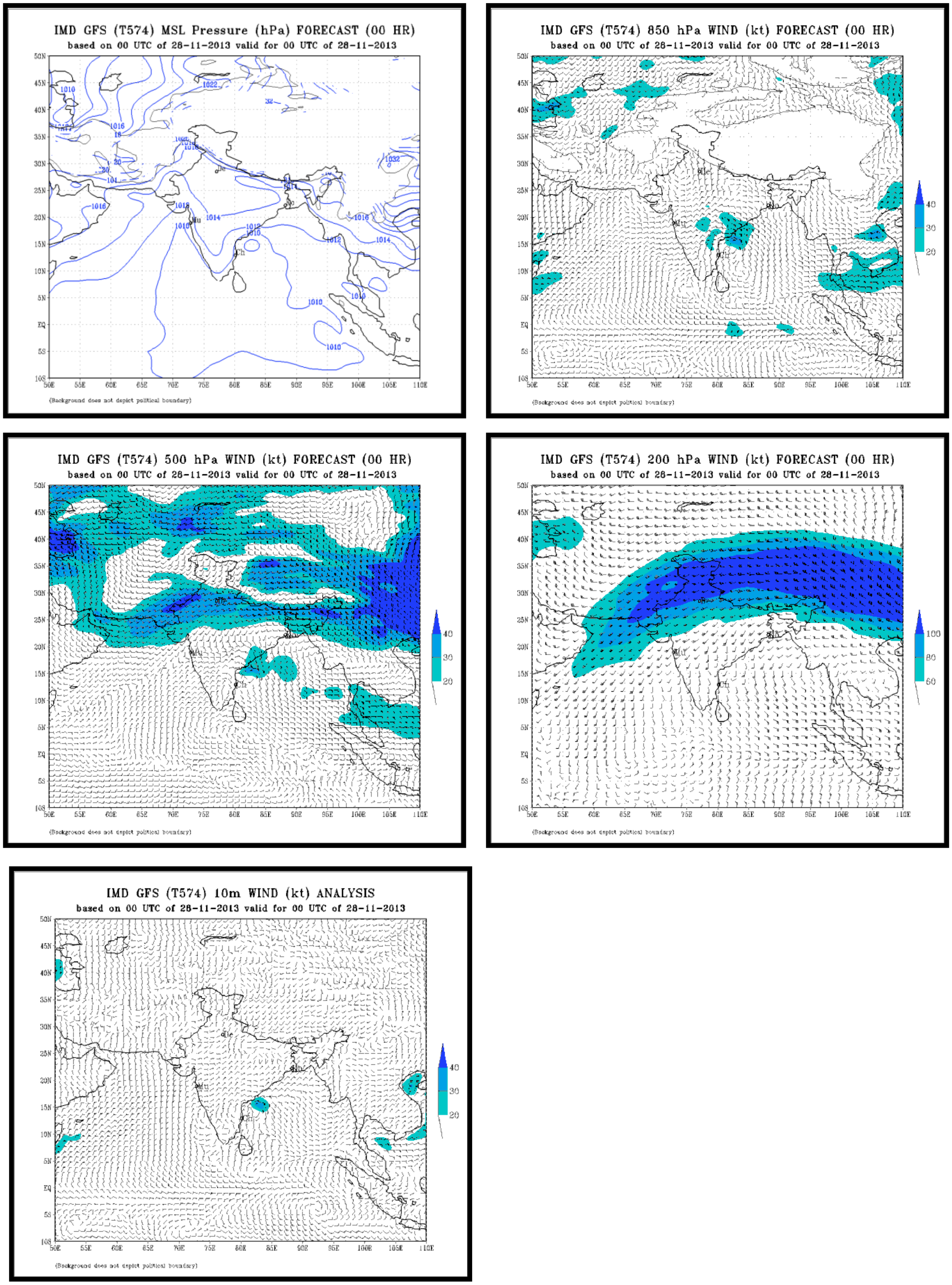


Fig.2.9.3(f) IMD GFS MSLP and winds at 850, 500 & 200 hpa levels analysis and 10meter wind based on 00 UTC of 28th November, 2013.

2.9.5 Realized Weather:

Chief amounts of 24 hrs. Rainfall (7 cm or more) ending at 0300 UTC from 23rd November to 29th November, 2013 are given below:

23 November 2013 - Nil

24 November 2013 – Nil

25 November 2013

Andaman & Nicobar Islands: Maya Bandar-24, Port Blair-21, Long Island-11,

26 and 27 November 2013 – Nil

28 November 2013

Kerala: Angadippuram-8,

29 November 2013

Coastal Andhra Pradesh: Macharla-7

2.9.6 Damage: No damage has been reported due to this system

2.10 Very Severe Cyclonic Storm ‘Madi’ (06-13 December 2013)

2.10.1 Introduction :

A cyclonic storm ‘Madi’ formed over southwest Bay of Bengal on 7th December. It initially moved northwards and intensified upto very severe cyclonic storm. After crossing Lat. 15^{0} N it wekened due to unfavourable conditions and recurved southwestwards. It crossed Tamil Nadu coast near Vedaranyam around 1330 UTC of 12th Dec as a depression, emerged into Palk strait around 1500 UTC and again crossed Tamil Nadu coast near Tondi around 1700 UTC of 12th December 2013. It then emerged into southeast Arabian Sea as a well marked low pressure area in the early morning of 13th Oct. 2013. Salient features of the system are given below:

(i) It has a unique track with near northerly movement till 15.7^{0}N and then recurving southwestwards to Tamil Nadu coast.

(ii) It moved very slowly during its northward journey and speed peaked up gradually after the recurvature to southwest.

2.10.2 Monitoring and Prediction

The very severe cyclonic storm, MADI was monitored mainly with satellite supported by meteorological buoys, coastal and Island observations. It was monitored by DWR, Chennai, Visakhapatnam and Machilipatnam. The half hourly INSAT/ Kalpana imageries, hourly coastal observations and every 10 minutes DWR imageries and products were used for monitoring of cyclone.

Various NWP models and dynamical-statistical models including IMD’s global and meso-scale models were utilized to predict the track and intensity of the storm. The Tropical Cyclone Module in the digitized forecasting system of IMD was utilized for analysis and comparison of various NWP models and decision making process.

2.10.3 Genesis

A low pressure area from south China Sea moved across Malay peninsula and emerged into south Andaman Sea on 01st December, morning. Moving westwards it lay over southeast Bay of Bengal on 02nd December. Continuing its westwards movement, it lay over southwest Bay of Bengal off Sri Lanka coast on 03rd December, 2013. It persisted over the same region and became well marked on 04th December. It further concentrated into a depression in the morning of 06th December over southwest Bay of Bengal and lay centered near latitude 10.0°N and longitude 84.0°E, about 350 km northeast of Tricomalee (Sri Lanka). The genesis was declared using the sea surface wind observations based on ASCAT and Ocean Sat-II alongwith satellite imageries. Also the ship and buoy observations near the centre supported the genesis. A ship near latitude 11.9°N and Longitude 85.4°E reported wind speed of 080/23 knots. The sea surface temperature during genesis was about 26-28°C and ocean thermal energy was about 60-80 KJ/cm$^{2.}$ The vertical wind shear was moderate (10-20 knots). The lower level convergence and relative vorticity increased from 05th to 06th December, 2013, along with increase in upper tropospheric divergence. The Madden Julian Oscillation (MJO) index lay over phase-3 i.e. equatorial Indian Ocean adjoining Bay of Bengal with amplitude less than1. Past studies indicate that phase 3 is favourable for genesis of the system.

2.10.4 Intensification and movement

As the system lay over the warmer sea surface alongwith higher ocean thermal energy and low to moderate vertical wind shear, it gradually intensified into a deep depression at 1800 UTC of 06th December while remaining practically stationary over the region. The depression remained practically stationary, as it lay close to the upper troposphere ridge which ran along 10°N. It led to very slow northward movement afterwards. The deep depression further intensified into a cyclonic storm 'MADI' with centre near latitude 10.5°N and longitude 84.0°E at 0000 UTC of 07th December, 2013. It intensified into a severe cyclonic storm over the same region at 0900 UTC of 07th December, 2013. As it lay slightly to the north of the ridge, the severe cyclonic storm then moved slightly north-northeastwards and intensified into a very severe cyclonic storm at 0600 UTC of 08th December, 2013 near latitude 12.3°N and longitude 84.7°E.

As the very severe cyclonic storm moved to the north of 13.0°N i.e. to west central Bay of Bengal, it experienced colder sea surface temperature and low Ocean thermal energy (< 50 KJ/cm^2). Also the vertical wind shear of horizontal wind gradually increased and became high (20-30 knots). As a result, the very severe cyclonic storm weakened into a severe cyclonic storm at 1200 UTC of 09th December and lay centered near latitude14.6°N and longitude 84.7°E. It continued to move slowly north-northeastwards till 0900 UTC of 10th December as a severe cyclonic storm upto latitude 15.7°N and longitude 85.3°E under the influence of the upper tropospheric steering ridge which moved northward alongwith northward movement of system. However, due to gradual weakening of system, the steering level changed from upper troposphere to lower and middle troposphere. The influence of the upper tropospheric anticyclonic circulation to the east of system centre decreased and that of lower and middle level anticyclonic circulation lying to the west of the system centre (over central India) increased. As a result, the severe cyclonic storm re-curved westwards initially and then southwestwards commencing from 0900 UTC of 10th December.

At the same time, the animation of Total Precipitated Water (TPW) imageries indicated that the dry and cold air penetrated into the southwestern periphery of the cyclone. It gradually penetrated further towards the centre of the cyclone from the southern side. As a result, it isolated the core of the cyclone from the warm and moist air from the southeast sector. Hence due to combined impact of colder sea surface temperature, low Ocean thermal energy, high vertical wind shear and incursion of cold and dry air into the core of the cyclone, it gradually weakened into a cyclonic storm near latitude 14.6°N and longitude 84.6°E at 2100 UTC of 10th December 2013, further into a deep depression near latitude14.0°N and longitude 83.8°E at 0300 UTC of 11th December and into a depression near latitude 12.9°N and longitude 82.7°E at 1800 UTC of 11th December.

The depression crossed Tamil Nadu coast close to Vedaranyam around 1330 UTC of 12th December. It then emerged into Palk strait at 1500 UTC, moved west-southwestwards and again crossed Tamil Nadu coast near Tondi around 1700 UTC of 12th December. It continued to move west-southwestwards across south peninsula and weakened further into a well-marked low pressure area over southeast Arabian Sea and adjoining Kerala at 0000 UTC of 13th December, 2013. It may be mentioned that due to increased convection and organization as per Dvorak estimate the system showed temporary increase in intensity upto very severe cyclonic storm stage during the weakening phase on 10th December (0300-0900 UTC). The best track position and other parameters of the very severe cyclonic Storm 'MADI' over the Bay of Bengal is given in Table 2.10.1 and the track is given in Fig. 2.1. The DWR imageries are shown in Fig.2.10.1. The satellite imageries are shown in fig. 2.10.2. The IMD GFS model analyses are shown in Fig. 2.10.3.

Table 2.10.1 Best track positions and other parameters of the Very Cyclonic Storm 'MADI' over the Bay of Bengal during 06-13 Dec 2013

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO	Estimated Central Pressure(hPa)	Estimated Maximum sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
06-12-2013	0300	10.0/84.0	1.5	1004	25	3	D
	0600	10.0/84.0	1.5	1004	25	3	D
	1200	10.2/84.0	1.5	1004	25	3	D
	1800	10.4/84.0	2.0	1002	30	5	DD
07-12-2013	0000	10.5/84.1	2.5	998	35	7	CS
	0300	10.5/84.1	2.5	998	35	7	CS
	0600	10.7/84.2	3.0	996	45	10	CS
	0900	10.8/84.3	3.5	992	55	14	SCS
	1200	11.0/84.4	3.5	992	55	14	SCS
	1500	11.0/84.5	3.5	992	55	14	SCS
	1800	11.2/84.5	3.5	990	55	16	SCS
	2100	11.5/84.6	3.5	990	55	16	SCS
08-12-2013	0000	11.8/84.6	3.5	988	60	18	SCS
	0300	12.0/84.6	3.5	988	60	18	SCS
	0600	12.3/84.7	4.0	986	65	20	VSCS
	0900	12.6/84.7	4.0	986	65	20	VSCS
	1200	13.0/84.7	4.0	986	65	20	VSCS
	1500	13.2/84.7	4.0	986	65	20	VSCS
	1800	13.4/84.7	4.0	986	65	20	VSCS
	2100	13.6/84.7	4.0	986	65	20	VSCS
09-12-2013	0000	13.8/84.7	4.0	986	65	20	VSCS
	0300	14.0/84.7	4.0	986	65	20	VSCS
	0600	14.3/84.7	4.0	986	65	20	VSCS
	0900	14.4/84.7	4.0	986	65	20	VSCS
	1200	14.6/84.7	3.5	988	60	18	SCS
	1500	14.7/84.7	3.5	988	60	18	SCS
	1800	14.8/84.8	3.5	988	60	18	SCS
	2100	14.8/84.8	3.5	988	60	16	SCS
10-12-2013	0000	15.0/85.0	3.5	988	60	16	SCS
	0300	15.3/85.3	4.0	986	65	20	VSCS
	0600	15.4/85.3	4.0	986	65	20	VSCS
	0900	15.7/85.3	4.0	986	65	20	VSCS
	1200	15.4/85.0	3.5	990	55	14	SCS

	1500	15.1/84.8	3.5	990	55	14	SCS
	1800	14.9/84.7	3.5	992	50	12	SCS
	2100	14.6/84.6	3.0	994	45	10	CS
11-12-2013	0000	14.3/84.2	3.0	996	40	8	CS
	0300	14.0/83.8	2.0	998	30	6	DD
	0600	13.7/83.5	2.0	998	30	6	DD
	0900	13.5/83.4	2.0	1000	30	5	DD
	1200	13.3/83.3	2.0	1000	30	5	DD
	1800	12.9/82.7	1.5	1000	25	4	D
12-12-2013	0000	12.5/82.0	1.5	1000	25	3	D
	0300	12.0/81.5	1.5	1000	25	3	D
	0600	11.5/81.2	1.5	1000	25	3	D
	0900	11.0/80.7	1.5	1000	25	3	D
	1200	10.5/80.0	1.5	1000	25	3	D
	The system crossed Tamil Nadu coast near Vedaranyam aound 1330 UTC and emerge into Palk straight and again crossed Tamil Nadu coast near Tondi around 1700 UTC						
	1800	10.0/78.8	-	1004	20	3	D
13-12-2013	0000	Weakened into a Well marked low pressure area over southeast Arabian Sea and adjoining Kerala.					

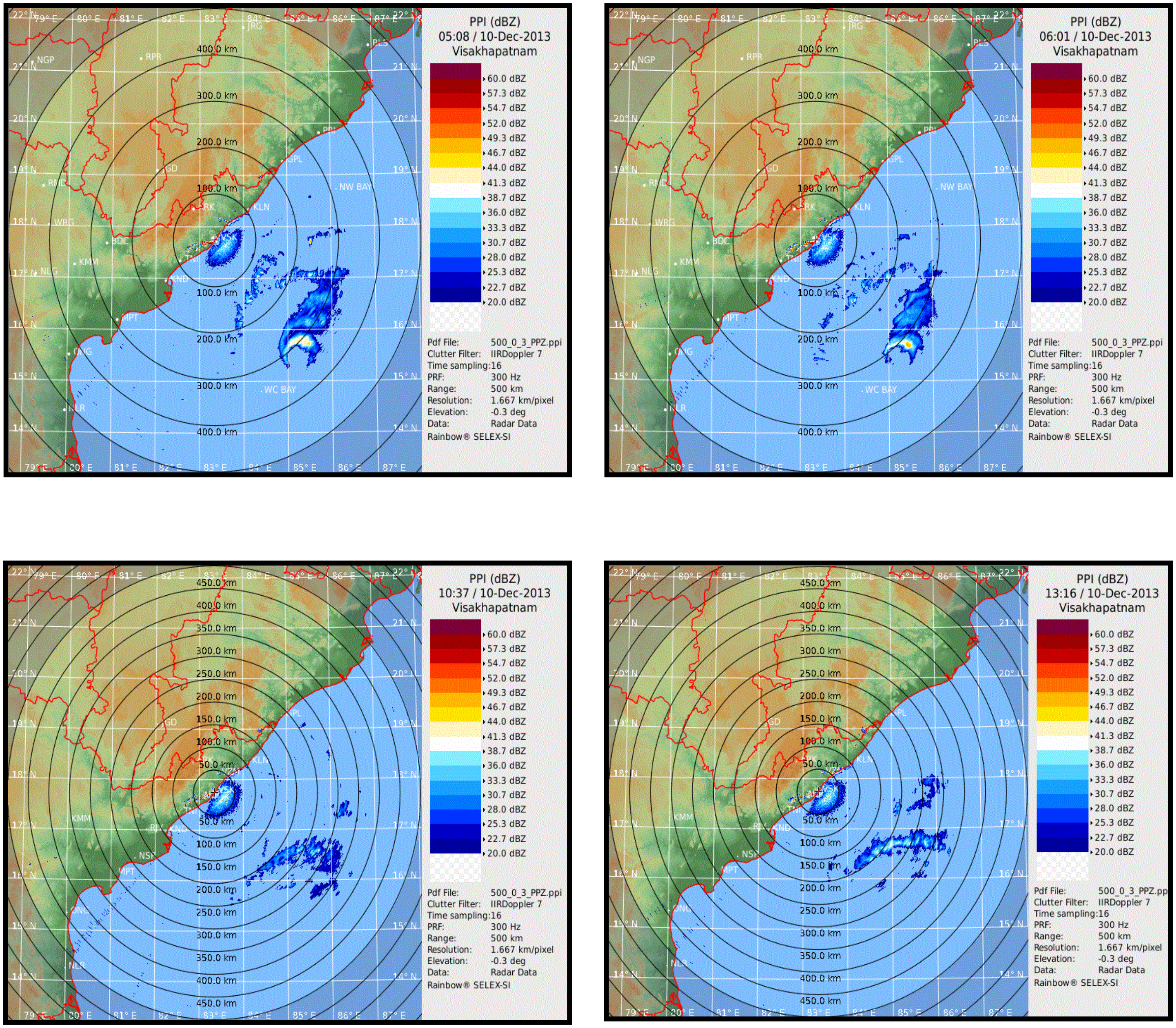


Fig. 2.10.1 Visakhapatnam RADAR imageries based on 0510, 0600, 1040 & 1320 UTC of 10th December, 2013

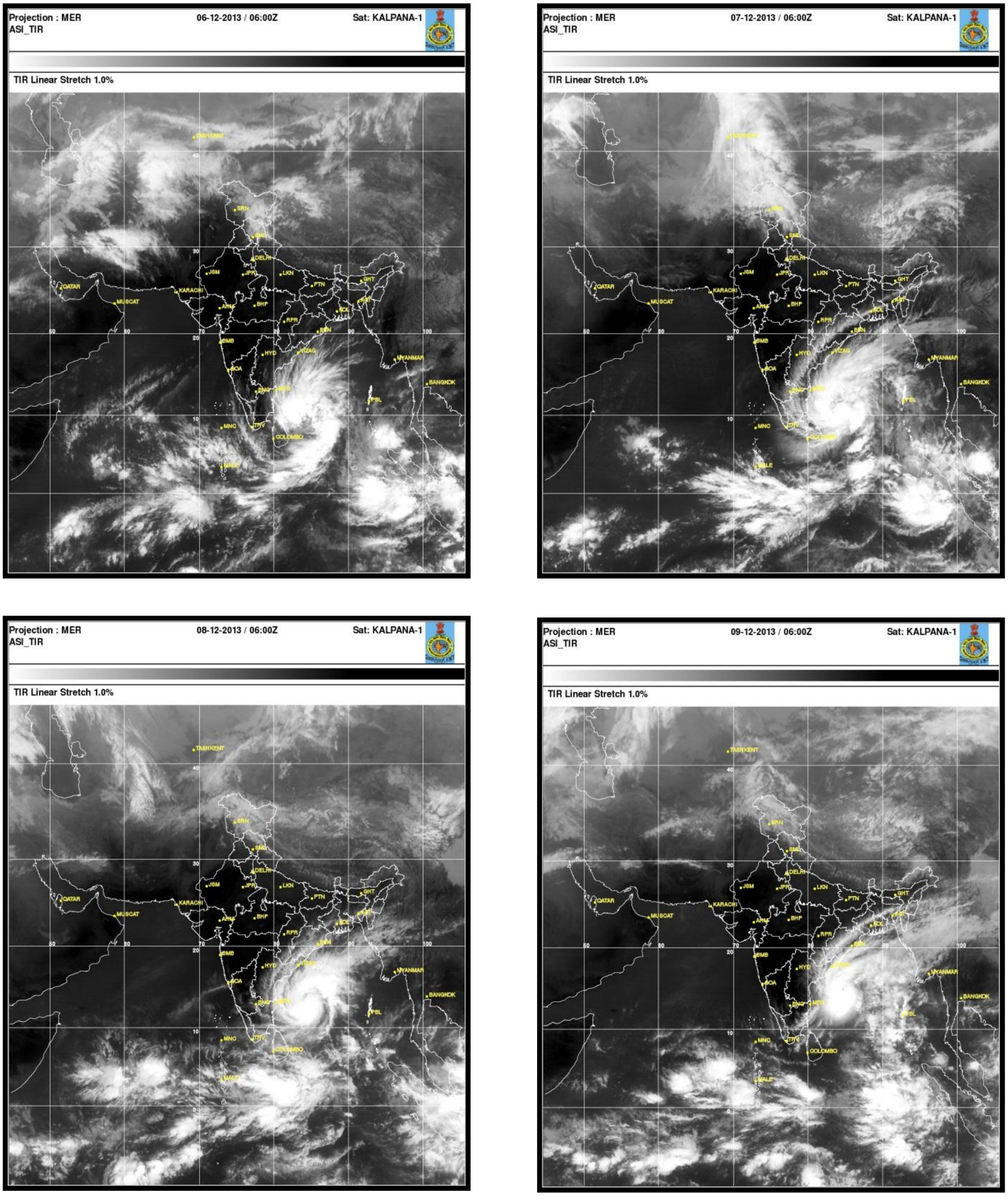


Fig. 2.10.2(a) Typical Kalpana-1 Satellite imageries of very severe cyclonic storm 'Madi' at 0600 UTC of 06th, 07th, 08th and 09th December 2013.

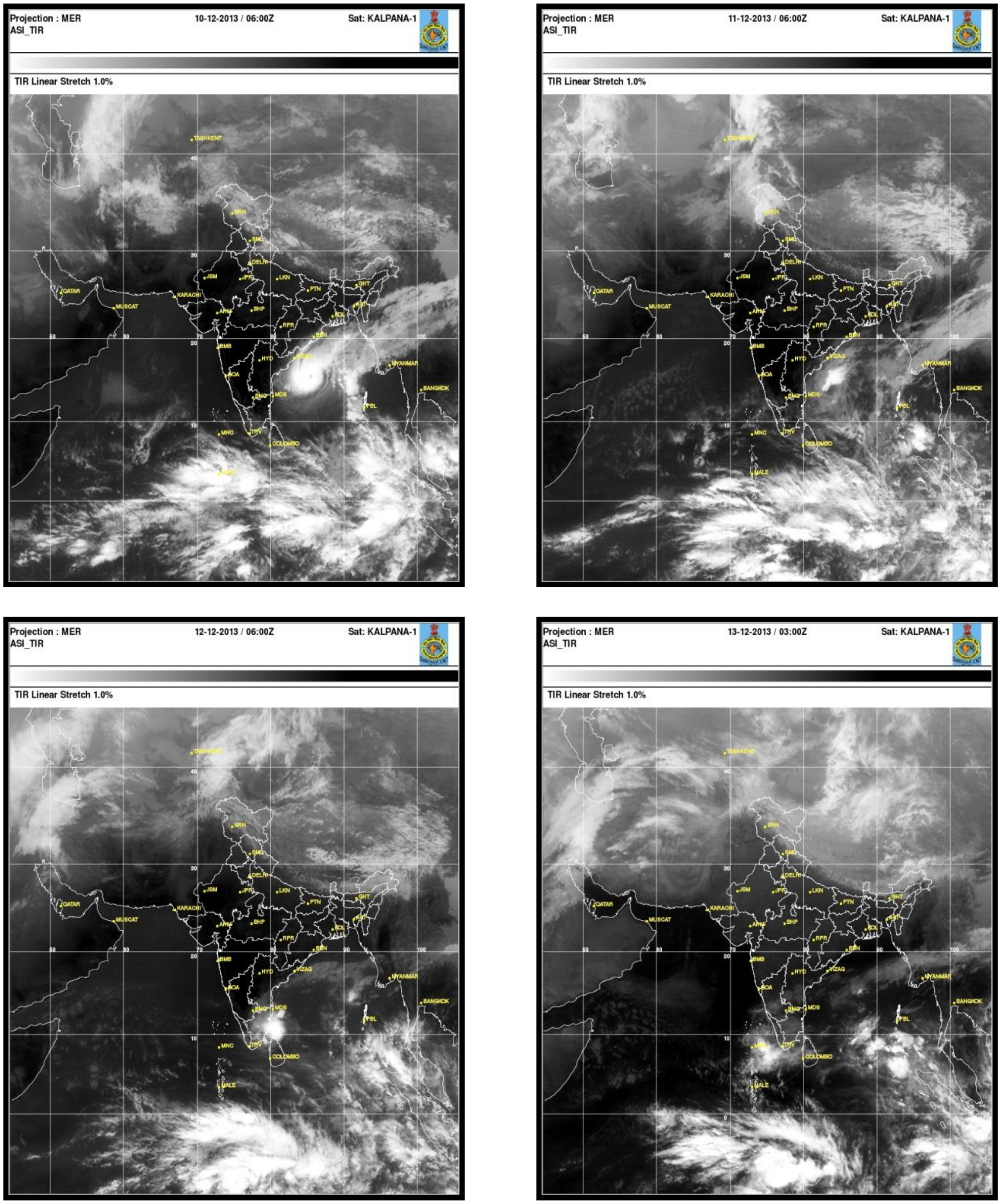


Fig.2.10.2(b) Typical Kalpana-1 Satellite imageries of very severe cyclonic storm 'Madi' at 0600 UTC of 10th, 11th, 12th and 0300 UTC of 13th December 2013.

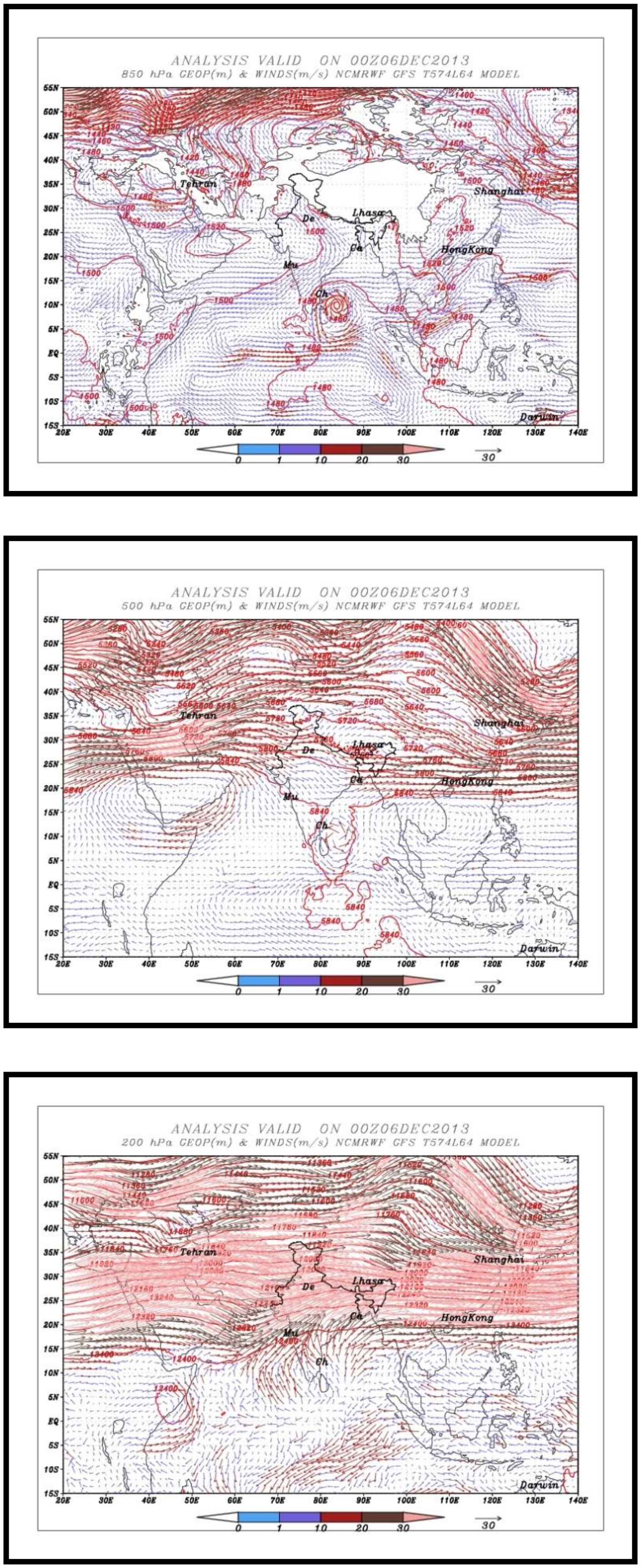


Fig. 2.10.3(a): NCMRWF GFS Analysis based on 00 UTC of 6th Dec. 2013 in association with VSCS MAADI

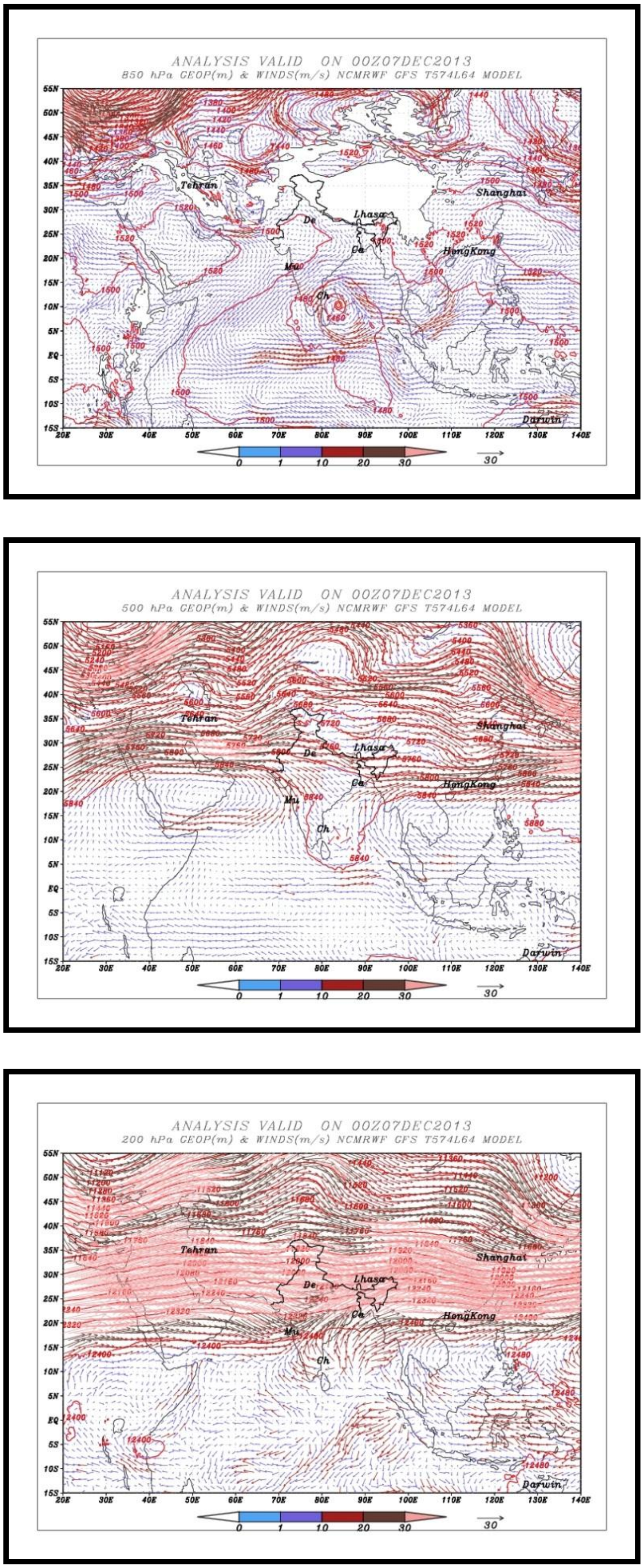


Fig 2.10.3(b) NCMRWF GFS Analysis based on 00 UTC of 7th Dec. 2013 in association with VSCS MAADI

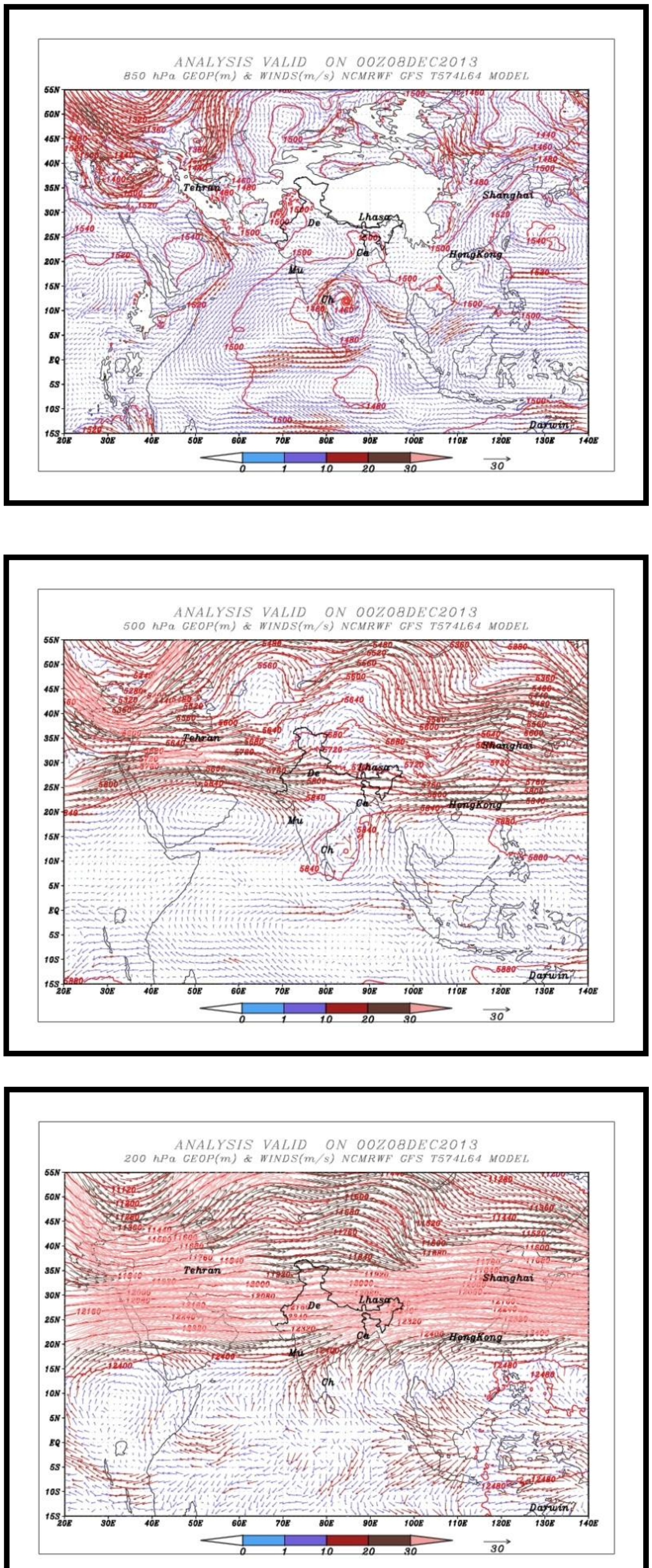
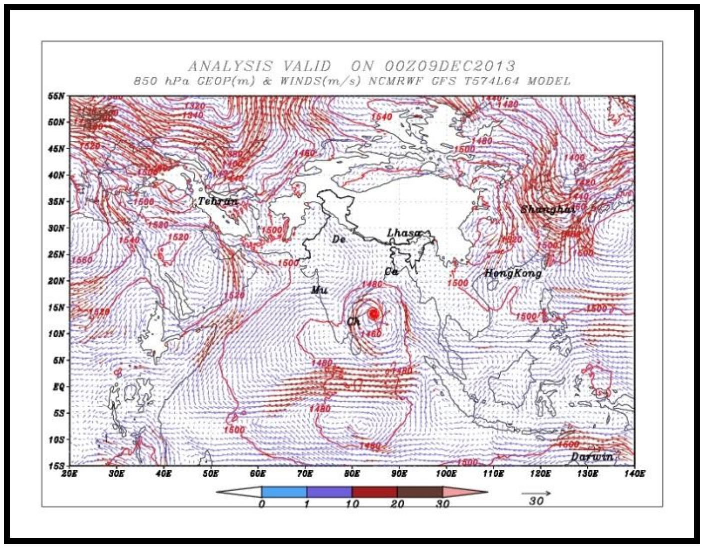
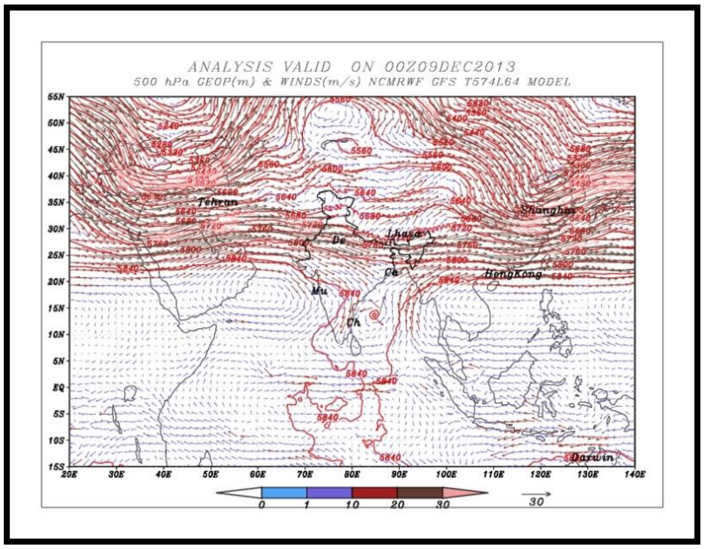


Fig 2.10.3(c) NCMRWF GFS Analysis based on 00 UTC of 8th Dec. 2013 in association with VSCS MAADI





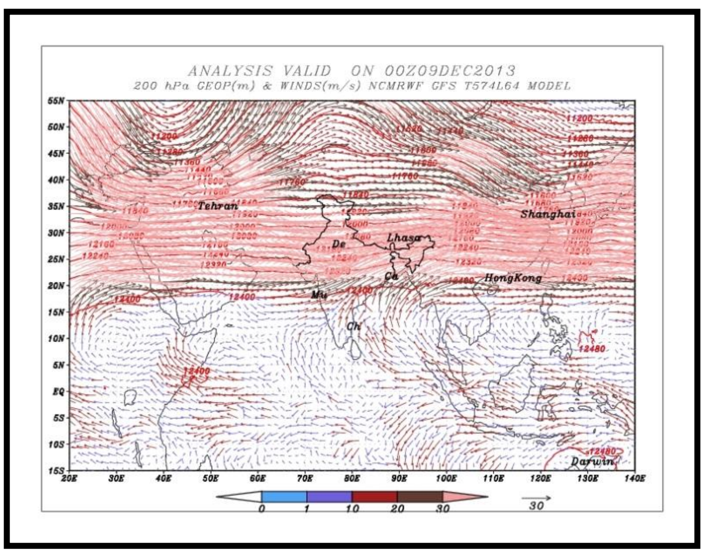


Fig 2.10.3(d) NCMRWF GFS Analysis based on 00 UTC of 9 Dec. 2013 in association with VSCS MAADI

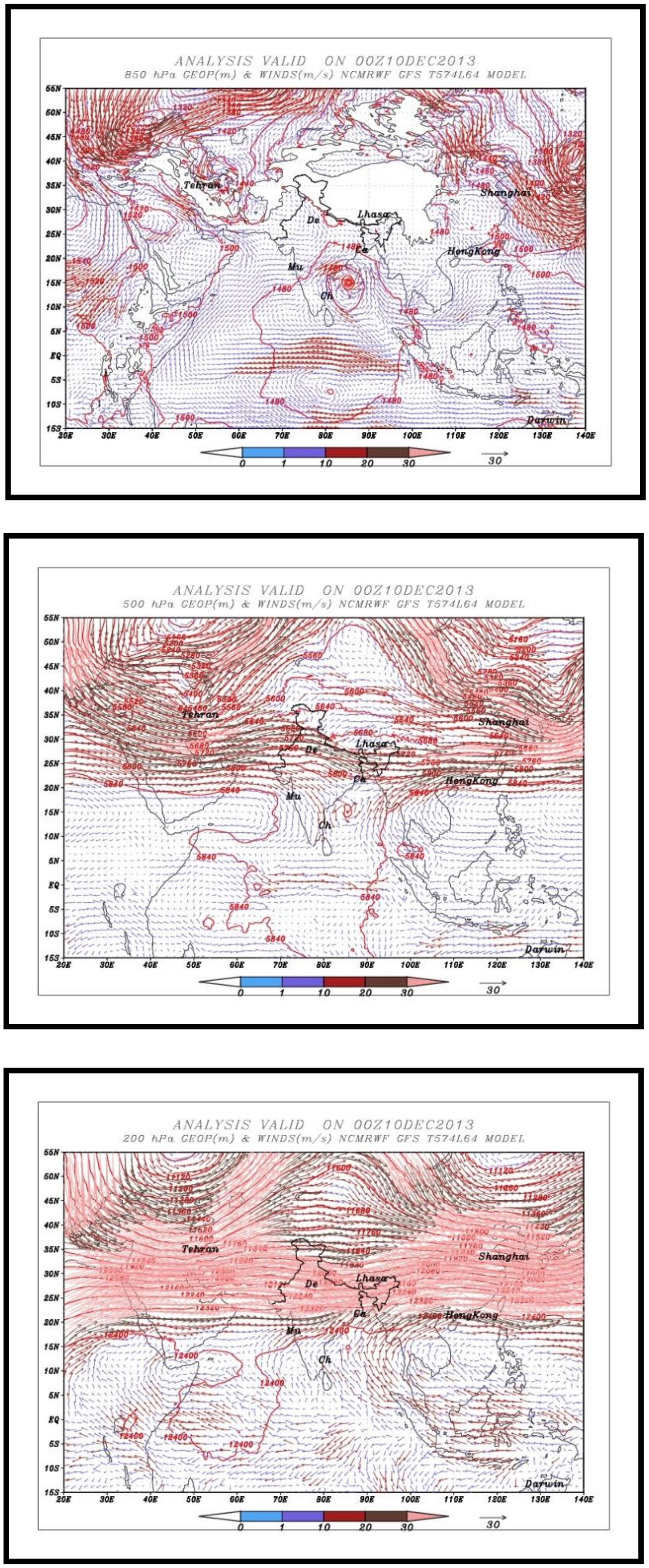


Fig 2.10.3(e) NCMRWF GFS Analysis based on 00 UTC of 10th Dec. 2013 in association with VSCS MAADI

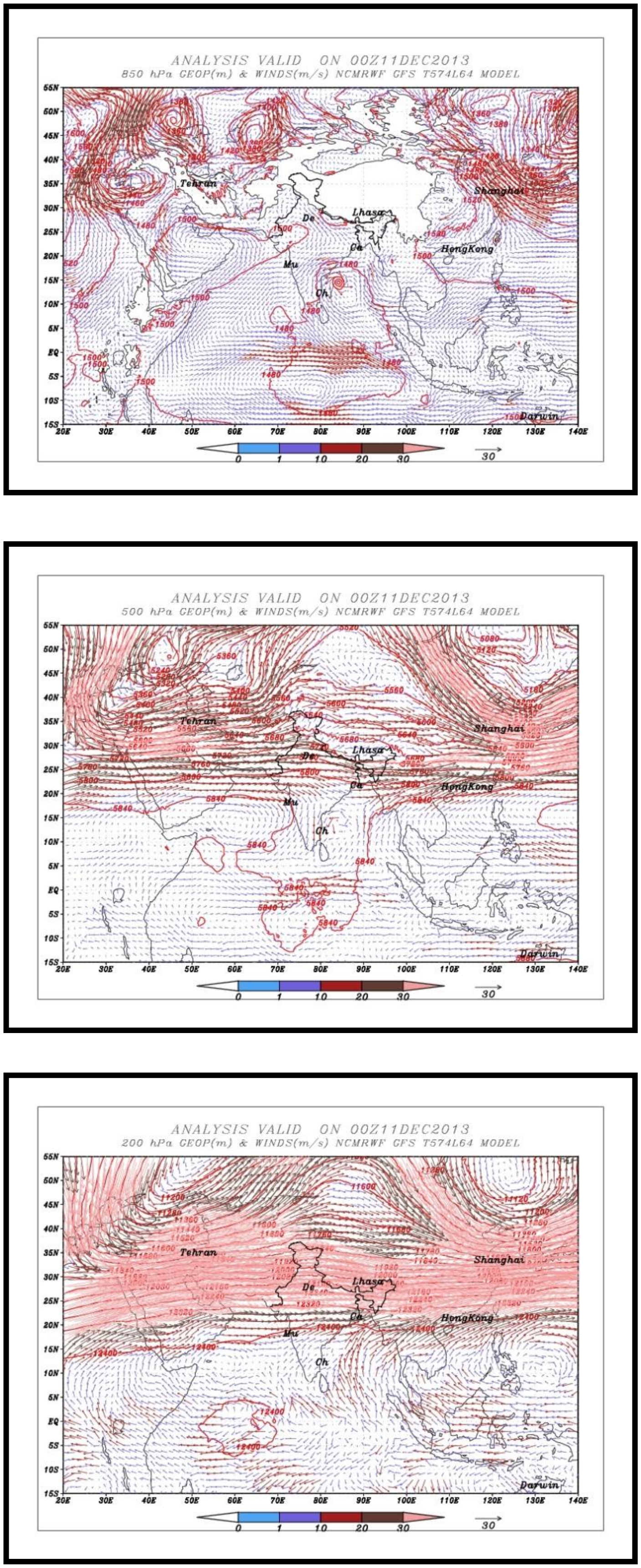


Fig 2.10.3(f): NCMRWF GFS Analysis based on 00 UTC of 11th Dec. 2013 in association with VSCS MAADI

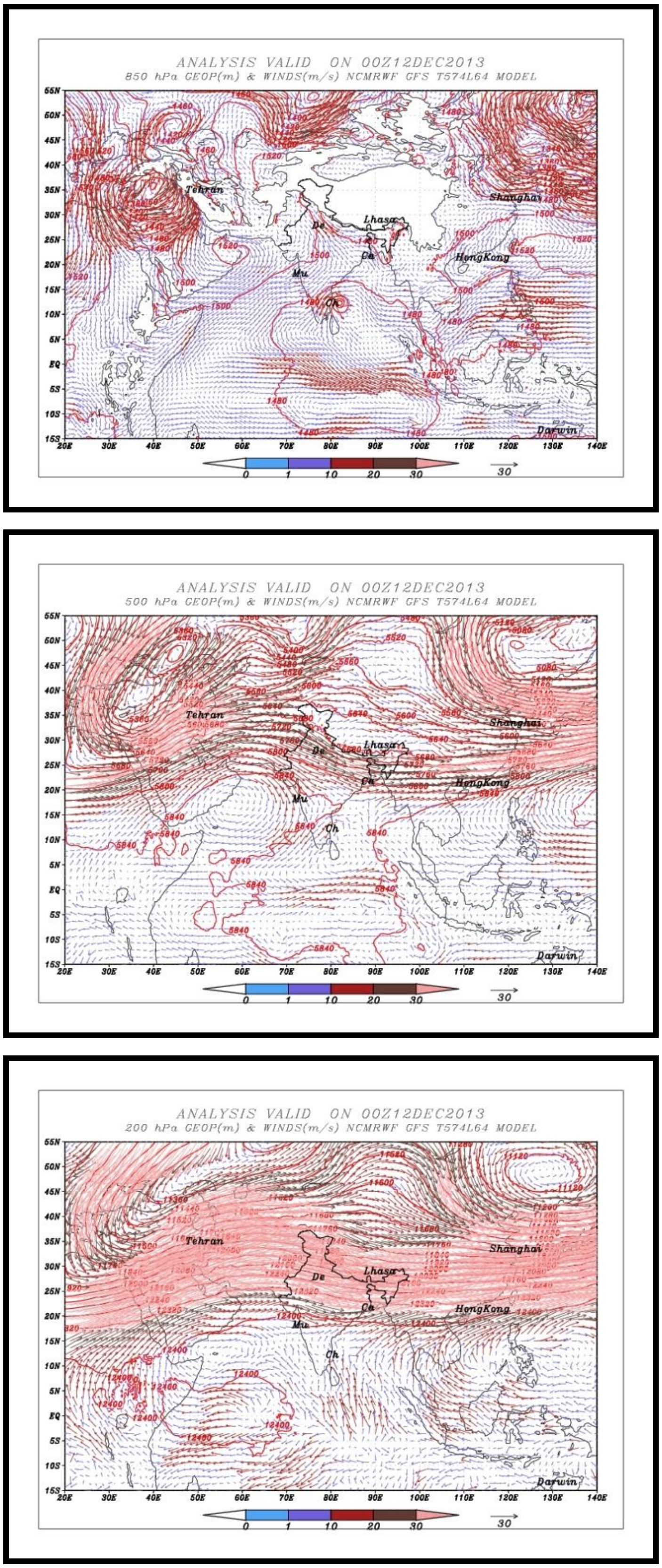


Fig 2.10.3(g) NCMRWF GFS Analysis based on 00 UTC of 12th Dec. 2013 in association with VSCS MAADI

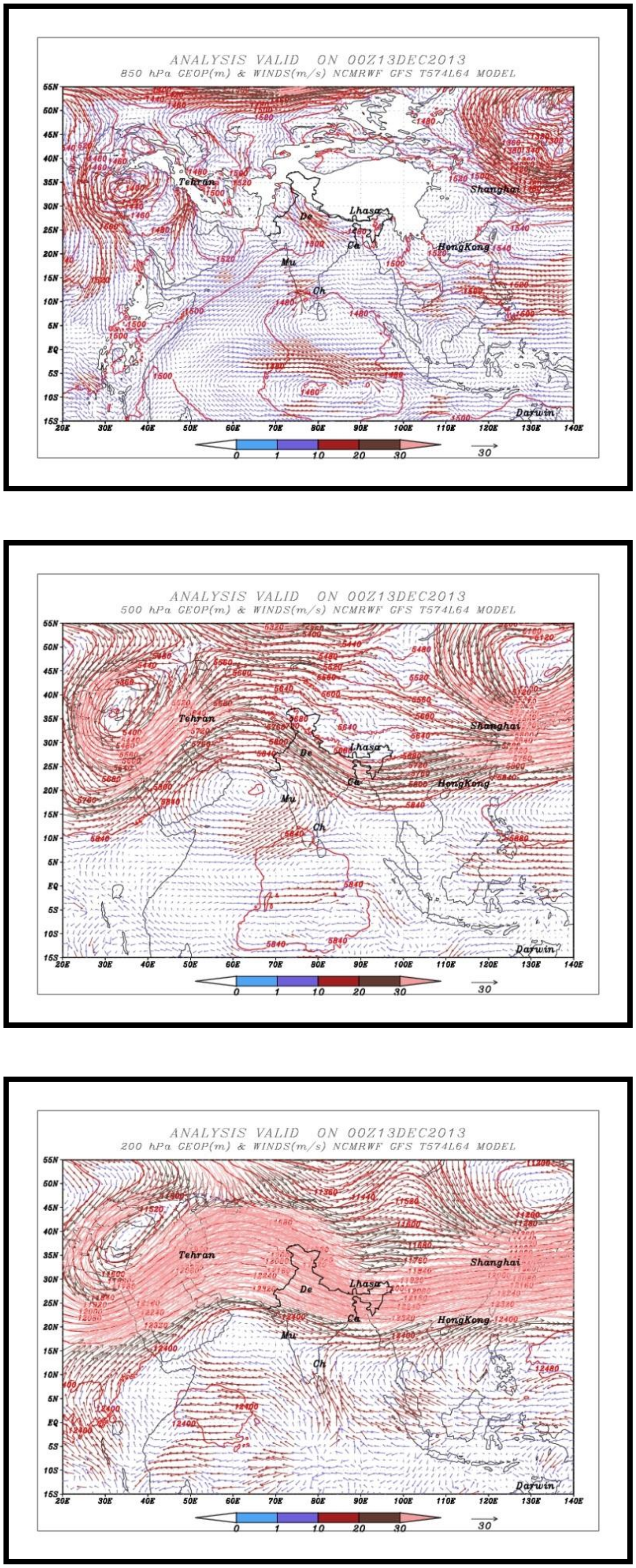


Fig 2.10.3(h) NCMRWF GFS Analysis based on 00 UTC of 13th Dec. 2013 in association with VSCS MAADI

2.10.5 Realised Weather

Chief amounts of 24 hrs. Rainfall (7 cm or more) ending at 0300 UTC from 07th December to 14th December, 2013 are given below:

7th December - Nil

8th DECEMBER 2013
ANDAMAN & NICOBAR ISLANDS: Hut Bay-9,

9th DECEMBER 2013
ANDAMAN & NICOBAR ISLANDS: Port Blair-10,

10thDECEMBER2013-Nil

11TH DECMBER 2013-NIL

12TH DECEMBER 2013-NIL

13th DECEMBER 2013
Tamilnadu & Puducherry: Colachel-11, Tindivanam-11, Kallakurichi-11, Eraniel-11, Cheyyur-11, Pondicherry-10, Ulundurpet-9, Virudhunagar-9, Attur-8, Airport Madurai-7, Tirumangalam-7, Vilupuram-7,

14TH DECEMBER 2013-NIL

2.10.7 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 2013

3.1 Introduction:

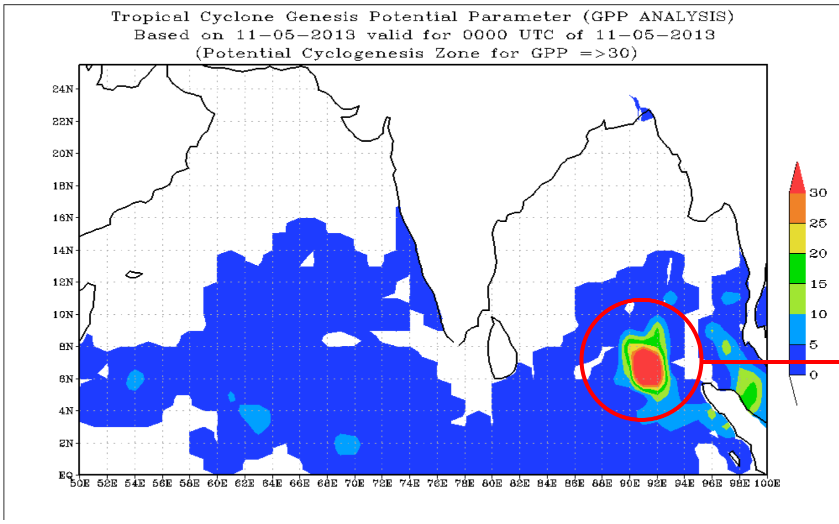
India Meteorological Department (IMD) operationally runs two regional models, WRF and Quasi-Lagrangian Model (QLM) for short-range prediction and one Global model T574L64 for medium range prediction (7 days). The WRF-Var model is run at the horizontal resolution of 27 km, 9 km and 3 km with 38 Eta levels 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 QLM model (resolution 40 km) is used for cyclone track prediction in case of cyclone situation in the NIO. IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency). Hurricane WRF (HWRF) model. The Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ and NCMRWF for operational forecasting of cyclones.

In addition to the above NWP models, IMD also run operationally “NWP based Objective Cyclone Prediction System (CPS)”. The method comprises of five forecast components, namely (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) Predicting decaying intensity after the landfall. Genesis potential parameter (GPP) is used for predicting potential of cyclogenesis and forecast for potential cyclogenesis zone. The multi-model ensemble (MME) for predicting the track (at 12h interval up to 120h) of tropical cyclones for the Indian Seas is developed applying multiple linear regression technique using the member models IMD-GFS, IMD-WRF, GFS (NCEP), ECMWF and JMA. The SCIP model is used for 12 hourly intensity predictions up to 72-h and a rapid intensification index (RII) is developed and implemented for the probability forecast of rapid intensification (RI). Decay model is used for prediction of intensity after landfall. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclones during 2013 are presented and discussed.

3.2 Cyclonic storm ‘Viyaru’ over the Bay of Bengal during 10-16 May, 2013

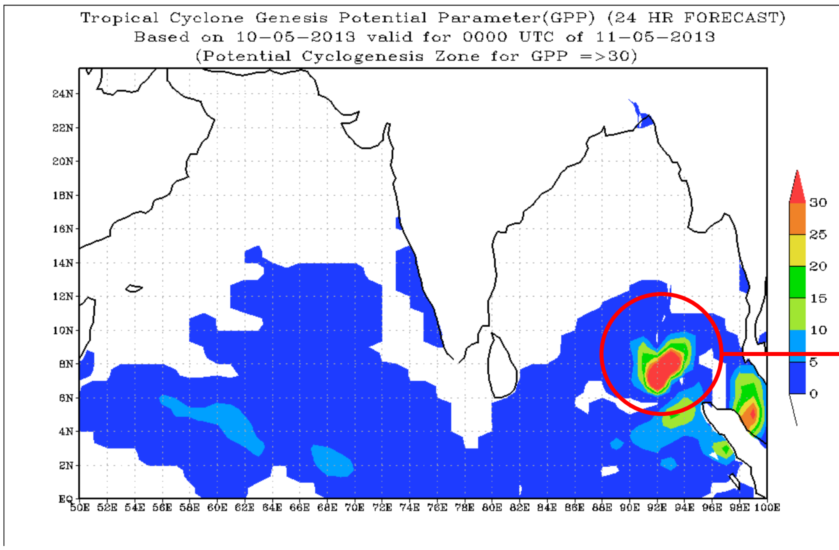
3.2.1 Grid point analysis and forecast of GPP

Grid point analysis and forecast of GPP is used to identify potential zone of cyclogenesis. Grid point analysis and forecasts of GPP (Fig.3.1(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation.
(Product available at http://www.imd.gov.in/section/nhac/dynamic/Analysis.htm).



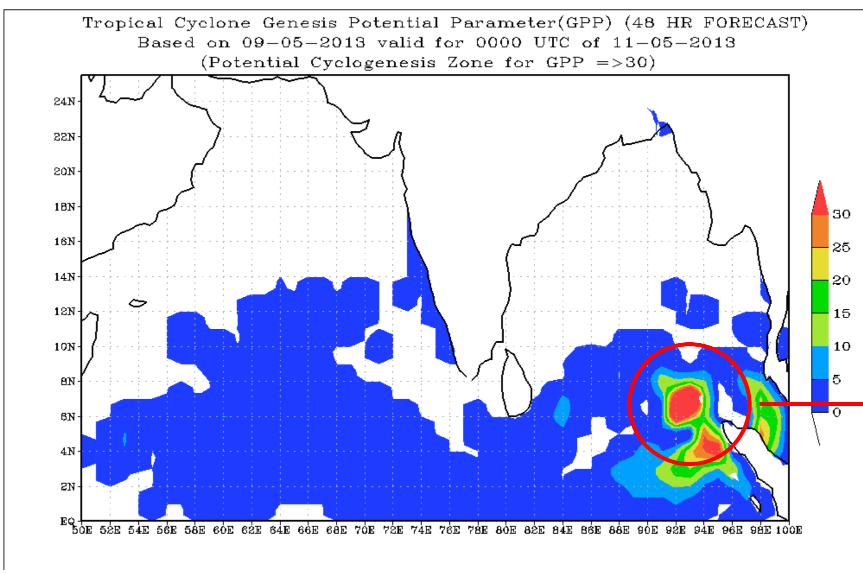
Analysis of GPP on 00 UTC 11 May 2013 indicates the location of DD.

Fig. 3.1a



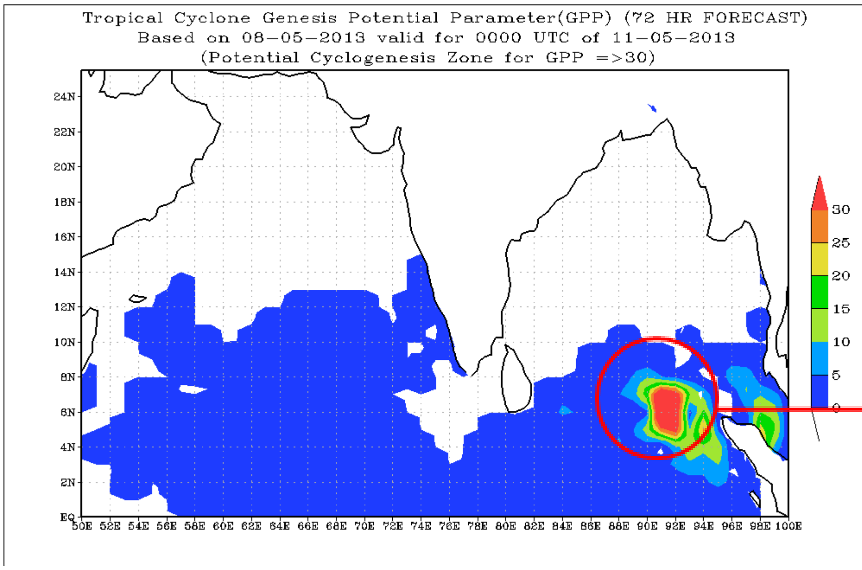
24 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 3.1b



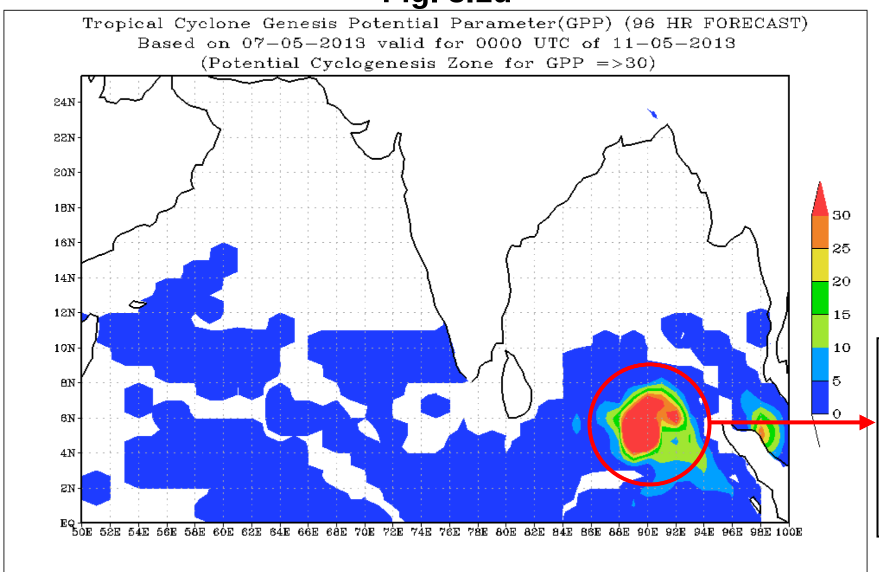
48 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 3.1c



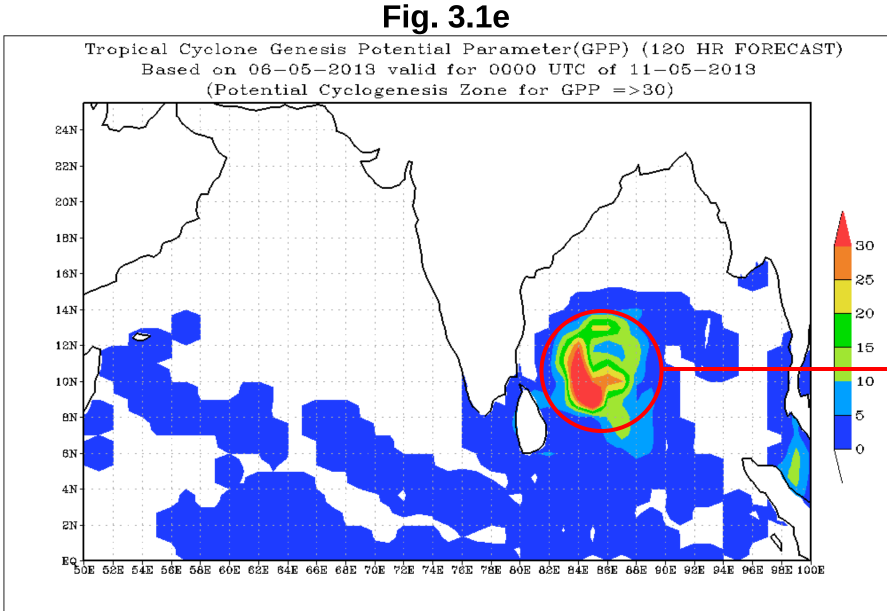
72 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 3.1d



96 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, where DD formed on that date.

Fig. 3.1e



120 hour forecast of GPP valid for 00 UTC 11 May 2013 indicated the potential cyclogenesis zone, but on the north-west side of actual position of DD on that date.

Fig. 3.1f

Fig. 3.1(a-f) Grid point analysis of GPP for Cyclone "Viyaru"

3.2.2 Area average analysis and forecast of GPP

Analysis of Genesis Potential Parameter (GPP) values computed (Kotal et al, 2009) for cyclone ‘VIYARU’ on the basis of real time model analysis fields along with the GPP values for Developing Systems and Non-Developing Systems are shown in Fig.3.2(a-b). The higher GPP values (> 8.0, the threshold value) at early stages of development (T.No. 1.0) have clearly indicated that the cyclone “VIYARU” had enough potential to intensify into a developing system.

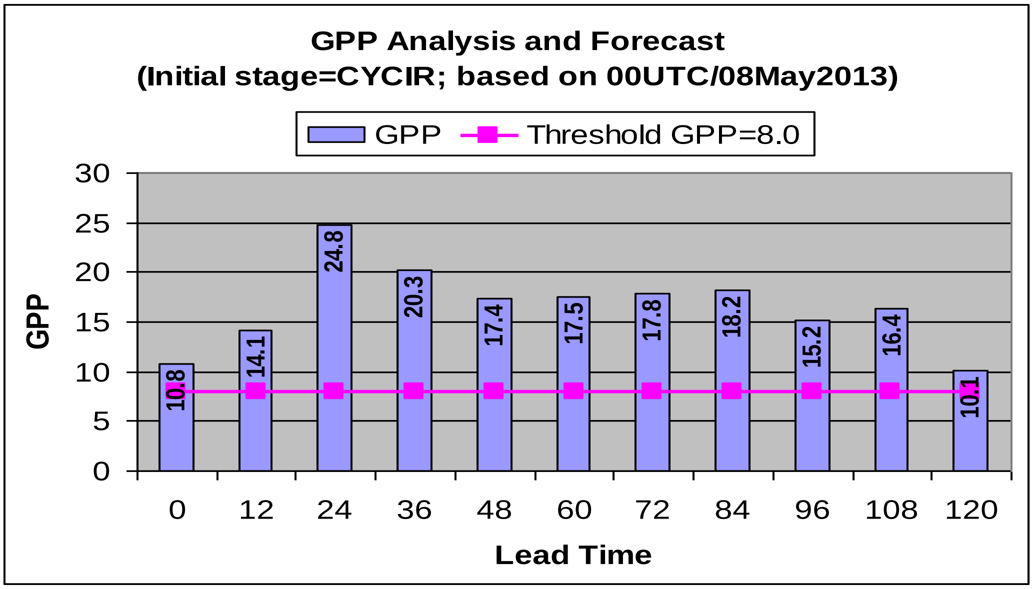


Fig 3.2a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 at very early stage of development (**CYCIR**) indicated its potential to intensify into a cyclone.

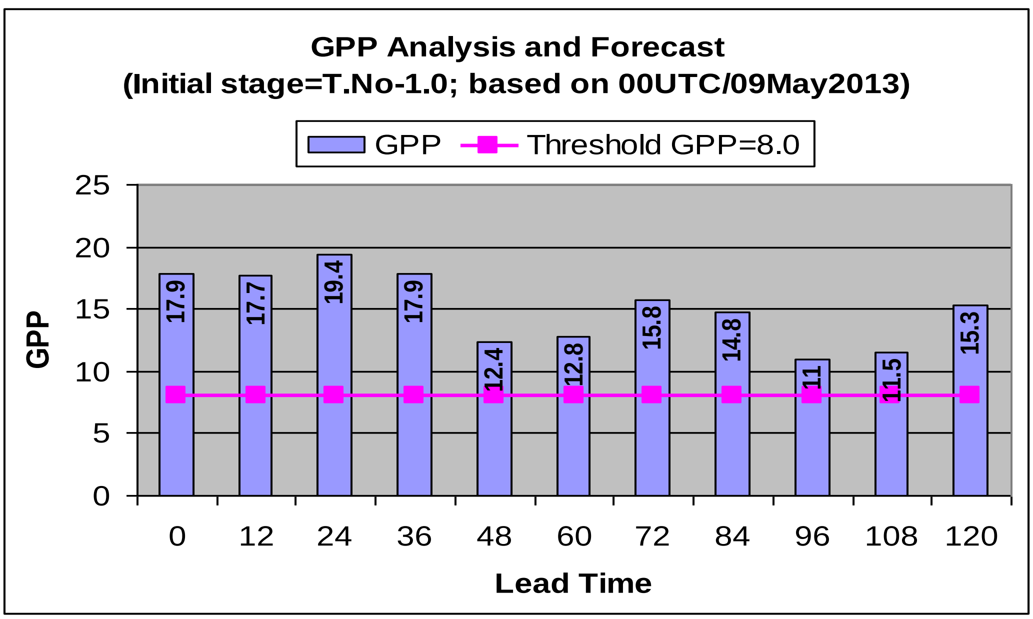


Fig 3.2b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

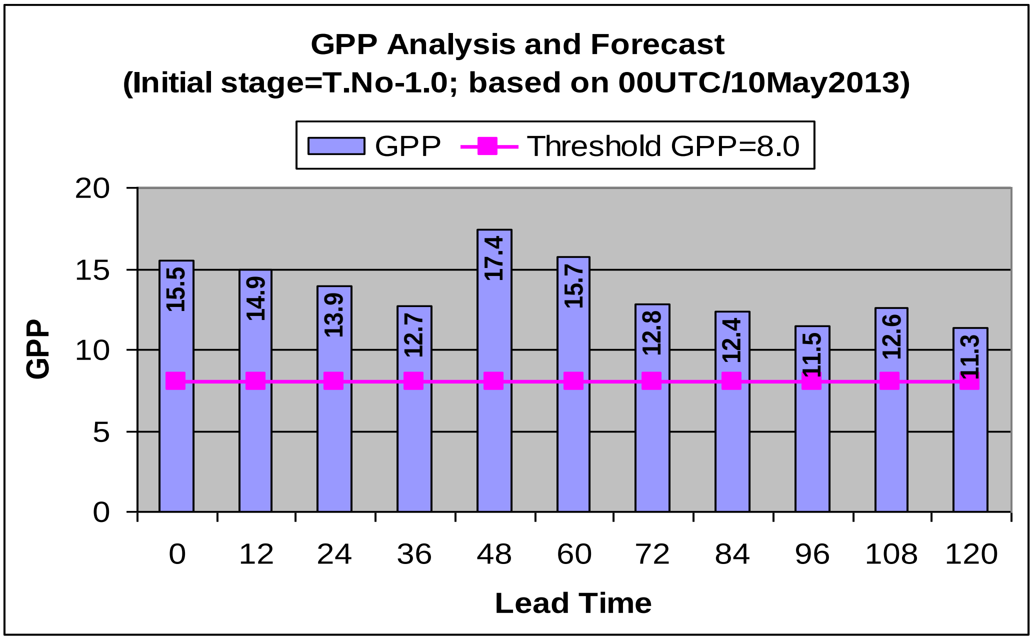


Fig 3.2c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

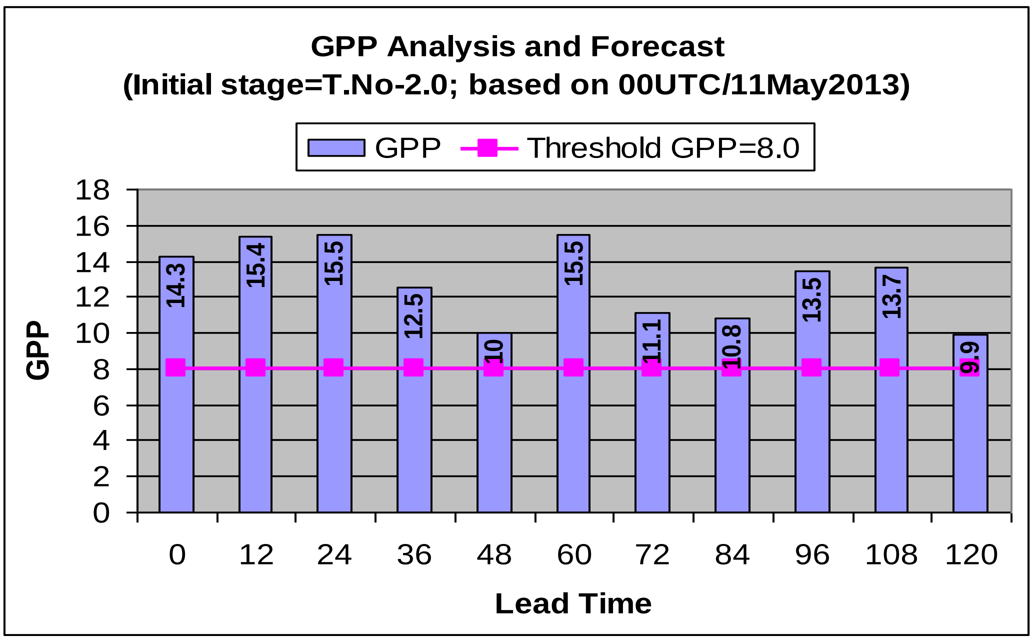


Fig 3.2d: Analysis and forecasts of GPP shows that GPP ≥ 8.0 at early stage of development (**T.No. 2.0**) indicated its potential to intensify into a cyclone.

Fig.3.2(a-d) Analysis and forecasts of GPP

3.2.3 Track prediction

The average track forecast errors of NWP models along with the consensus forecast by MME and IMD official (OFFICIAL) forecast is presented in the Table 3.1. The landfall point error (km) and landfall time (hour) is presented in Table-3.2 and Table-3.3 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig.3.3. The figure shows that from the day1 (00 UTC 10 May 2013), MME was able to predict the recurvature and landfall at southeast coast of Bangladesh near Chittagong.

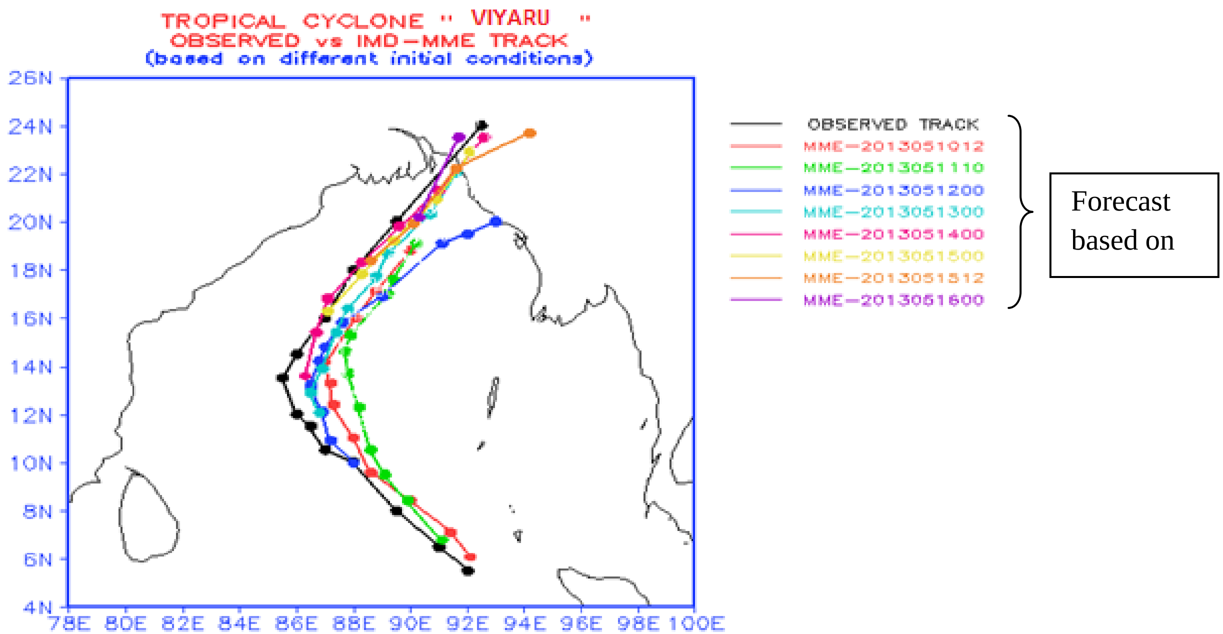


Fig. 3.3. MME forecasts track based on different initial conditions

Table-3.1. Average track forecast errors (km) (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	69(7)	114(7)	217(6)	257(4)	425(4)	388(3)	573(3)	553(2)	433(1)	453(1)
IMD-WRF	101(8)	196(7)	318(6)	373(5)	536(5)	402(4)	-	-	-	-
IMD-QLM	163(7)	230(6)	292(5)	252(4)	289(4)	238(3)	-	-	-	-
JMA	110(8)	150(7)	191(6)	158(5)	207(5)	196(4)	339(4)	-	-	-
NCEP-GFS	102(8)	81(7)	143(6)	154(5)	210(5)	190(4)	232(4)	229(3)	300(2)	307(2)
ECMWF	105(8)	149(7)	202(6)	153(5)	199(5)	173(4)	224(4)	104(3)	255(3)	233(2)
IMD-MME	79(8)	120(7)	168(6)	122(5)	189(5)	169(4)	253(4)	245(3)	295(3)	176(2)
IMD-HWRF	77(10)	186(9)	299(8)	392(7)	516(6)	635(5)	753(4)	836(3)	892(2)	1008(1)
OFFICIAL	90(24)	152(22)	189(20)	205(18)	208(16)	268(14)	251(10)	308(8)	291(6)	222(4)

The consensus forecast MME outperformed all the forecasts upto 72 h, and it ranged from 79 km at 12 h to 169 km at 72 h. ECMWF model forecast is superior to other model forecasts for 84 h to 108 h forecast (104 km-255km) and again MME forecast error (176 km) is lowest at 120 h.

Table-3.2. Landfall point forecast errors (km) at different lead time (hour)

Model	FC based on 00 UTC/14.05.2013 Lead time: 56 h	FC based on 00 UTC/15.05.2013 Lead time: 32 h	FC based on 12 UTC/15.05.2013 Lead time: 20 h	FC based on 00 UTC/16.05.2013 Lead time: 8 h
IMD-GFS	NO LF	NO LF	136	-
IMD-WRF	NO LF	147	49	45
IMD-QLM	NO LF	63	137	243
JMA	137	63	98	49
NCEP-GFS	289	169	136	136
ECMWF	259	274	127	15
IMD-MME	63	63	63	25
IMD-HWRF	84	174	121	-

Landfall point error shows that MME forecast error is least, 63 km to 25 km before 56 h to 8 h of landfall respectively.

Table-3.3.Landfall time forecast errors (hr) ('+' for Delay, '-' for early, LF = landfall) (Observed landfall time = 0800 UTC 16 may 2013)

Model	FC based on 00 Lead time: 56 h	FC based on 00 Lead time: 32 h	FC based on 12 Lead time: 20 h	FC based on 00 Lead time: 8 h
IMD-GFS	NO LF	NO LF	-4	Dissipated
IMD-WRF	NO LF	+5	+2	+4
IMD-QLM	NO LF	+15	+4	+4
JMA	+10	+12	+4	0
NCEP-GFS	-4	+4	-5	-4
ECMWF	+4	+12	+4	+1
IMD-MME	+10	+13	+5	+1
IMD-HWRF	+10	+4	-2	-

Landfall time error shows that NCEP consistently predicted landfall at lowest landfall time error (± 4 h), but before 8 h, JMA, ECMWF, and MME predicted at near landfall time.

3.2.4 Average Intensity prediction Error

Average absolute error (AAE) and Root mean square error (RMSE) of SCIP and HWRF along with the official forecast error is presented in the following Table-3.4 and Table-3.5. Intensity forecasts by SCIP, HWRF and OFFICIAL shows that Statistical-dynamical model forecast (SCIP) is superior to other model forecasts.

Table-3.4 Average absolute errors (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	1.3 (6)	4.3 (6)	6.4 (5)	3.8 (4)	11.3 (4)	10.0 (3)	-	-	-	-
IMD-HWRF	27.2(10)	21.3(9)	8.6(8)	10.9(7)	19.2(6)	23.0(5)	29.5(4)	14.0(3)	22.0(2)	29.0(1)
OFFICIAL	3.6 (24)	6.8(22)	8.7(20)	10.0(18)	13.0(16)	15.0(14)	14(10)	13(8)	17(6)	14(4)

Table-3.5 Root Mean Square (RMSE) errors (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	2.2 (6)	8.0 (6)	8.5 (5)	4.3 (4)	14.9 (4)	11.6 (3)	-	-	-	-
IMD-HWRF	30.0(10)	24.3(9)	12.2(8)	12.8(7)	22.8(6)	28.0(5)	31.5(4)	14.3(3)	22.4(2)	29.0(1)
OFFICIAL	4.6 (24)	8.9(22)	10.8(20)	12.5(18)	16.1(16)	17.8(14)	16.1(10)	15.7(8)	17.5(6)	16.4(4)

3.2.5 Probability of Rapid intensification (by RI-Index)

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour.

Table-3.6 Probability of Rapid intensification

Forecast based on	**Probability of RI predicted**	**Chances of occurrence predicted**	**Occurrence**
00 UTC/11.05.2013	9.4 %	VERY LOW	NO
00 UTC/12.05.2013	5.2 %	VERY LOW	NO
00 UTC/13.05.2013	2.6 %	VERY LOW	NO
00 UTC/14.05.2013	5.2 %	VERY LOW	NO
00 UTC/15.05.2013	9.4 %	VERY LOW	NO
12 UTC/15.05.2013	22.0 %	LOW	NO
Inference: RI-Index was able to predict non-occurrence of Rapid Intensification of cyclone VIYARU during its lifetime.			

3.2.6 Decay after landfall

Decay (after landfall) prediction curve (6-hourly) shows slow decay compared to observed decay. The error is -8 kt and -7 kt at 6 h and 12 h respectively. (Fig. 3.4)

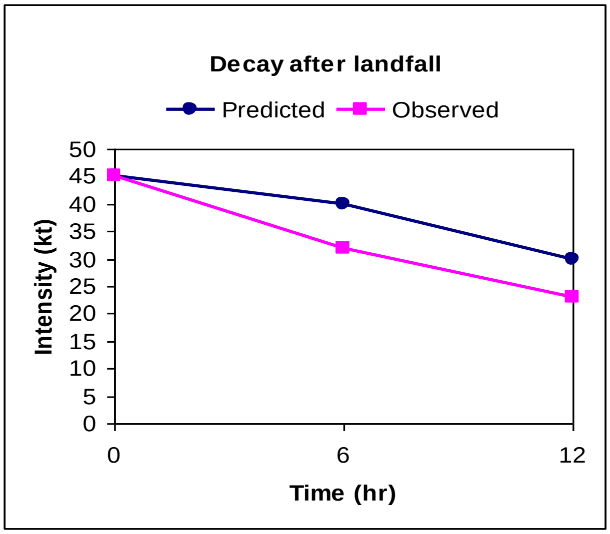


Fig.3.4. Decay after landfall

3.2.7 Ensemble track and Strike Probability forecast

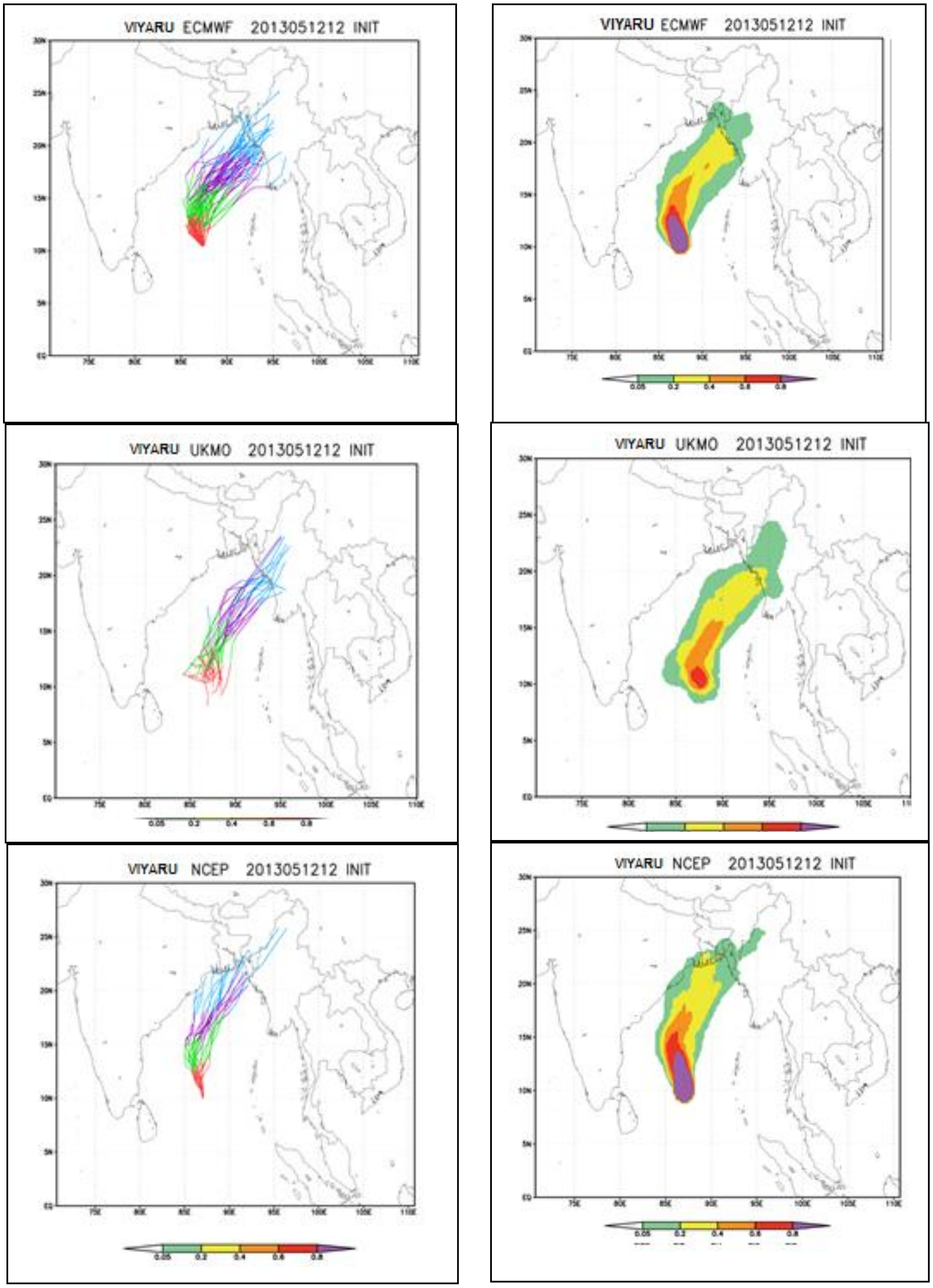


Fig. 3.5(a) EPS forecast based on 12 UTC of 12.05.2013

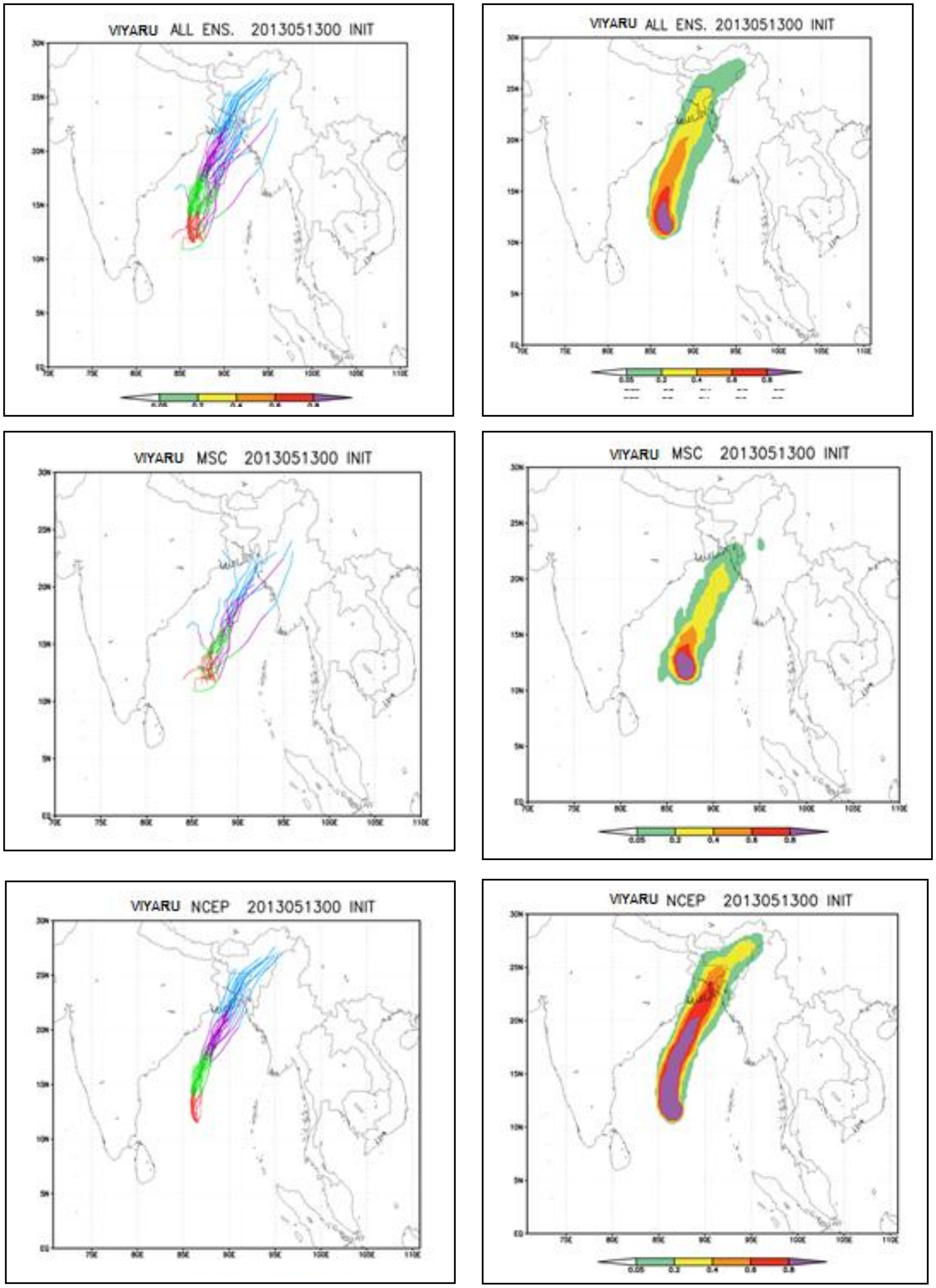


Fig. 3.5(b) EPS forecast based on 00 UTC of 13.05.2013

Fig.3.5. Ensemble track and strike probability forecast based on 12 UTC 12.05.2013 and 00 UTC 13.05.2013 shows that ECMWF, UKMO, MSC and NCEP predicted re-curvature and to cross south of actual landfall point except NCEP, which predicted landfall near actual landfall point.

3.3. Very Severe Cyclonic storm 'PHAILIN' (8-14 October, 2013) over the Bay of Bengal

3.3.1 *Grid point analysis and forecast of GPP*

Figure 3.6(a-e) below shows the analysis and predicted zone of formation of cyclogenesis. Grid point analysis and forecasts of GPP (Fig.3.6(a-e)) shows that it was able to predict the formation and location of the system before 168 hours of its formation.
(Product available at http://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)

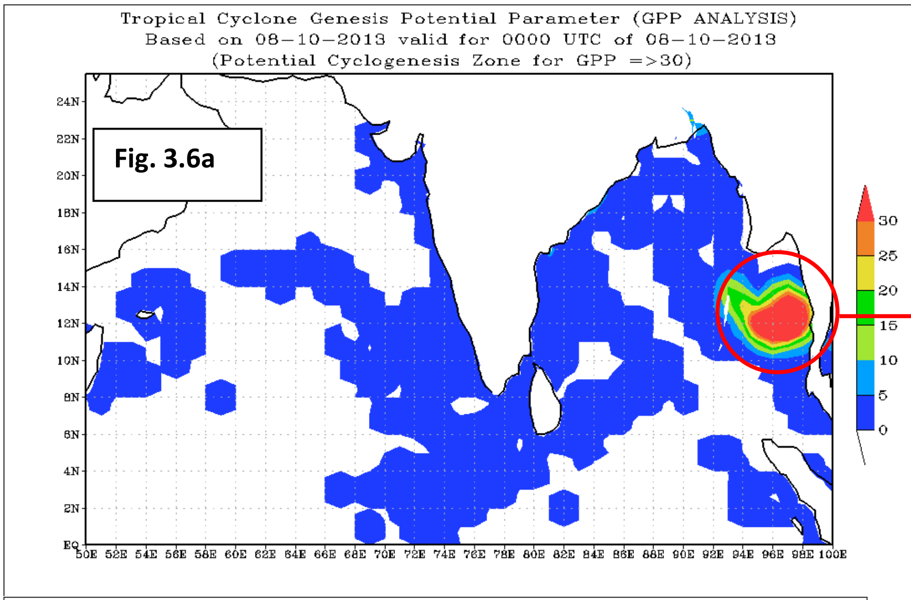


Fig. 3.6a

Analysis of GPP valid for 00 UTC 08 October 2013, where Depression formed on that day.

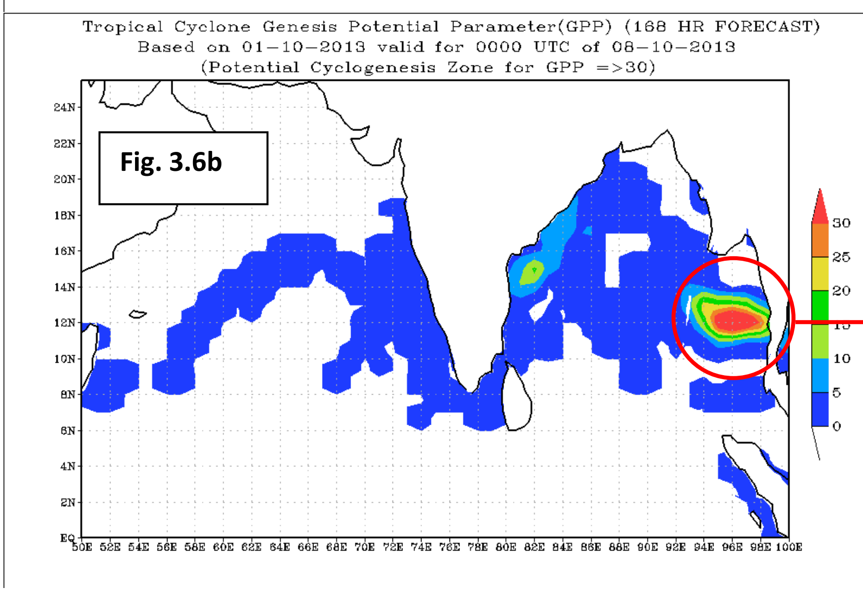
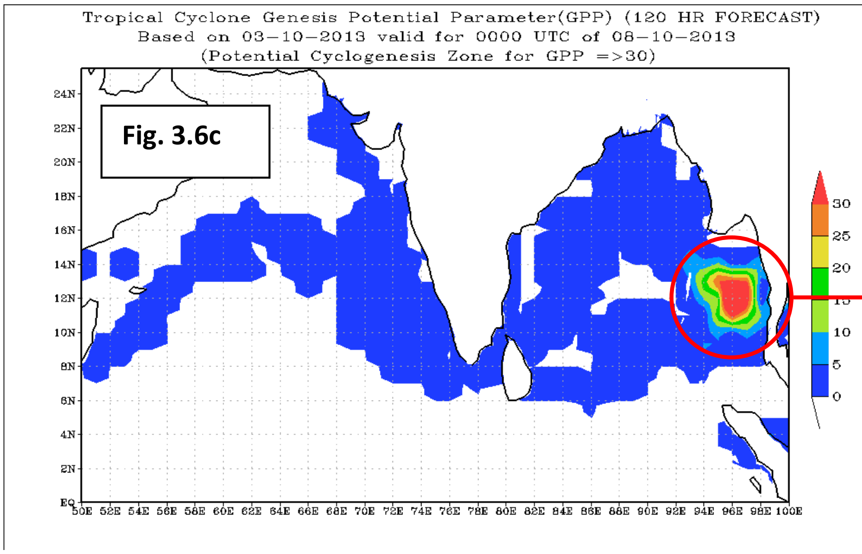
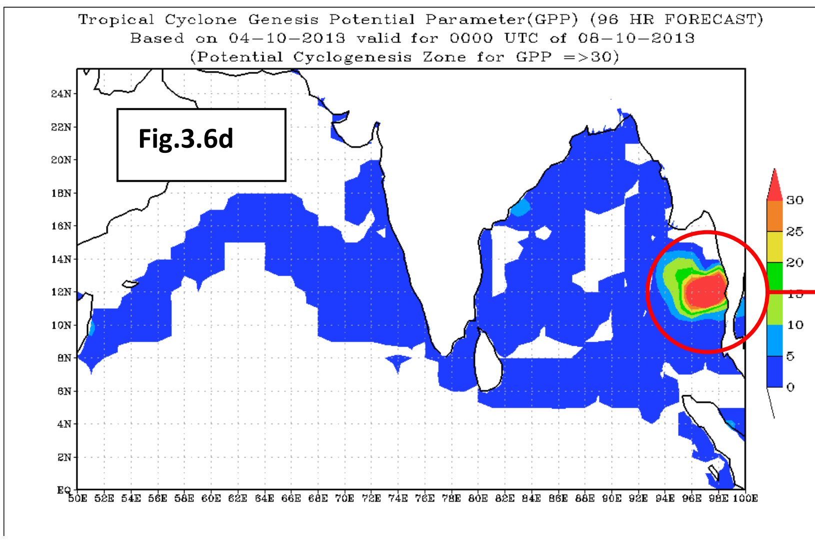


Fig. 3.6b

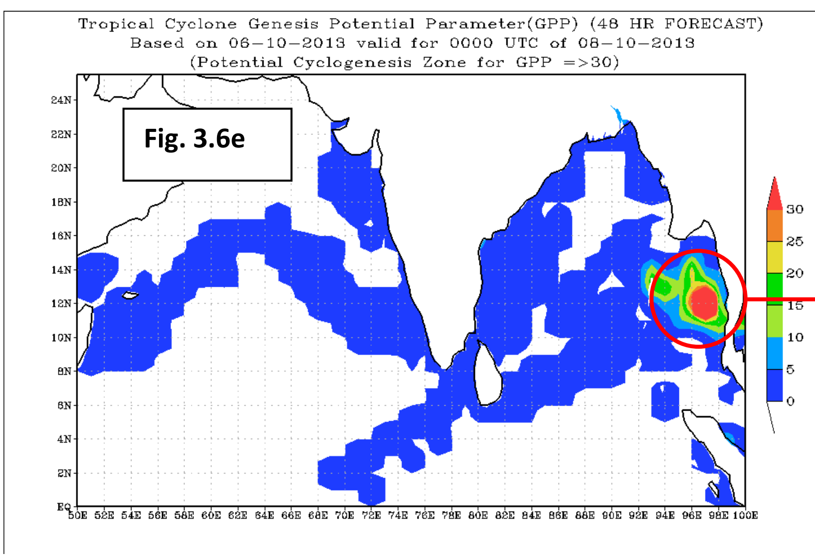
168 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



120 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



96 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 00 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.

Figure 3.6(a-e): Predicted zone of cyclogenesis.

3.3.2 Area average analysis of GPP

Analysis and forecasts of GPP (Fig.3.7(a-c)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

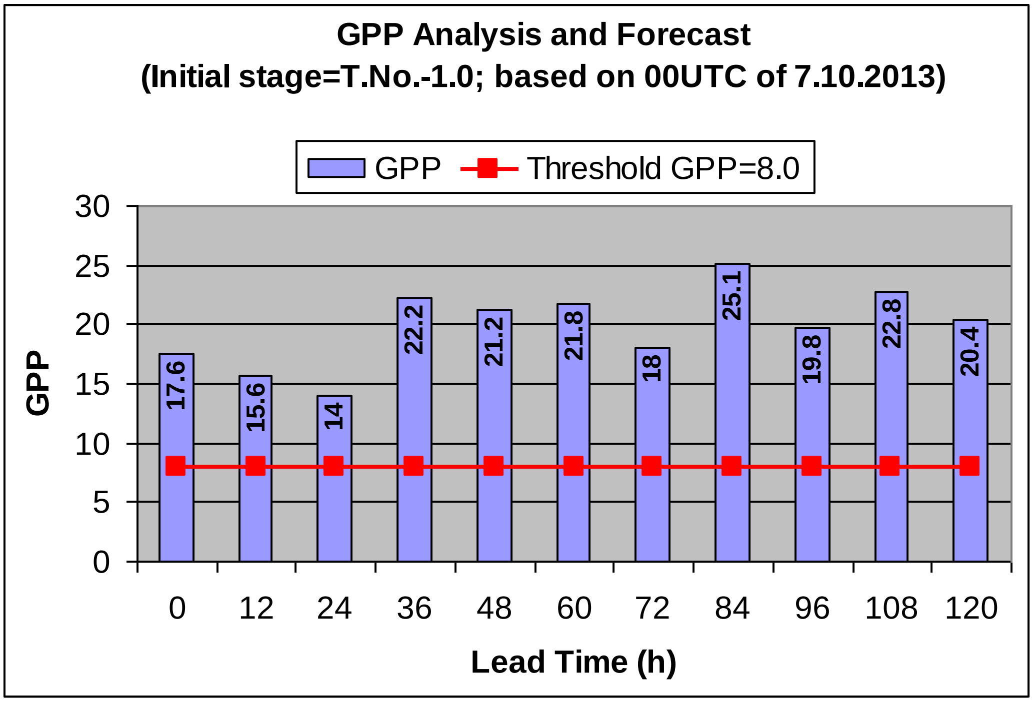


Fig.3.7a

Fig 3.7a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No.-1.0**) indicated its potential to intensify into a cyclone.

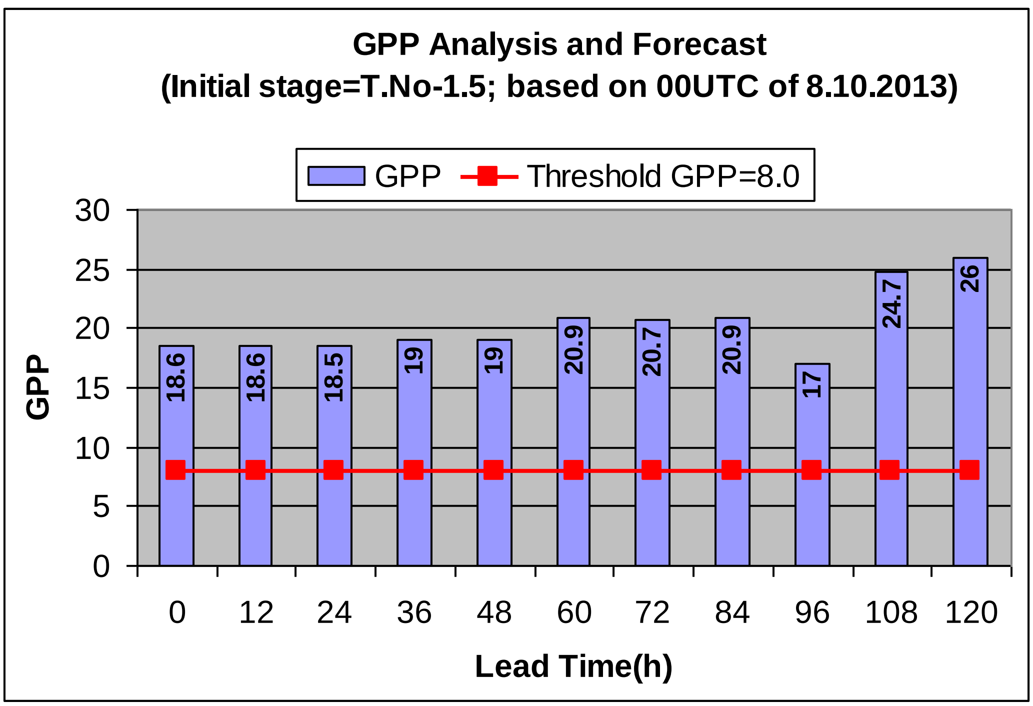


Fig. 3.7b

Fig 8b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.5**) indicated its potential to intensify into a cyclone.

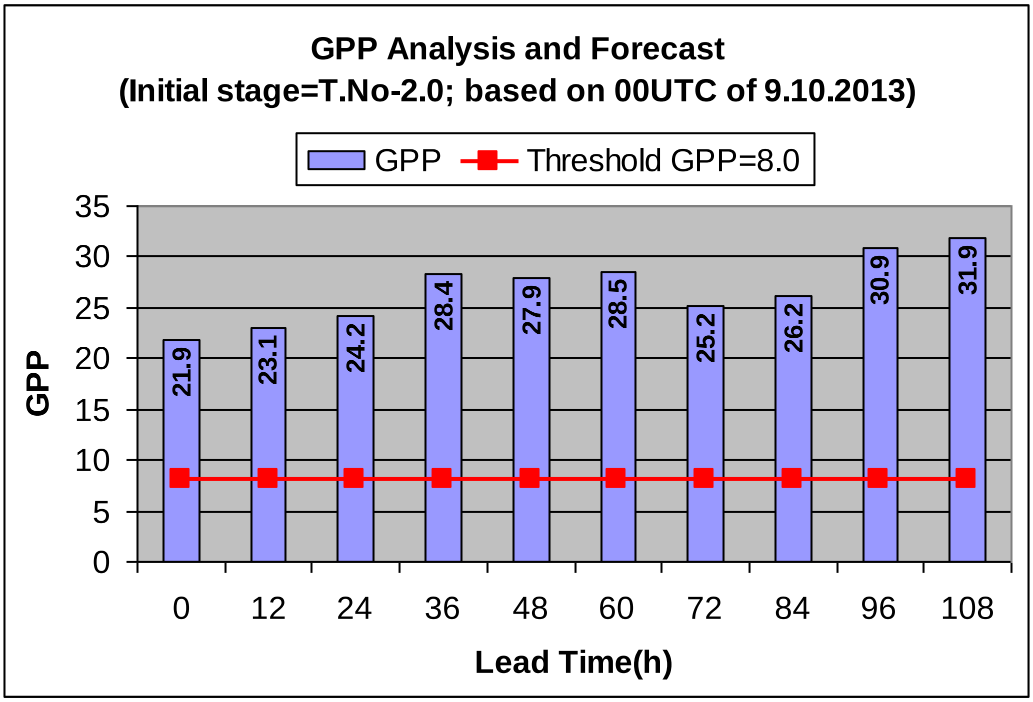


Fig 3.7c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 2.0**) indicated its potential to intensify into a cyclone.

Fig. 3.7c

Fig. 3.7(a-c) Area average analysis of GPP

3.3.3 Track and landfall prediction

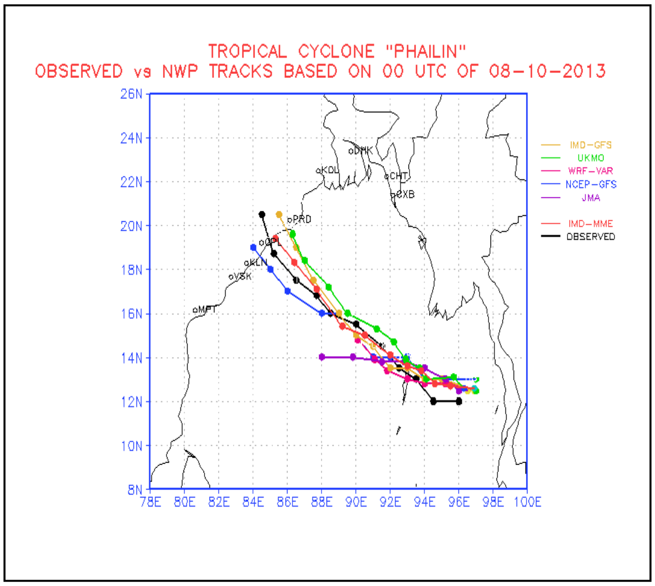
Direct position errors (DPE), cross track error (CTE) and along track error (ATE) are calculated based on the Heming (1994). The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by MME are presented in the Table 3.7, Table 3.8 and Table 3.9 respectively. The landfall point error (km) and landfall time error(hour) is presented in Table-3.10 and Table-3.11 respectively. The model forecasts track based on different initial conditions along with the observed track is depicted in Fig 3.8. The figure shows that from the day1 (00 UTC 8 October to 12 UTC 12 October 2013), MME was able to predict correctly and consistently the landfall near Gopalpur (Odisha).

The average DPE was highest for WRF (about 95 km at 12 h to 265 km at 72 h) and JMA (about 85 km at 12 h to 305 km at 84 h). Average DPE was lowest for UKMO, NCEP-GFS and MME up to 60 h (about 65 km at 12 h to 100 km at 60 h), thereafter NCEP-GFS lowest (about 90 km) upto 108 h. The DPE for MME was about 65 km at 12 h to 150 km at 120 h (Table3.7). The DPE of all models are shown in Fig. 3.9.

The average CTE was highest for WRF (about 70 km at 12 h to 195 km at 72 h) and JMA (about 60 km at 12 h to 280 km at 84 h). Average CTE was lowest for UKMO and MME for all forecast hours (about 45 km at 12 h to 50 km at 120 h). IMD-GFS was also comparable with UKMO and MME up to 96 h (Table-3.8). The CTE of all models are shown in Fig. 3.10.

The average ATE was highest for WRF, HWRF and IMD-GFS (about 50 km at 12 h to

150 km at 48 h). ATE of WRF is largest at 72 h (about 150 km). Average ATE was highest for UKMO from 84 h to 120 h (about 130 km at 84 h to 210 km at 120 h). ATE of NCEP-GFS was lowest at all forecast hours (about 40 km at 12 h to 55 km at 120 h). The ATE for MME was about 40 km at 12 h to 140 km at 120 h (Table-3.9). The ATE of all models is shown in Fig. 3.11.



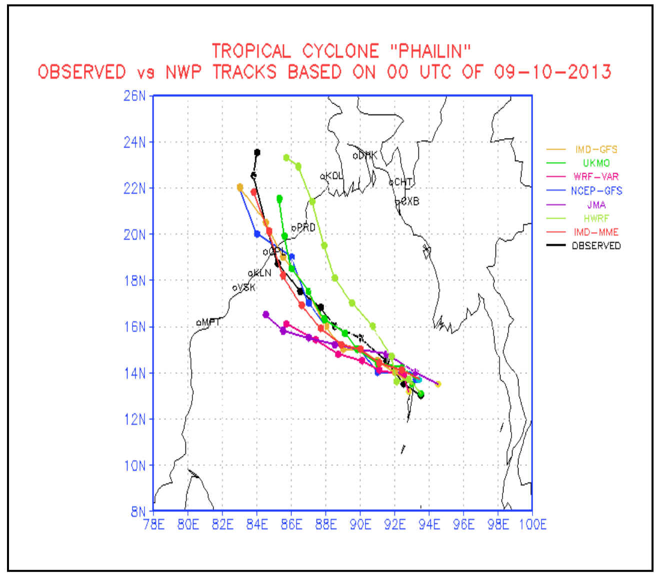


Fig. 3.8. NWP model track forecasts based on different initial conditions

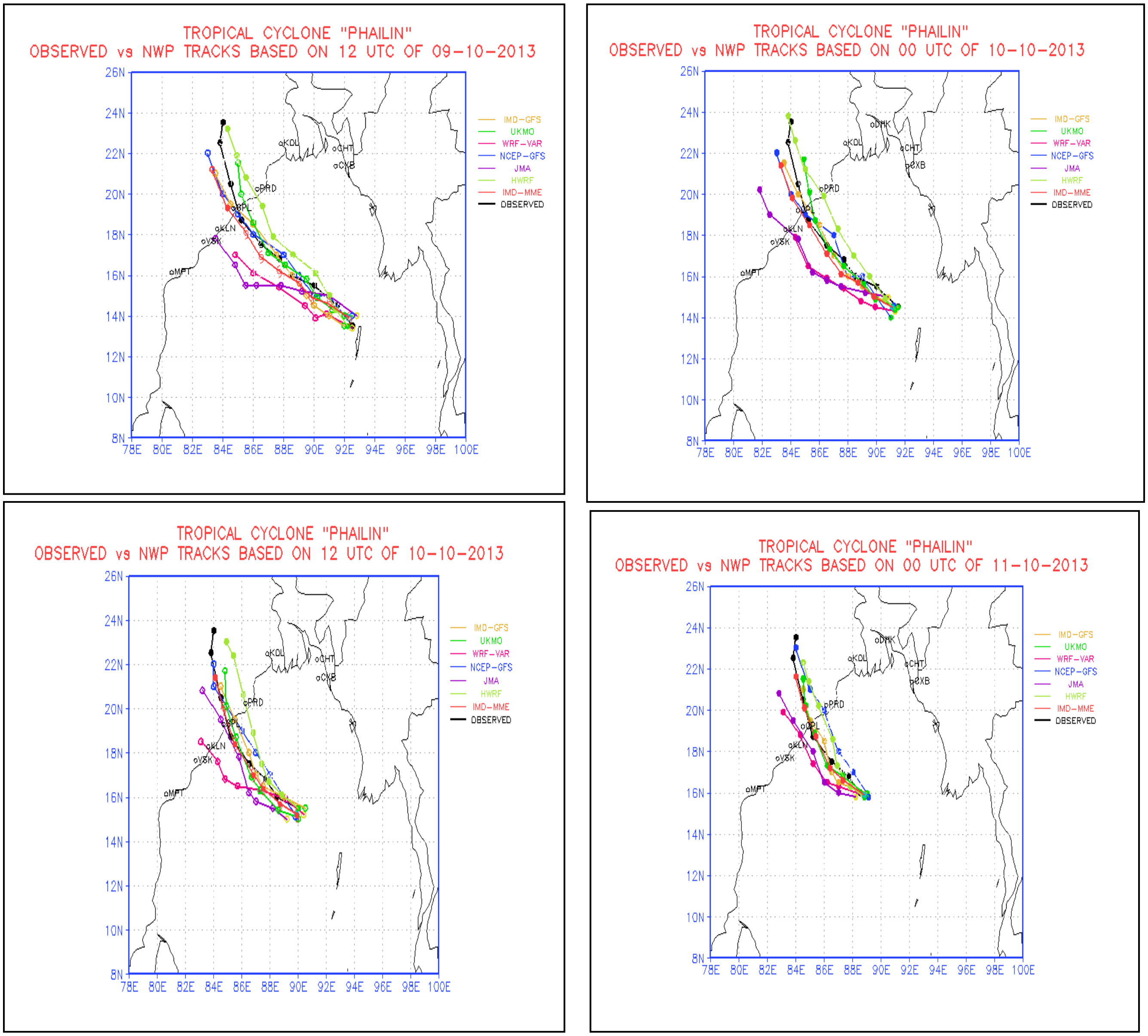


Fig. 3.8(contd.) NWP model track forecasts based on different initial conditions

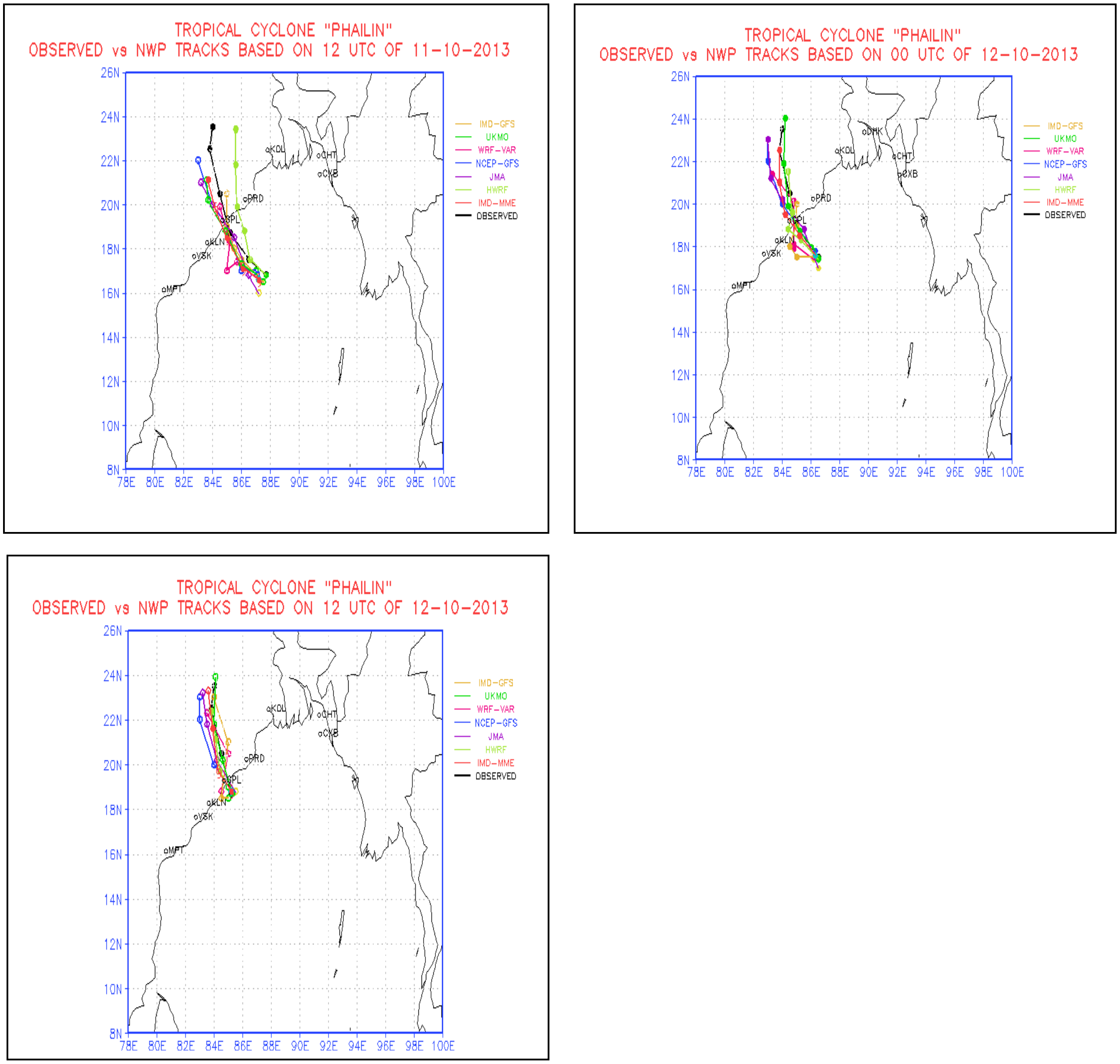


Fig. 3.8(contd.) NWP model track forecasts based on different initial conditions

Table-3.7.Average track forecast errors (DPE) in km (Number of forecasts verified)

Lead time →	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**	**108 hr**	**120 hr**
IMD-GFS	98(9)	107(9)	129(9)	173(8)	132(6)	115(5)	109(4)	92(3)	120(2)	104(1)
IMD-WRF	97(9)	150(9)	167(9)	193(8)	234(6)	266(5)	-	-	-	-
JMA	86(9)	97(9)	114(9)	149(8)	185(6)	239(5)	304(4)	-	-	-
NCEP-GFS	69(9)	63(9)	91(9)	87(8)	91(6)	61(5)	90(4)	84(3)	90(2)	175(1)
UKMO	63(9)	62(9)	71(9)	77(8)	104(6)	134(5)	134(4)	168(3)	191(2)	213(1)
IMD-MME	64(9)	67(9)	81(9)	95(8)	103(6)	119(5)	139(4)	112(3)	106(2)	148(1)
IMD-HWRF	49(8)	111(8)	169(8)	176(7)	183(6)	170(5)	154(4)	159(3)	187(2)	182(1)

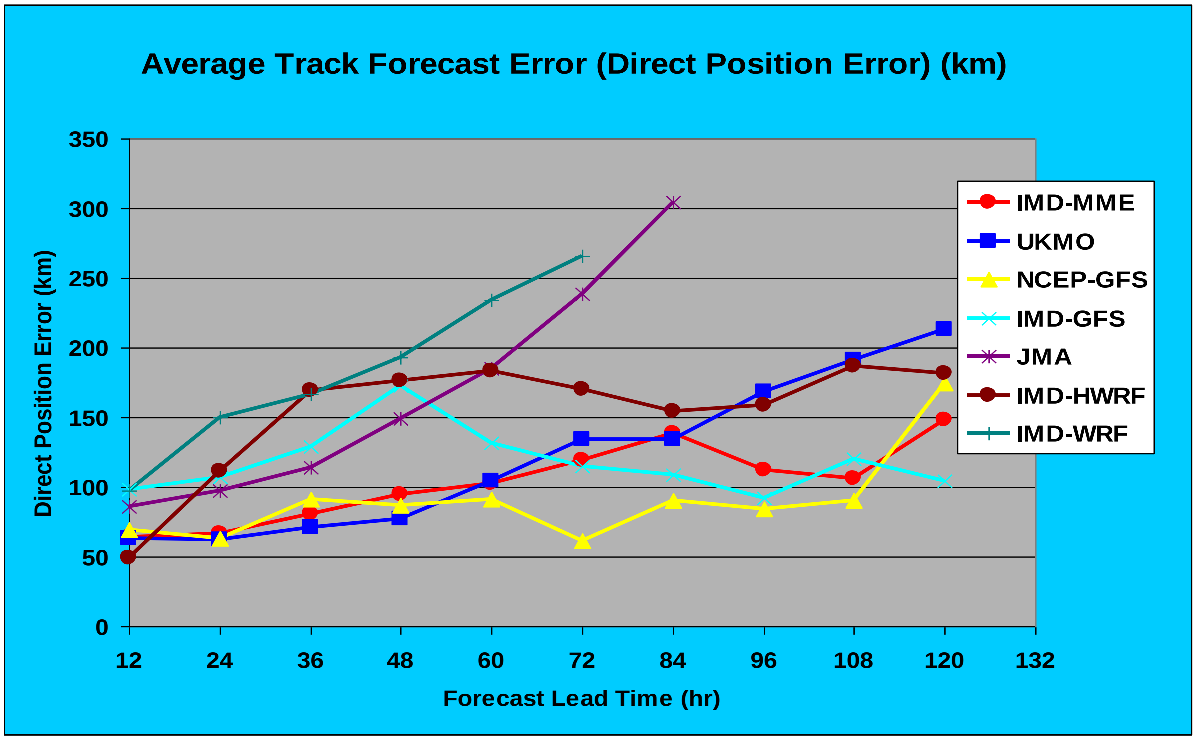


Fig.3.9: Average track forecast errors (DPE) of NWP models for cyclone PHAILIN

Table-3.8. Average cross track error (CTE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	63	56	41	37	31	36	59	64	98	61
IMD-WRF	68	89	88	133	180	194	-	-	-	-
JMA	59	72	92	112	148	201	280	-	-	-
NCEP-GFS	43	51	81	71	39	31	78	83	87	166
UKMO	47	31	39	25	21	36	19	35	50	30
IMD-MME	46	41	46	43	41	46	80	61	42	50
IMD-HWRF	20	46	66	101	105	130	117	115	124	94

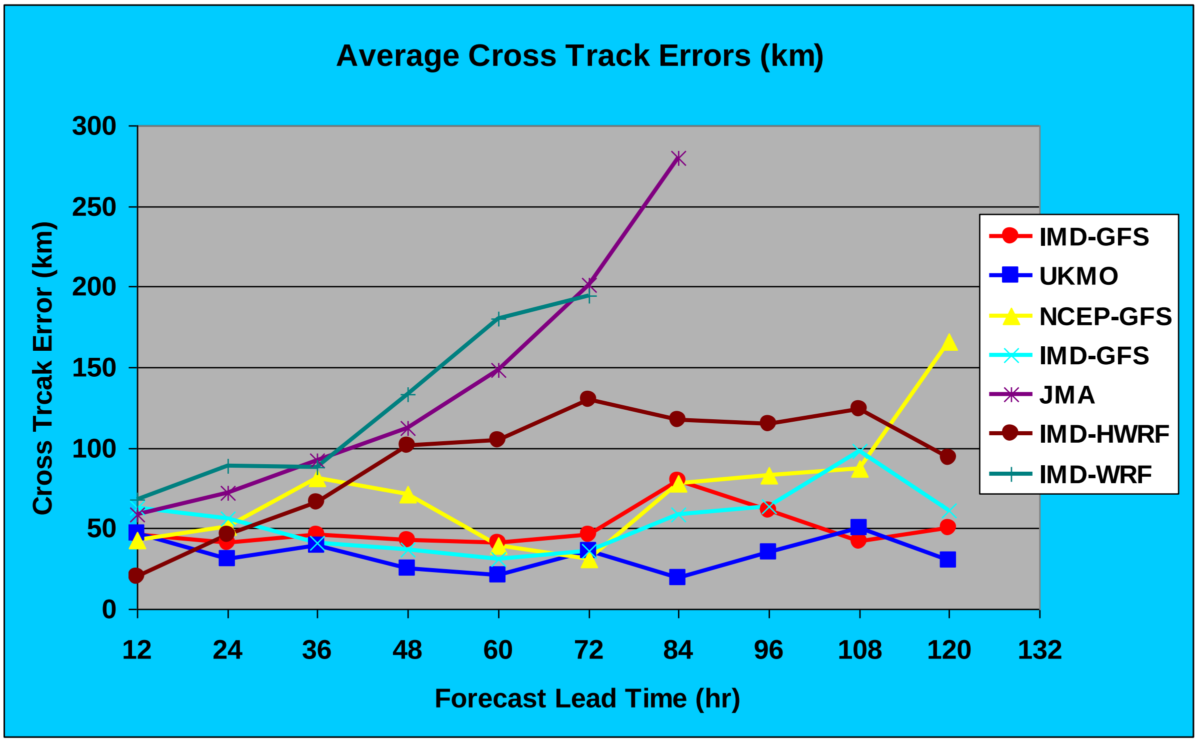


Fig. 3.10: Average cross track errors (CTE) of NWP models

Table-3.9. Average along track error (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	63	86	120	166	126	106	76	63	60	84
IMD-WRF	56	104	127	130	138	152	-	-	-	-
JMA	48	49	57	67	77	100	104	-	-	-
NCEP-GFS	42	27	31	35	79	43	35	14	21	55
UKMO	38	46	50	69	100	127	132	163	184	211
IMD-MME	40	44	59	80	87	97	100	82	93	139
IMD-HWRF	43	97	146	140	142	111	99	102	126	156

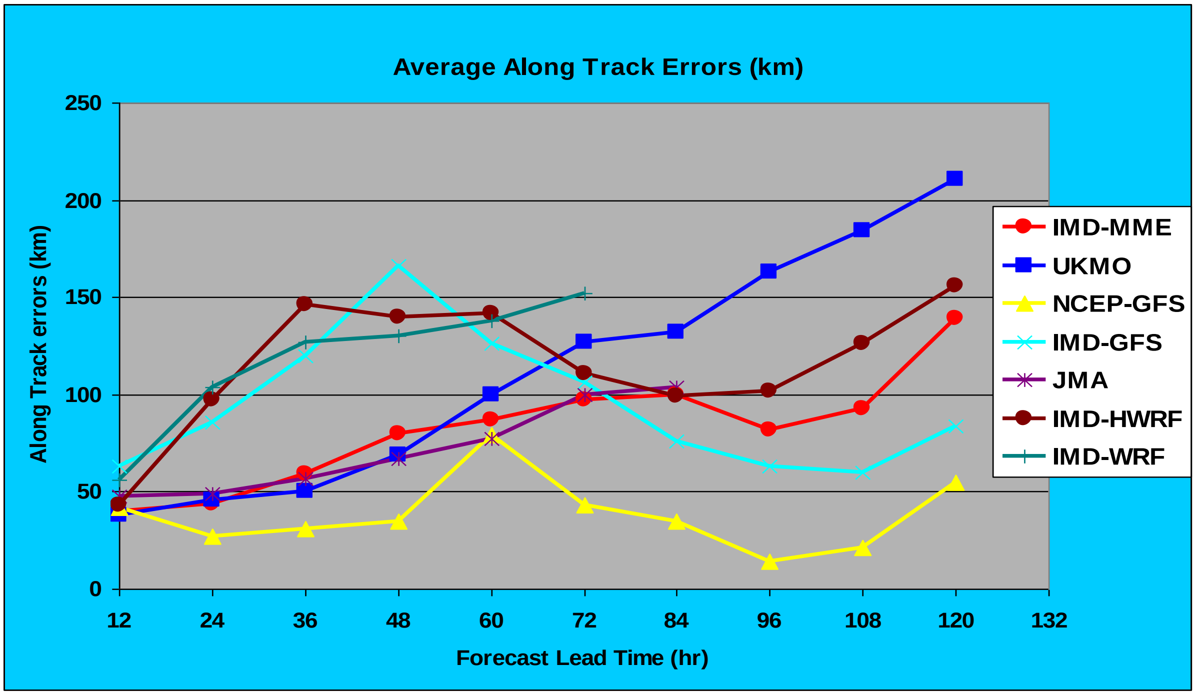


Fig. 3.11: Average along track errors (ATE) of NWP models

Landfall Point Error: Landfall point forecasts errors of NWP model at different forecast lead times (Fig.3. 12) show that some model predicted north of actual landfall point and some predicted south of actual landfall point with a maximum limit upto about 340 km towards north and upto 215 km towards south. Under this wide extent of landfall point forecasts, MME was able to predict near actual landfall point (Gopalpur) consistently (Table-3.10).

Landfall Time Error: Landfall time forecasts errors of NWP model at different forecast lead times (Fig. 3.13) show that some model predicted earlier than actual landfall time and some predicted delayed than actual landfall time with a maximum limit upto 21 hr delayed and upto 6 hr earlier than actual landfall time. Under this wide extent of landfall time forecasts, MME landfall time error was consistently low (Table-3.11).

Table-3.10 Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	5 h	17 h	29 h	41 h	53 h	65 h	77 h	89 h	113 h
UKMO	25	0	24	25	47	69	69	92	-
NCEP GFS	0	0	0	148	61	15	0	25	79
JMA	25	25	0	70	15	161	214	-	-
HWRF	25	94	81	109	166	166	166	342	-
IMD-GFS	70	11	0	25	71	25	15	25	124
WRF-VAR	61	24	0	70	191	-	-	-	-
IMD-MME	0	39	39	0	0	25	35	0	39

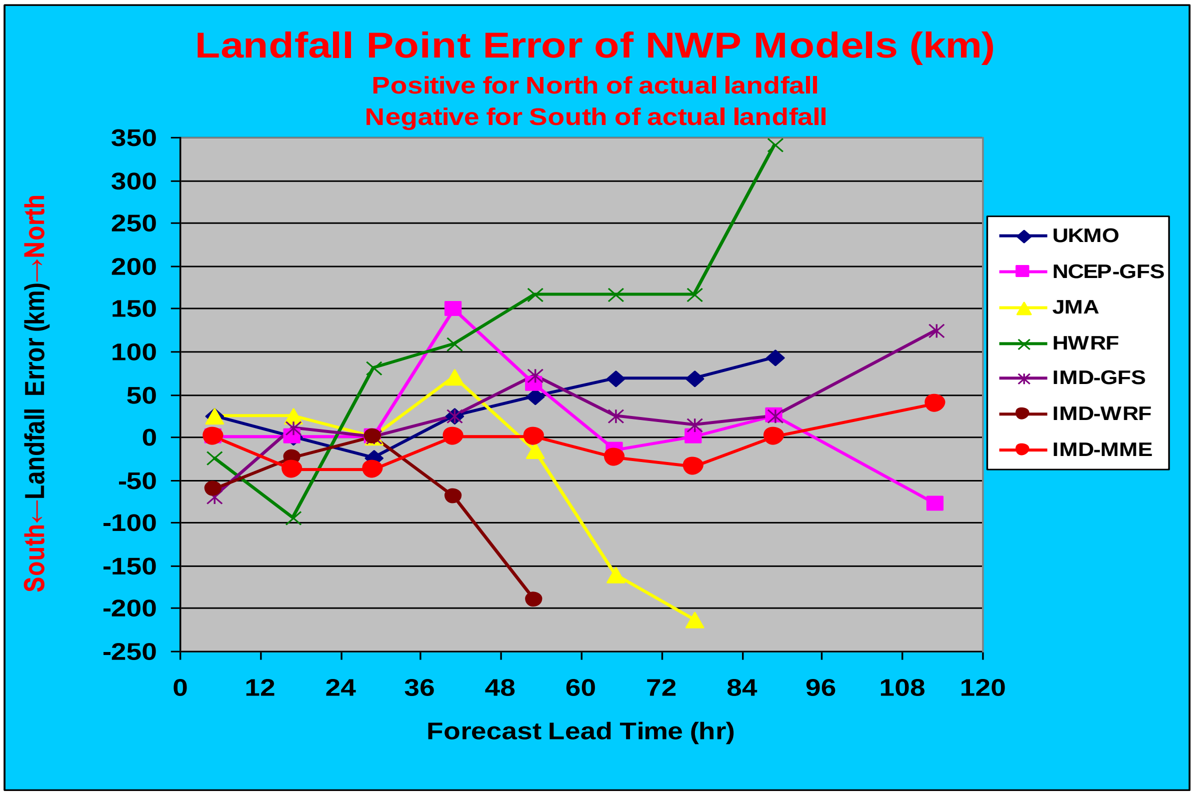


Fig.3. 12: Landfall point error (hr) of Models

Table-3.11 Landfall time forecast errors (hour) at different lead time (hr)('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	5 h	17 h	29 h	41 h	53 h	65 h	77 h	89 h	113 h
UKMO	0	0	-4	-2	+2	+2	+4	+5	-
NCEP GFS	-2	-4	-4	-6	-1	-3	-4	0	+2
JMA	0	-1	+1	+1	+4	-2	+7	-	-
HWRF	-3	+5	+5	+4	+2	-5	0	+7	-
IMD-GFS	+8	+21	+8	+6	+7	+2	+4	-1	+2
WRF-VAR	-5	+13	+13	+6	+13	-	-	-	-
IMD-MME	0	+1	0	+1	+1	+1	+3	+3	+7

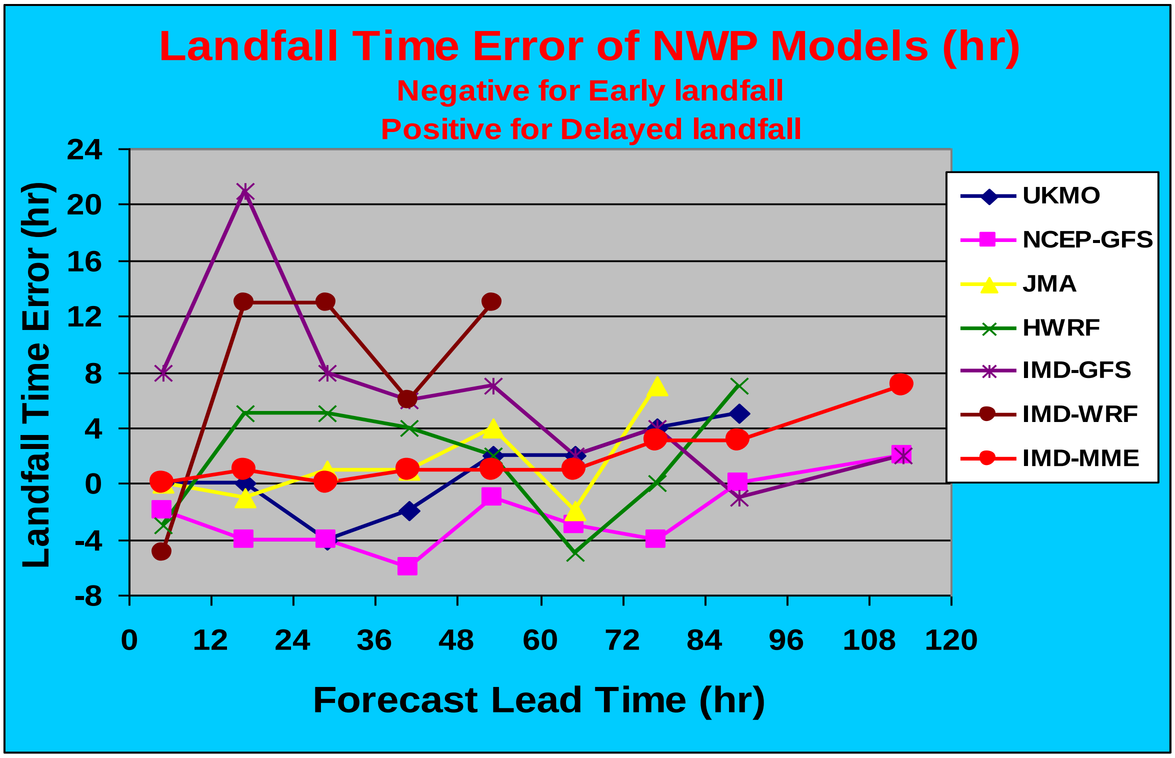


Fig. 3.13: Landfall time error (km) of models at different lead time (hr)

3.3.4 Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig. 3.14 and Fig. 3.15 respectively. Both the SCIP and HWRF model was able to predict the very severe stage of the PHAILIN at all stages of forecast. But none of the two models could predict the non-intensification phase of the PHAILIN from 0300 UTC of 11 October to 1200 UTC of 12 October 2013 during which the cyclone maintained constant intensity of 115 kt. The SCIP model continued to predict intensification and HWRF model continued to predict weakening during this stagnation phase of the very severe cyclone.

Average absolute error (AAE) and Root mean square error (RMSE) of SCIP and HWRF forecast error is presented in the following Table-3.12 and Table-3.13. Intensity forecasts by SCIP, and HWRF shows that SCIP was superior to HWRF up to 48 hour, HWRF was better at 60 h and 72 h forecasts. AAE of SCIP was 31 kt at 60 hr and 37 kt at 72 hr. AAE of HWRF was 28 kt, 19 kt and 11 kt at 60 hr, 72 hr and 84 hr respectively.

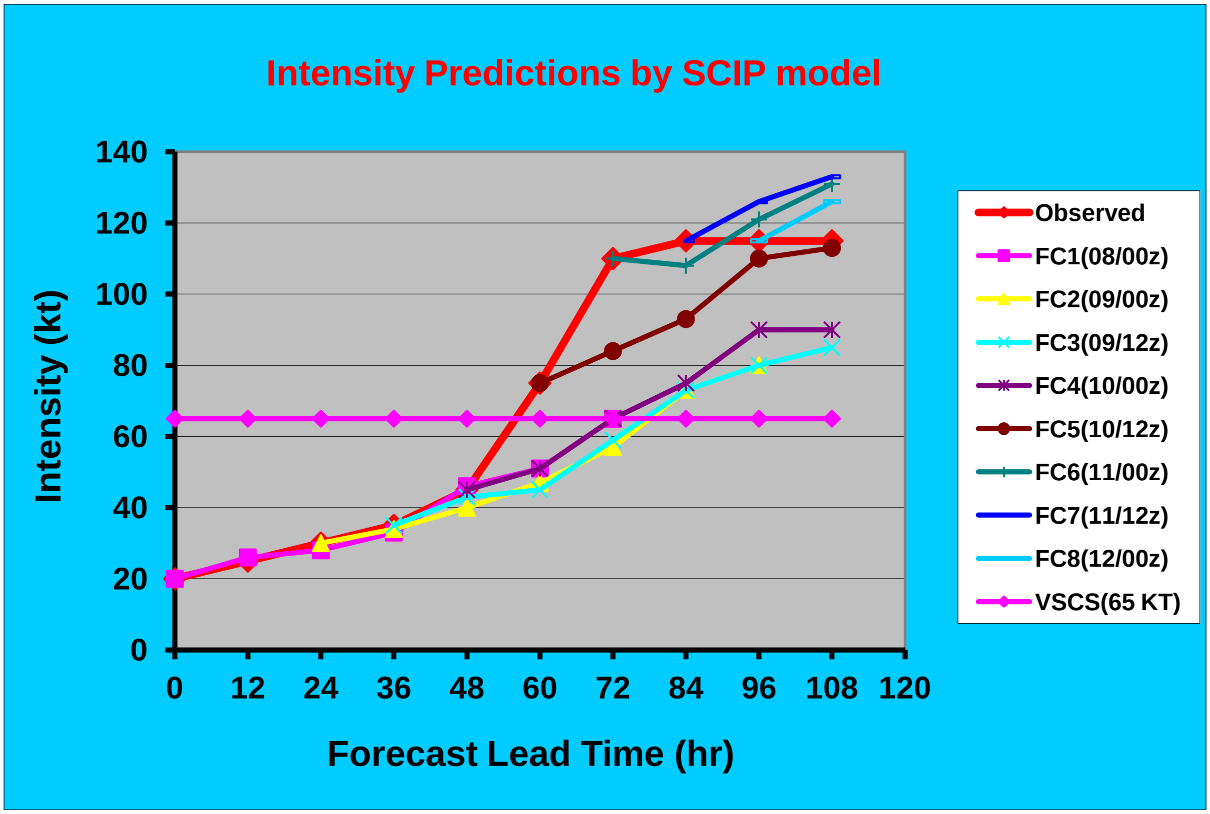


Fig. 3.14. Intensity forecasts of SCIP model

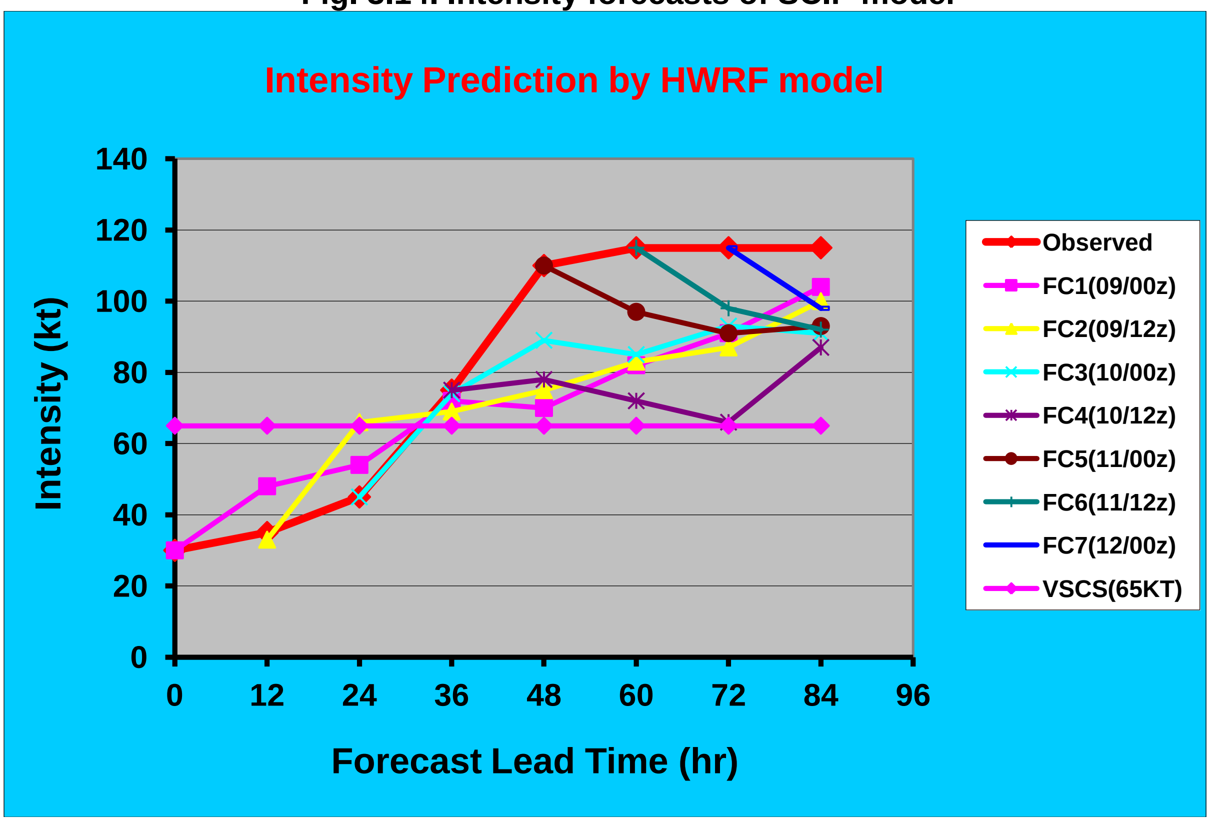


Fig. 3.15. Intensity forecasts of HWRF model

Table-3.12 Average absolute errors (Number of forecasts verified is given in t he parentheses)

(Intensity forecasts prior to landfall (1200 UTC of 12.10.2013) are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	10.4(8)	18.3(7)	23.7(6)	24.6(5)	31.5(4)	36.7(3)	-
IMD-HWRF	17.0(6)	21.0(5)	27.8(5)	30.5(4)	28.3(3)	19.5(2)	11.0(1)

Table-3.13 Root Mean Square (RMSE) errors (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
IMD-SCIP	13.9(8)	23.3(7)	29.6(6)	32.3(5)	32.4(4)	37.2(3)	-
IMD-HWRF	19.0(6)	24.2(5)	31.7(5)	31.2(4)	28.6(3)	20.0(2)	14.9(1)

Landfall intensity predicted by **SCIP** model in 2-3 days before landfall (from initial cyclonic storm stage at 1200 UTC of 09 October 2013) shows that the model could predict the landfall intensity of very severe cyclonic storm with a reasonable success (Fig.3.16).

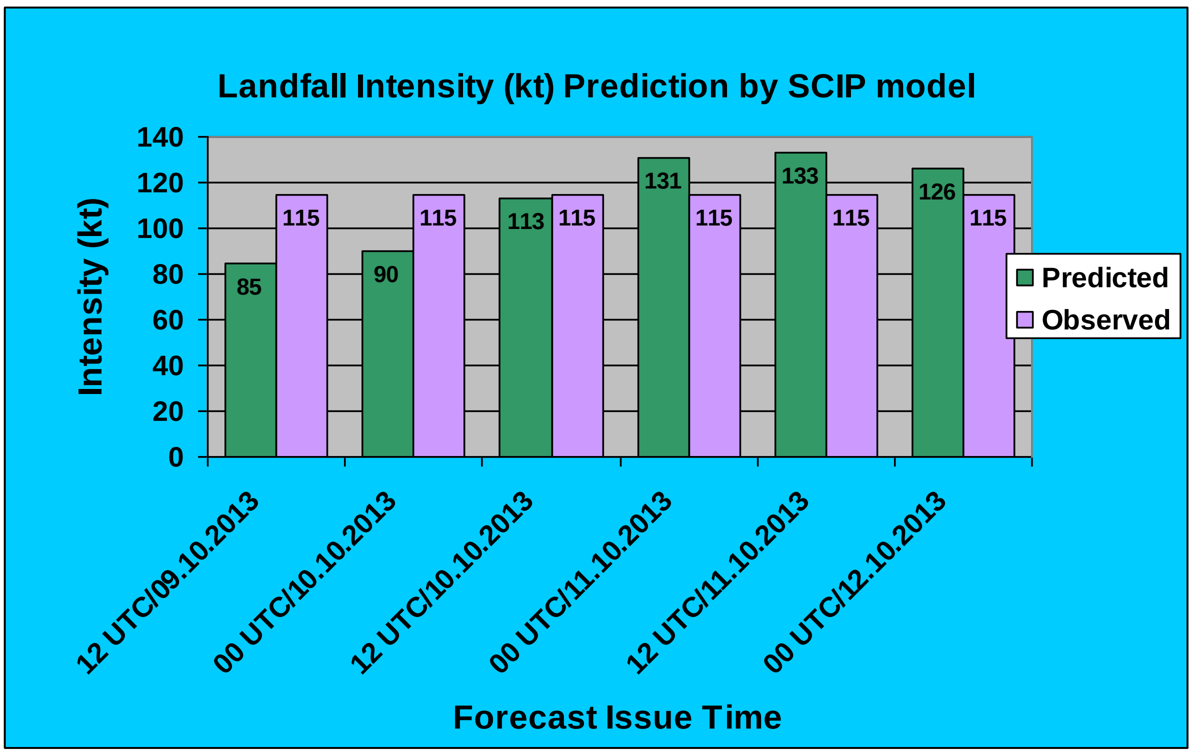


Fig. 3.16: Landfall Intensity (kt) prediction by SCIP Model

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

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour. RI-Index was able to predict **OCCURENCE** as well as **NON-OCCURENCE** of Rapid Intensification of cyclone PHAILIN during its lifetime except forecast for 12 UTC of 09.10.2013 and 00 UTC of 11.10.2013.(Table-3.14

Table-3.14 Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/08.10.2013	9.4 %	VERY LOW	5	NO
00 UTC/09.10.2013	9.4 %	VERY LOW	15	NO
12 UTC/09.10.2013	**9.4 %**	**VERY LOW**	**40**	**YES**
00 UTC/10.10.2013	**72.7 %**	**HIGH**	**65**	**YES**
12 UTC/10.10.2013	**72.7 %**	**HIGH**	**40**	**YES**
00 UTC/11.10.2013	**72.7 %**	**HIGH**	**5**	**NO**
12 UTC/11.10.2013	32.0 %	MODERATE	0	NO

3.3.6 Decay after landfall

Decay (after landfall) prediction curve (6-hourly up to 30 hr) (Fig. 3.17) shows slightly fast decay compared to observed decay.

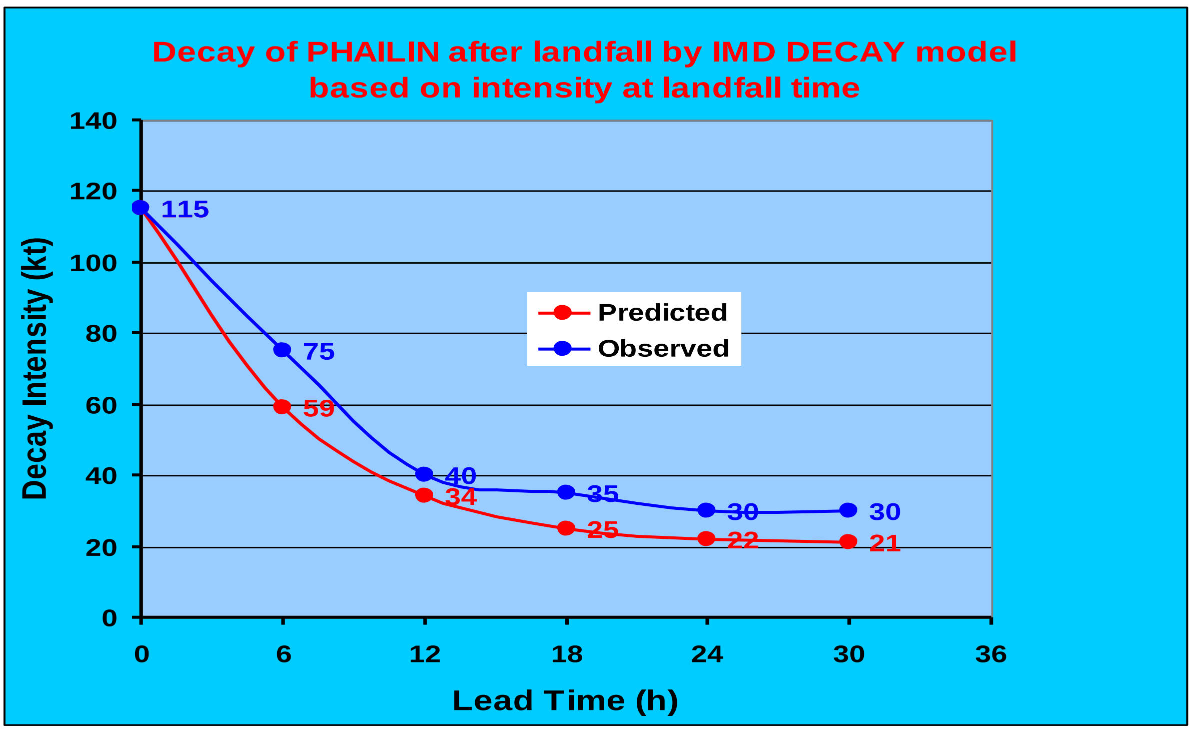


Fig. 3.17. Decay after landfall

3.3.7. Ensemble track and Strike Probability forecast

Ensemble track and strike probability forecast based on 00 UTC 10.10.2013 and 12 UTC 10.10.2013 shows that ECMWF, UKMO, MSC and NCEP all predicted towards Odisha coast(Fig.3.18).

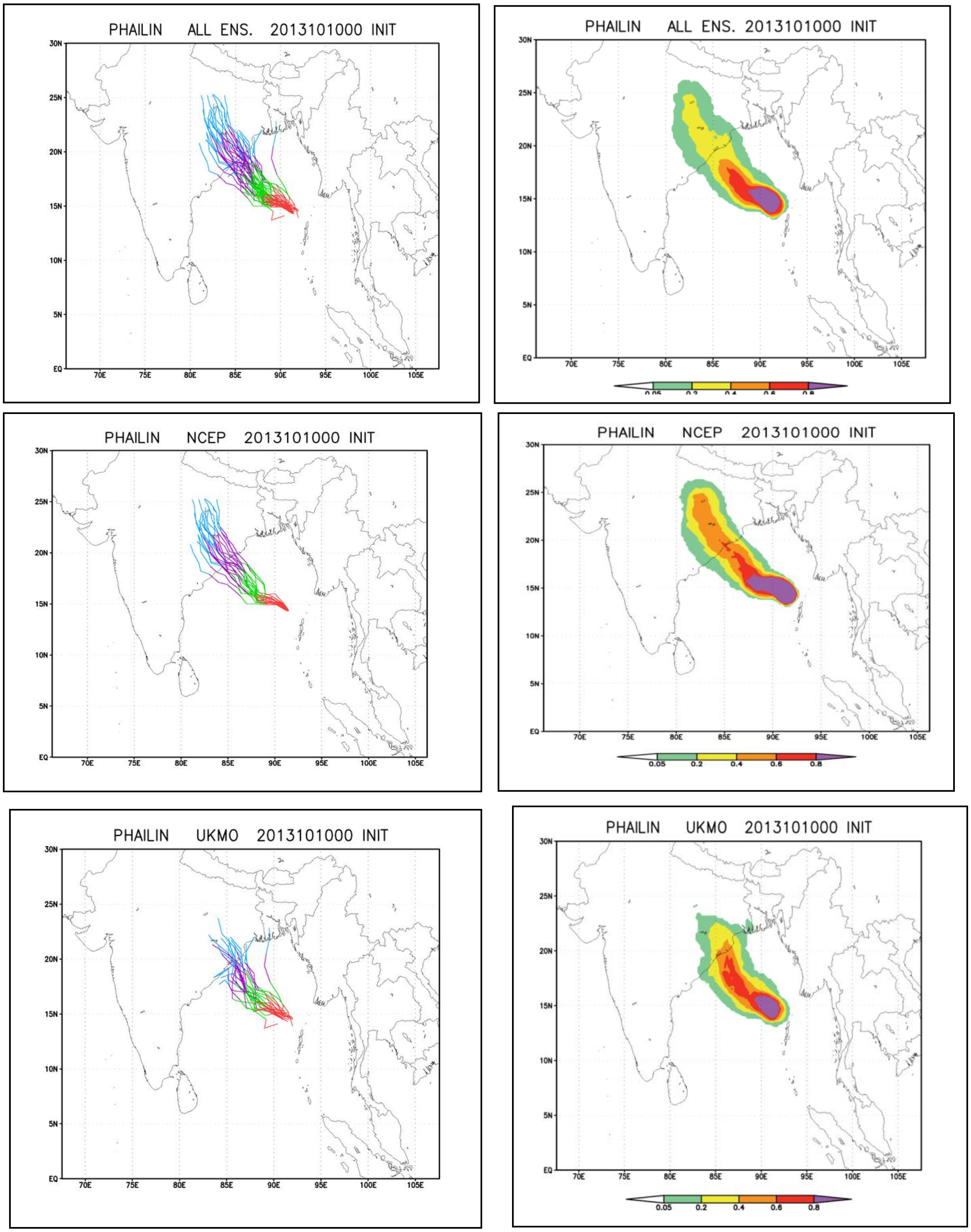


Fig. 3.18(a) Ensemble track and Strike Probability forecast based on 00 UTC of 10 Oct. 2013

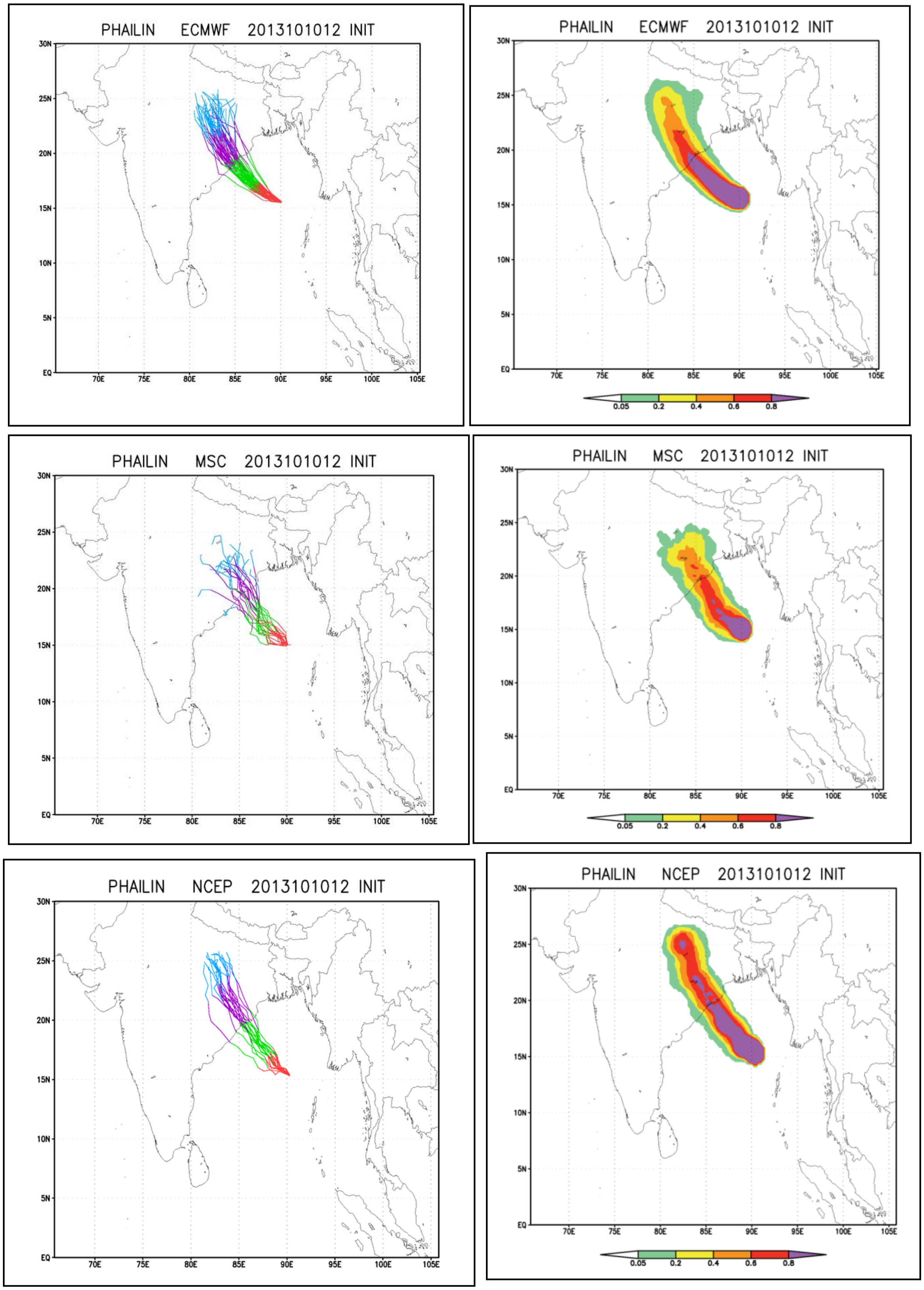
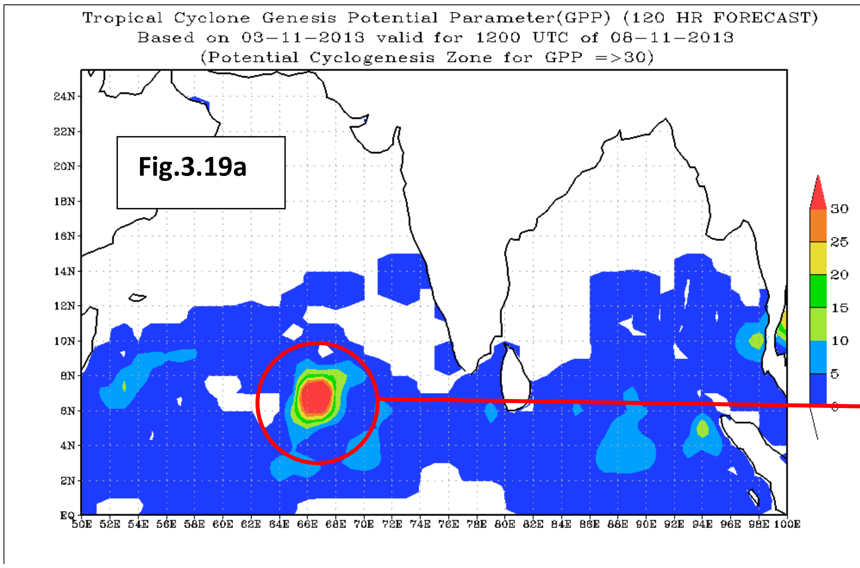


Fig. 3.18(b) Ensemble track and Strike Probability forecast based on 12 UTC of 10 Oct. 2013

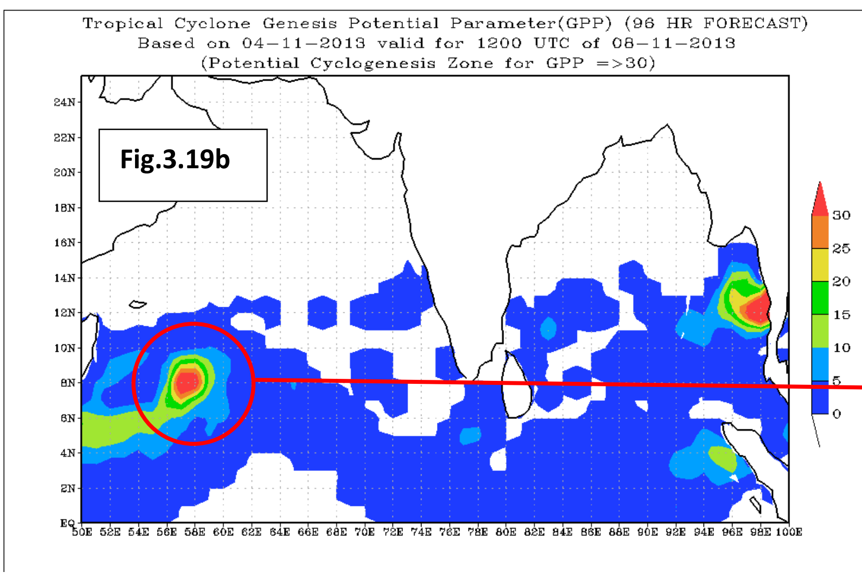
3.4 'Deep Depression' over the Arabian Sea during (8-11) November 2013

3.4.1. *Grid point analysis and forecast of GPP*

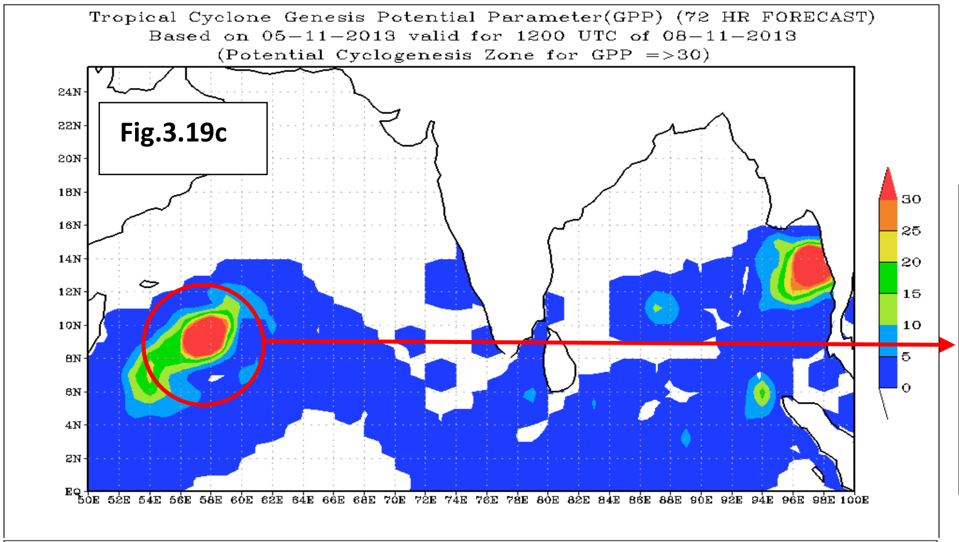
Grid point analysis and forecasts of GPP (Fig.3.19(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation. However, contrary to prediction, the did not intensify to a cyclone



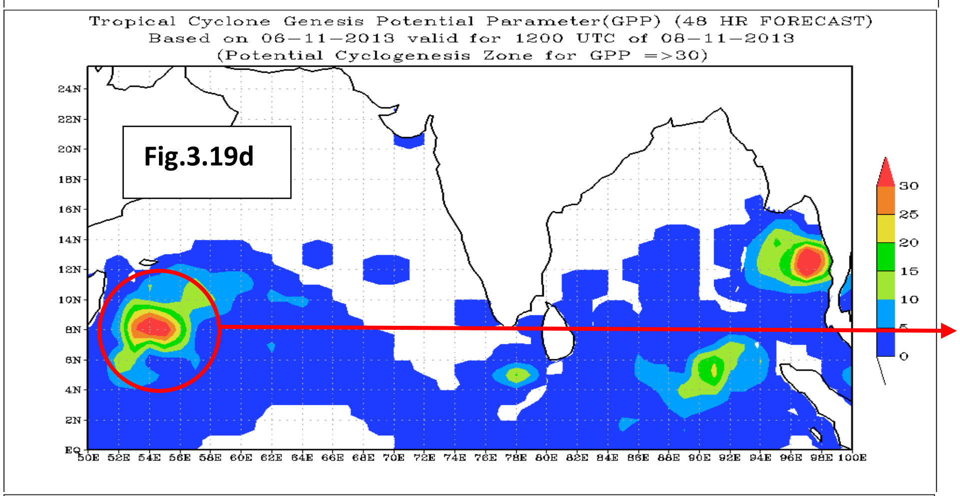
120 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



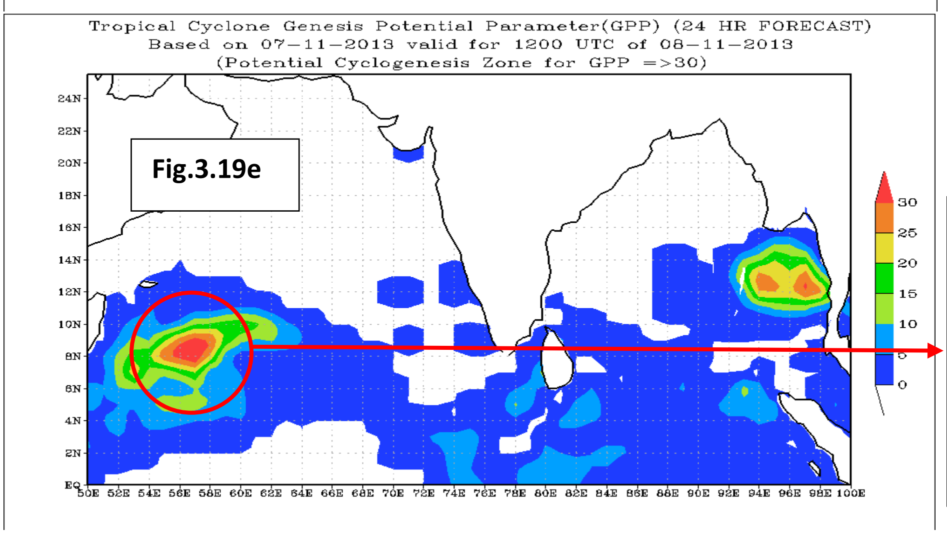
96 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



72 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



24 hour forecast of GPP valid for 12 UTC 08 October 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.

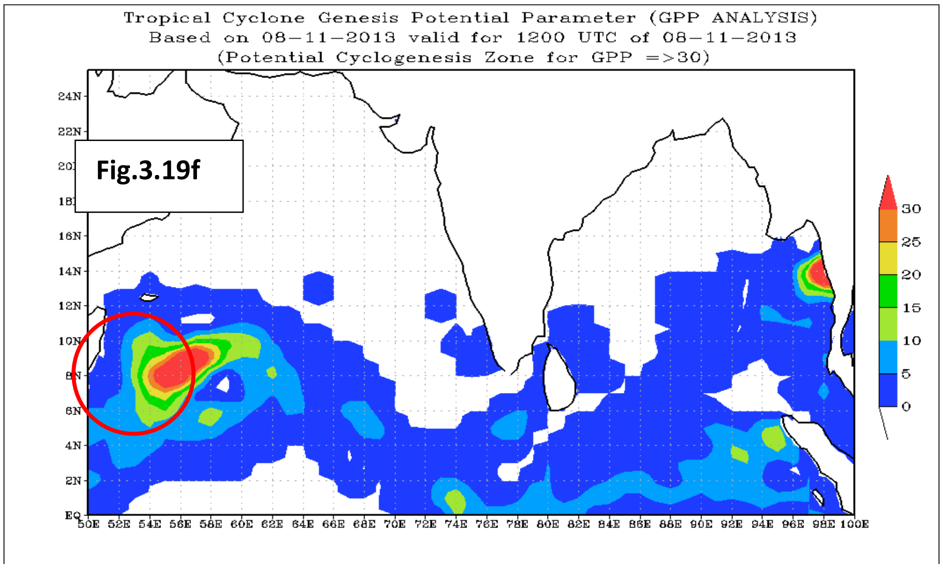


Figure 3.19(a-f): Predicted zone of cyclogenesis

3.4.2 Area average analysis of GPP

Analysis and forecasts of GPP (Fig.3.20(a-b)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0) and weakening in the later phase.

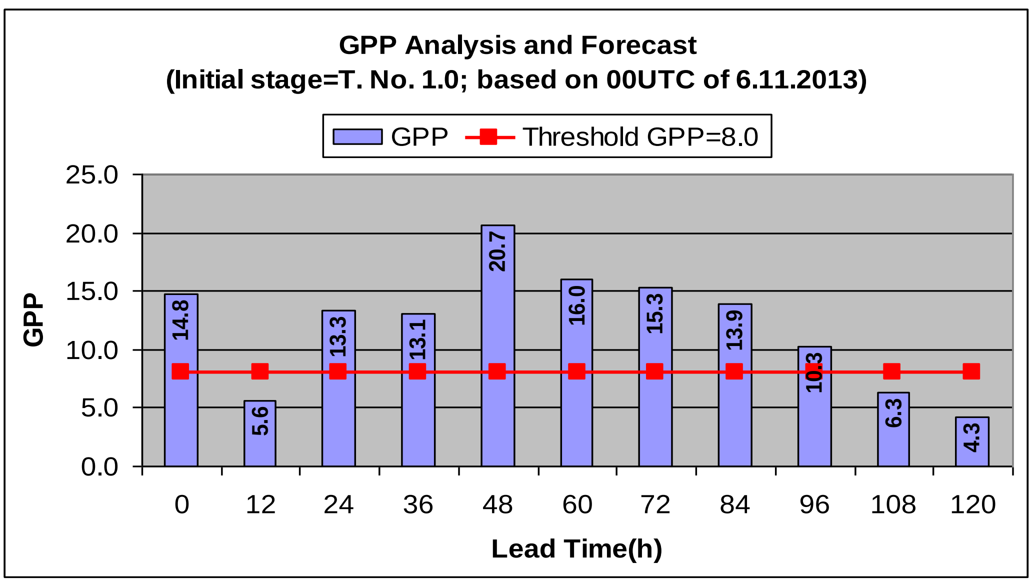


Fig3.20a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (T.No.-1.0) indicated its potential to intensify into a cyclone and weakening in the later phase.

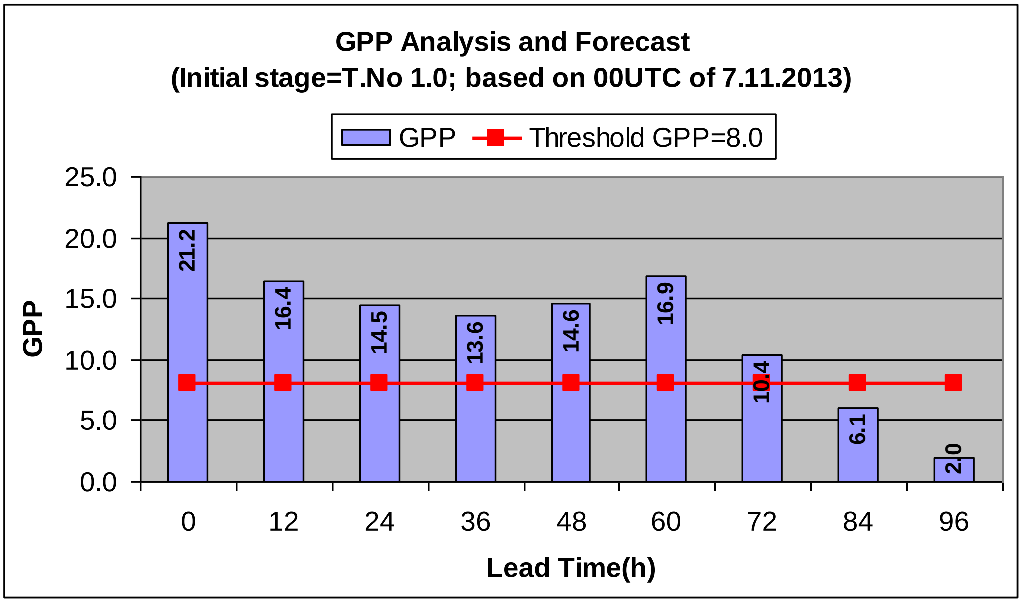


Fig3.20b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (T.No. 1.0) indicated its potential to intensify into a cyclone and weakening in the later phase.

Fig. 3.20(a-b) Area average analysis of GPP

3.4.3 Track prediction

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 3.15, Table 3.16 and Table 3.17 respectively. The landfall point error (km) and landfall time (hour) is presented in Table-3.18 and Table-3.19 respectively. The model forecasts track based on different initial conditions along with the observed track is depicted in Fig. 3. 21.

The average DPE was highest for JMA (about 250 km at 12 h to 530 km at 48 h)(Fig. 3.22). Average DPE was lowest for MME (about 50 km at 12 h to 130 km at 48 h. The DPE of all models are shown in Fig. 3.22.

The average CTE of all models is shown in Fig.3.23. The CTE was lowest for IMD-GFS and MME at 24h (50 km) and for 36h (10km) and 48h (15km) UKMO was lowest.

The average ATE was lowest for MME (about 6 km at 12 h to 50 km at 48 h) (Table-3.17). The ATE of all models is shown in Fig. 3.24.

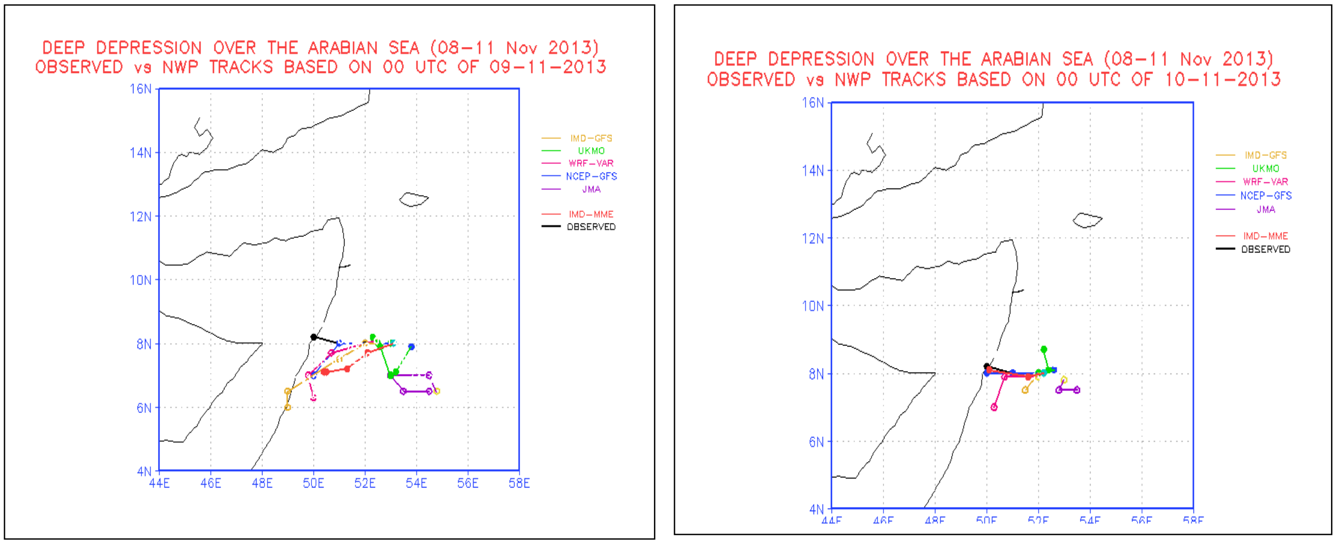


Fig. 3.21. Model forecasts track based on different initial conditions

Table-3.15 Average track forecast errors (DPE) in km (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-GFS	39(2)	119(2)	276(1)	268(1)
IMD-WRF	91(2)	155(2)	219(1)	211(1)
JMA	251(2)	320(2)	322(1)	531(1)
NCEP-GFS	55(2)	89(2)	156(1)	133(1)
UKMO	160(2)	247(2)	176(1)	253(1)
IMD-MME	51(2)	55(2)	114(1)	130(1)

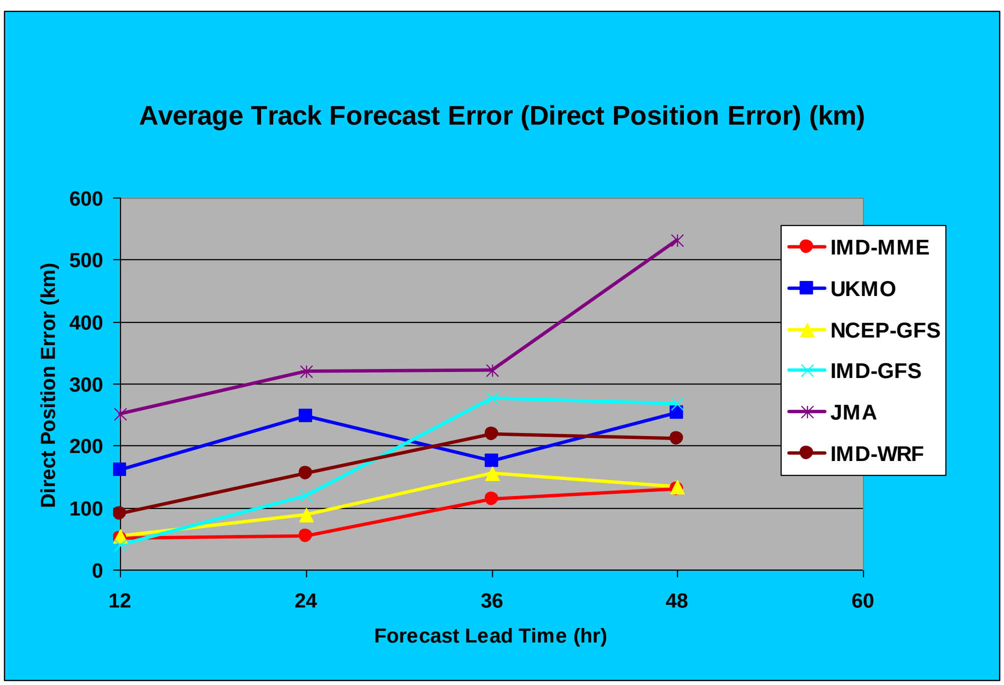


Fig. 3.22: Average track forecast errors (DPE) of NWP models

Table-3.16. Average cross track error (CTE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-GFS	39	49	166	251
IMD-WRF	34	117	189	211
JMA	158	56	167	154
NCEP-GFS	1	66	111	133
UKMO	127	107	11	17
IMD-MME	50	49	100	119

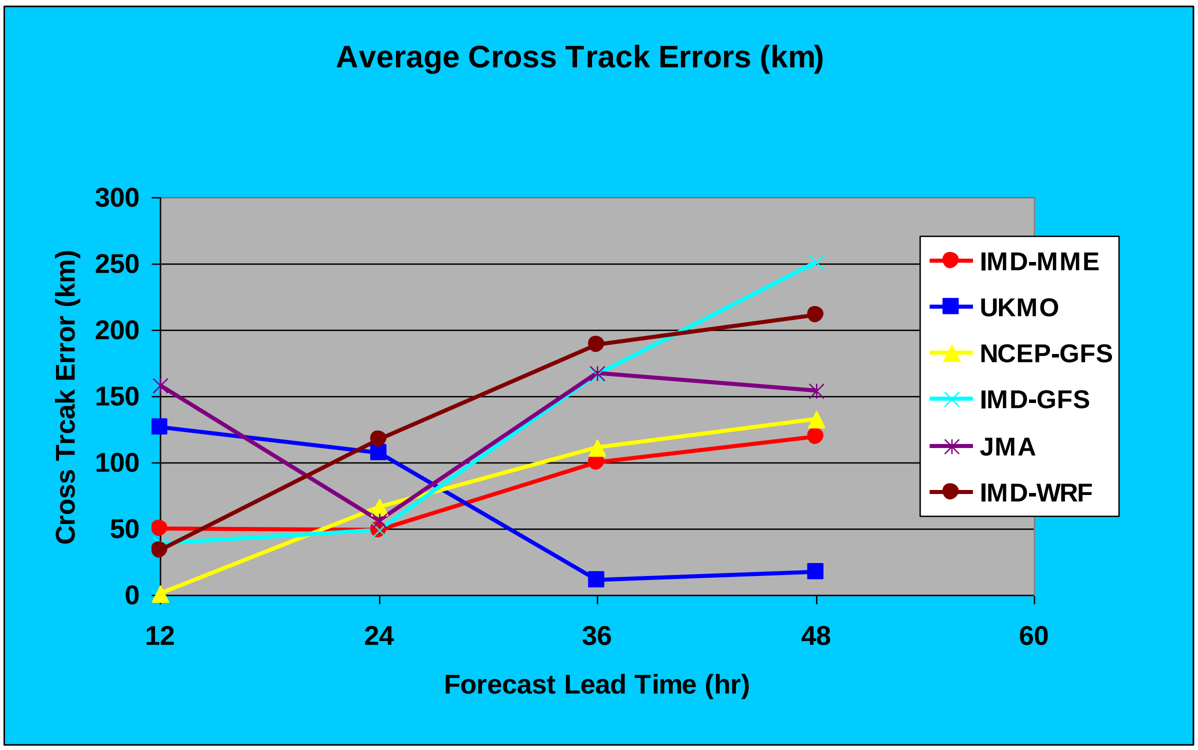


Fig. 3.23 Average cross track errors (CTE) of NWP models

Table-3.17 Average along track error (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-GFS	0	89	221	95
IMD-WRF	72	96	111	13
JMA	138	307	276	508
NCEP-GFS	55	57	111	8
UKMO	66	223	176	252
IMD-MME	6	23	55	52

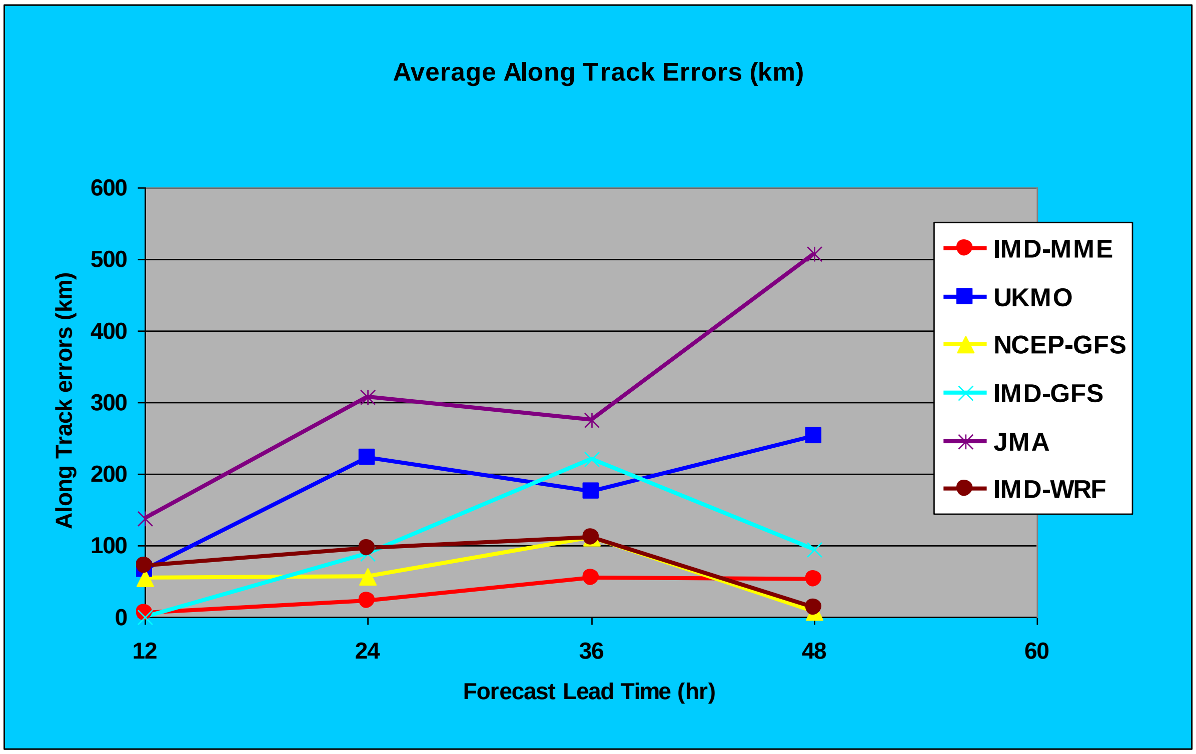


Fig. 3.24: Average along track errors (ATE) of NWP models

Table-3.18 Landfall point forecast errors (km) of NWP Models at different lead time (hour)Landfall time forecast errors (hr) ('+' for North, '-' for South, LF = landfall)

Forecast Lead Time (hour) →	24 h	48 h
UKMO	No LF	No LF
NCEP GFS	-22	-179
JMA	No LF	No LF
IMD-GFS	-278	-219
WRF-VAR	No LF	No LF
IMD-MME	-16	-160

The landfall error was 160 km for IMD-MME in 48 hrs lead period forecast and the time error was 7 hrs. for the same lead period. Many NWP models could not predict the landfall for this system.

Table3.19 Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour)	24 h	48 h
UKMO	No LF	No LF
NCEP GFS	00:00	03:00
JMA	No LF	No LF
IMD-GFS	+12:00	-12:00
WRF-VAR	No LF	No LF
IMD-MME	00:00	+07:00

3.4.4 Intensity prediction

Average absolute error (AAE) and Root mean square error (RMSE) of SCIP forecast error is presented in the following Table-3.21. AAE of SCIP was 3 kt at 12 hr and 12 kt at 48 hr. The Table shows that the SCIP model was able to predict the intensity.

Table-3.20 Average absolute errors (Number of forecasts verified is given in the parentheses)

(Intensity forecasts prior to landfall are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr
AAE	3.0(2)	2.5(2)	7.0(1)	12.0(1)
RMSE	3.6(2)	2.9(2)	7.0(1)	12.0(1)

3.4.5 Probability of Rapid intensification (by RI-Index)

Rapid intensification (RI) is defined as: Increase of intensity by 30 kts or more during subsequent 24 hour. RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of the DEPRESSION during its lifetime

Table-3.21 Probability of Rapid intensification

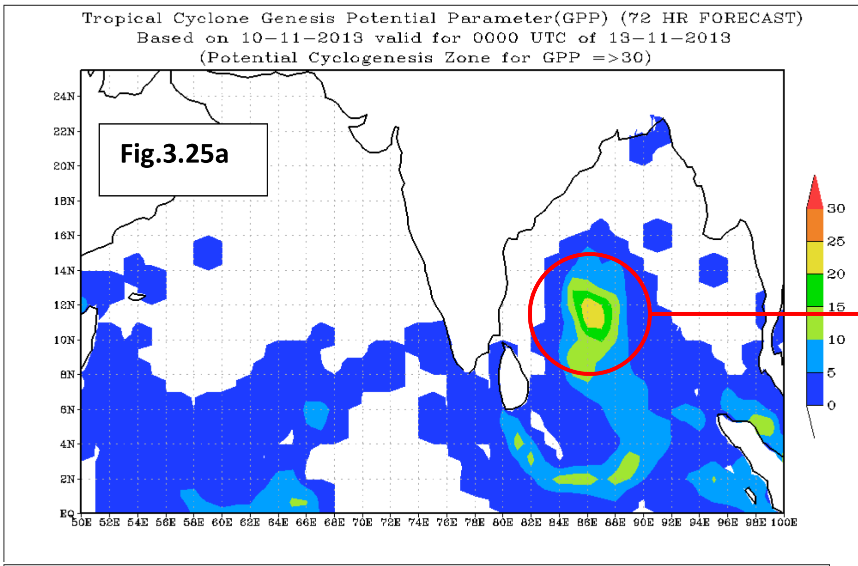
Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/09.11.2013	5.2 %	VERY LOW	0	NO
00 UTC/10.11.2013	2.6 %	VERY LOW	0	NO

3.5 'Depression' over the Bay of Bengal (13-16) November 2013

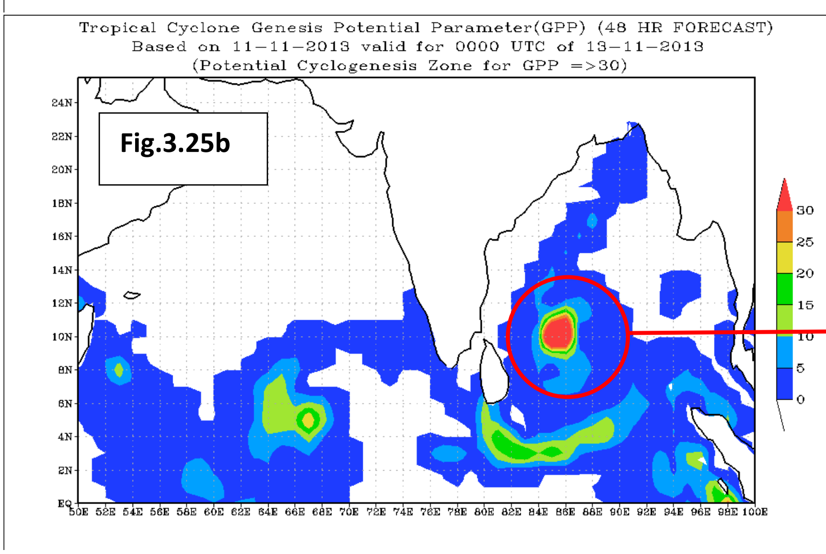
3.5.1 Grid point analysis and forecast of GPP

Figure 3.25(a-d) below shows the predicted zone of formation of cyclogenesis. Grid point analysis and forecasts of GPP (Fig.3.31(a-d)) shows that it was able to predict the

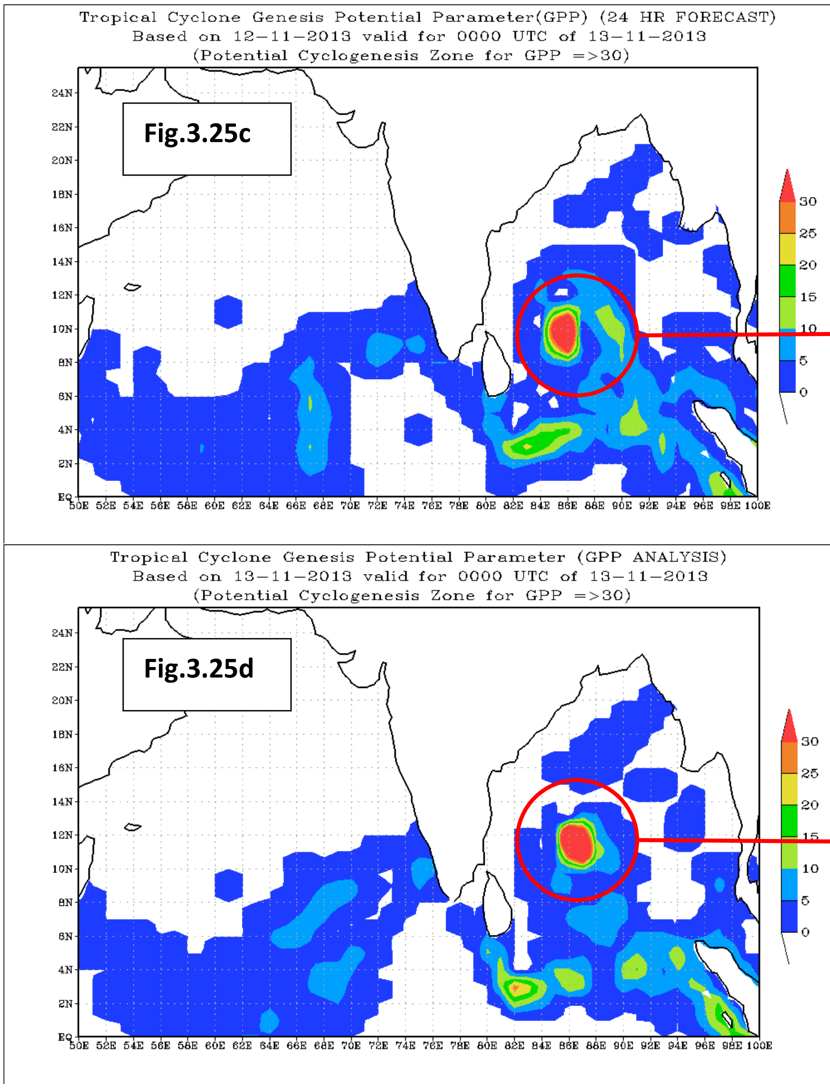
formation and location of the system before 72 hours of its formation. However unlike prediction the system did not intensify into a cyclone.
(Product available athttp://www.imd.gov.in/section/nhac/dynamic/Analysis1.htm)



72 hour forecast of GPP valid for 00 UTC 13 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 00 UTC 13 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



24 hour forecast of GPP valid for 00 UTC 13 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.

Analysis of GPP on 00 UTC 23 November 2013 indicates the zone of cyclogenesis.

Figure 3.25(a-d): Predicted zone of cyclogenesis.

3.5.2 *Area average analysis of GPP*

Analysis and forecasts of GPP (Fig.3.26(a-e)) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5). 36h to 72h forecasts based on 00 UTC of 13.11.2013 indicated non-intensification of the system and analysis and forecasts of based on 00 UTC of 13.11.2013 and 15.11.2013 indicated its potential to intensify into a marginal cyclone, though the system ended as a depression.

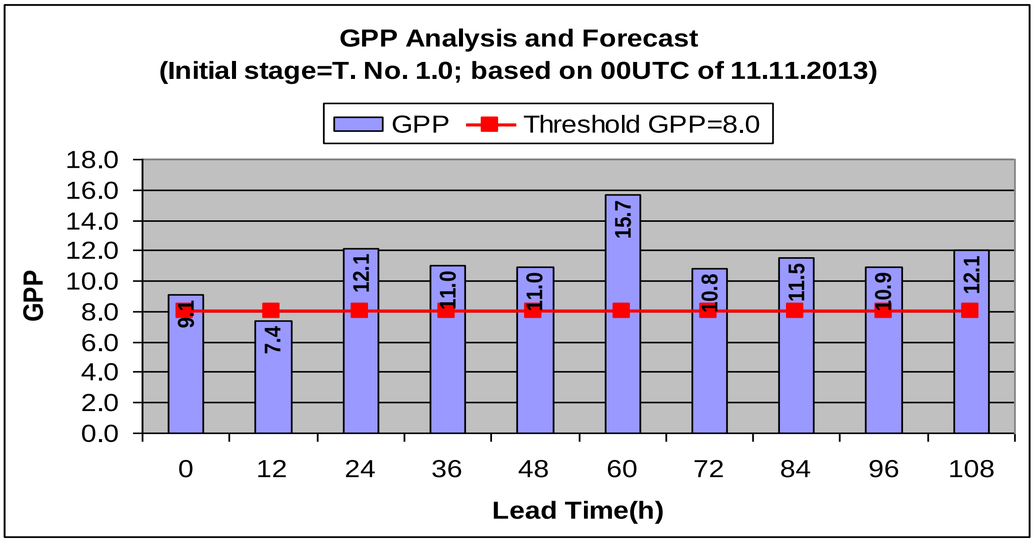


Fig3.26a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No.-1.0**) indicated its potential to intensify into a cyclone except at 12 h.

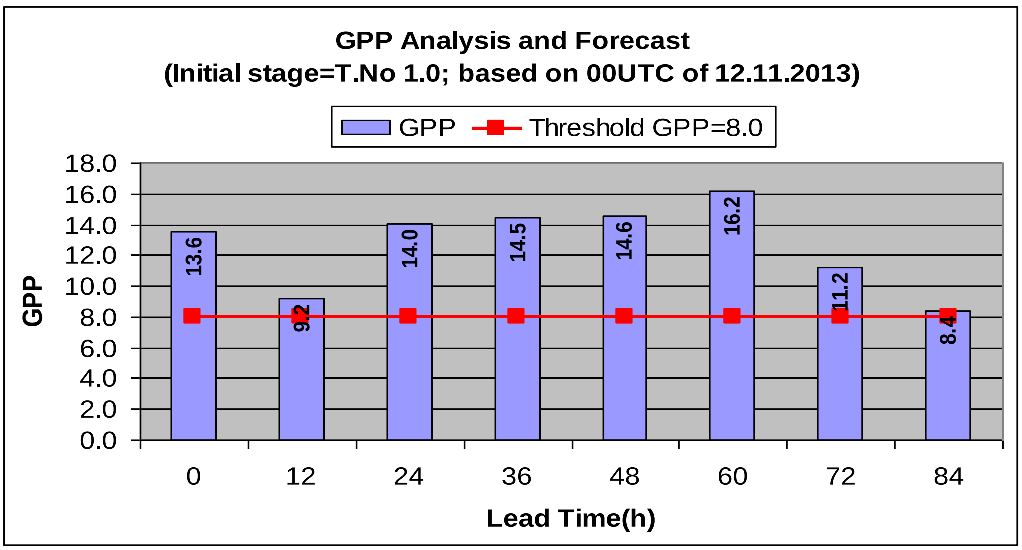


Fig3.26b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

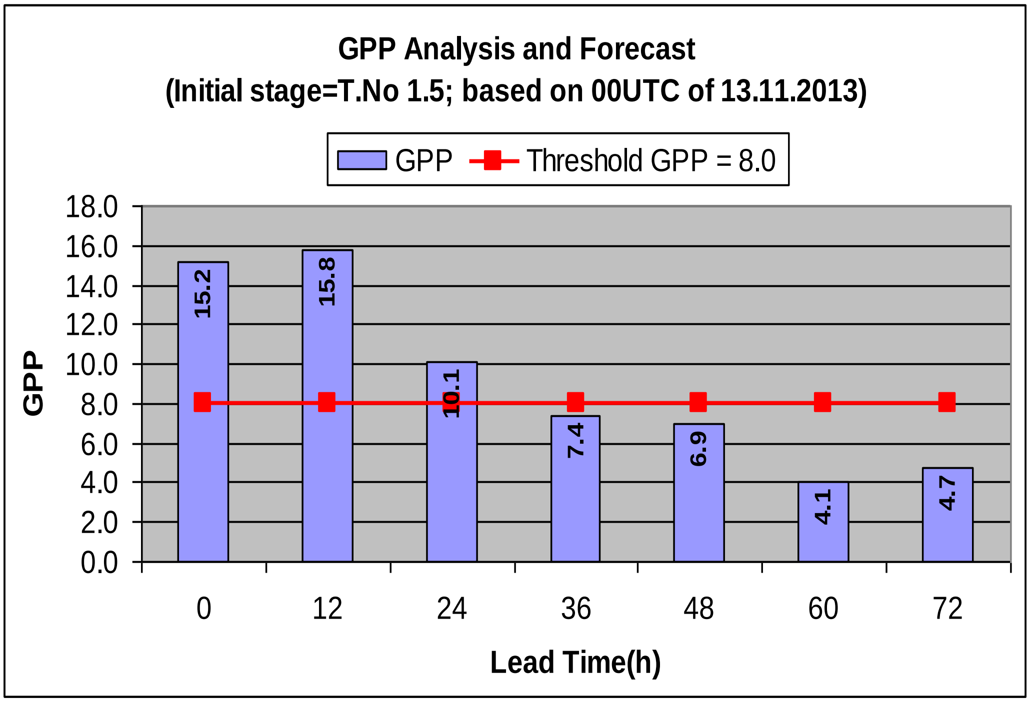


Fig3.26c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at early stage of development (**T.No. 1.5, & up to 24h**) indicated its potential to intensify into a cyclone. 36h to 72h forecasts indicated non-intensification of the system.

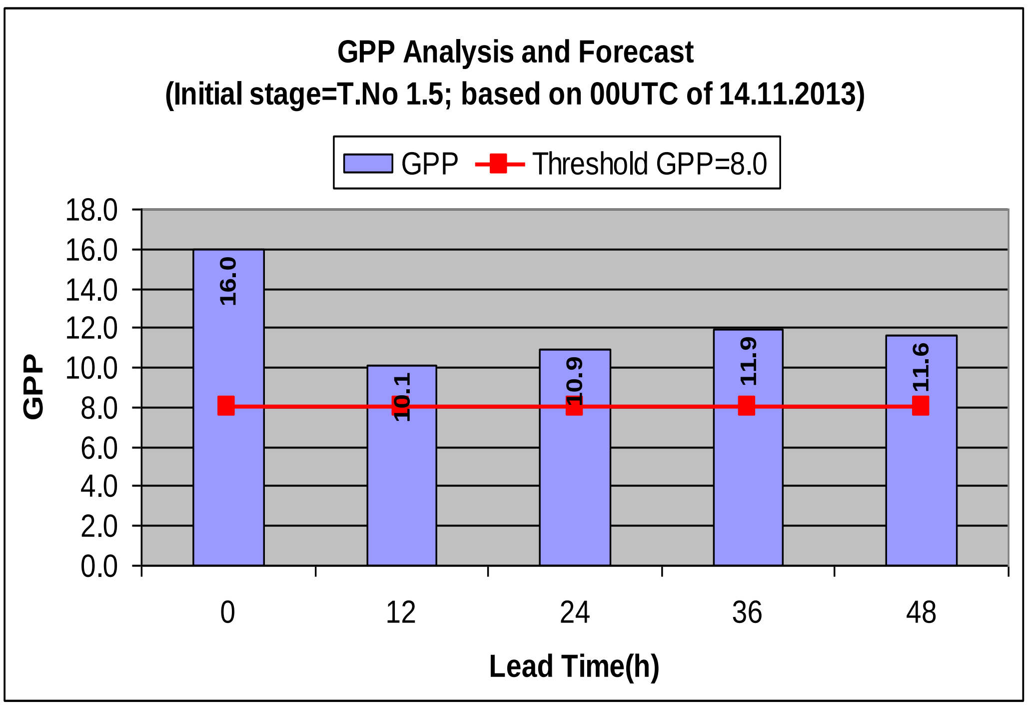


Fig 3.26d: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at early stage of development (**T.No. 1.5**) indicated its potential to intensify into a cyclone.

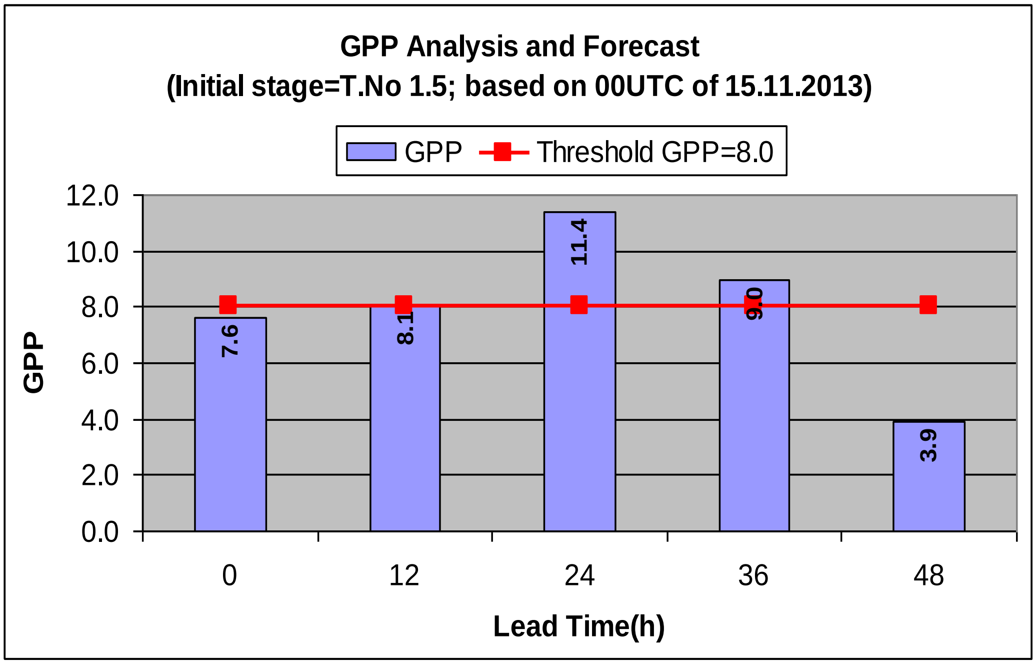


Fig3.26e: Analysis and forecasts of GPP at early stage of development (**T.No. 1.5**) indicated its potential to intensify into a marginal cyclone.

Fig. 3. 26(a-e) Area average analysis of GPP

(Product available at http://www.imd.gov.in/section/nhac/dynamic/gpp.pdf)

3.5.3 Track prediction

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the MME forecast are presented in the Table3.22, Table 3.23 and Table 3.24 respectively. The landfall point error (km) and landfall time error(hour) is presented in Table 3.25 and Table 3.26 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 3.27.

The average DPE of MME was lowest at all forecast hours except at 24h and 72h. The DPE for MME was about 65 km at 12 h to 85 km at 84 h (Table-3.22) with highest at 36h (160km). The DPE of all models are shown in Fig. 3.28.

The average CTE was lowest for MME up to 48 h (45 km to 115 km) and comparable to UKMO and JMA at 60h, 72h and 84h (105 km to 25 km) (Table-3.23). The CTE of all models are shown in Fig. 3.29.

The average ATE was lowest for NCEP-GFS and MME was comparable to NCEP-GFS and below 100km at all forecast hours (Table-3.24). The ATE of all models is shown in Fig. 3.30.

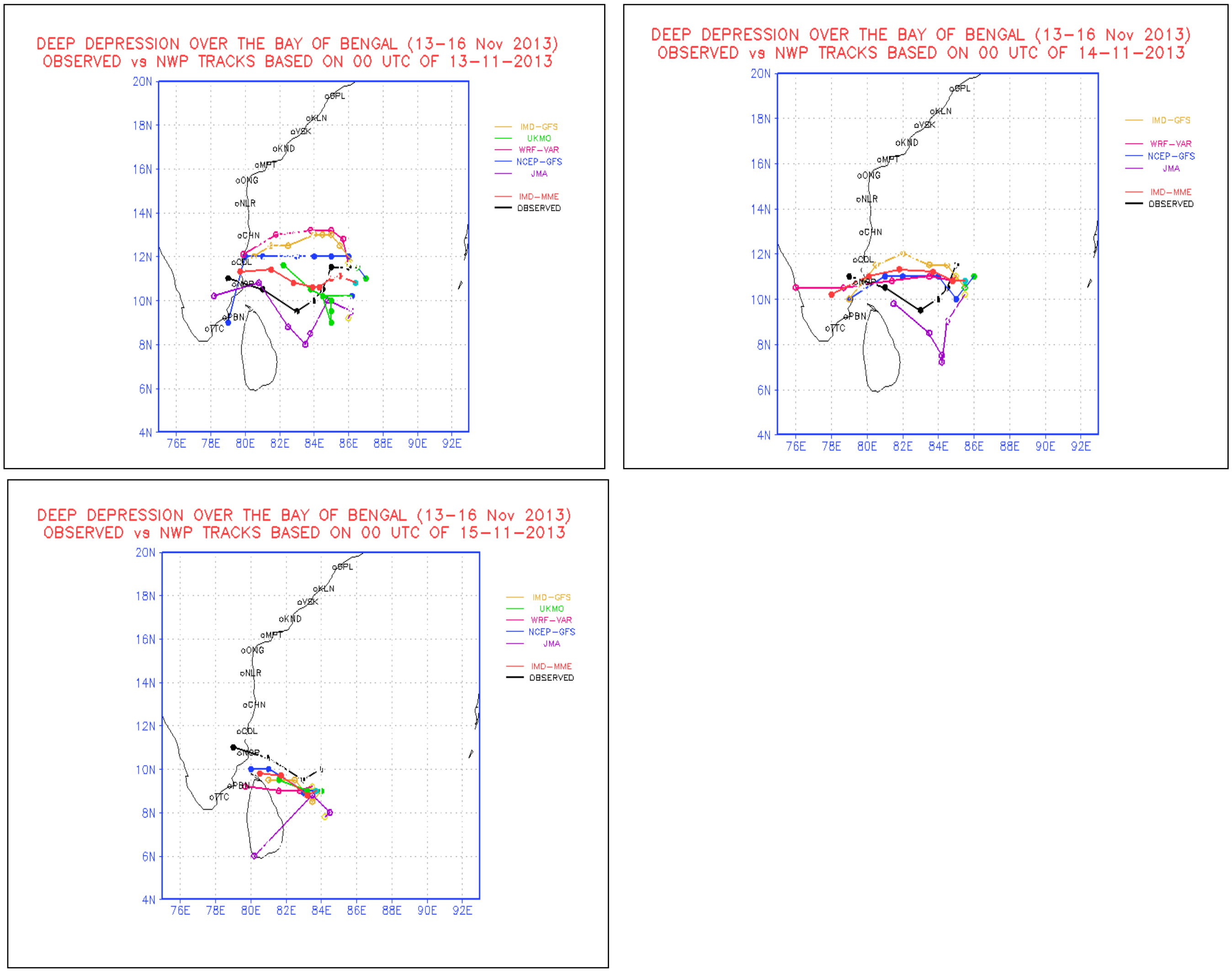


Fig. 3.27. Model forecast tracks based on different initial conditions

Table-3.22. Average track forecast errors (DPE) in km (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-GFS	120(3)	180(3)	284(3)	229(2)	224(2)	229(1)	198(1)
IMD-WRF	85(3)	164(3)	250(3)	331(2)	389(2)		
JMA	208(3)	271(3)	355(3)	291(2)	200(2)	40(1)	125(1)
NCEP-GFS	63(3)	74(3)	177(3)	152(2)	232(2)	199(1)	222(1)
UKMO	139(2)	203(2)	175(1)	123(1)	226(1)	306(1)	355(1)
IMD-MME	66(3)	103(3)	158(3)	90(2)	143(2)	114(1)	83(1)

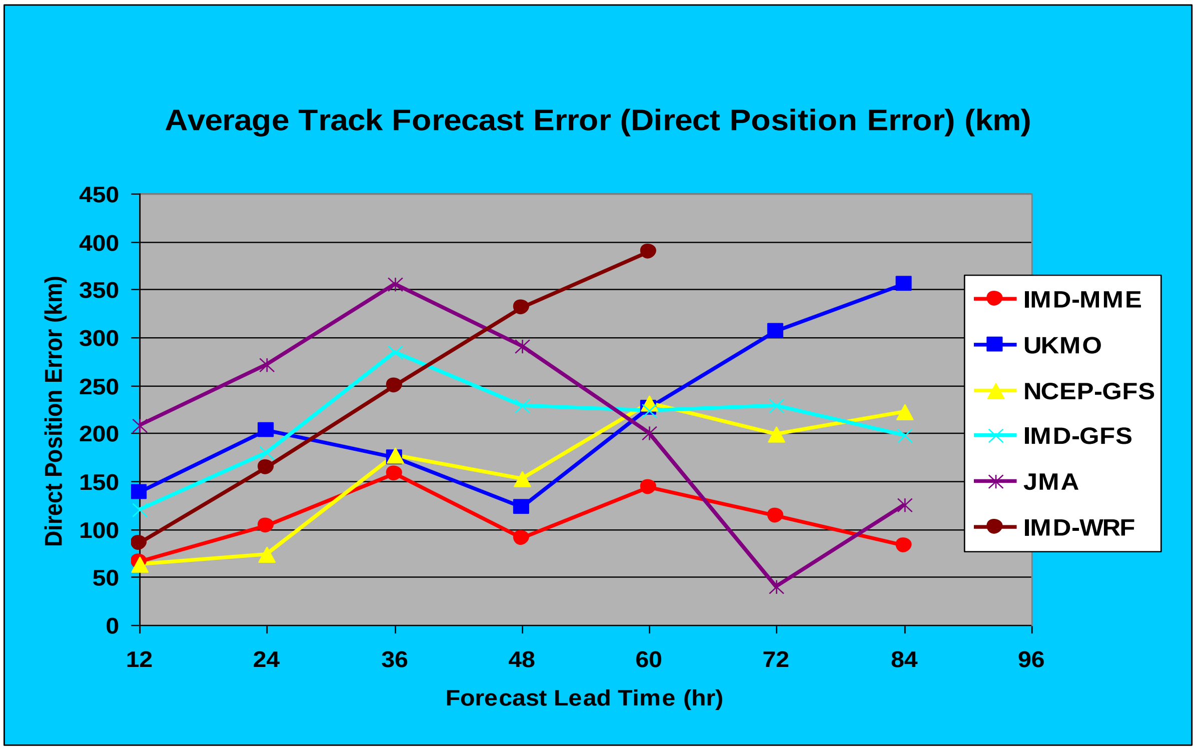


Fig. 3.28: Average track forecast errors (DPE) of NWP models

Table-3.23. Average cross track error (CTE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-GFS	95	129	213	203	213	208	98
IMD-WRF	66	150	236	237	222	-	-
JMA	173	165	311	222	98	37	81
NCEP-GFS	60	57	152	150	230	185	222
UKMO	102	188	173	105	63	57	40
IMD-MME	46	77	117	71	107	88	27

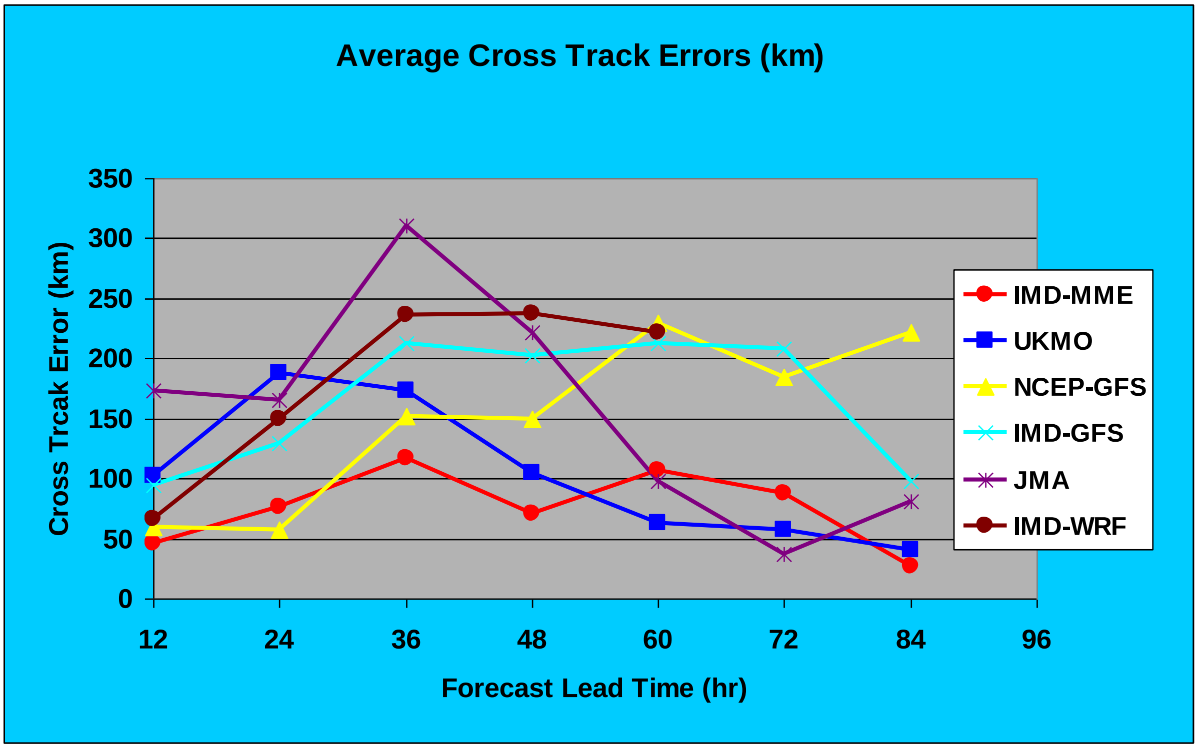


Fig. 3.29: Average cross track errors (CTE) of NWP models

Table-3.24. Average along track error (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-GFS	52	97	166	100	66	96	172
IMD-WRF	40	52	67	135	237		
JMA	81	191	158	187	173	15	94
NCEP-GFS	17	34	67	19	28	75	18
UKMO	85	42	27	64	217	301	353
IMD-MME	38	61	84	53	86	73	79

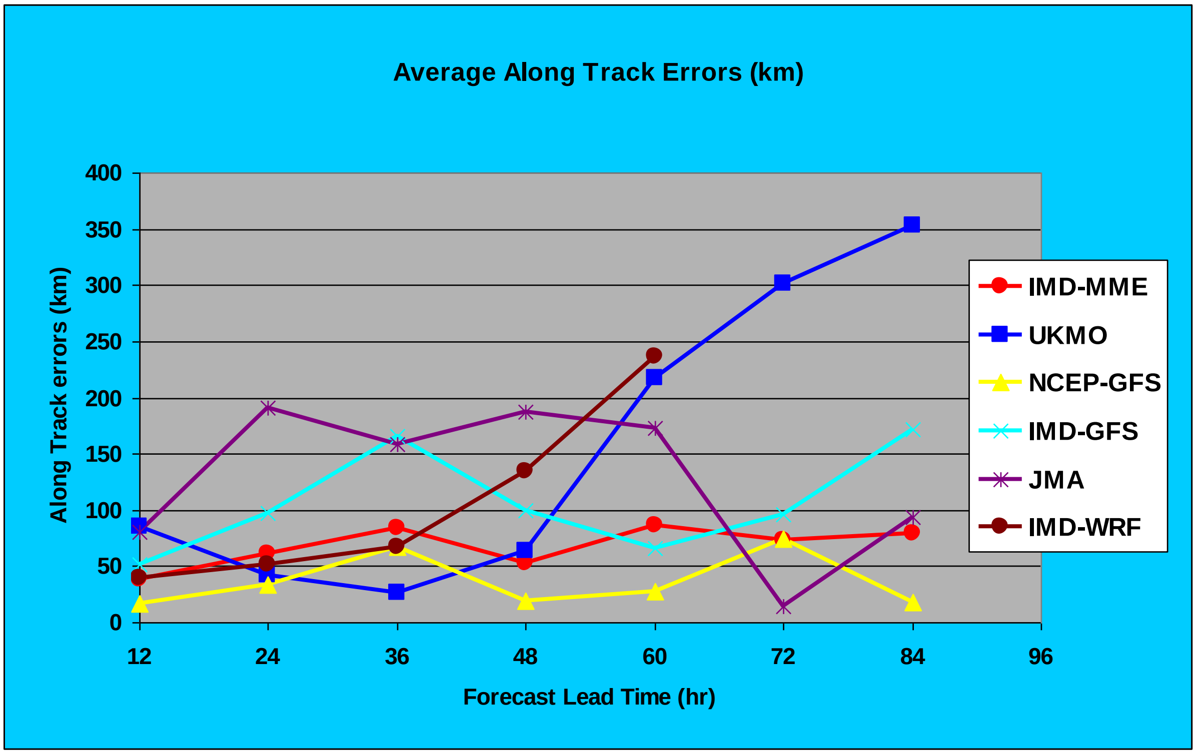


Fig. 3.30: Average along track errors (ATE) of NWP models

Table-3.25. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	31 h	55 h	79 h	103 h
UKMO	No LF	-	No LF	No LF
NCEP GFS	-148	-55	+112	+148
JMA	No LF	No LF	-45	No LF
IMD-GFS	No LF	-15	No LF	+25
WRF-VAR	-233	-45	+112	No LF
IMD-MME	-148	00	+40	00

Table-3.26. Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	31 h	55 h	79 h	103 h
UKMO	No LF	-	No LF	No LF
NCEP GFS	+7:00	0:00	-7:00	-7:00
JMA	No LF	No LF	-0200	No LF
IMD-GFS	No LF	-2:00	No LF	-4:00
WRF-VAR	+11:00	-12:00	-19:00	No LF
IMD-MME	+11:00	-06:00	+5:00	-04:00

3.5.4 Intensity prediction

Average absolute error (AAE) and Root mean square error (RMSE) of SCIP model is presented in Table-3.27. The AAE of SCIP was 2 kt at 12 hr and 1 kt at 72 hr with maximum error 4.5 kt at 48h. The RMSE was 2.6 kt at 12 hr and 1 kt at 72 hr with maximum error 5.1 kt at 48h.

Table-3.27 Average absolute errors (Number of forecasts verified is given in the parentheses)

(Intensity forecasts prior to landfall are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-SCIP (AAE)	2.0(3)	4.0(3)	3.0(3)	4.5(2)	0.0(2)	1.0(1)
IMD-SCIP (RMSE)	2.6	4.7	4.2	5.1	0.0	1.0

3.5.6 Probability of Rapid intensification (by RI-Index)

RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of the Depression during its lifetime (able 3.28).

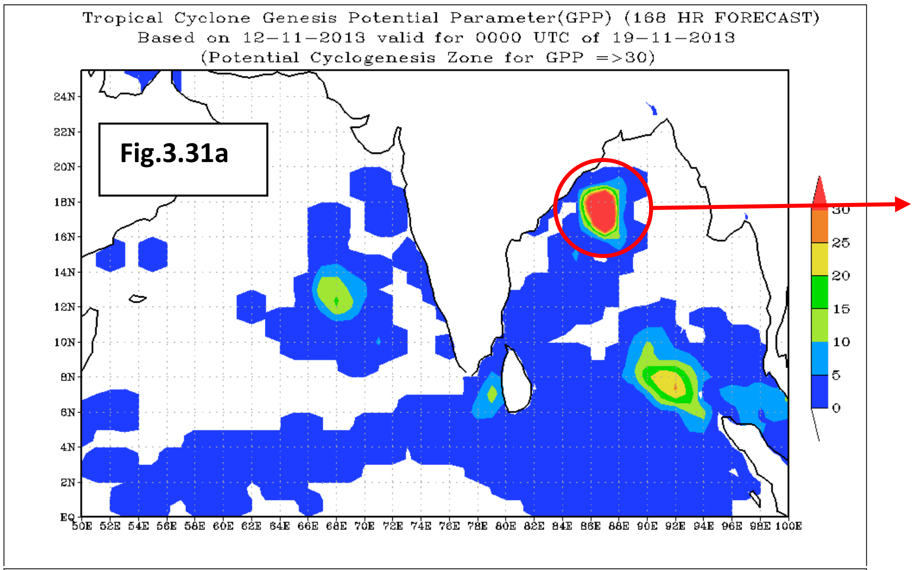
Table-3.28 Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/13.11.2013	0 %	NIL	0	NO
00 UTC/14.11.2013	2.6 %	VERY LOW	0	NO
00 UTC/15.11.2013	5.2 %	VERY LOW	0	NO

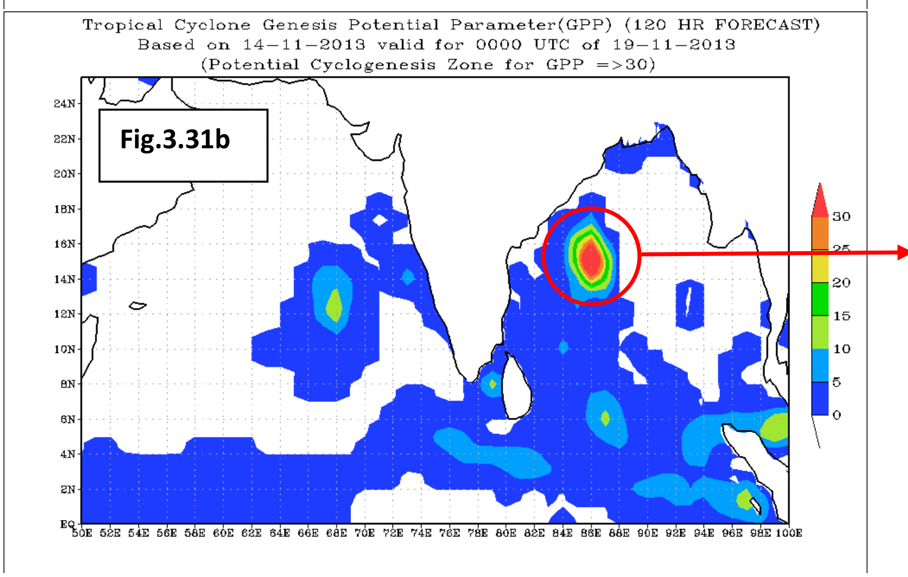
3.6 Severe Cyclonic storm 'HELEN' (19-22) November 2013

3.6.1. Grid point analysis and forecast of GPP

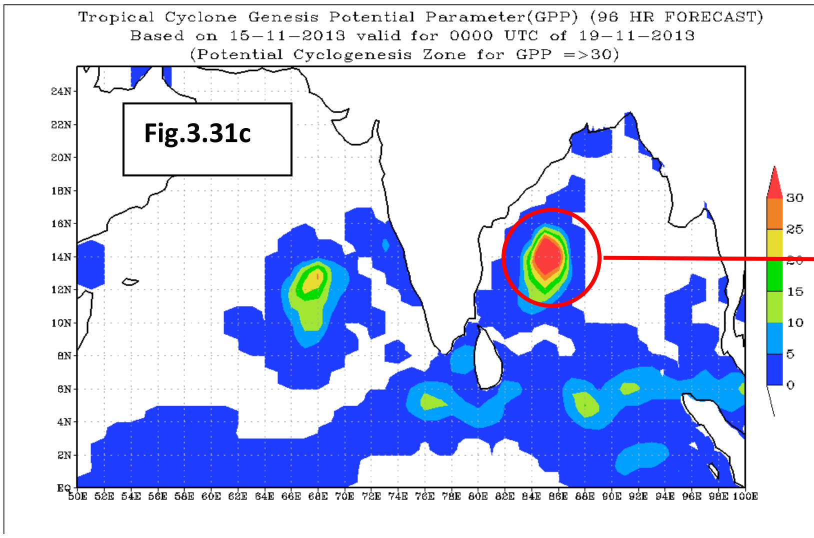
Grid point analysis and forecasts of GPP (Fig.3.31(a-g)) shows that it was able to predict the formation and location of the system before 168 hours of its formation.



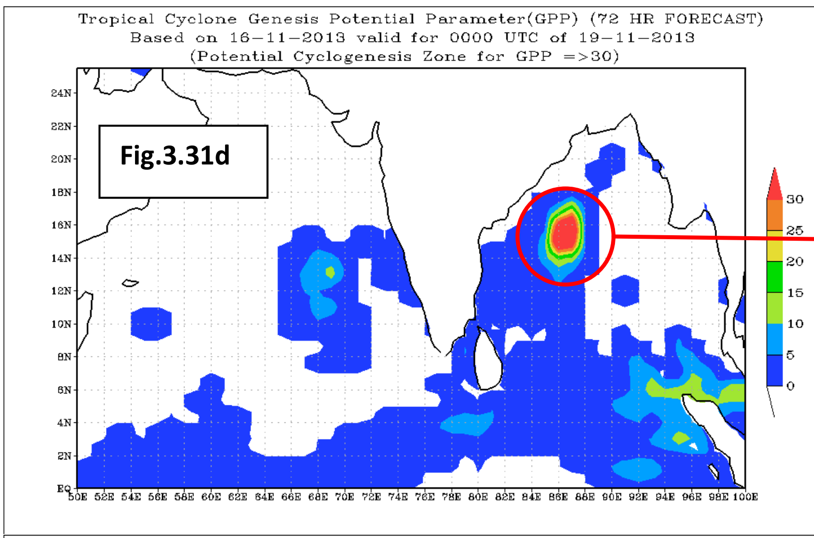
168 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



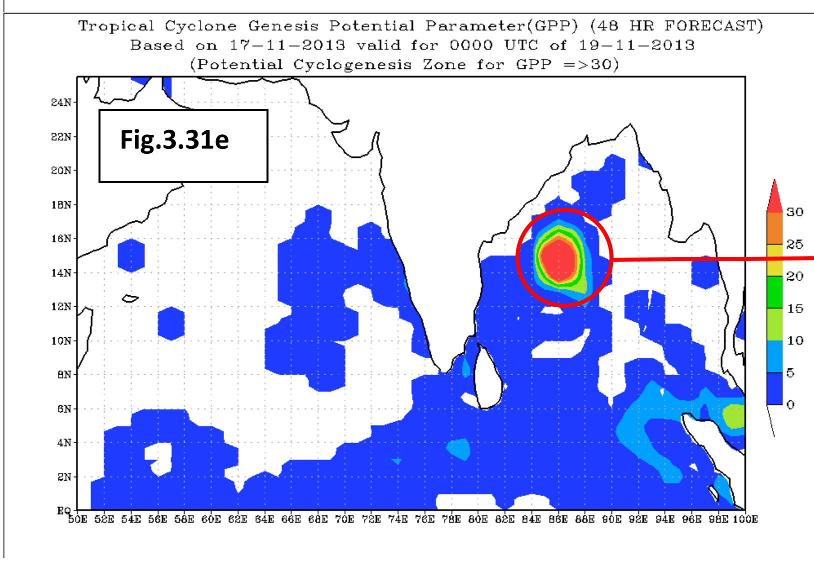
120 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



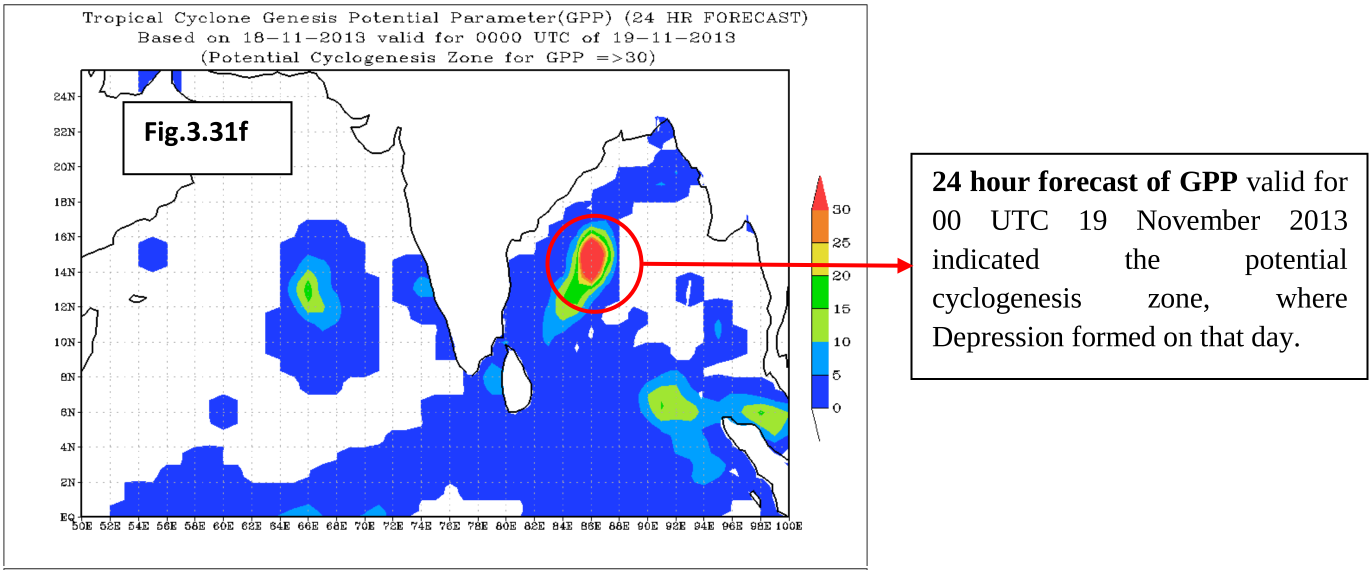
96 hour forecast of GPP valid for 00 UTC 19 November indicated the potential cyclogenesis zone, where Depression formed on that day.



72 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 00 UTC 19 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



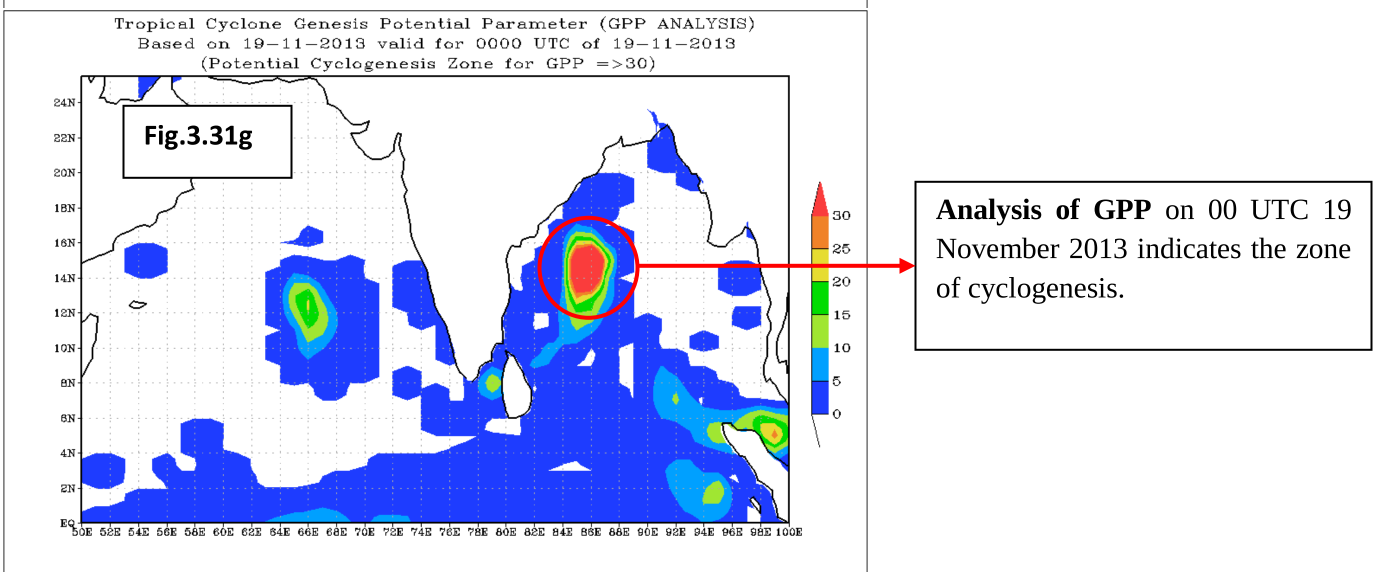


Figure 3.31(a-g): Predicted zone of cyclogenesis.

3.6.2 Area average analysis of GPP

Analysis and forecasts of GPP based on 00 UTC of 19 November 2013 indicated no potential to intensify into a cyclone (GPP < 8.0 at stage T. No. 1.5 (Fig 3.32a)) but updated forecast based on 00 UTC of 20 November 2013 (Fig 3.32b) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at stage T.No. 2.0.

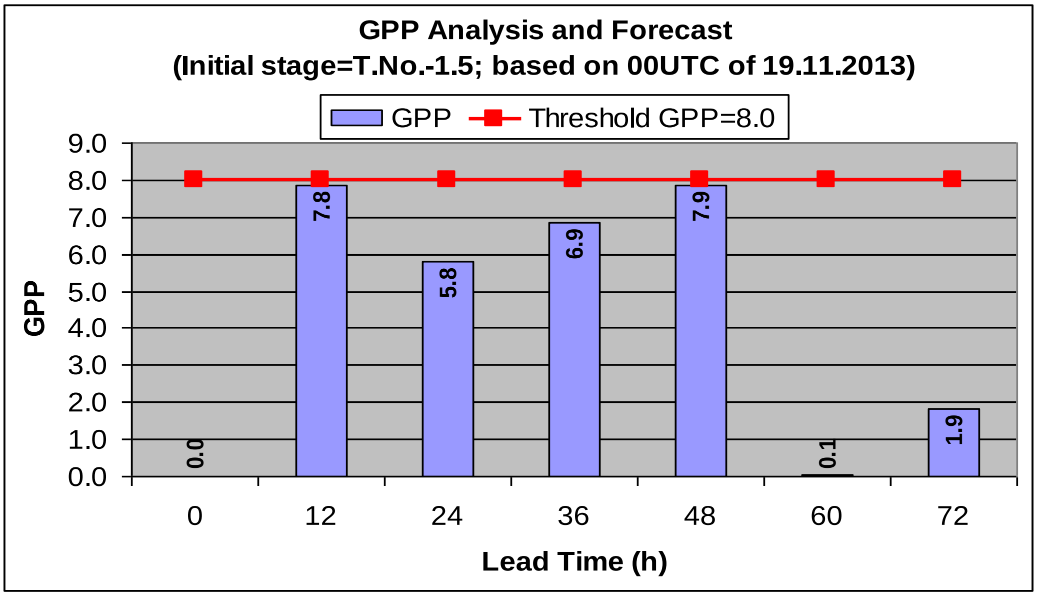


Fig 3.32a: Analysis and forecasts of GPP shows that GPP < 8.0 (Threshold) at very early stage of development (**T.No.-1.5**) indicated no potential to intensify into a cyclone.

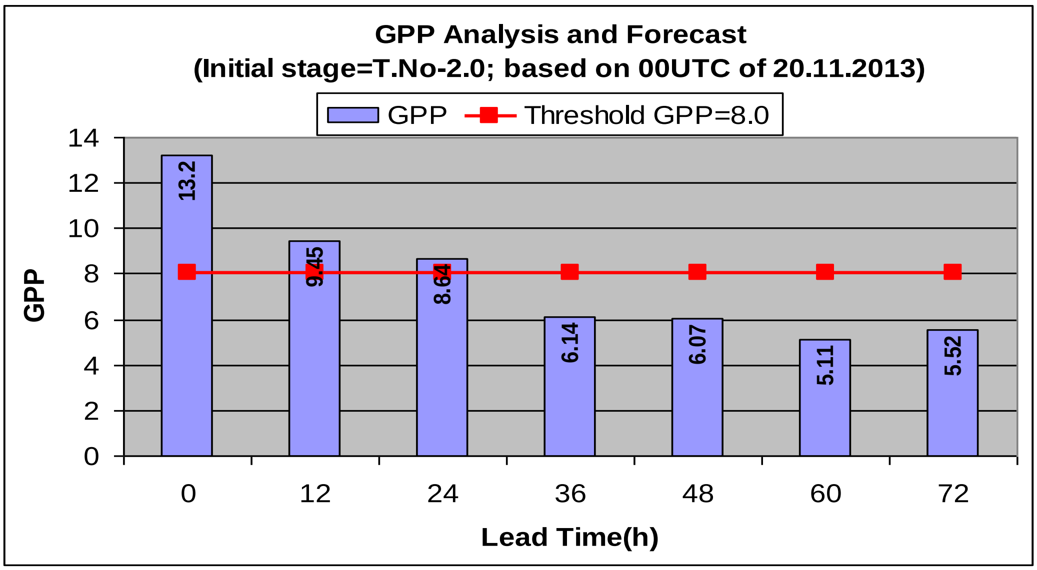


Fig 3.32b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 2.0**) indicated its potential to intensify into a cyclone.

Fig. 3.32(a-b) Area average analysis of GPP

3.6.3 Track prediction

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the MME forecast are presented in the Table 3.29, Table 3.30 and Table 3.31 respectively. The landfall point error (km) and landfall time error (hour) is presented in Table-3.32 and Table-3.33 respectively. The model forecast tracks based on different initial conditions along with the observed track is depicted in Fig 3.33. The figure shows the track from 00 UTC 19 November to 00 UTC 21 November 2013.

Average DPE was highest for JMA (about 570 km at 12 h to 705 km at 60 h). Average DPE was lowest for HWRF (about 45 km at 12 h to 180 km at 60 h). The DPE for MME was about 80 km at 12 h to 260 km at 72 h (Table-3.29). The DPE of all models are shown in Fig. 3. 34.

Average CTE was highest for JMA (about 430 km at 12 h to 655 km at 60 h). Average CTE was lowest for HWRF (about 30 km at 12 h to 160 km at 60 h). MME forecast error was about 55 km at 12 h to 260 km at 72 h (Table-3.30). The CTE of all models are

shown in Fig. 3.35.
Average ATE was highest for JMA (about 315 km at 12 h to 260 km at 60 h). ATE was lowest for UKMO (35 km at 12h to 72 km at 36h and 5 km at 48h) and MME (46km at 12h, 36km at 48h with maximum 68km at 24h) up to 48 h and for 60h and 72h forecast, ATE of MME was lowest (less than 10 km) (Table-3.32). The ATE of all models is shown in Fig. 3.36

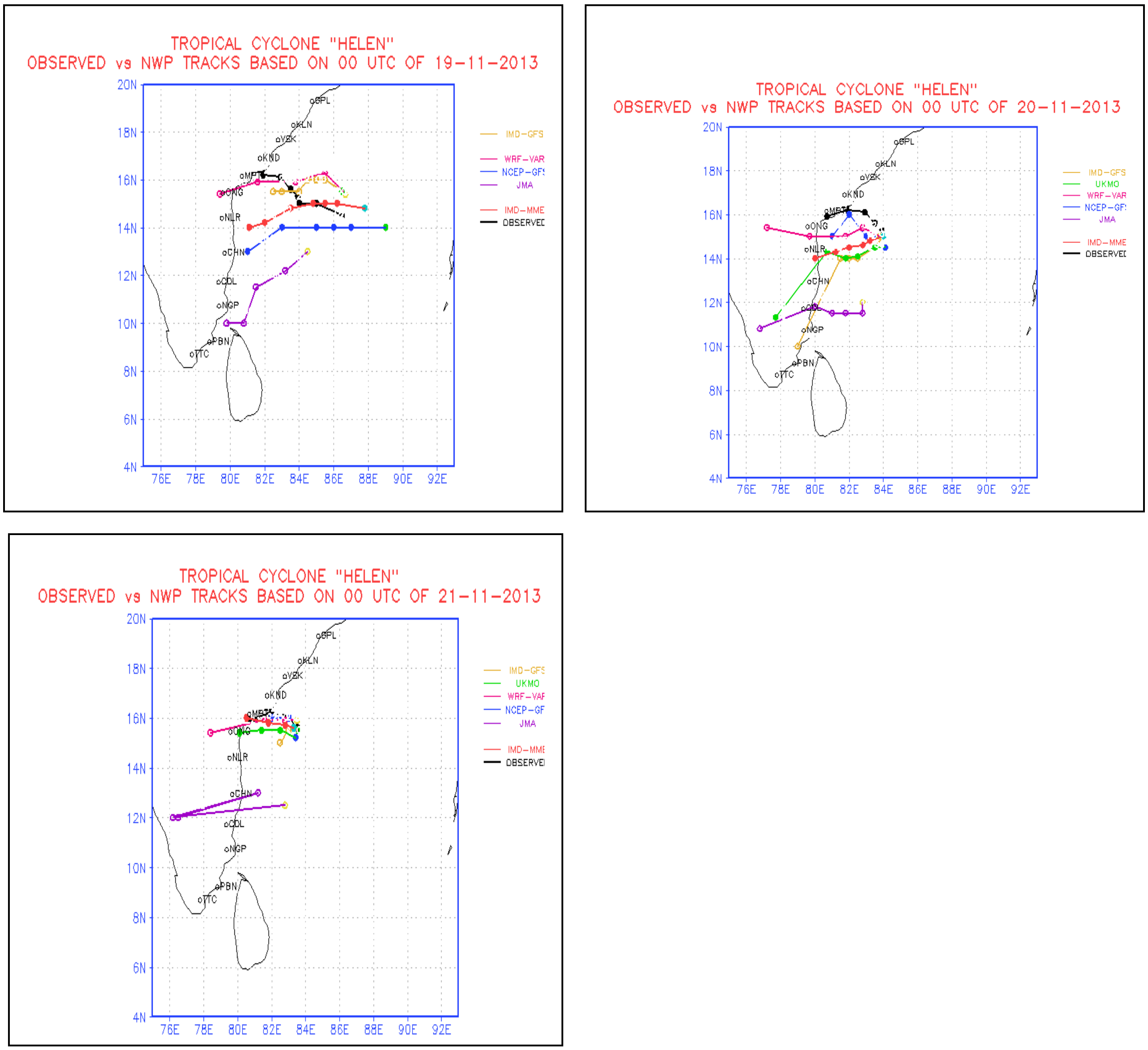


Fig.3.33 MME forecasts track based on different initial conditions

Table 3.29 Average track forecast errors (DPE) in km (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-GFS	135(4)	170(3)	177(2)	151(2)	374(2)	101(1)
IMD-WRF	82(4)	114(3)	290(3)	475(2)	-	-
JMA	571(4)	443(3)	618(3)	635(2)	706(1)	-
NCEP-GFS	121(4)	117(3)	142(2)	105(2)	253(2)	368(1)
UKMO	75(3)	146(2)	173(2)	247(1)	605(1)	-
IMD-MME	78(4)	114(3)	109(3)	156(2)	228(2)	259(1)
IMD-HWRF	46(4)	111(4)	128(3)	122(2)	178(1)	-

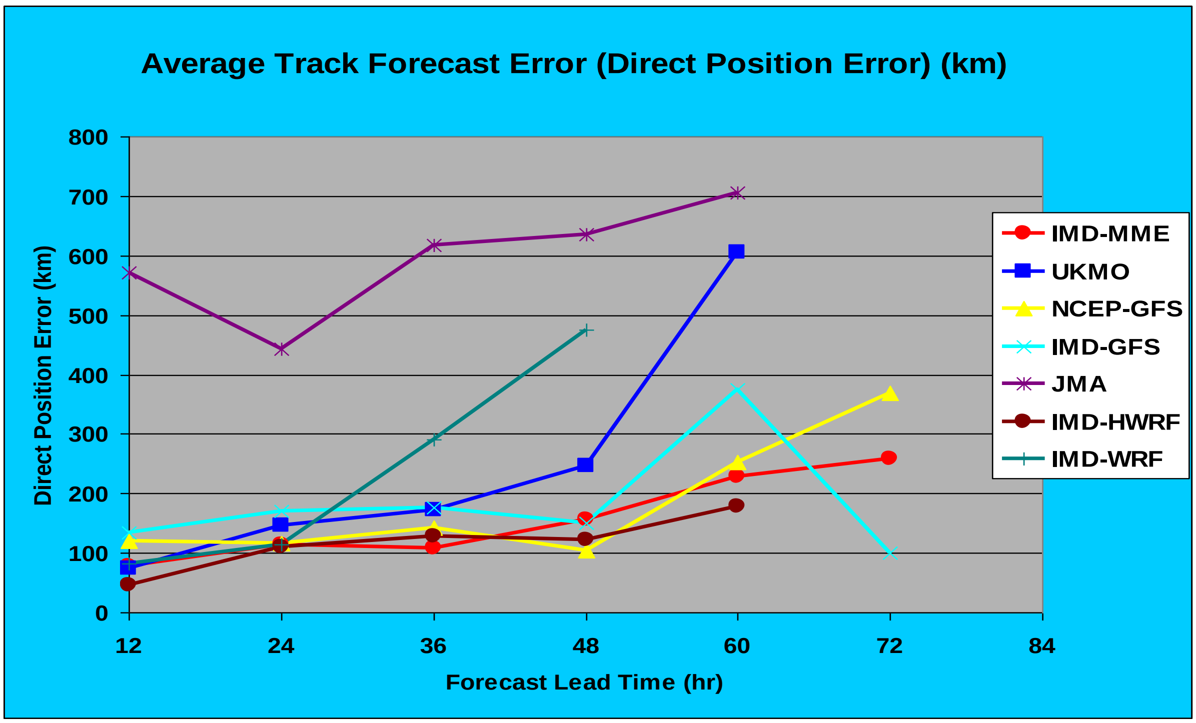


Fig. 3.34 Average track forecast errors (DPE) of NWP models

Table-3.30. Average cross track error (CTE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-GFS	85	142	163	120	369	50
IMD-WRF	76	107	139	248	-	-
JMA	428	407	547	624	656	-
NCEP-GFS	54	55	89	100	243	367
UKMO	62	140	155	247	578	-
IMD-MME	54	69	68	152	228	259
IMD-HWRF	27	70	78	95	161	-

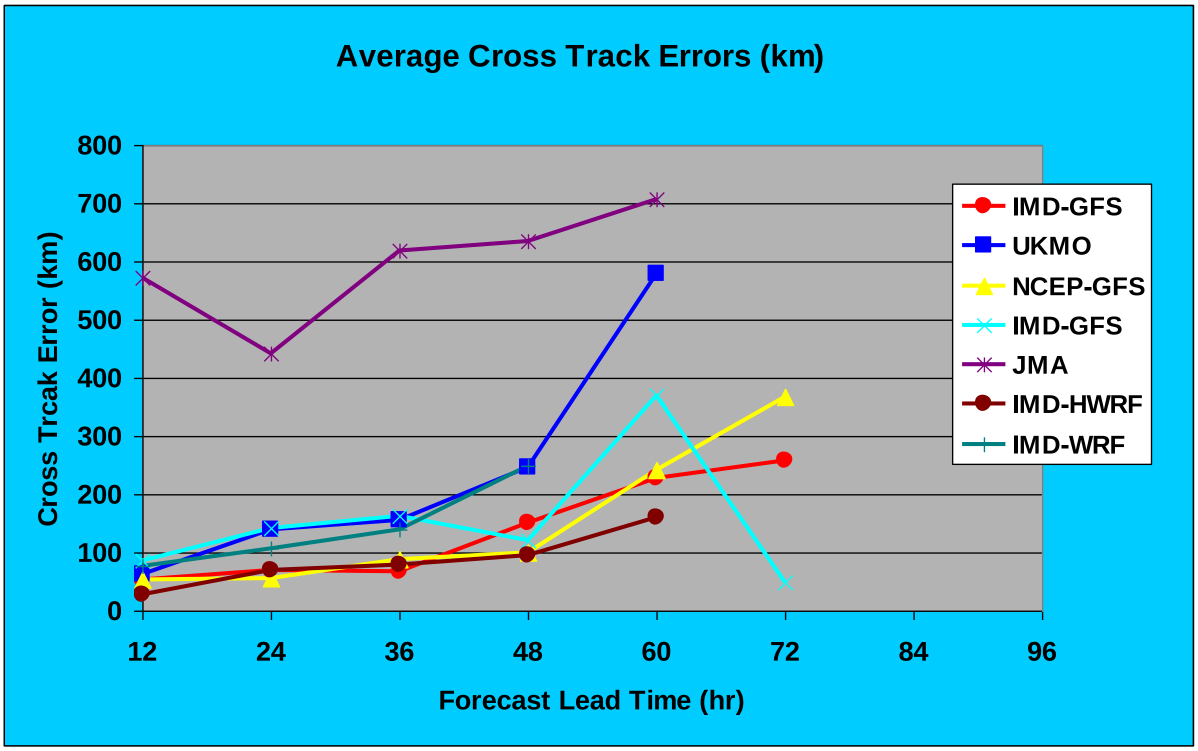


Fig. 3.35 Average cross track errors (CTE) of NWP models

Table-3.31 Average along track error (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
IMD-GFS	91	87	69	70	21	87
IMD-WRF	21	41	216	399	-	-
JMA	315	162	260	116	261	-
NCEP-GFS	89	90	108	16	52	32
UKMO	35	42	72	5	180	-
IMD-MME	46	68	62	36	9	4
IMD-HWRF	29	83	94	75	76	-

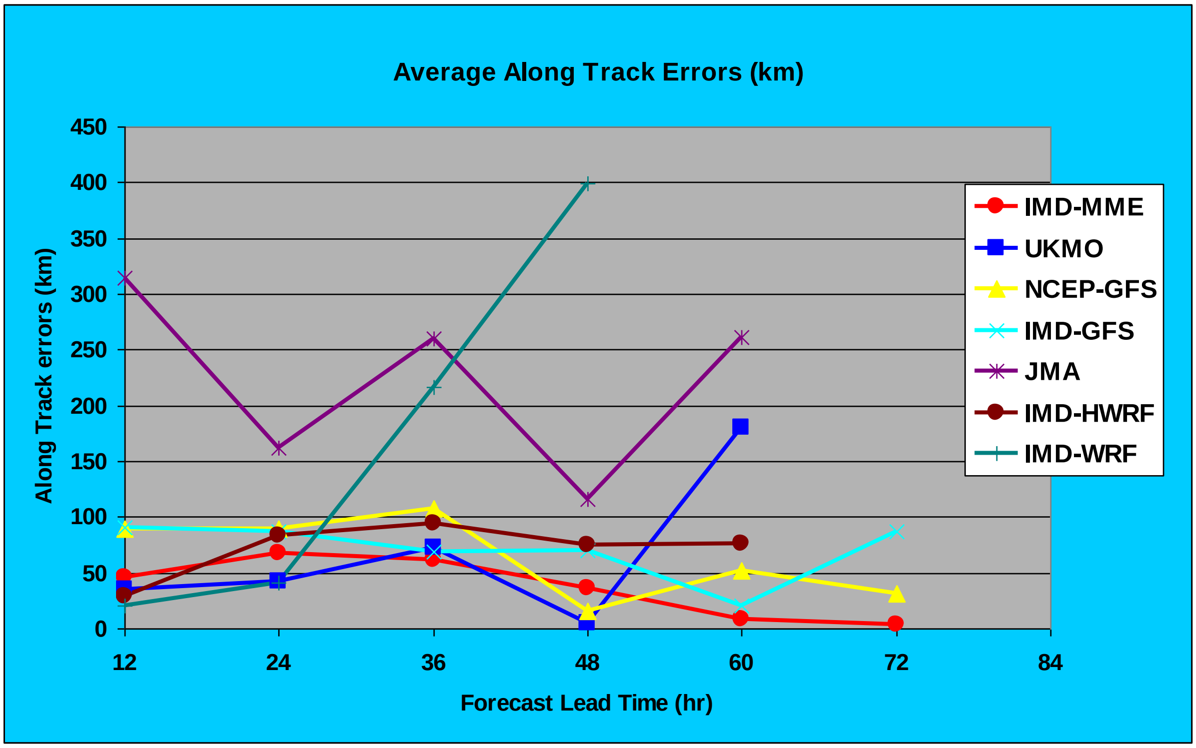


Fig. 3.36 Average along track errors (ATE) of NWP models

Landfall Point Error: Landfall point forecasts errors of NWP model at different forecast lead times show that some model predicted north of actual landfall point and some predicted south of actual landfall point with a maximum limit up to about 126 km (HWRF) towards north and up to 568 km (IMD-GFS) towards south (Table-3.32). MME landfall point error was ranged from near landfall point (before 8h of landfall) to 250 km (before 56h of landfall) south of actual landfall point.

Table 3.32 Landfall point forecast errors (km) of NWP Models at different lead time (hour) ('+' indicated north of actual landfall; '-' indicates south of actual landfall point)

Forecast Lead Time (hour) →	08.5 h	32.5 h	56.5 h	80.5 h
UKMO	00	-141	-277	-
NCEP GFS	-170	No LF	-170	No LF
JMA	-257	-	-501	No LF
HWRF	-	+126	+141	-
IMD-GFS	No LF	No LF	-568	No LF
WRF-VAR	00	-49	-170	-121
IMD-MME	00	-24	-252	No LF

Landfall Time Error: Landfall time forecasts errors of NWP model at different forecast lead times show that some model predicted earlier than actual landfall time and some predicted delayed than actual landfall time with a maximum limit up to 22 hr delayed (IMD-WRF) and up to 15 hr earlier (NCEP-GFS) than actual landfall time. Under this wide extent of landfall time forecasts, MME landfall time error (±1.5 h) was consistently low (Table-3.33).

Table-3.33. Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	08.5 h	32.5 h	56.5 h	80.5 h
UKMO	-1.5	+3.5	-6.5	-
NCEP GFS	+2.5	No LF	+15.5	No LF
JMA	-5.5	-	-7.5	No LF
HWRF	-	+1.5	-3.5	-
IMD-GFS	No LF	No LF	+0.5	No LF
WRF-VAR	-0.5	-3.5	-22.5	-36.5
IMD-MME	-1.5	+1.5	+1.5	No LF

3.6.4 Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig.3.37 and Fig.3.38 respectively. The figure shows that the SCIP model underestimated and HWRF model over estimated the intensity at all forecasts.

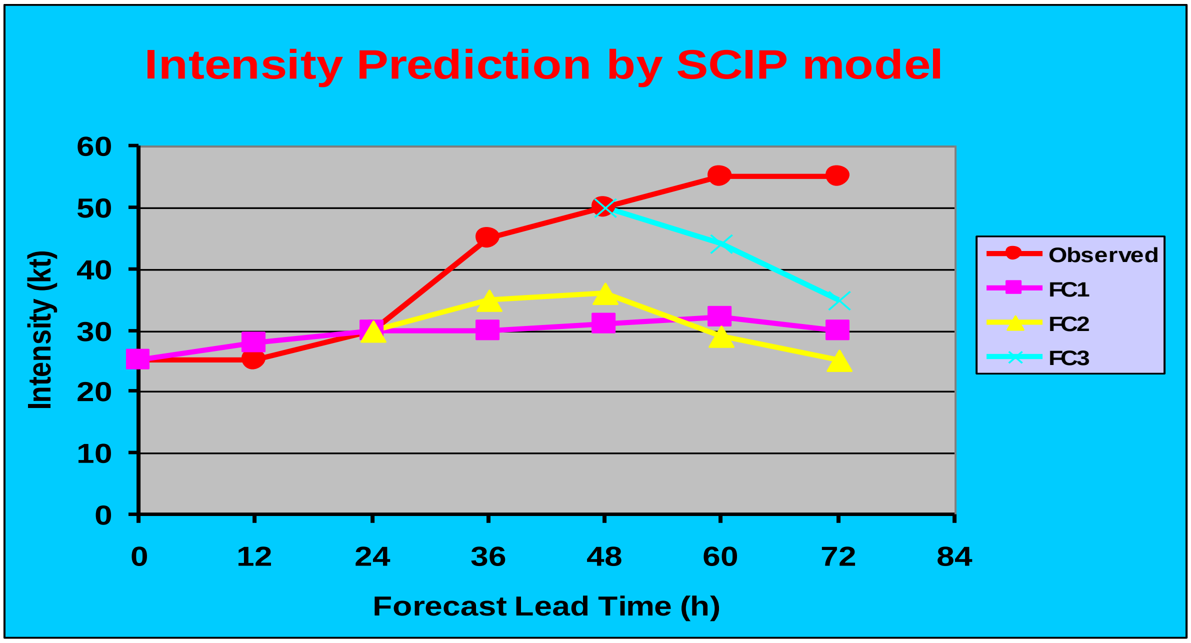


Fig. 3.37 Intensity forecasts of SCIP model

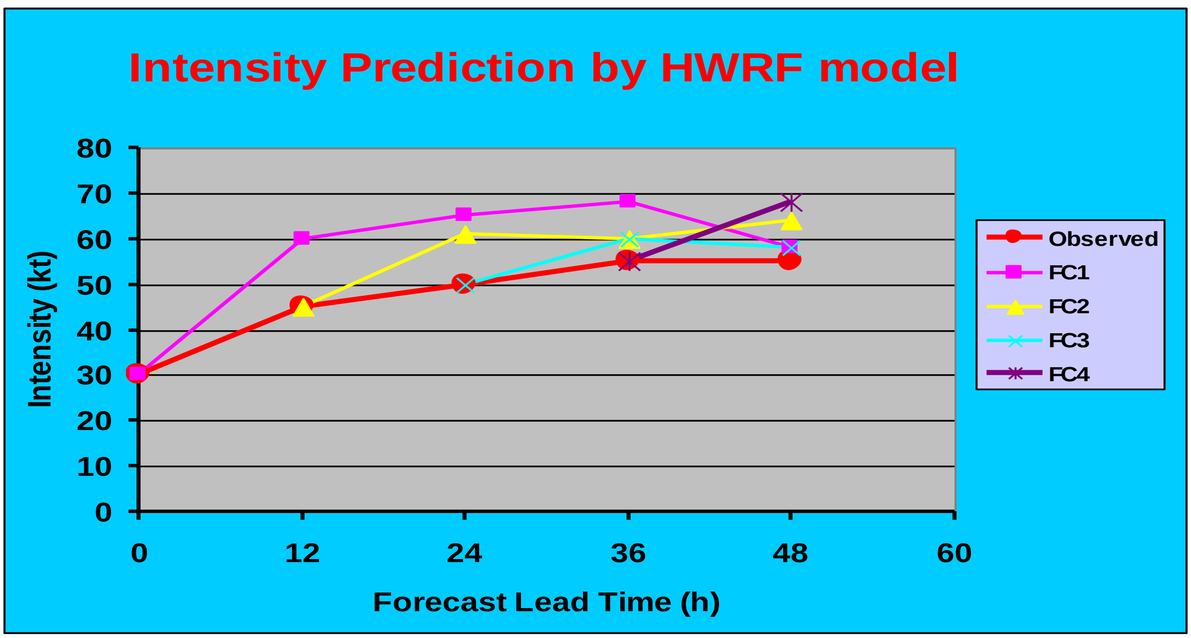


Fig. 3.38 Intensity forecasts of HWRF model

Average absolute error (AAE) and Root mean square error (RMSE) of SCIP and HWRF forecast error is presented in the following Table-3.34 and Table-3.35. The AAE of SCIP was ranged from 8 kt at 12 hr and 25 kt at 72 hr and the AAE of HWRF was ranged from 7.9 kt at 12 h to 6 kt at 48 h.

Table-3.34 Average absolute errors (Number of forecasts verified is given in the

parentheses)

(Intensity forecasts prior to landfall (1200 UTC of 12.10.2013) are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr
IMD-SCIP	8.0(3)	11.3(3)	20.5(2)	24.5(2)	14.0(2)	25.0(1)	-
IMD-HWRF	5.3(4)	11.0(4)	7.0(3)	6.0(2)	-	-	-

Table-3.35 Root Mean Square (RMSE) errors (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
IMD-SCIP	8.8(3)	14.1(3)	21.2(2)	25.1(2)	16.6(2)	25.0(1)	-
IMD-HWRF	7.9(4)	11.6(4)	8.2(3)	6.7(3)	-	-	-

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

RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of cyclone HELEN during its lifetime (Table 3.36)

Table-3.36 Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/19.12.2013	5.2 %	VERY LOW	5	NO
00 UTC/20.12.2013	9.4 %	VERY LOW	20	NO
00 UTC/21.10.2013	9.4 %	VERY LOW	5	NO

3.6.7 Ensemble track and Strike Probability forecast

Ensemble track and strike probability forecasts based on 00 UTC 19.11.2013 and 00 UTC 20.11.2013 shows that ALL, MSC and NCEP predicted movement towards Andhra Pradesh coast (Fig. 3.39)

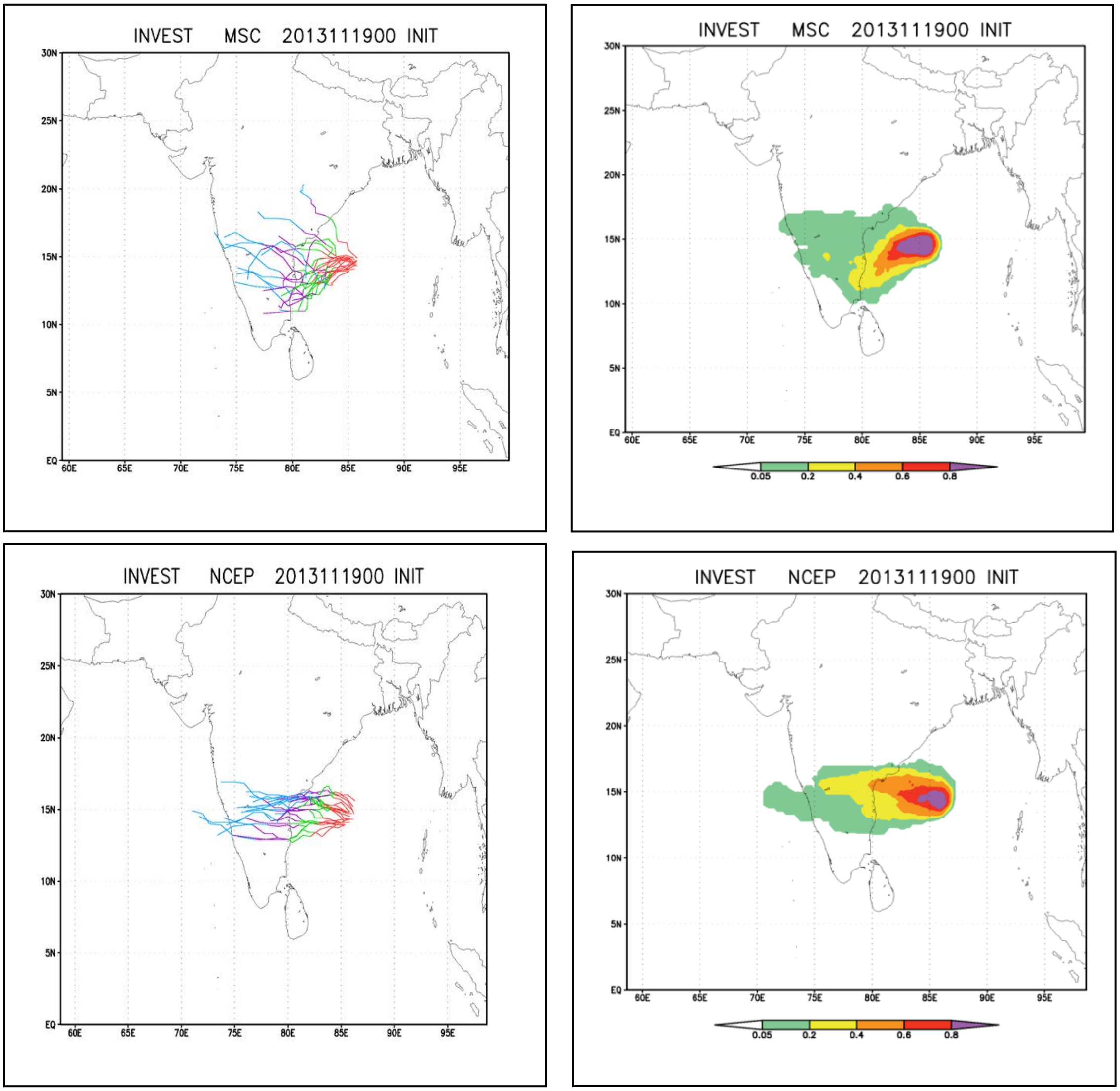


Fig. 3.39(a) Ensemble track and Strike Probability forecasts based on 00 UTC of 19.11.2013

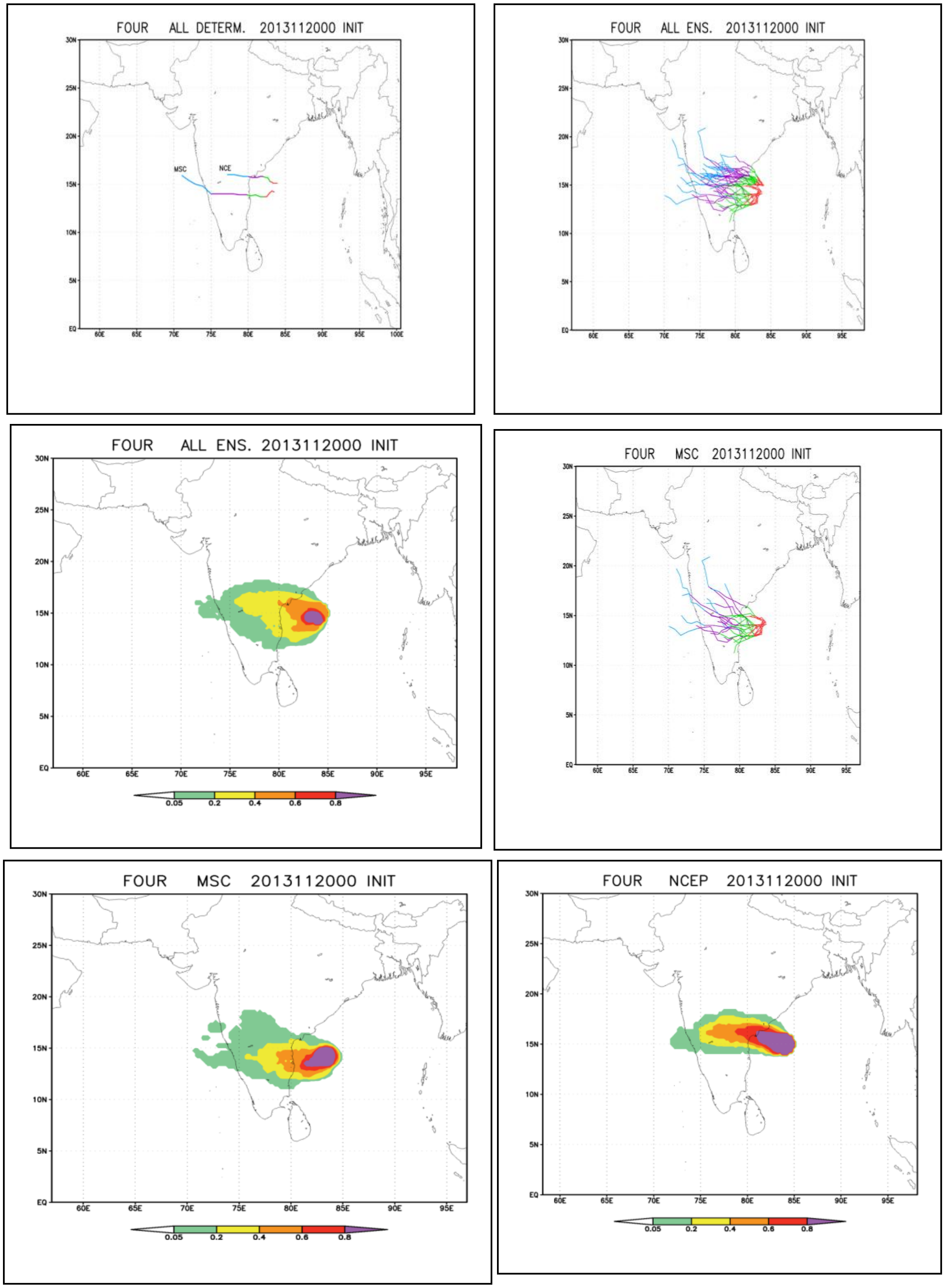
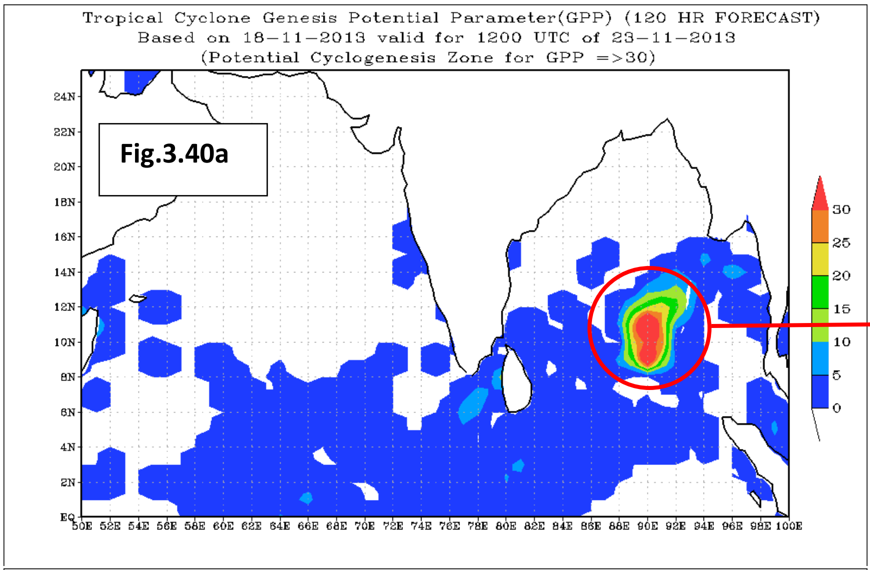


Fig. 3.39(b) Ensemble track and Strike Probability forecasts based on 00 UTC of 20.11.2013

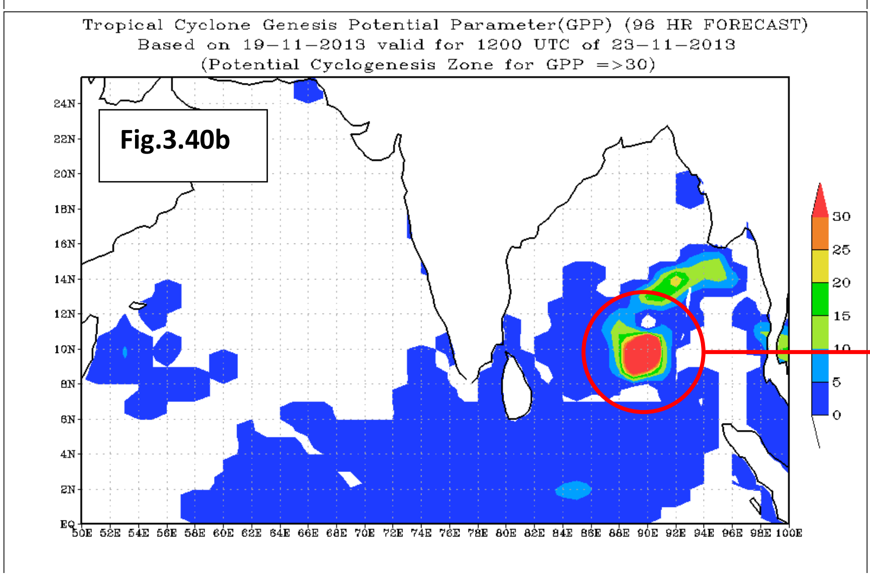
3.7 Very Severe Cyclonic storm 'LEHAR' (23-28) November 2013

3.7.1 Grid point analysis and forecast of GPP

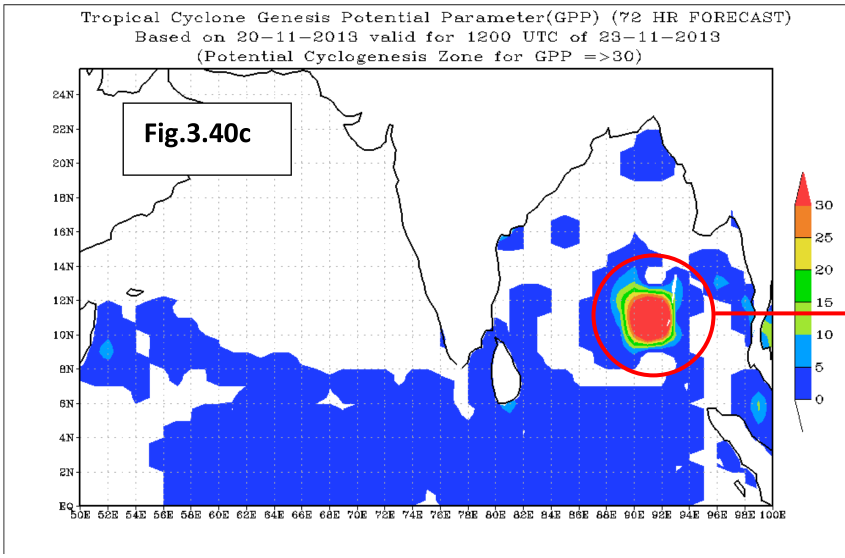
Grid point analysis and forecasts of GPP (Fig.3.40(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation. However forecast area of genesis differed significantly from the actual as cyclone formed over south Andaman Sea except for forecast on 23 November.



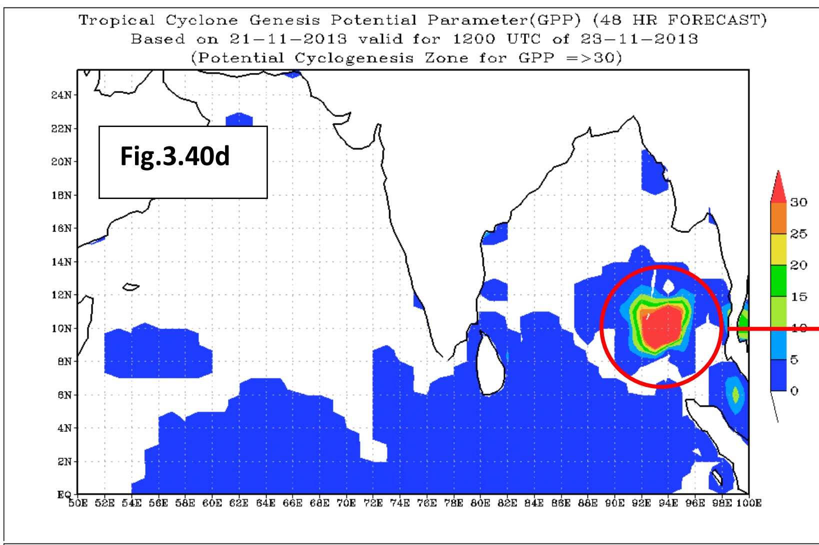
120 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



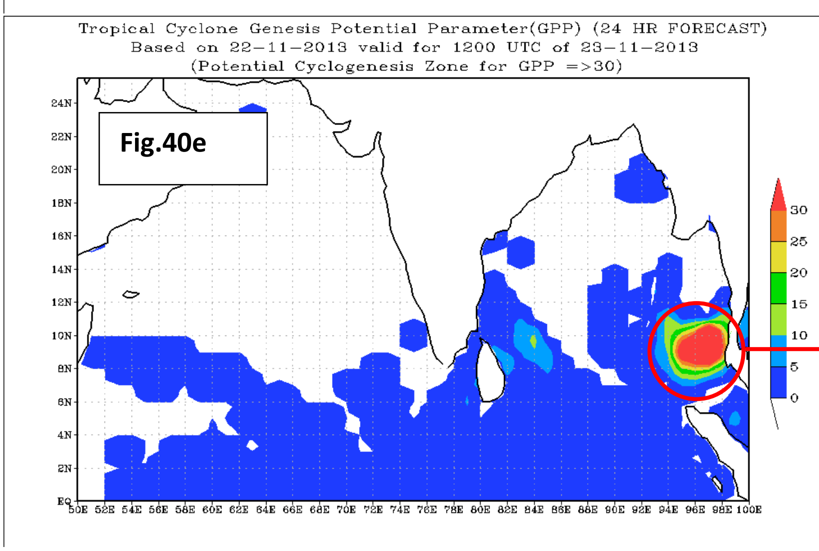
96 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



72 hour forecast of GPP valid for 12 UTC 23 November indicated the potential cyclogenesis zone, where Depression formed on that day.



96 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



72 hour forecast of GPP valid for 12 UTC 23 November 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.

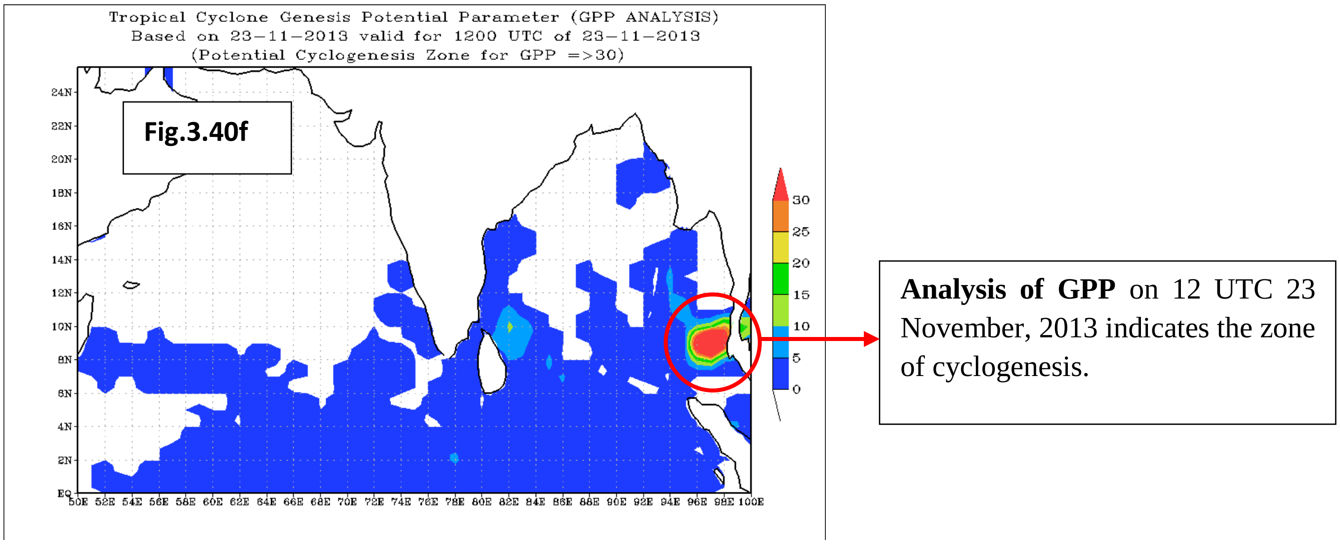
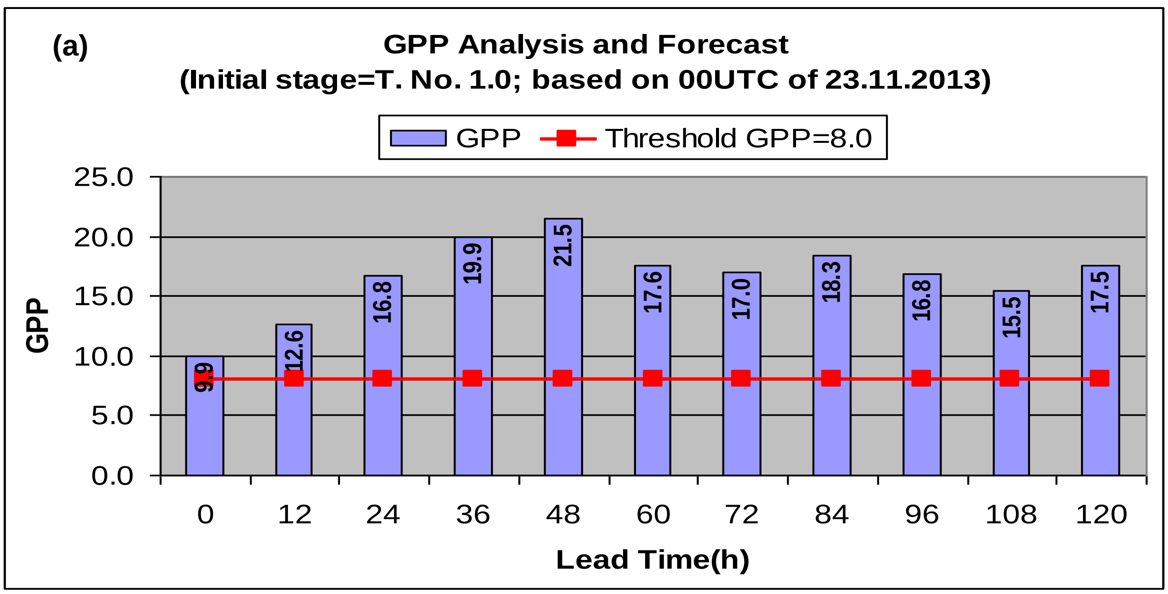


Figure3.40(a-f): Predicted zone of cyclogenesis.

3.7.2 Area average analysis of GPP

Analysis and forecasts of GPP (Fig.3.41(a-b)) shows GPP ≥ 8.0 (threshold value for intensification into cyclone) and hence indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5).



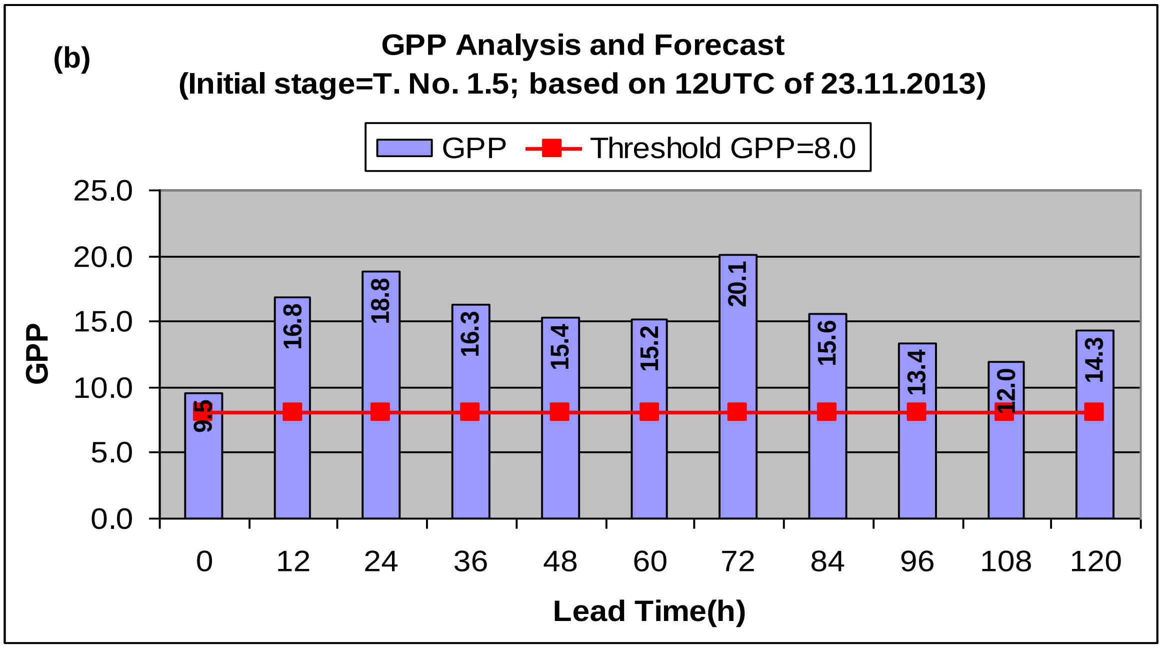


Fig. 3.41 (a-b) Area average analysis of GPP

3.7.3 Track prediction

The average track forecast errors (DPE, CTE, ATE) of NWP models along with the consensus forecast by Multi-model ensemble (MME) forecast are presented in the Table 3.37, Table 3.38 and Table 3.39 respectively. The landfall point error (km) and landfall time error (hour) is presented in Table-3.40 and Table-3.41 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 3.42.

Average track forecast error (direct position error (DPE)) was highest for WRF (about 80 km at 12 h to 360 km at 72 h) up to 72 h, for forecast hours 84 h to 96h UKMO forecast error was highest (about 290 km at 84 h to 300 km at 96 h) and for forecast hours 108h and 120h HWRF forecast error was highest (about 325 km at 108 h to 425 km at 120 h). Average DPE was lowest for MME up to 84 h (about 65 km at 12 h to 150 km at 84 h), (Table-3.37). The DPE of all models are shown in Fig. 3.43.

Average cross track error (CTE) was highest for WRF (about 40 km at 12 h to 275 km at 72 h). Average CTE was lowest for MME for all forecast hours (about 35 km at 12 h to 170 km at 120 h) except for forecast hours from 96 h to 120 h where NCEP-GFS forecast errors are found to be lowest (Table-3.38). The CTE of all models are shown in Fig. 3.44.

Average along track error (ATE) was highest for UKMO (about 80 km at 12 h to 205 km at 96 h) up to 96 h and for forecast hours 108h (220km) and 120h (345km) HWRF forecast hours were highest. Average ATE was lowest for MME for all forecast hours (about 45 km at 12 h to 155 km at 120 h) except for forecast hours from 120 h where NCEP-GFS forecast errors are found to be lowest (Table-3.39). The ATE of all models is shown in Fig. 3.45.

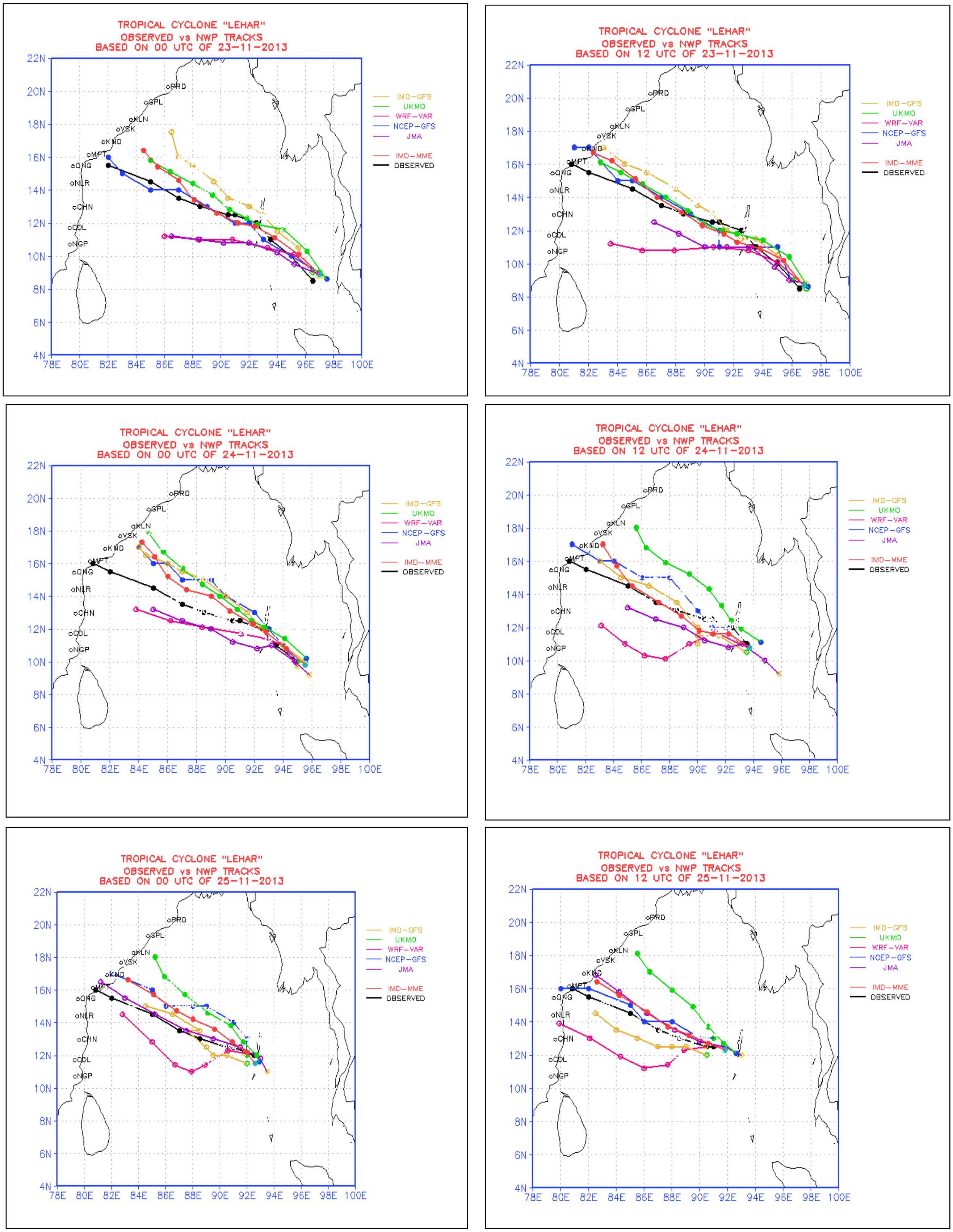


Fig. 3.42 MME forecasts track based on different initial conditions

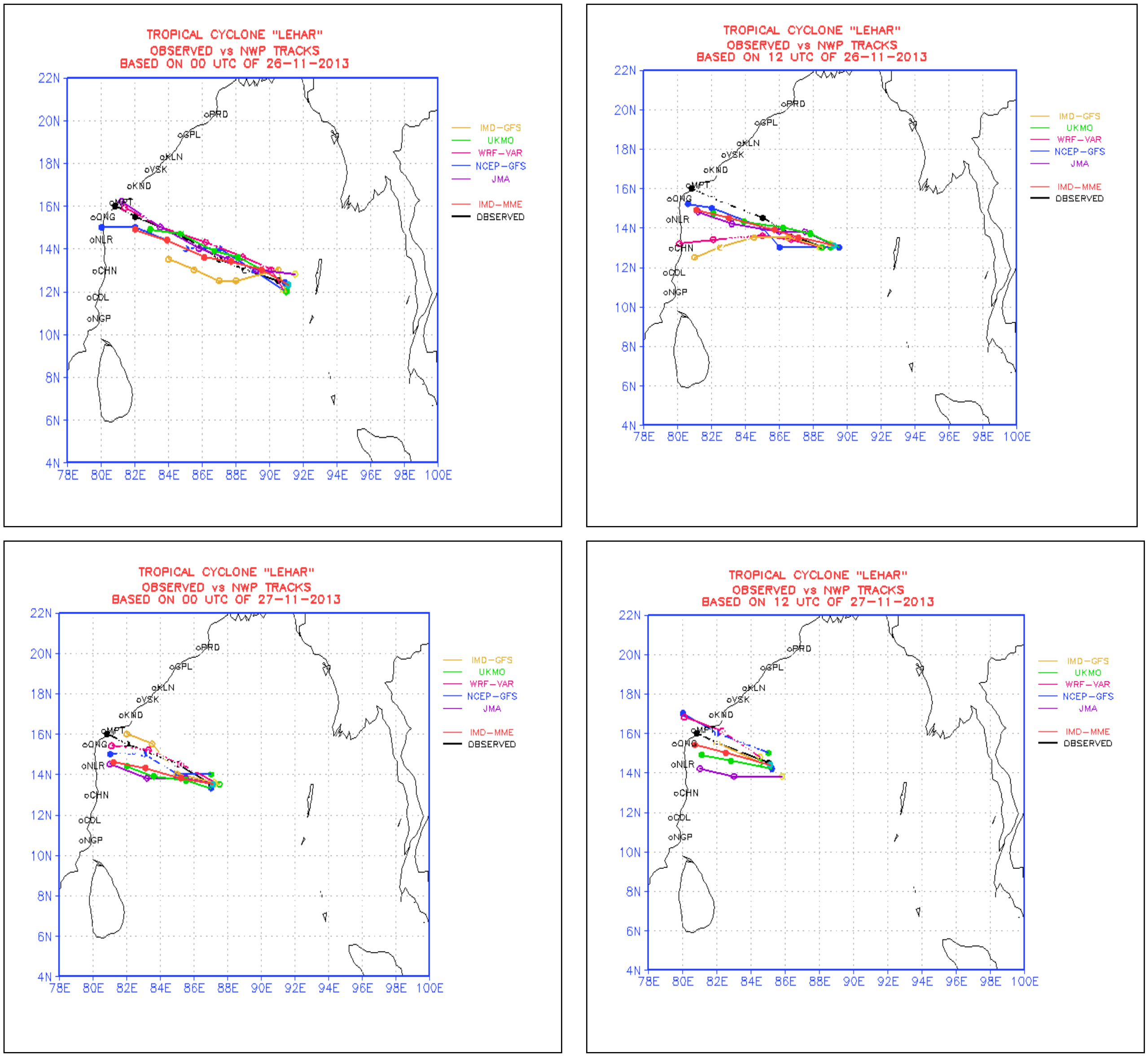


Fig. 3.42(contd.) MME forecasts track based on different initial conditions

Table-3.37 Average track forecast errors (DPE) in km (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	85(10)	103(9)	144(9)	202(8)	244(7)	226(6)	247(5)	231(4)	301(3)	394(2)
IMD-WRF	78(10)	132(10)	193(9)	281(8)	291(7)	361(6)	-	-	-	-
JMA	138(10)	151(10)	144(9)	136(8)	130(7)	152(6)	151(5)	-	-	-
NCEP-GFS	78(10)	84(10)	114(9)	114(8)	139(7)	191(6)	191(5)	196(4)	249(3)	84(2)
UKMO	111(10)	138(10)	182(9)	196(8)	240(7)	266(6)	288(5)	301(4)	288(3)	268(2)
IMD-MME	67(10)	79(10)	110(9)	107(8)	127(7)	128(6)	152(5)	204(4)	230(3)	232(2)
IMD-HWRF	77 (9)	129 (9)	141 (8)	144 (7)	113 (7)	173 (6)	194 (5)	255 (4)	323 (3)	424 (2)

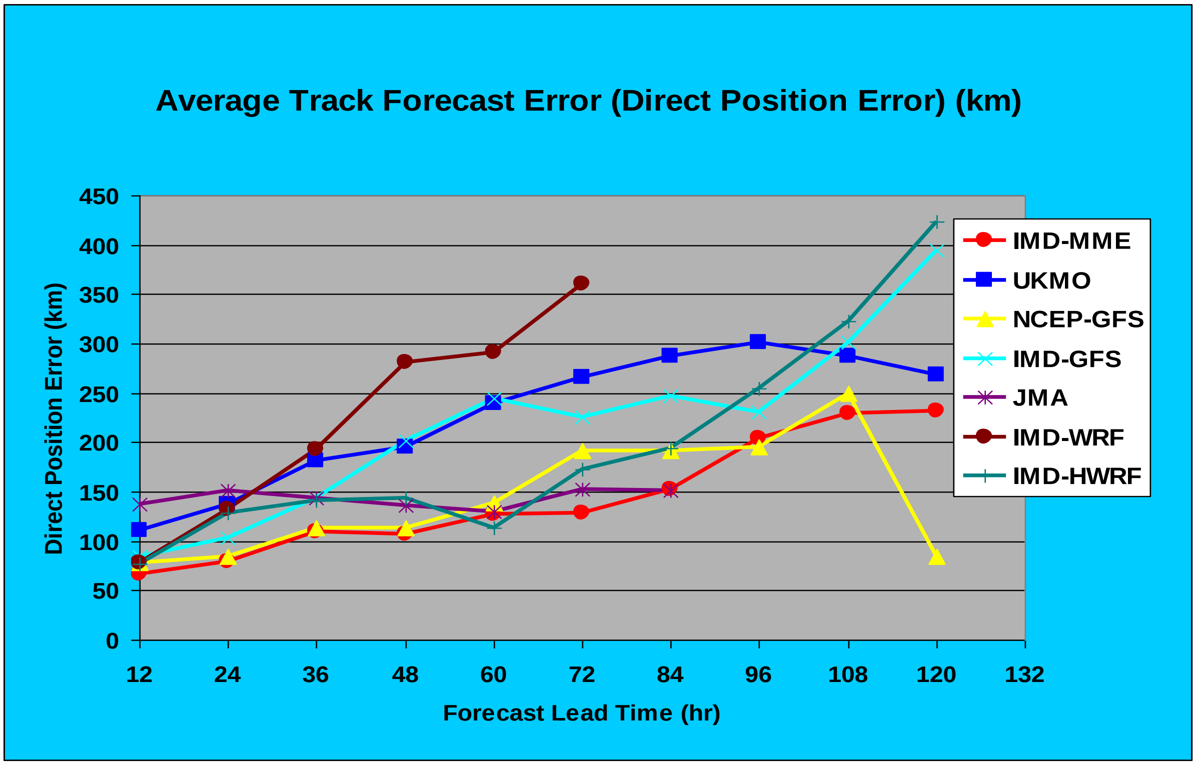


Fig. 3.43: Average track forecast errors (DPE) of NWP models

Table-3.38 Average cross track error (CTE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	44	75	104	113	103	101	121	170	213	301
IMD-WRF	41	92	168	241	242	274	-	-	-	-
JMA	41	52	61	75	93	122	123	-	-	-
NCEP-GFS	57	58	90	97	100	85	100	84	143	80
UKMO	54	70	96	108	150	192	209	216	193	132
IMD-MME	35	41	68	54	66	64	83	148	175	170
IMD-HWRF	50	112	94	96	82	130	159	193	209	245

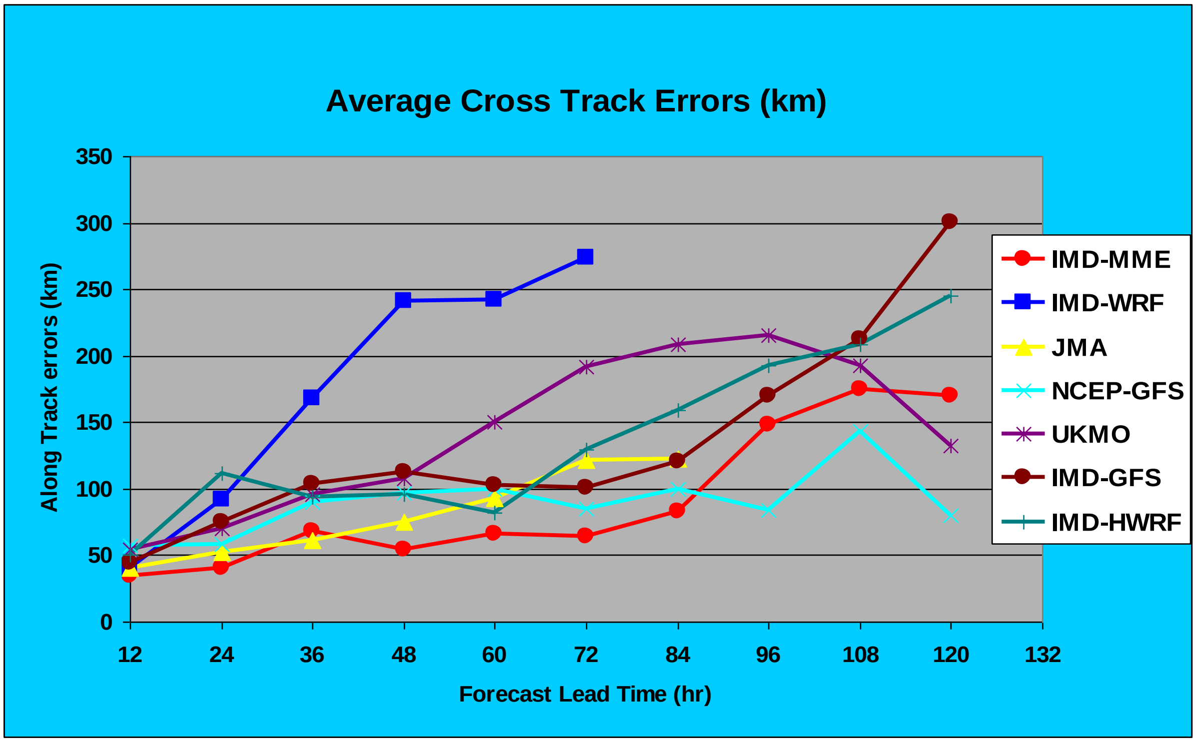


Fig. 3.44 Average cross track errors (CTE) of NWP models

Table-3.39 Average along track error (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	60	55	81	146	202	181	154	119	203	254
IMD-WRF	55	78	71	99	145	207	-	-	-	-
JMA	120	133	125	100	75	77	60	-	-	-
NCEP-GFS	48	47	50	55	78	160	132	158	187	25
UKMO	82	109	139	147	174	178	189	203	207	233
IMD-MME	46	61	77	88	98	102	123	134	135	157
IMD-HWRF	52	56	83	92	61	104	93	147	220	345

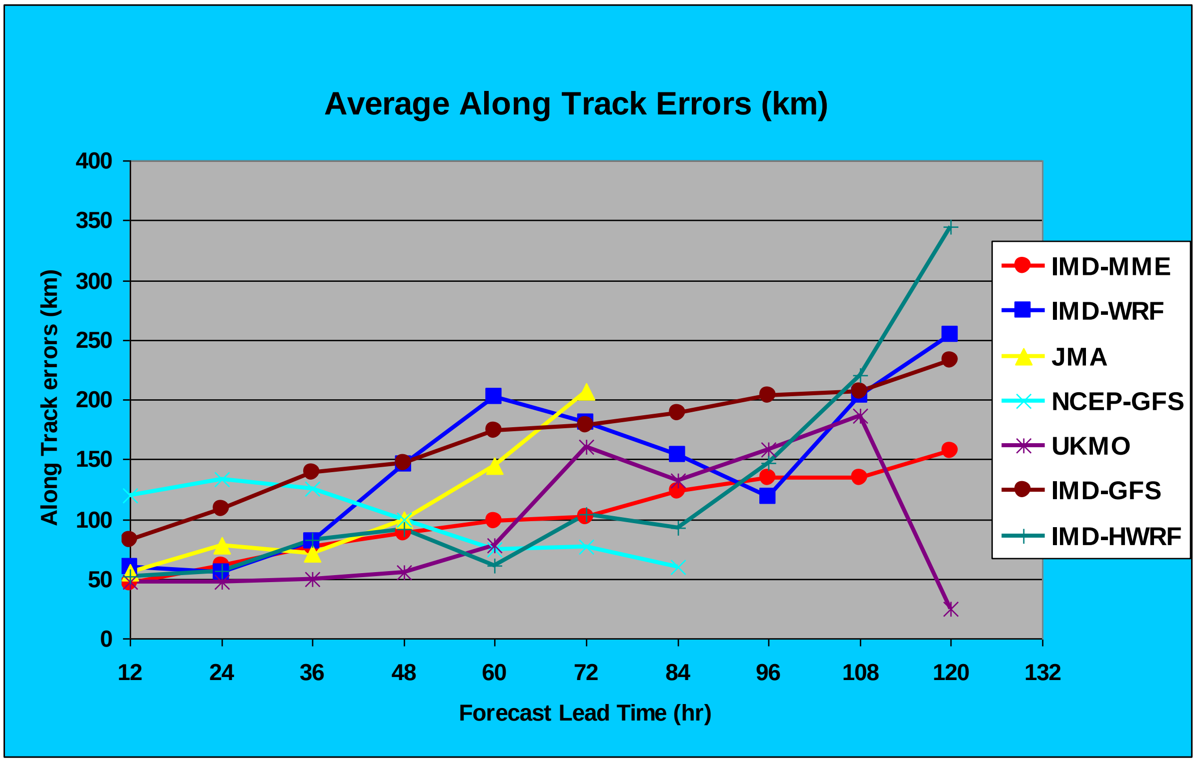


Fig. 3.45 Average along track errors (ATE) of NWP models

Landfall Point Error: Landfall point forecasts errors of NWP model at different forecast lead times (Table-3.40) show that some model predicted north of actual landfall point and some predicted south of actual landfall point with a maximum limit upto about 552 km towards north and up to 487 km towards south. Under this wide extent of landfall point forecasts, MME was able to predict landfall point with reasonable success.

Table-3.40. Landfall point forecast errors (km) of NWP Models at different lead time (hour) ('+' indicates North; '-'indicates South of landfall point; No LF indicates no landfall)

Forecast Lead Time (hour)	**20.5 h**	**32.5 h**	**44.5 h**	**56.5 h**	**68.5 h**	**80.5 h**	**92.5 h**	**104.5 h**	**116.5 h**
UKMO	-139	No LF	No LF	No LF	No LF	**+552**	No LF	+445	No LF
NCEP GFS	+35	-135	-132	-141	+11	+154	+102	No LF	+147
JMA	-163	-155	-141	+25	+147	+82	No LF	No LF	No LF
HWRF	+93	-106	**-487**	+11	+141	+117	+147	+208	No LF
IMD-GFS	No LF	No LF	-385	No LF	+102	+102	No LF	No LF	No LF
WRF-VAR	+82	No LF	-78	+16	-247	No LF	No LF	No LF	No LF
IMD-MME	-121	-162	-141	+53	+147	+169	+232	+323	+156

Landfall Time Error: Landfall time forecasts errors of NWP model at different forecast lead times (Table-3.41) show that some model predicted earlier than actual landfall time and some predicted delayed than actual landfall time with a maximum limit up to 15 hr delayed and up to 9 hr earlier than actual landfall time.

Table-3.41. Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour)	**20.5 h**	**32.5 h**	**44.5 h**	**56.5 h**	**68.5 h**	**80.5 h**	**92.5 h**	**104.5 h**	**116.5 h**
UKMO	+11.5	No LF	No LF	No LF	No LF	**+15.5**	No LF	+10.5	No LF
NCEP GFS	-5.5	+8.5	+14.5	+3.5	-2.5	+1.5	-2.5	No LF	**-9.5**
JMA	+8.5	+9.5	+12.5	+3.5	+3.5	+1.5	No LF	No LF	No LF
HWRF	+0.5	+7.5	**+9.5**	+4.5	-7.5	-2.5	-7.5	-0.5	No LF
IMD-GFS	No LF	No LF	**+15.5**	No LF	No LF	+3.5	+15.5	No LF	No LF
WRF-VAR	-5.5	No LF	+3.5	+4.5	+2.5	No LF	No LF	No LF	No LF
IMD-MME	+8.5	+6.5	+6.5	+12.5	+4.5	+7.5	+8.5	**+15.5**	+3.0

3.7.4 Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP and dynamical model HWRF are shown in Fig. 3.46 and Fig. 3.47 respectively. Both the SCIP and HWRF model was able to predict the very severe stage of the LEHAR. None of the two models could predict the decay phase over the Sea initially but updated forecast able to predict the decay phase in the later stage.

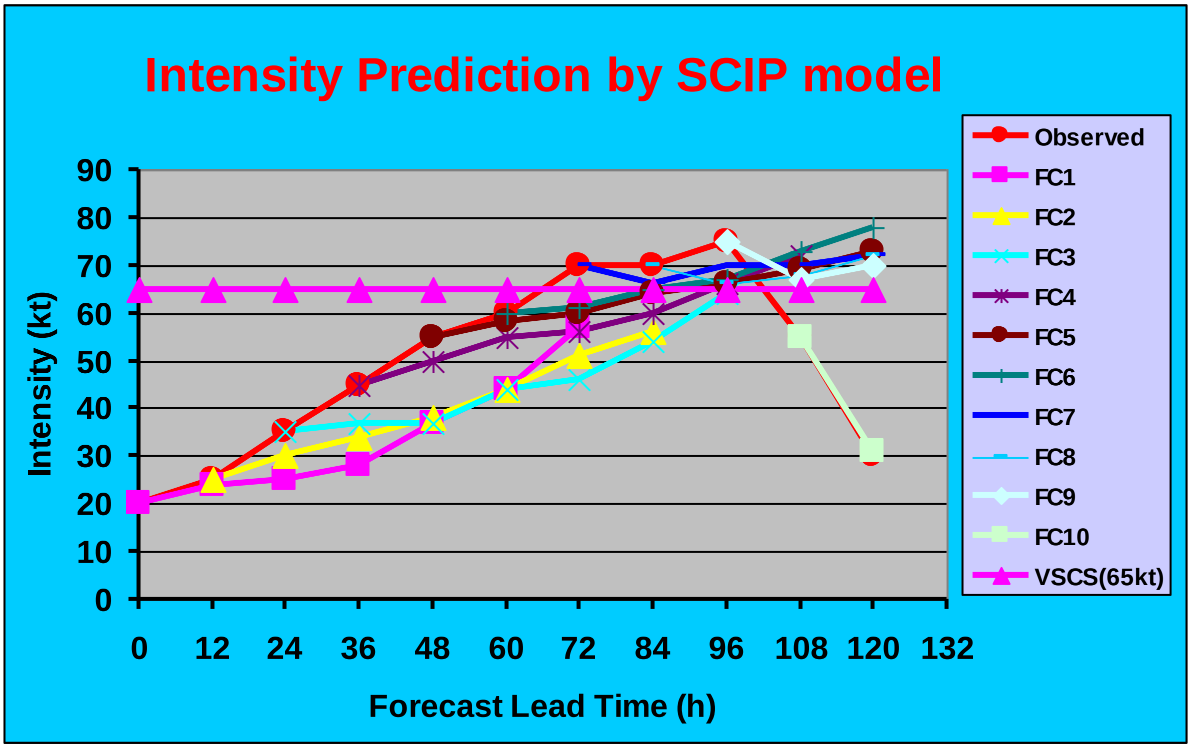


Fig. 3.46. Intensity forecasts of SCIP model

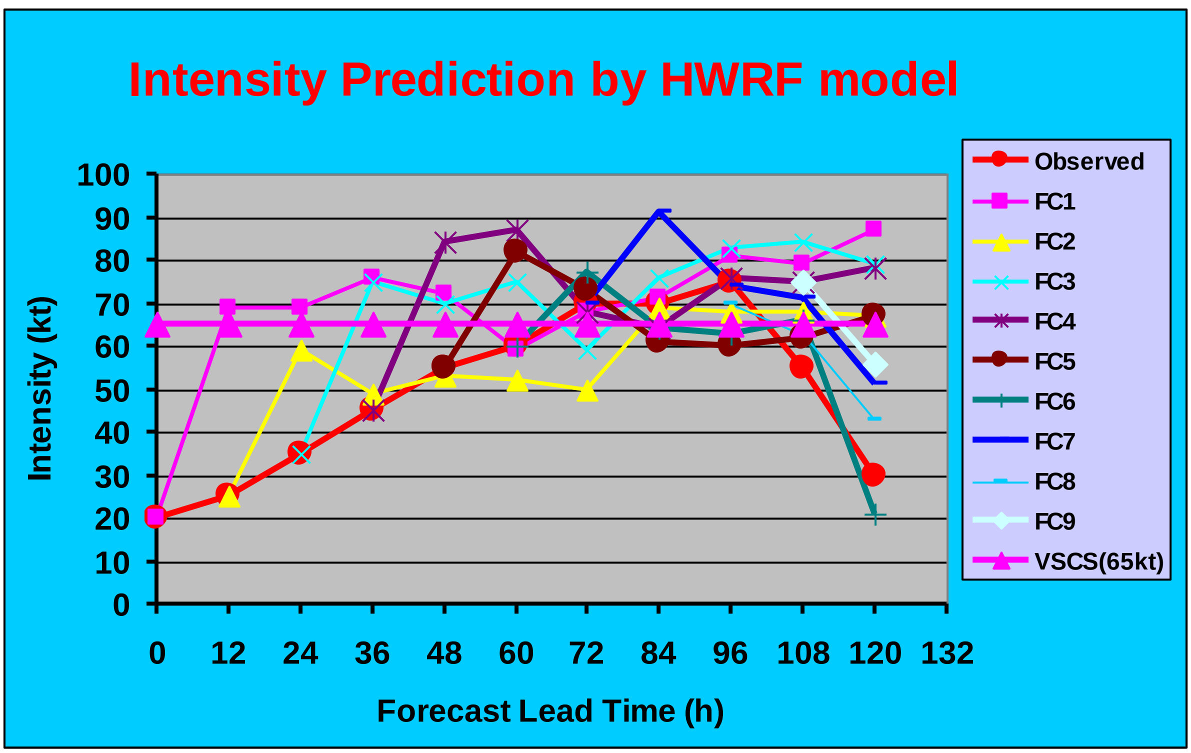


Fig. 3.47 Intensity forecasts of HWRF model

Average absolute error (AAE) and Root mean square error (RMSE) of SCIP and HWRF forecast error is presented in the following Table-3.42 and Table-3.43.

Table-3.42 Average absolute errors (Number of forecasts verified is given in the parentheses)

(Intensity forecasts prior to landfall are considered)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-SCIP	5.6 (10)	13.0 (9)	16.9 (8)	19.6 (7)	20.3 (6)	19.6 (5)	-	-	-	-
IMD-HWRF	23.4(9)	12.9(8)	12.4(7)	12.7(7)	7.3(6)	13.6(5)	21.3(4)	22.7(3)	30.5(2)	57(1)

Table-3.43 Root Mean Square (RMSE) errors (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	6.6 (10)	16.6 (9)	19.7 (8)	22.1 (7)	24.0 (6)	22.9 (5)	-	-	-	-
IMD-HWRF	25.7(9)	17.1(8)	15.5(7)	13.6(7)	9.7(6)	19.2(5)	28.3(4)	29.5(3)	31.2(2)	57(1)

3.7.5 Probability of Rapid intensification (by RI-Index)

RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of cyclone LEHAR during its lifetime (Table 3.44).

Table-3.44 Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/23.11.2013	5.2 %	VERY LOW	5	NO
12 UTC/23.11.2013	5.2 %	VERY LOW	20	NO
00 UTC/24.11.2013	22.0 %	LOW	20	NO
12 UTC/24.11.2013	22.0 %	LOW	15	NO
00UTC/25.11.2013	32.0 %	MODERATE	15	NO
12 UTC/25.11.2013	9.4 %	VERY LOW	10	NO
00 UTC/26.11.2013	9.4%	VERY LOW	5	NO
12 UTC/26.11.2013	5.2%	VERY LOW	-15	NO
00 UTC/27.11.2013	9.4%	VERY LOW	-45	NO
12 UTC/27.11.2013	0.0%	NIL	-30	NO

3.7.8 Ensemble track and Strike Probability forecast

Ensemble track and strike probability forecasts (Fig. 3.48(a-c)) based on 00 UTC 25.11.2013, 26.11.2013 and 27.11.2013 shows that ALL, NCEP and UKMO all predicted movement towards Andhra Pradesh coast.

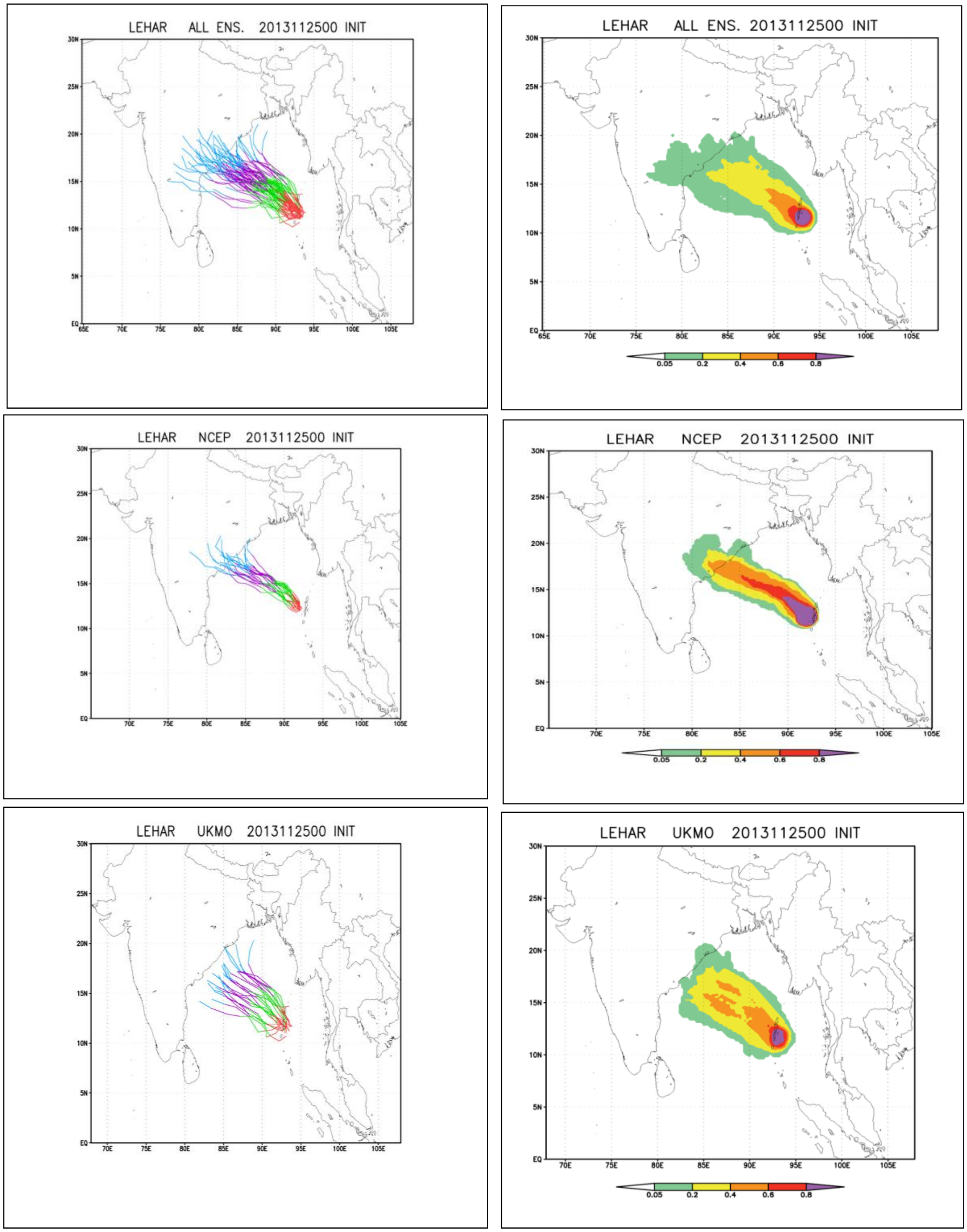


Fig. 3.48(a) Ensemble track and strike probability forecasts based on 00UTC of 25.11.2013

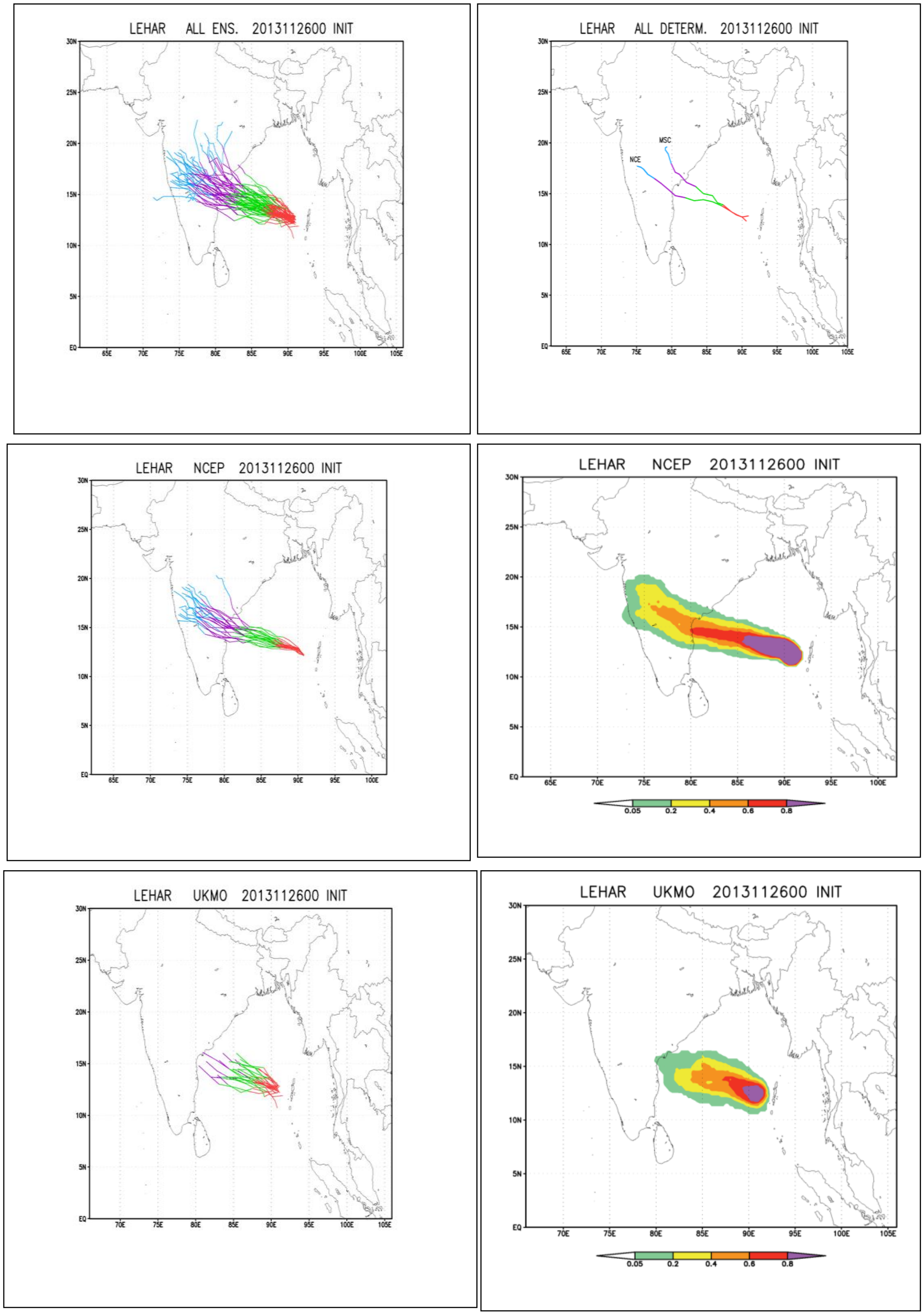


Fig. 3.48(b) Ensemble track and strike probability forecasts based on 00UTC of 26.11.2013

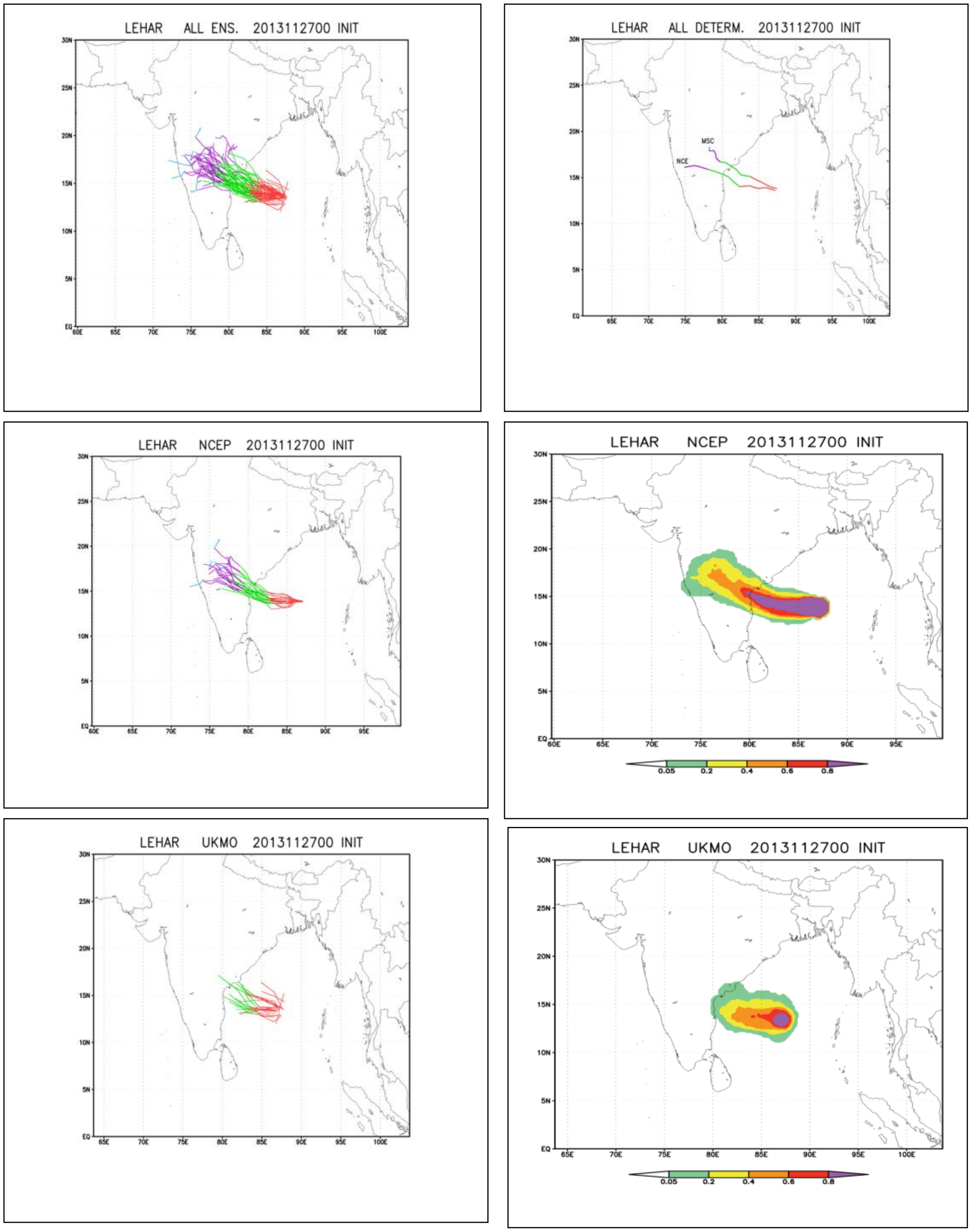
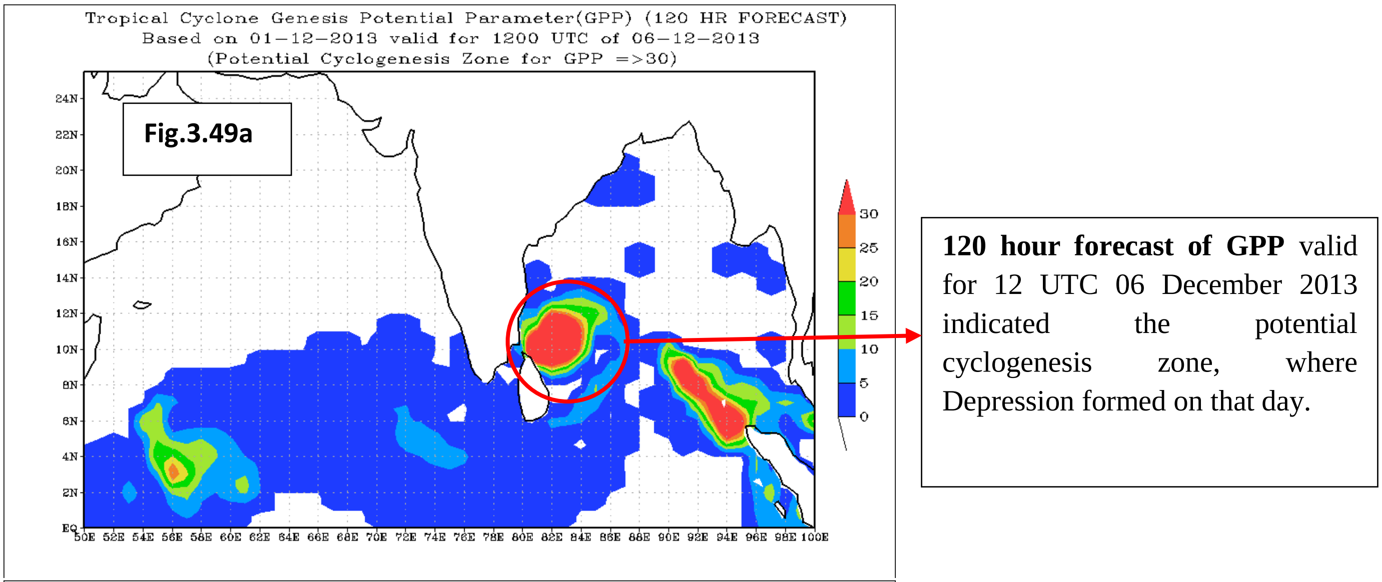


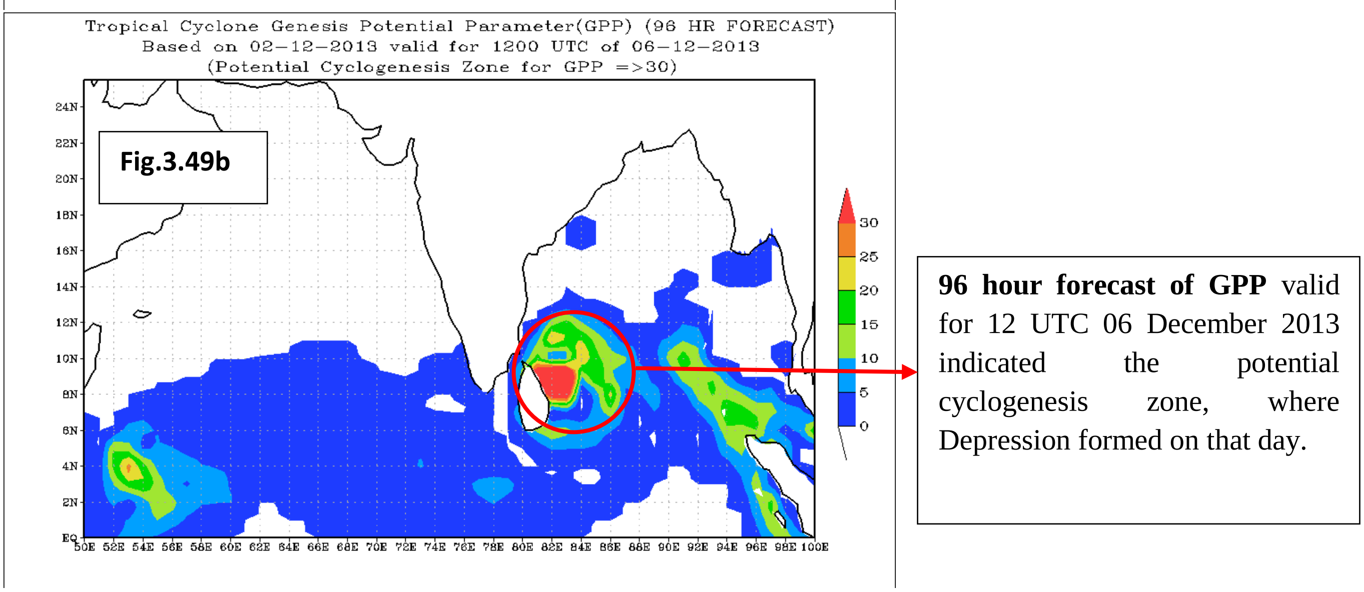
Fig. 3.48(c) Ensemble track and strike probability forecasts based on 00UTC of 27.11.2013

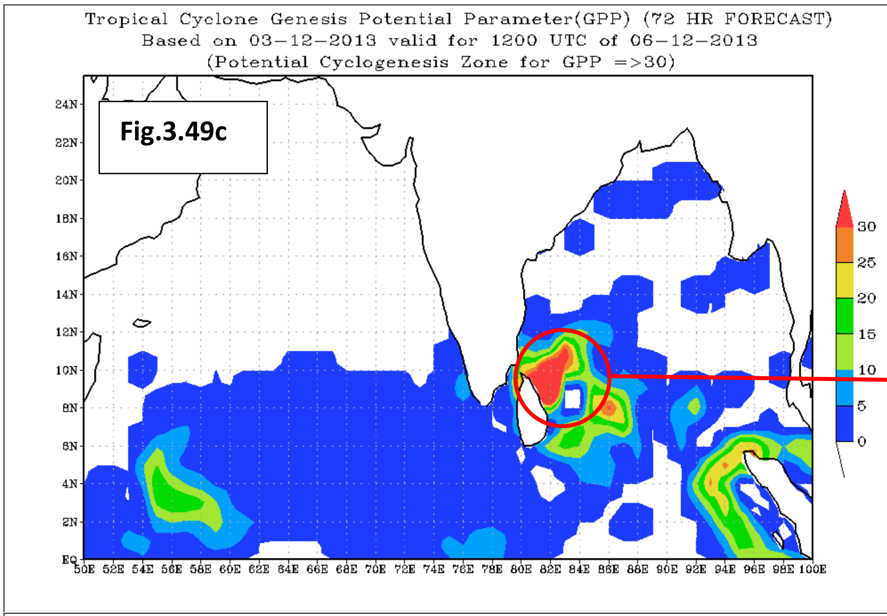
3.8 Very Severe Cyclonic storm 'MADI' (6-12) December 2013

3.8.1 Grid point analysis and forecast of GPP

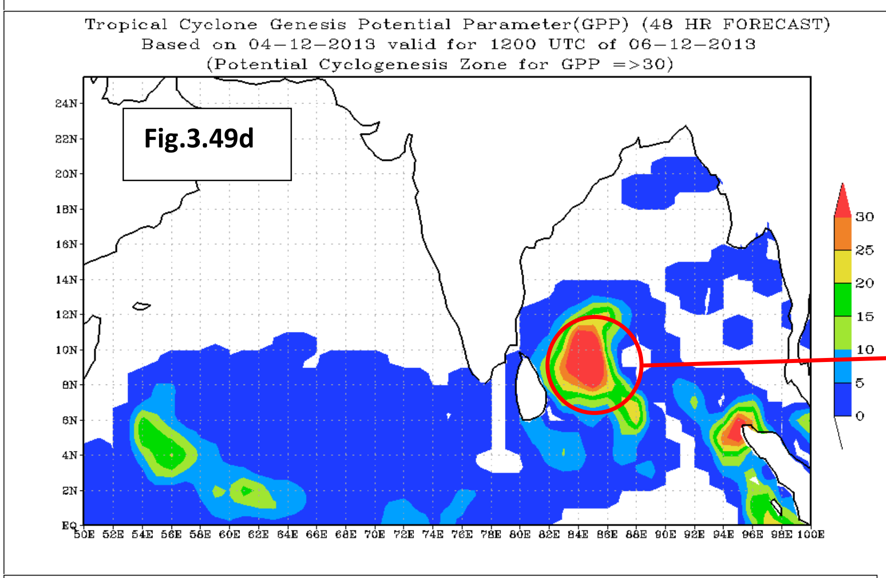
Grid point analysis and forecasts of GPP (Fig.3.49(a-f)) shows that it was able to predict the formation and location of the system before 120 hours of its formation.



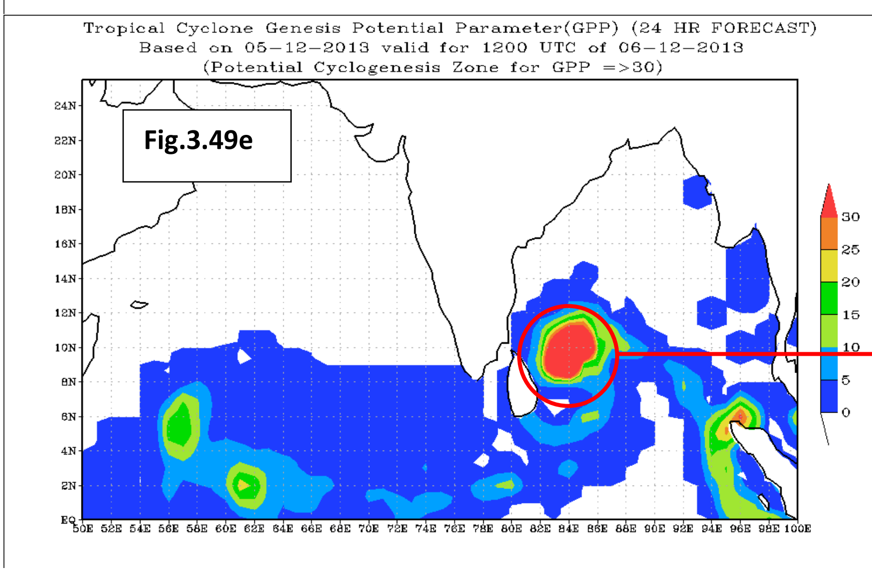




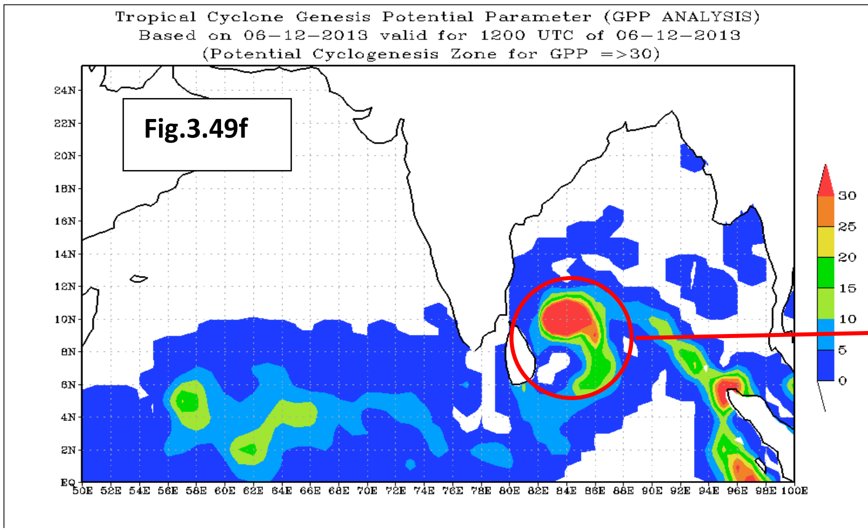
72 hour forecast of GPP valid for 12 UTC 06 December 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



48 hour forecast of GPP valid for 12 UTC 06 December 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



24 hour forecast of GPP valid for 12 UTC 06 December 2013 indicated the potential cyclogenesis zone, where Depression formed on that day.



Analysis of GPP on 12 UTC 06 December 2013 indicates the zone of cyclogenesis (Depression).

Figure3.49(a-f): Predicted zone of cyclogenesis.

3.8.2. Area average analysis of GPP

Analysis and forecasts of GPP (Fig.3.50(a-e)) shows GPP ≥ 8.0 (threshold value for intensification into cyclone) and hence indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0).

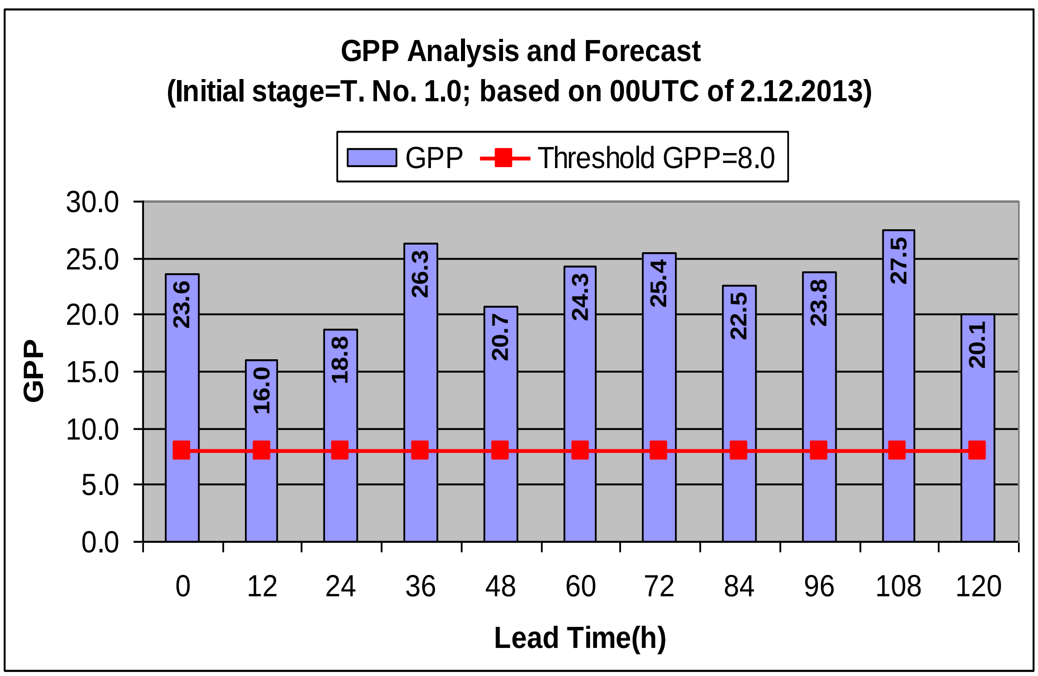


Fig 3.50a: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No.-1.0**) indicated its potential to intensify into a cyclone.

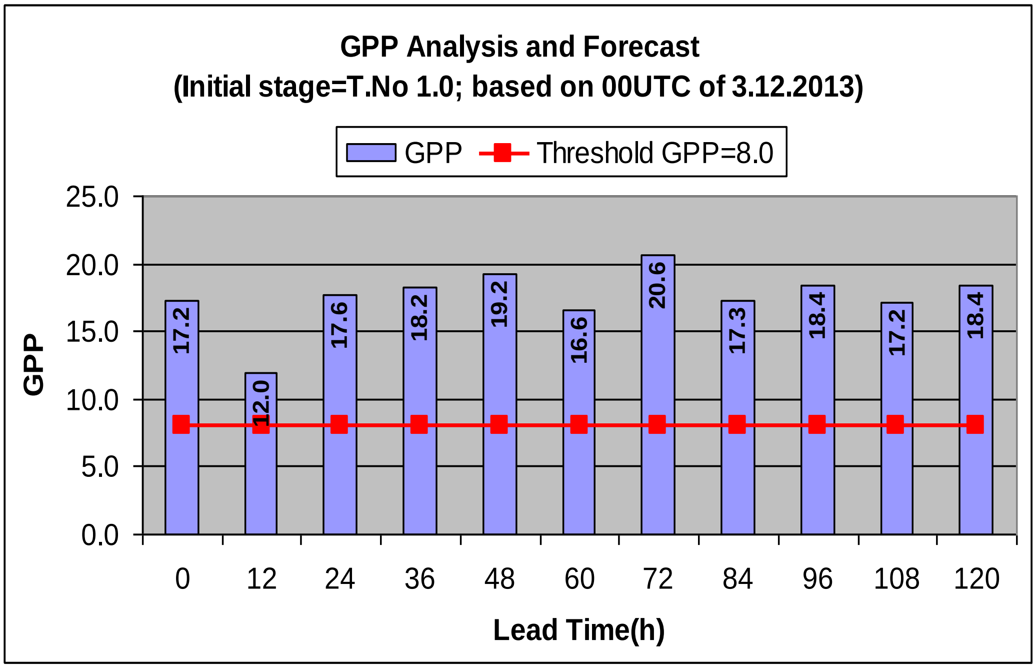


Fig 3.50b: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

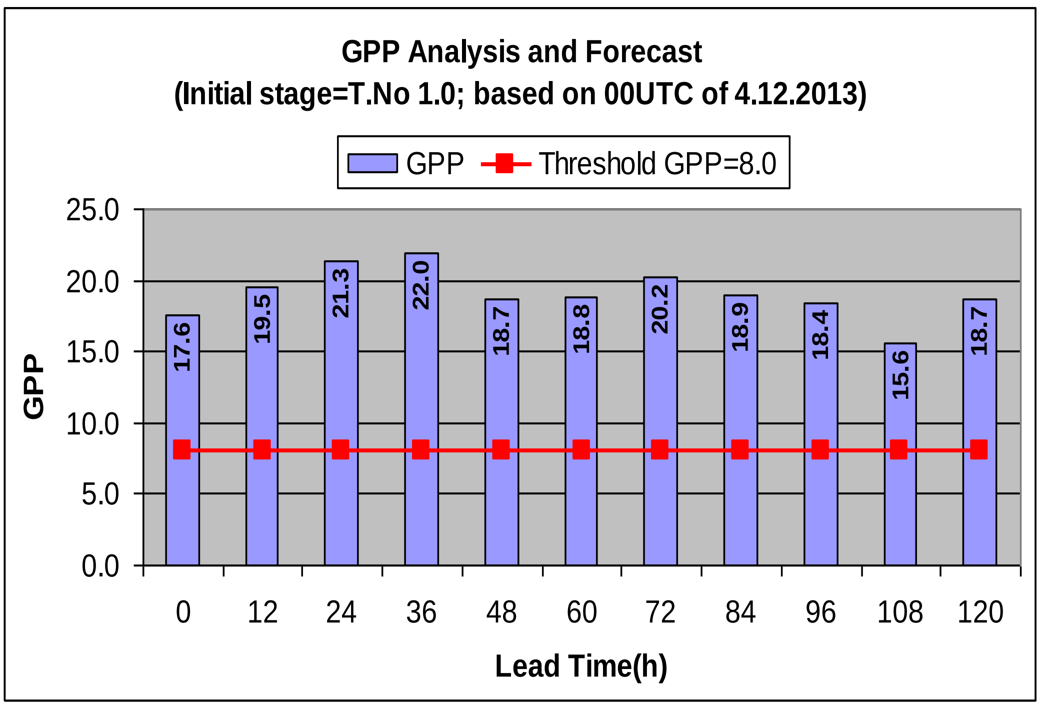


Fig3.50c: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

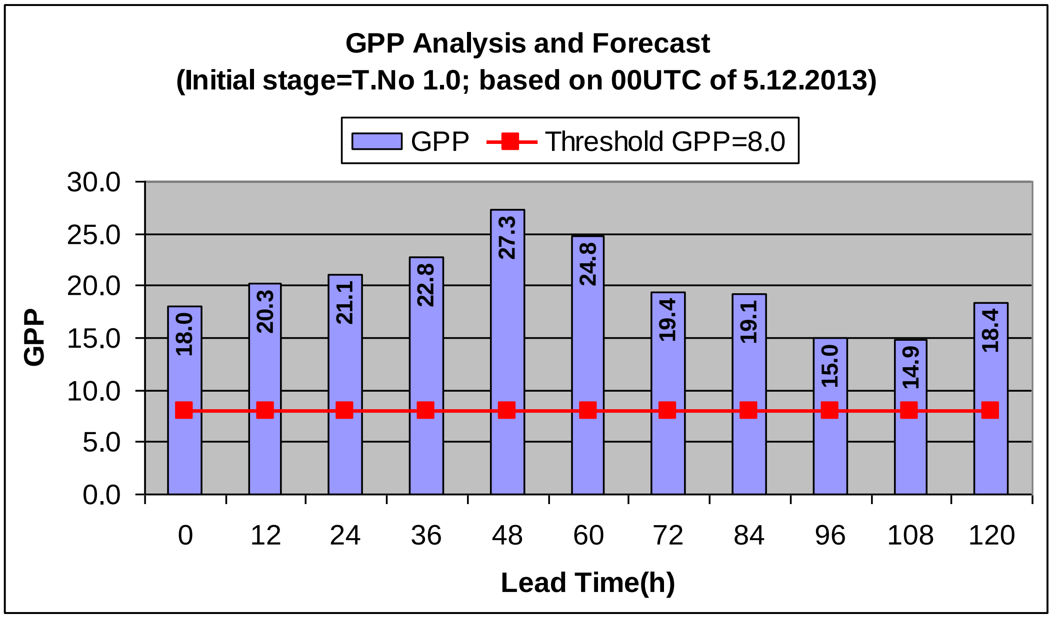


Fig 3.50d: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

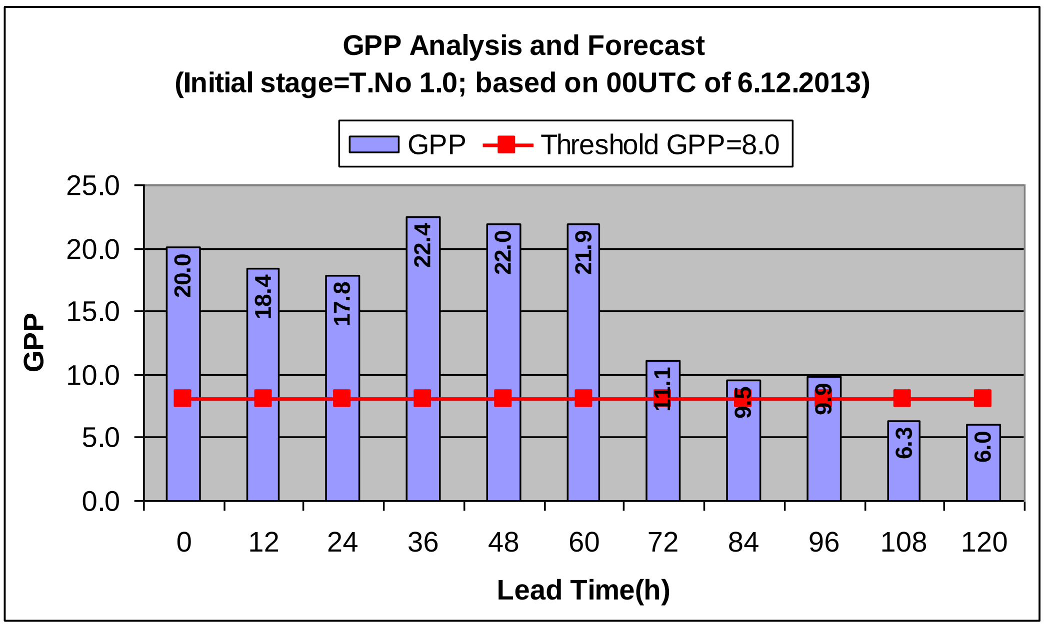


Fig.3.50e: Analysis and forecasts of GPP shows that GPP ≥ 8.0 (Threshold) at very early stage of development (**T.No. 1.0**) indicated its potential to intensify into a cyclone.

Fig. 3.50(a-e) Area average analysis of GPP

3.8.3. Track prediction

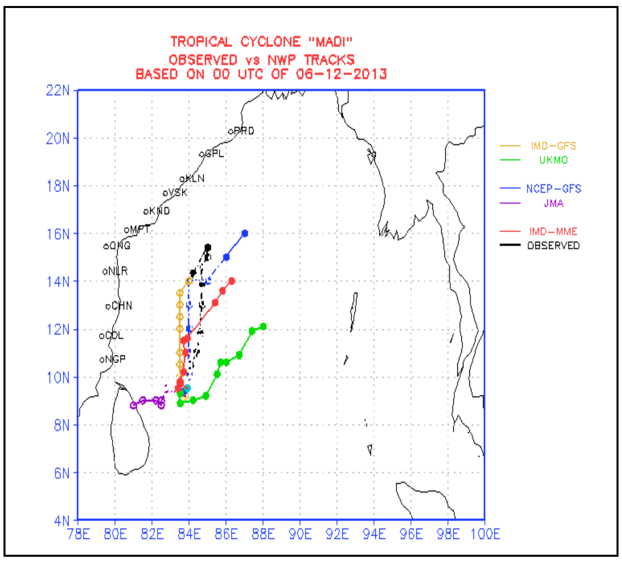
The average track forecast errors (DPE, CTE, ATE) of NWP models along with the MME forecast are presented in the Table 3.45, Table 3.46 and Table 3.47 respectively. The MME forecasts track based on different initial conditions along with the observed track is depicted in Fig 3.51. The figure shows that from 00 UTC of 6 December to 00 UTC of 11 December 2013, MME was able to predict correctly initially north-northeastward movement then southwestward direction towards Tamil Nadu coast.

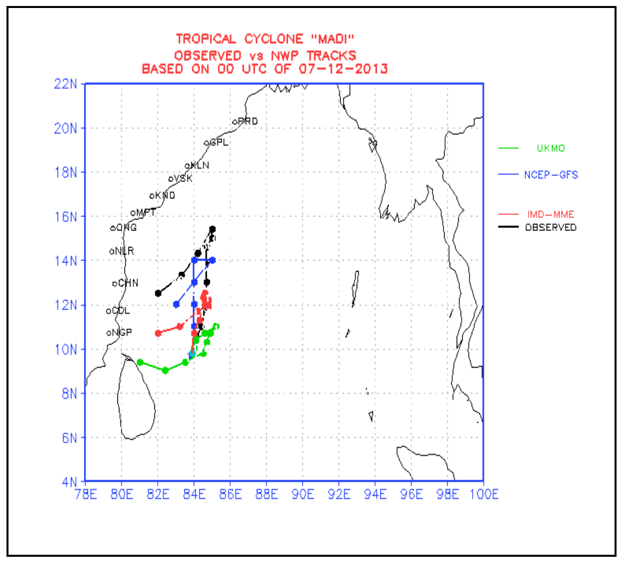
Average track forecast error (direct position error (DPE)) was highest for JMA (about

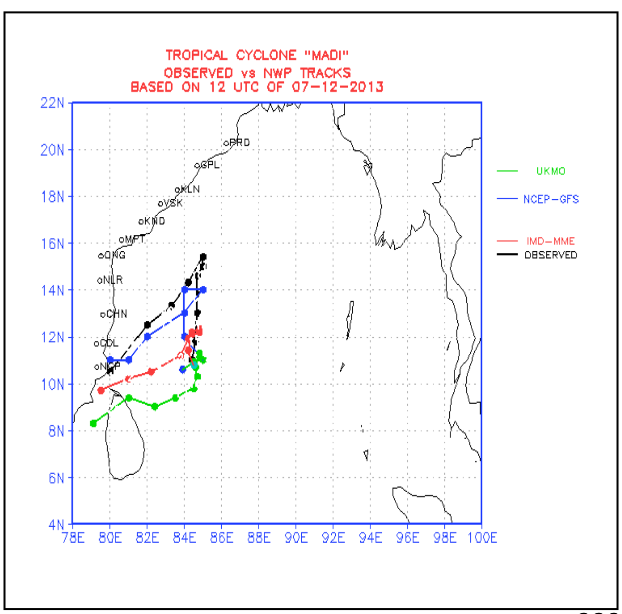
155 km at 12 h to 760 km at 84 h) for one forecast only and UKMO (about 115 km at 12 h to 500 km at 96 h and 370 at 120 h). Average DPE was lowest for NCEP-GFS (about 75 km at 12 h to 250 km at 72 h and 175 at 120h), IMD-GFS (about 60 km at 12 h to 230 km at 84 h and 40 at 120h for one forecast only), and for MME (about 65 km at 12 h to 280 km at 84 h and 180 at 120 h)(Table-3.45). The DPE of all models are shown in Fig. 3.52

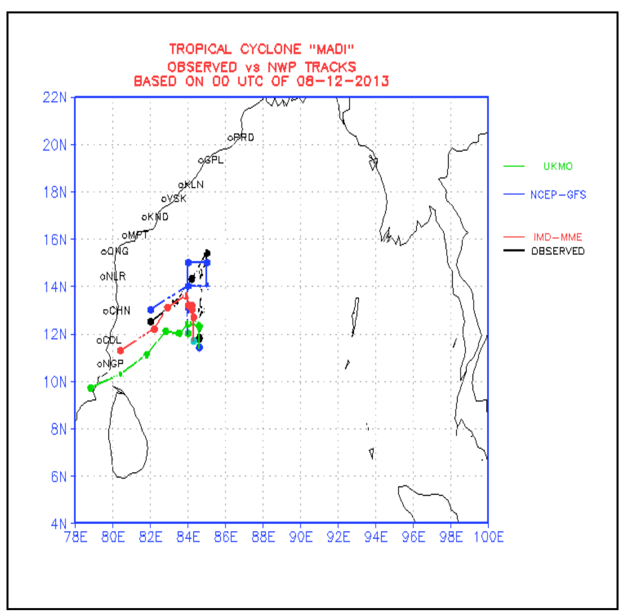
Average cross track error (CTE) was highest for JMA (about 130 km at 12 h to 305 km at 84 h) and UKMO (about 35 km at 12 h to 325 km at 120 h). Average CTE was lowest for IMD-GFS (for one forecast only), NCEP-GFS and MME (about 40 km at 12 h to 125 km at 120 h) (Table-3.46). The CTE of all models are shown in Fig. 3.53.

Average along track error (ATE) was highest for JMA (about 80 km at 12 h to 695 km at 84 h). ATE was lowest for IMD-GFS (one forecast only), NCEP-GFS, MME (about 45 km at 12 h to 140 km at 120 h). The ATE for MME was highest at 96h about 200 km (Table-3.47). The ATE of all models is shown in Fig. 3.54.









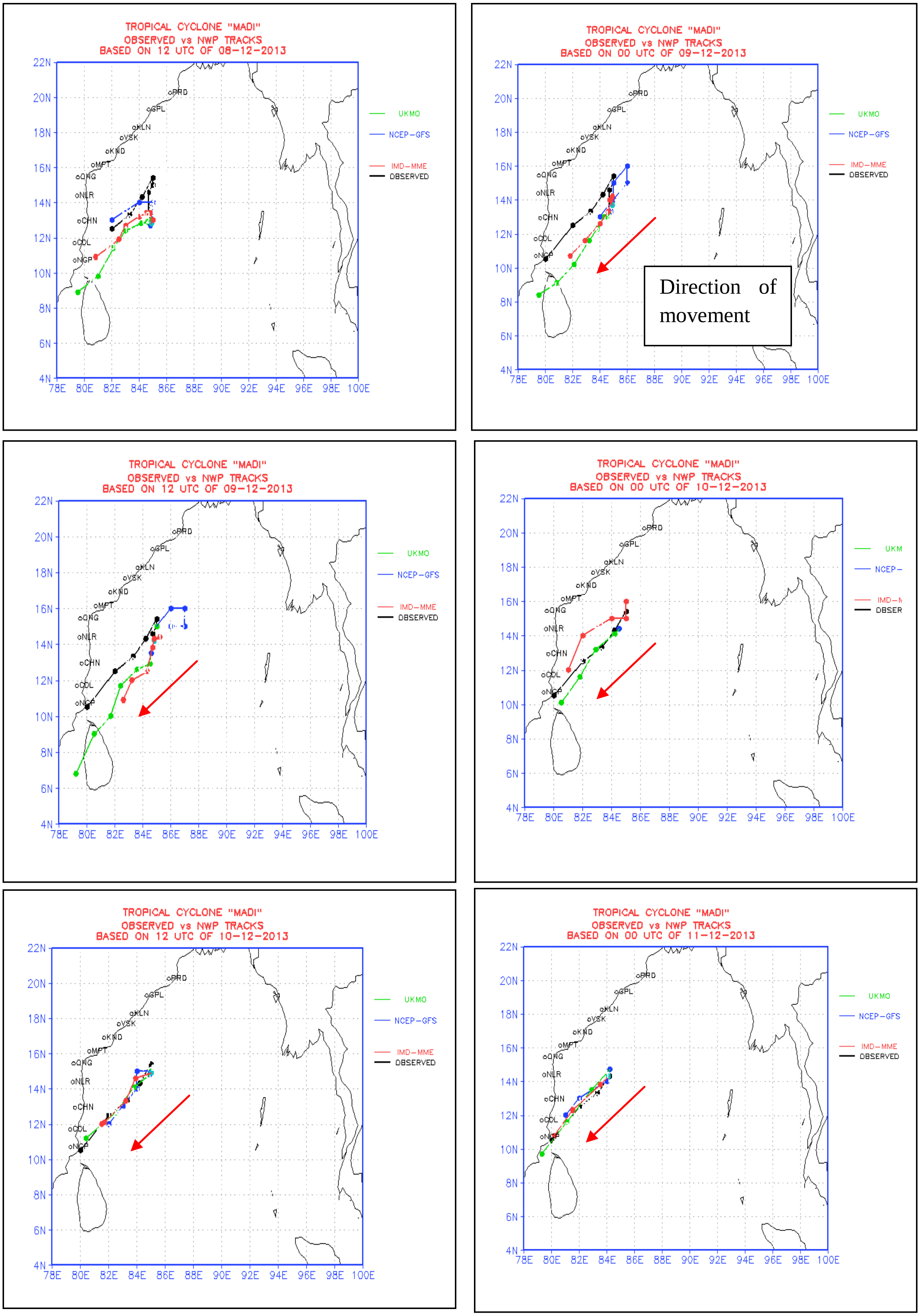


Fig. 3.51 NWP model tracks forecast based on different initial conditions

Table-3.45. Average track forecast errors (DPE) in km (Number of forecasts verified)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	59(1)	86(1)	113(1)	149(1)	171(1)	194(1)	220(1)	232(1)	189(1)	40(1)
JMA	153(1)	242(1)	321(1)	405(1)	521(1)	637(1)	760(1)	-	-	-
NCEP-GFS	77(10)	76(10)	145(10)	175(9)	179(8)	250(7)	176(6)	131(5)	149(4)	177(3)
UKMO	114(10)	190(10)	256(10)	356(8)	416(7)	463(7)	471(6)	499(4)	439(3)	368(3)
IMD-MME	65(10)	95(10)	133(10)	197(9)	214(8)	255(7)	278(6)	264(4)	250(3)	178(3)

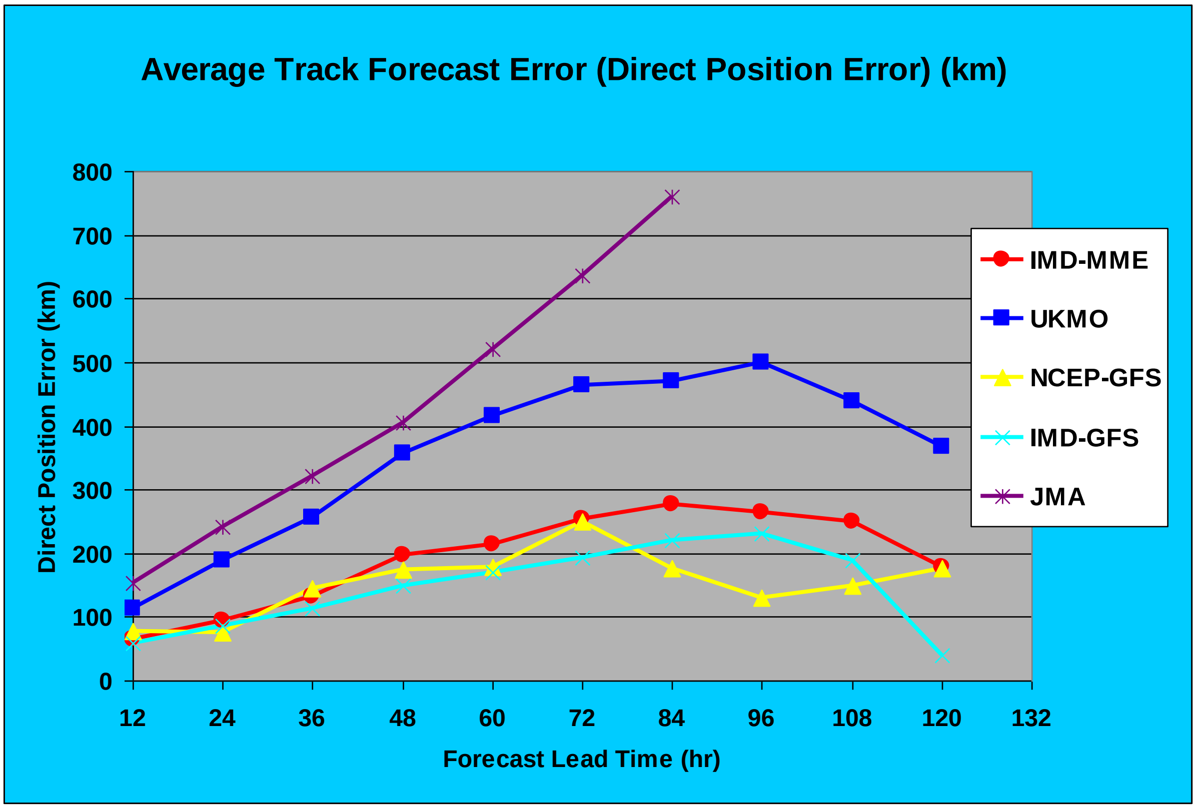


Fig. 3.52 Average track forecast errors (DPE) of NWP models

. **Table-3.46 Average cross track error (CTE) in km**

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	55	54	71	86	102	102	102	127	78	20
JMA	132	140	105	115	168	251	307	-	-	-
NCEP-GFS	44	39	53	79	46	50	49	106	126	127
UKMO	37	24	59	134	184	220	221	254	300	326
IMD-MME	36	27	46	77	104	139	144	147	161	96

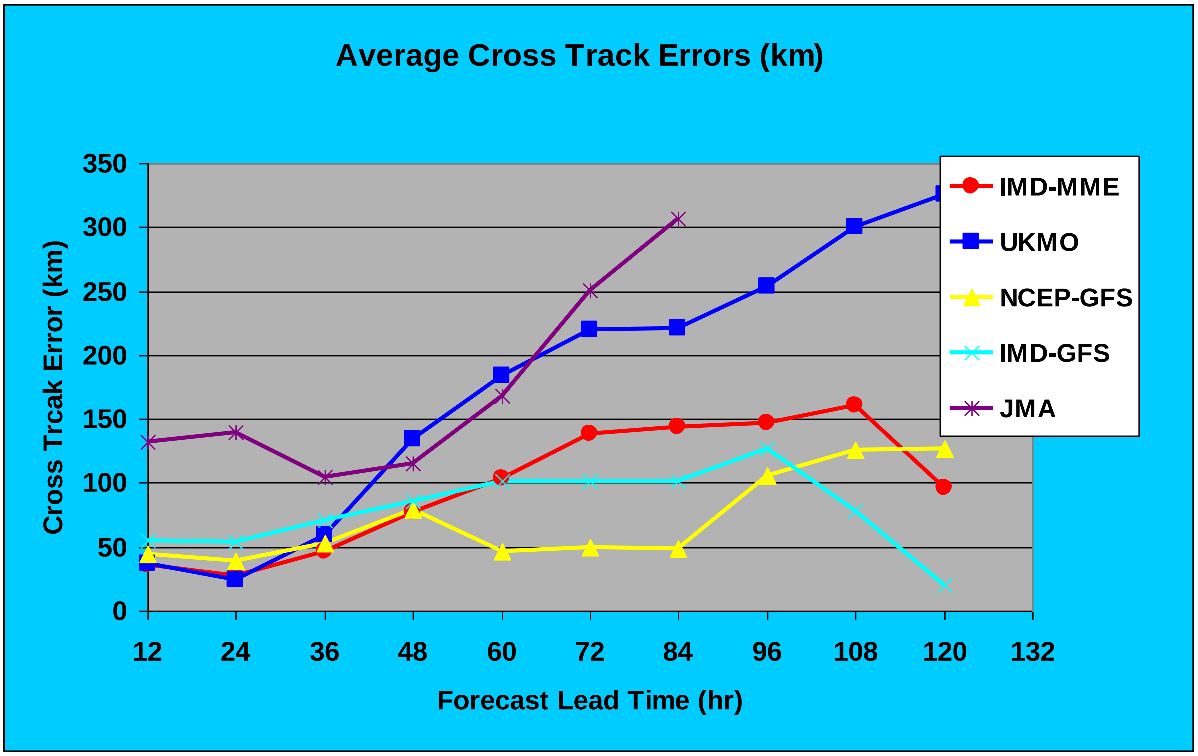


Fig. 3.53 Average cross track errors (CTE) of NWP models

Table-3.47 Average along track error (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr	120 hr
IMD-GFS	22	67	88	122	137	165	195	194	172	34
JMA	78	197	303	388	494	586	695	-	-	-
NCEP-GFS	46	51	125	135	164	229	149	63	58	109
UKMO	103	188	247	315	352	368	359	401	286	170
IMD-MME	46	85	114	156	152	165	192	198	154	141

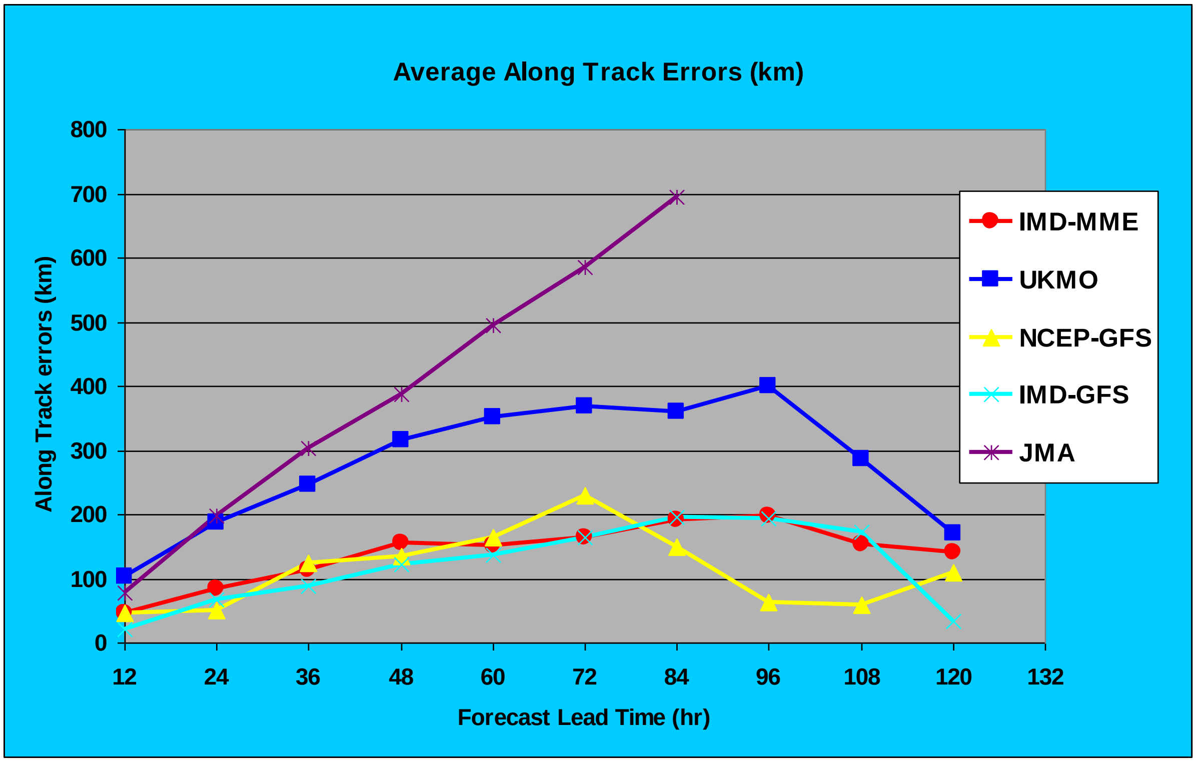


Fig. 3.54 Average along track errors (ATE) of NWP models

3.8.4 Intensity prediction

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP using different initial conditions is shown in Fig. 3.55. The model was able to predict the intensification in the initial stage and decay over Sea after attaining the VSCS intensity the later stage.

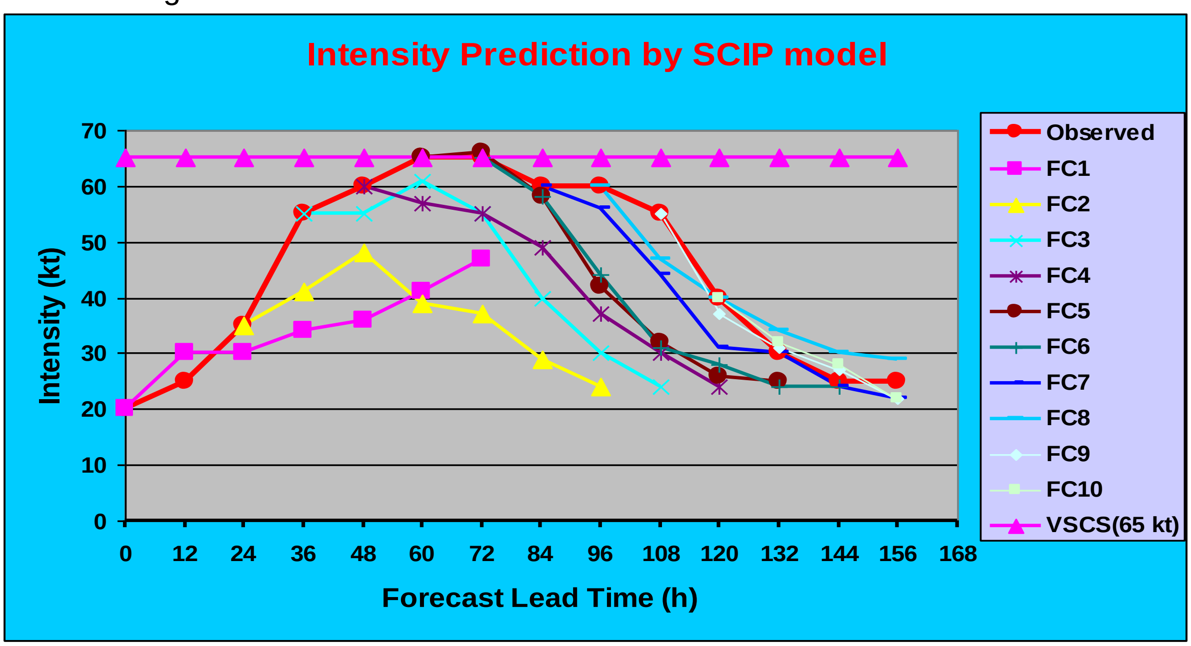


Fig. 3.55 Intensity forecasts of SCIP model

Average absolute error (AAE) and Root mean square error (RMSE) of SCIP forecast error is presented in the following Table 4.48. AAE of SCIP was 5.2 kts at 12h and 15.7 kt at 72h and RMSE varies from 6.4 kt at 12h to 20.3 kt at 72 h.

Table-3.48 Average absolute errors (AAE) and Root Mean Square (RMSR) of SCIP (Number of forecasts verified is given in the parentheses)

(Intensity forecasts prior to landfall are considered)

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
AAE	5.2 (10)	6.4 (10)	12.8(10)	15.3 (9)	16.9 (8)	15.7 (7)
RMSE	6.4 (10)	8.2 (10)	15.3(10)	18.2 (9)	20.3 (8)	20.3 (7)

3.8.5 Probability of Rapid intensification (by RI-Index)

RI-Index was able to predict **NON-OCCURENCE** of Rapid Intensification of cyclone MADI during its lifetime by all ten forecasts issued (Table 4.49).

Table-3.49 Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) in 24h	Occurrence
00 UTC/06.12.2013	5.2 %	VERY LOW	10	NO
00 UTC/07.12.2013	22.0 %	LOW	25	NO
12 UTC/07.12.2013	5.2 %	VERY LOW	10	NO
00 UTC/08.12.2013	22.0 %	LOW	5	NO
12 UTC/08.12.2013	9.4 %	VERY LOW	-5	NO
00 UTC/09.12.2013	9.4 %	VERY LOW	-5	NO
12 UTC/09.12.2013	22.0 %	LOW	-5	NO
00 UTC/10.12.2013	9.4 %	VERY LOW	-20	NO
12 UTC/10.12.2013	0 %	NIL	-25	NO
00 UTC/11.12.2013	0 %	NIL	-15	NO

3.8.6. Ensemble track and Strike Probability forecasts

Ensemble track and strike probability forecast (Fig. 3.56) based on 00 UTC of 8.12.2013, 12 UTC of 9.12.2013 and 00 UTC of 10.12.2013 shows that UKMO, ECMWF, and NCEP were able to predict north-northeastward movement initially and southwestwards thereafter towards Tamil Nadu coast.

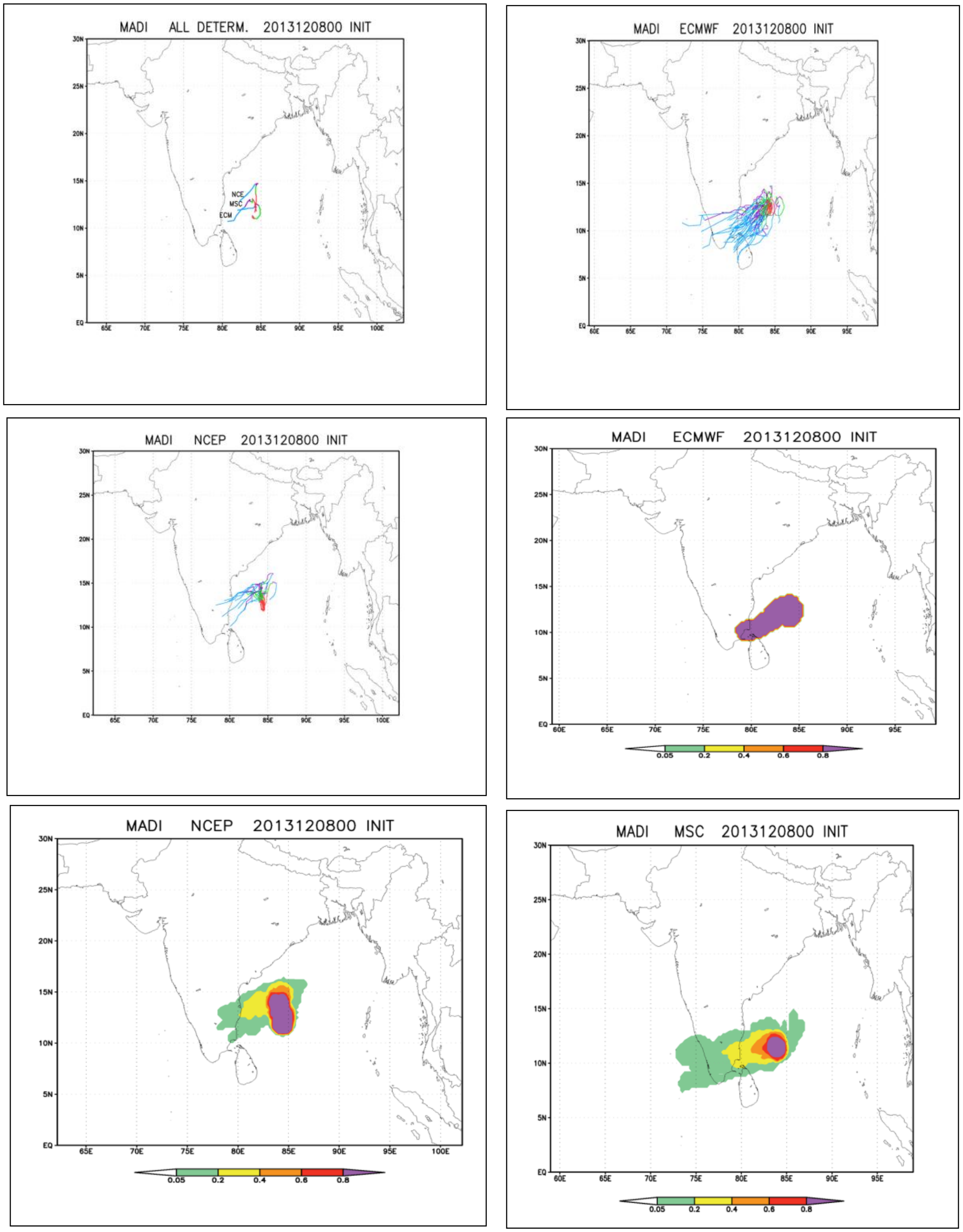


Fig. 3.56(a) Ensemble track and strike probability forecasts based on 00 UTC of 08.12.2013

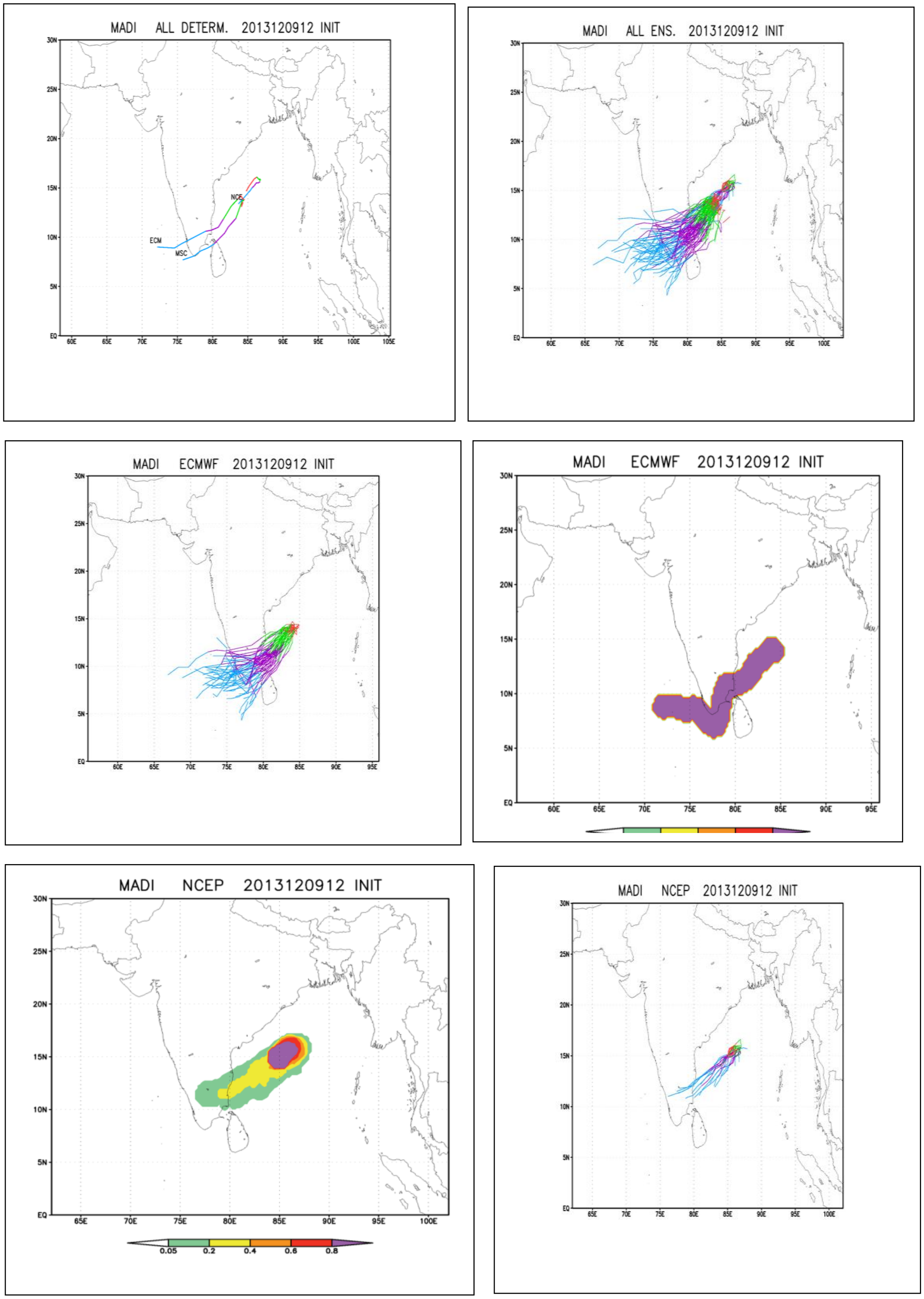


Fig. 3.56(b) Ensemble track and strike probability forecasts based on 12 UTC of 09.12.2013

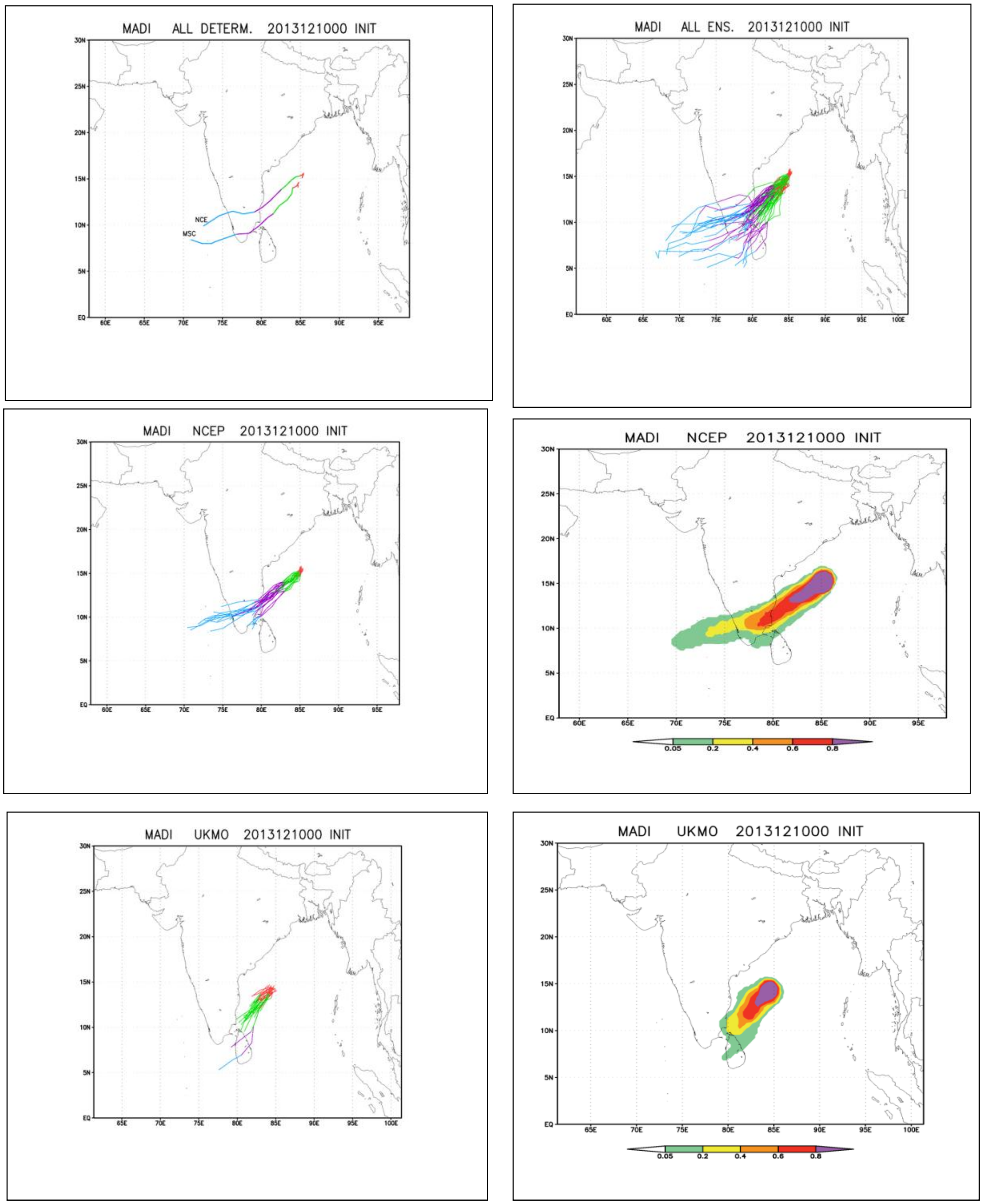


Fig. 3.56(c) Ensemble track and strike probability forecasts based on 00 UTC of 10.12.2013

3.9. YEARLY AVERAGE TRACK AND INTENSITY FORECAST ERRORS FOR 2013

3.9.1. Mean track forecast error (km) – 2013

The annual average track forecast errors (DPE) of various models for the year 2013 are shown in Table 3.50. It includes the cyclones and depressions. The 24 hr track forecast errors is less than 100 km for NCEP and MME, 48 hr track forecast errors is less than 150 km for NCEP and MME, 72hr track forecast errors is less than 200 km for NCEP, ECMWF and MME, 96hr track forecast errors is less than 200 km for NCEP, ECMWF and 210 km for MME, 120hr track forecast errors is less than 200 km for NCEP and MME.

Table-3.50: annual average track forecast errors (DPE) of various models for the year 2013) (Number of forecast verified)

FORECAST HOUR	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	90(36)	119(34)	173(31)	200(26)	253(22)	213(17)	272(14)	254(10)	252(7)	277(5)
IMD-WRF	90(36)	153(34)	225(31)	288(26)	345(20)	340(15)	-	-	-	-
JMA	178(37)	184(35)	220(32)	217(27)	213(22)	210(17)	281(15)	-	-	-
NCEP	82(46)	79(44)	128(40)	131(35)	166(30)	189(24)	220(24)	159(15)	193(11)	186(8)
UKMO	101(36)	144(35)	173(32)	209(27)	275(22)	306(19)	322(16)	337(11)	320(8)	309(6)
ECMWF	105(8)	149(7)	202(6)	153(5)	199(5)	173(4)	224(4)	104(3)	255(3)	233(2)
QLM	163(7)	230(6)	292(5)	252(4)	289(4)	238(3)	-	-	-	-
HWRF	65(32)	139(30)	195(27)	227(23)	258(20)	316(16)	354(13)	401(10)	447(7)	510(4)
IMD-MME	68(46)	90(44)	121(41)	132(35)	164(30)	175(24)	204(20)	210(14)	231(11)	187(8)

3.9.2 Mean Intensity forecast error (kt) -2013

I. SCIP model -2013

The annual average intensity forecast errors of SCIP model are shown in Table 3.51 for SCIP model. The error is 10 kts at 24hr, 17 kts at 48hr and 20 kts at 72hr for all the systems during 2013 (VIYARU, PHAILIN, HELEN, LEHAR and MADI).

Table-3.51: The annual average intensity forecast errors of SCIP for all the systems during 2013.

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
AAE	5.9	9.9	15.0	17.3	17.7	19.8
RMSE	7.3	12.8	17.6	19.9	20.5	22.0
Number of forecasts verified	49	46	41	35	29	24

II. HWRF model -2013

The annual average intensity forecast errors for 2013 are shown in Table 3.52 for HWRF model. The error is 16 kts at 24hr, 11 kts at 48hr and 18 kts at 72hr and 96 hr and 43 kts at 120hr for the cyclones VIYARU, PHAILIN, HELEN and LEHAR during 2013.

Table-3.52: Annual average intensity forecast errors of HWRF for the cyclones VIYARU, PHAILIN, HELEN and LEHAR during 2013

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84h	96h	108h	120h
AAE	21.9	16.1	9.8	11.1	13.3	18.3	25.4	18.3	26.3	43.0
RMSE	23.1	17.4	11.4	11.9	15.1	20.8	26.4	18.5	26.5	43.0
Number of forecasts verified	23	21	18	16	12	10	8	6	4	2

3.9.3 Mean Decay (after landfall) forecast error (kt) by DECAY model

Yearly average decay (after landfall) forecast errors (kt) at 6h interval up to 24h during 2013 is shown in Fig 3.75. The figures show that model was able to predict decay after landfall with reasonable success.

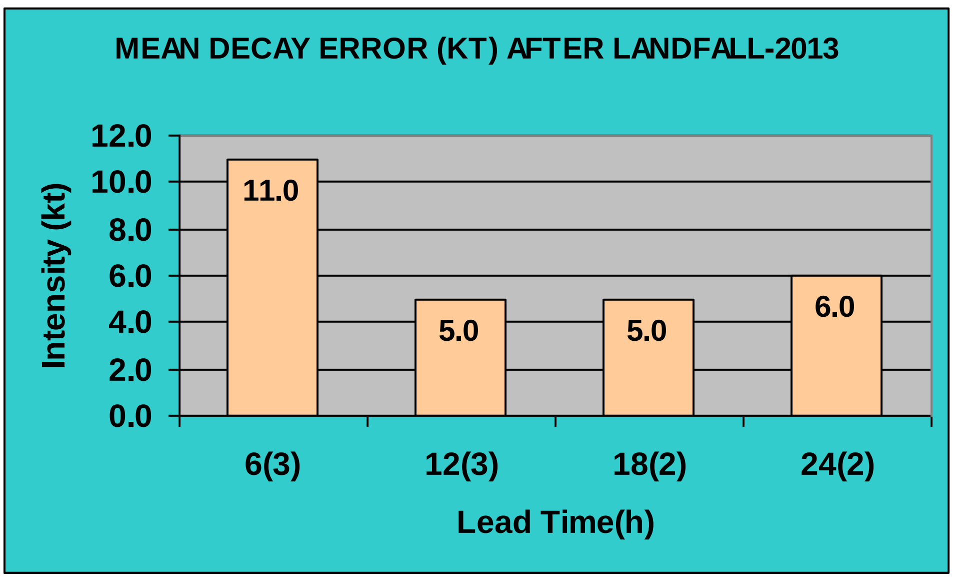


Fig. 3.75 Yearly average decay (after landfall) forecast error (kt) during 2013

CHAPTER-IV

PERFORMANCE OF RSMC, NEW DELHI IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2013

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 over the north Indian Ocean during 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).

IMD continuously monitored, predicted and issued bulletins containing track & intensity forecast at +06, +12, +18, +24, +36, +48, +60, +72, +84, +96, +108 and +120. hrs or till the system weakened into a low pressure area. The above structured track and intensity forecasts were issued from the stage of deep depression onwards. The cone of uncertainty in the track forecast was also given for all cyclones. The radius of maximum wind and radius of ≥ 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 IMD'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 last meeting of Panel on Tropical Cyclone (PTC) held during March, 2009 at Muscat, Oman based on IITD model. The prognostics and diagnostics 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 2013 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 2013

Bulletins issued during ' Viyaru '

Bulletins for national disaster management agencies : 36

Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 47

Tropical cyclone advisory for international civil aviation: 23

Bulletins issued during 'Phailin'

Bulletins for national disaster management agencies	:	45
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	27
Tropical cyclone advisory for international civil aviation :		19

Bulletins issued during 'Helen'

Bulletins for national disaster management agencies	:	29
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	24
Tropical cyclone advisory for international civil aviation :		12

Bulletins issued during 'Lehar'

Bulletins for national disaster management agencies	:	40
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	36
Tropical cyclone advisory for international civil aviation :		18

Bulletins issued during 'Madi'

Bulletins for national disaster management agencies	:	47
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	44
Tropical cyclone advisory for international civil aviation :		18

Bulletins issued for all cyclones during 2013

Bulletins for national disaster management agencies	197
RSMC bulletin for WMO/ESCAP Panel member countries (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	178
TCAC bulletin for international civil aviation	90

Bulletins issued for all cyclonic disturbances (depression and above) during 2013

Bulletins for national disaster management agencies	254
RSMC bulletin for WMO/ESCAP Panel member countries : (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	206
TCAC bulletin for international civil aviation	90

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 five cyclones and one deep depression during 2013 are described below.

4.3.1. Cyclonic storm 'Viyaru' over the Bay of Bengal (10-16 May, 2013)

4.3.1.1 Track forecast error

In the first bulletin issued in the afternoon of 10th May (six days in advance of landfall), when the system was a depression over southeast Bay of Bengal, located at 1900 km south of Chittagong, it was predicted that the system would intensify into a cyclonic storm and move towards Bangladesh-Myanmar. The average track forecast error is shown in Table 1. It was 152 km, 205 and 268 km respectively for 24, 48 and 72 hrs. forecast period against the long period average of 146, 254 and 376 km based on the *per*iod of 2003-2012. Further, for the first time the track forecast was issued for 120 hrs lead period. The 96 and 120 hr average track forecast errors were about 308 and 222 km respectively.

Usually the track forecast errors are higher world-wide for the recurving cyclones like Viyaru. Hence, the track forecast errors of Viyaru has been compared with the average errors of recurving cyclones during 2003-12. It is found that the errors in case of Viyaru are significantly less than the average errors in case of recurving cyclones, as the average errors of recurving cyclones are about 91, 167, 249, 325, 398 and 474 km for 12, 24, 36, 48, 60 and 72 hrs lead period respectively.

The performance of the operational forecast has been compared with forecast by climatology and persistence (CLIPER) model as per international practice. CLIPER model is taken as a reference model to find out the relative performance of NWP models and operational forecasts of cyclones in different Ocean basins.

The gain in skill on operational forecast in relation to CLIPER, is quantified in percentage terms by;

$$\text{Gain in skill} = \frac{(\text{CLIPER DPE} - \text{DPE})}{\text{CLIPER DPE}} \times 100\%$$

The DPE is the direct position error or simply track forecast error. The results are shown in Table 4.1. It is found that the operational forecasts were highly skillful compared to CLIPER model forecast.

Table 4.1 Average Track Forecast Error and skill of Cyclonic Storm, Viyaru

Lead Period (hr)	Track forecast Error (km)	Track forecast skill (%)	Number of six hourly forecasts verified
12	90	28.6	24
24	152	31.8	22
36	189	46.5	20
48	205	60.0	18
60	208	68.0	16
72	268	69.5	14
84	251	75.2	10
96	308	76.9	8
108	291	80.8	6
120	222	86.3	4

4.3.1.2 Landfall forecast error

Considering the landfall forecast error, the landfall on Bangladesh coast, near Chittagong was predicted in the first bulletin itself. The landfall point forecast errors 5 days before the landfall was about 100 km. It was 72, 125, and 165 km 24, 48 and

72 hrs respectively before landfall. However, the landfall time error was relatively higher in different forecast times (Table 4.2). It was mainly due to the fact that the cyclonic storm, Viyaru moved very fast on the day of landfall which could not be predicted by most of the numerical weather prediction models.

Table 4.2 Landfall point & landfall time forecast error (forecast-actual) of Cyclonic Storm, Viyaru

Lead Period (hrs) of forecast from the time of landfall	Landfall Point Forecast Error (km)	Landfall Time Forecast Error (hrs.)
12	57	+7
24	72	+8
36	94	+13
48	125	+10
60	89	+10
72	165	+5
96	184	+10
120	100	-8

4.3.1.3 Intensity forecast error

The intensity forecast error (average absolute error (AAE) and root mean square error(RMSE)) of IMD for cyclonic storm, Viyaru are shown in Table 4.3. The AAE was about 7, 10 15 knots against the long period average of 12, 13 and 19 knots based on the period of 2003-2012. The RMSE was about 09, 13 and 18 knots against the long period average of 15, 18 and 24 knots. Hence, both the AAE and RMSE are below the long period average.

Table 4.3 Average Intensity Forecast Error of Cyclonic Storm, Viyaru

Lead Period (hr)	Intensity forecast error (kt)		Number of six hourly forecasts verified
	Absolute Average Error (AAE)	Root Mean Square Error (RMSE)	
12	3.6	4.6	24
24	6.8	8.9	22
36	8.7	10.8	20
48	10	12.5	18
60	13	16.1	16
72	15	17.8	14
84	14	16.1	10
96	13	15.7	8
108	17	17.5	6
120	14	16.4	4

4.3.1.4. Gale and squally wind forecast over Bangladesh and northeastern states of India.

Considering the gale and squally wind speed forecast error over the land surface at the time of landfall and thereafter, the realized wind speed at the time of landfall was about 85-95 kmph as recorded by meteorological observatories in Bangladesh against the forecast of 75-85 kmph gusting to 95 kmph along and off

Bangladesh coast (Table 4.4). The surface wind speed of 35-45 kmph has been reported over Mizoram, Manipur and Tripura against the forecast wind of 55-65 kmph gusting to 75 kmph. Due to the faster movement and increase in wind shear in association with trough in westerlies, the cyclonic storm Viyaru rapidly weakened over land leading to lower wind speed over Mizoram, Manipur and Tripura.

Table 4.4. Gale and squally wind forecast issued by IMD, New Delhi

Lead Period from landfall	Forecast wind	Actual wind
12	Bangladesh: 75-85 kmph gusting to 95 kmph Mizoram, Manipur and Tripura : 55-65 kmph gusting to 75 kmph	Bangladesh: Patuakhali : 92 kmph Mizoram, Manipur and Tripura : 35-45 kmph Agartala (Tripura) : 35 kmph Lengpui (Mizoram : 33 kmph
24	Bangladesh: 80-90 kmph gusting to 100 kmph Mizoram, Manipur and Tripura : 55-65 kmph gusting to 75 kmph	
36	Bangladesh: 65-75 kmph gusting to 85 kmph Mizoram and Tripura : 45-55 kmph gusting to 65 kmph	
48	Bangladesh: 65-75 kmph gusting to 85 kmph Mizoram and Tripura : 45-55 kmph gusting to 65 kmph	
60	Bangladesh: 65-75 kmph gusting to 85 kmph	
72	Bangladesh: 65-75 kmph gusting to 85 kmph	

4.3.1.5 Rainfall forecast verification

Widespread rainfall with isolated heavy to very heavy rainfall occurred over Bangladesh. Fairly widespread rainfall with isolated heavy rainfall also occurred over Mizoram, Manipur and Tripura. Detailed forecast and actual heavy rainfall are shown in Table 4.5.

Table 4.5 Heavy rainfall forecast issued by IMD, New Delhi

Lead Period from landfall	Forecast for heavy rainfall	Actual heavy rainfall
12	Mizoram, Manipur and Tripura, south Assam, Nagaland : Rainfall at most places with isolated heavy fall on 16th and 17th	Rainfall at most places occurred over Mizoram, Tripura, south Assam with isolated heavy fall over Tripura 24 hrs cumulative rainfall (5 cm or more) recorded at 0300 UTC **16.05.2013** : Tripura : Agartala, Bishalgarh 8 cm each and Sonamura 7 cm **17.05.2013** Tripura : Gokulpur : 6 cm, Agartala : 5 cm
24	Mizoram, Manipur and Tripura : Rainfall at most places with isolated heavy fall on 16th and 17th	
36	Mizoram, Manipur and Tripura : Rainfall at many places with isolated heavy fall on 16th and 17th	
48	Mizoram and Tripura : Rainfall at many places with isolated heavy fall on 16th and 17th	

4.3.1.6. Storm surge

The maximum storm surge height of 1-1.5 m above the astronomical tide (Table 4.6) was predicted by RSMC, New Delhi based on IIT, Delhi and INCOIS model over Bangladesh coast at the time of landfall. A storm surge of height of about 1 metre has been reported in section of media.

Table 4.6 Storm surge forecast issued by RSMC, New Delhi

Lead Period	Forecast storm surge above astronomical tide for Bangladesh	Actual storm surge
12	1.0-1.5 metre	1 metre storm surge has been reported in media.
24	1.0-1.5 metre	

4.3.2 Depression over the Bay of Bengal (30 July- 01 August)

A depression formed over northwest Bay of Bengal lay centred at Lat. 21.0°N and Long. 88.5°E at 0300 UTC of 30 July, 2013 about 120 km southwest of Digha and 180 km east-southeast of Balasore. It was forecasted that the system would move west-northwards and cross north Odisha coast between Digha and Chandbali close to Balasore by night of 30th – 31st July 2013 and the system crossed north Odisha and adjoining West Bengal coast between Balasore and Digha around 1230 hours IST of 30th July, 2013.

4.3.2.1 Rainfall forecast verification

The heavy rainfall warning issued by IMD along with the actual heavy rainfall is given in Table 4.7.

Table 4.7: Heavy rainfall warning issued by IMD, New Delhi

Date	Warning issued	24 hr heavy rainfall realised at 0830 IST of date
30th July 2013 0300 UTC	**Isolated extremely heavy rainfall** - Odisha during next 24 hrs. **Heavy to very heavy rainfall –at a few places over** Odisha, Chattisgarh and Vidharba during next 48 hours.	**31.07.2013** **Isolated heavy to very heavy rainfall –** Odisha, Vidarbha, Chhattisgarh

30th July 2013 0900 UTC	**Heavy to very heavy rainfall at a few places -** Odisha and south Chattisgarh during next 24 hours. **isolated heavy to very heavy rainfall -** north Vidarbha ,Chattisgarh and Jharkhand during next 24 hrs. **Heavy to very heavy rainfall at a few places over –** Vidarbha during subsequent 24 hours. **isolated heavy to very heavy falls -** east Madhya Pradesh during next 48 hours.	**Isolated heavy rainfall –** Jharkhand **01.08.2013** **Isolated heavy to very heavy rainfall -** Vidarbha, West Madhya Pradesh, Telangana, Madhya Maharashtra & Marathawada.
30th July 2013 1200 UTC	**Heavy to very heavy rainfall at a few places -** Odisha and south Chattisgarh during next 24 hours. **isolated heavy to very heavy rainfall -** north Vidarbha ,Chattisgarh and Jharkhand during next 24 hrs. **Heavy to very heavy rainfall at a few places over –** Vidarbha during subsequent 24 hours. **isolated heavy to very heavy rainfall -** east Madhya Pradesh during next 48 hours.	**Isolated heavy rainfall -** Odisha & Chhattisgarh, East Madhya Pradesh **02.08.2013** **Heavy to very heavy rainfall-** Gujarat Region**,**
31st July 2013 0300 UTC	**Isolated heavy to very heavy rainfall –** Chhattisgarh, and Telengana during next 24 hours. **Isolated heavy to very heavy rainfall –** Madhya Pradesh, Marathwada and Madhya Maharashtra during next 48 hrs. **Heavy to very heavy rainfall -** Vidarbha during next 24 hours and **isolated heavy to very heavy rainfalls** during subsequent 24 hours.	**Isolated heavy to very heavy rainfall –** West Madhya Pradesh, East Rajasthan, West Rajasthan, Konkan & Goa **Isolated heavy rainfall –** Vidarbha, Madhya Maharashtra
31st July 2013 1200 UTC	**Isolated heavy to very heavy rainfall –** Vidarbha, Chhattisgarh and Telengana	**03.08.2013**

	during next 24 hrs. **Heavy to very heavy rainfall at a few places –** Vidarbha during next 24 hours and **isolated heavy to very heavy rainfalls during** subsequent 24 hrs. **Isolated heavy to very heavy rainfall -** Madhya Pradesh, remaining Maharashtra, Gujarat region, Saurashtra and east Rajasthan during next 48 hrs.	**Isolated heavy rainfall –** West Madhya Pradesh, Madhya Maharashtra, Konkan & Goa and West Rajasthan. **Isolated heavy to very rainfall –** Saurashtra & Kutch
01st August 2013 0300 UTC	**Heavy to very heavy rainfall at a few places –** Gujarat region and **isolated heavy to very heavy rainfalls** during subsequent 24 hours. **Isolated heavy rainfall -** east Madhya Pradesh, Vidarbha and Marathawada during next 24 hours and at isolated places during subsequent 24 hours. **Isolated very heavy rainfall** - Isolated places over west Madhya Pradesh. east Rajasthan, Saurashtra & Kutch, Konkan & Goa and Madhya Maharashtra during next 48 hours.	**Heavy to very heavy**- Gujarat region.

4.3.3 Land Depression (20-23 August)

A land depression formed over Gangetic West Bengal, adjoining northwest Bay of Bengal, north Orissa and Jharkhand at 0000 UTC of 20th August, 2013. It was forecasted that the system would move west northwestwards and weaken gradually. The system first moved west northwestwards for some time and then west-southwestwards and weakened into a well marked low pressure area over central part of south Madhya Pradesh and adjoining Vidarbha at 0300 UTC of today, the 23rd August, 2013

4.3.3.1 Rainfall forecast verification

The heavy rainfall warning issued by IMD along with the actual heavy rainfall is given in Table 4.8.

Table 4.8: Heavy rainfall warning issued by IMD, New Delhi

Date	Warning issued	24 hr heavy rainfall realised at 0830 IST of date
20th August 2013 0300 UTC	**Extremely heavy rainfalls-** isolated places over north Odisha during next 48 hrs. **Heavy to very heavy rainfall at a few places –** north Odisha during next 48 hours **Heavy to very heavy rainfall at Isolated places -** Gangetic West Bengal, south Odisha, Jharkhand, Chhattisgarh and Madhya Pradesh during next 48 hours	**<u>21.08.2013:</u>** **Heavy to very heavy rainfall at a few places-** North Odisha and Gangetic West Bengal. **Heavy to very heavy rainfall at a few places-** East & West Madhya Pradesh, Chhattisgarh and Jharkhand.
20th August 2013 1200 UTC	**Extremely heavy rainfalls-** isolated places over north Odisha during next 24 hrs. **Heavy to very heavy rainfalls at a few places** - north Odisha during next 48 hours. **Heavy to very heavy rainfalls at isolated places -** Gangetic West Bengal, south Odisha, Jharkhand, Chhattisgarh, Madhya Pradesh and Vidarbha during next 48 hours	**<u>22.08.2013:</u>** **Isolated Heavy to very heavy rainfall-** Jharkhand, East & West Madhya Pradesh **Isolated heavy rainfall -** Chhattisgarh and Vidarbha. **<u>23.08.13</u>** **Isolated extremely Heavy**

21st August 2013 0300 UTC	**Heavy to very heavy rainfall at isolated places** – Gangetic West Bengal, Jharkhand and Odisha during next 24 hours and isolated heavy falls in subsequent 24 hrs. **Heavy to very heavy rainfall at isolated places-** Chhattisgarh, Madhya Pradesh and Vidarbha during next 48 hours.	**to very heavy rainfall-** West Madhya Pradesh **Isolated heavy rainfall-** Chhattisgarh, east Madhya Pradesh and Vidarbha. **24.08.2013** **Isolated Heavy to very heavy rainfall-** West Madhya Pradesh **Isolated heavy rainfall-** east Rajasthan, Gujarat region and Vidarbha. **25.08.2013** **Isolated heavy rainfall-** East Rajasthan and Gujarat region.
21st August 2013 1200 UTC	**Heavy to very heavy rainfall at isolated places –** Chhattisgarh and Madhya Pradesh during next 48 hrs. **Heavy rainfall at Isolated places** - Gangetic West Bengal, Jharkhand and Odisha during next 24 hrs and over Vidarbha during next 48 hours.	
22nd August 2013 0300 UTC	**Heavy to very heavy rainfalls at isolated places-** west Madhya Pradesh during next 48 hrs. **Isolated heavy rainfalls** - east Madhya Pradesh during next 24 hrs and over Vidarbha during next 48 hrs. **Heavy rainfalls at Isolated places -** east Rajasthan, Gujarat region and north Madhya Maharashtra on 23rd and 24th August 2013.	
22nd August 2013 1200 UTC	**Heavy to very heavy rainfalls at isolated places**-west Madhya Pradesh during next 48 hrs. **Heavy rainfalls at Isolated places -** east Madhya Pradesh during next 24 hrs. **Heavy rainfalls at Isolated places -** east	

	Rajasthan on 23rd and 24th and over north Madhya Maharashtra and Vidarbha on 23rd August 2013	
23rd August 2013 0300 UTC	**Heavy to very heavy rain falls at isolated places-** west Madhya Pradesh during next 48 hrs. **Heavy rainfalls at Isolated places -** Vidarbha and Gujarat region during next 24 hrs. and over southeast Rajasthan and north Madhya Maharashtra during next 48 hours.	

4.3.4 Very Severe Cyclonic Storm (VSCS) Phailin over the Bay of Bengal (08-14 October 2013)

4.3.4.1 Operational track forecast error and skill

The operational track forecast errors are shown in Table 4.9. It was less than 100 km for all forecast time scales upto 84(Table 4.9). It was also significantly less for 96-120 hr forecast times. The track forecast skill varied from 25% to 80 % for various time scales and was significantly higher than long period average (Table 4.10).

Table 4.9 Operational Track Forecast Error (km) of PHAILIN

Lead period (hrs)	Track forecast error	Long period average (2008-2012)
12	62.6	75.4
24	98.4	132.6
36	90.6	190.2
48	91.0	253.6
60	90.0	308.9
72	76.7	376.1
84	94.8	-
96	135.8	-
108	112.4	-
120	77.8	-

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

Table 4.10 Operational Track Forecast Skill (%)

Lead period (hrs)	Track forecast skill	Long period skill (2008-2012)
12	25.7	23.1
24	25.7	34.8
36	52.3	35.1
48	65.4	41.8
60	73.1	47.4
72	81.4	50.0
84	79.8	-
96	75.1	-
108	77.7	-
120	71.4	-

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

4.3.4.2 Operational Intensity forecast error and skill

The operational intensity forecast error in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 4.11(a). The AE varied from about 2 knots to 19 knots in different time scales. The error was higher than the long period average based on 2008-2012 by about 5 knots. The slightly higher error in intensity may be attributed to rapid intensification of cyclone on 10th October 2013. However, comparing the skill, the skill in intensity forecast compared to persistence forecast varies from 44% to 97% [Table 4.11(b)].

Table 4.11(a) Intensity Forecast error (knots)

Lead period (hrs)	Absolute Error (knots)	RMS Error (knots)	Long period Average (2008-2012):Absolute Error (knots)	Long period Average (2008-2012): RMS Error (knots)
12	9.1	12.8	7.3	9.9
24	14.9	21.0	10.4	13.5
36	17.4	22.2	12.7	16.1
48	18.7	22.9	13.4	17.8
60	17.7	20.5	13.4	15.3
72	11.1	13.9	19.0	24.0
84	19.7	31.2	-	-
96	10.5	16.5	-	-
108	1.8	2.2	-	-
120	5.4	5.4	-	-

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

Table 4.11(b) Operational Intensity Forecast skill (%)

Lead period (hrs)	Absolute Error (knots)	RMS Error (knots
12	44.3	50.0
24	62.1	55.6
36	70.9	65.1
48	77.9	75.5
60	75.3	84.2
72	91.7	91.6
84	80.4	80.4
96	87.3	85.4
108	97.0	96.6
120	89.6	89.7

4.3.4.3 Landfall forecast error

The operational landfall forecast error varied from 3 to 13 km for 12 to 72 hrs forecast (Table 4.12). Considering the size of the eye of the cyclone as 15-20 km, the landfall error was negligible for all forecast time scales. The landfall time error was also very less varying from 1 to 3 hrs.

Table 4.12. Operational landfall point and time forecast errors of PHAILIN

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)
12	3	3 hr delay	41.6	2.5
24	13	3 hr delay	90.8	5.5
36	5	3 hr delay	102.7	8.5
48	11	3 hr delay	95.8	7.3
60	2	3 hr delay	67.7	2.2
72	6	01 hr early	134.8	1.2
84	41	01 hr early	-	-

4.3.4.4 Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 4.13-15. It is found that all the three types of adverse weather were predicted very accurately and well in advance.

Table 4.13 .Verification of Heavy Rainfall Forecast

<table>
<tr><th>Date/ Time(IST)</th><th>Forecast Rainfall</th><th>Observed Rainfall</th></tr>
<tr><td>08.10.13/ 0830</td><td>Andaman and Nicobar Islands during next 48 hrs: Heavy to very heavy rainfall at a few places with isolated extremely heavy falls (≥ 25cm)</td><td rowspan="4">Andaman & Nicobar Islands:
08 October: scattered heavy to very heavy rainfall.
09 October: scattered heavy to very heavy rainfall with isolated extremely heavy.
10 October: isolated heavy to very heavy rainfall.

Odisha
12 October: Isolated heavy over coastal Odisha
13 October: scattered heavy to very heavy with isolated extremely heavy.
14 October: Isolated heavy
15 October : Isolated heavy
Coastal Andhra Pradesh</td></tr>
<tr><td>09.10.13/ 0830</td><td>Andaman and Nicobar Islands during next 24 hrs: Heavy to very heavy rainfall at a few places with isolated extremely heavy falls (≥ 25cm)</td></tr>
<tr><td>09.10.13/ 1730</td><td>Andaman and Nicobar Islands during next 12 hrs: Heavy to very heavy rainfall at a few places with isolated extremely heavy falls (≥ 25cm)</td></tr>
<tr><td>10.10.13/ 0830</td><td>Odisha : heavy to very heavy falls at a few places with isolated extremely heavy falls (≥ 25cm) would occur over coastal Odisha commencing from 12th October 2013 morning. It would continue and extend to interior</td></tr>
</table>

<table>
<tr><td></td><td>Odisha and coastal areas of Gangetic West Bengal from 13th morning.
North Coastal Andhra Pradesh : Heavy to very heavy rainfall would also occur at a few places over north coastal Andhra Pradesh commencing from 12th Oct 2013</td><td rowspan="5">13 October : isolated heavy to very heavy rainfall
Chhattisgarh
13 October: Isolated heavy rainfall.
Gangetic West Bengal
13 October: Isolated heavy
14 October: Isolated heavy to very heavy
15 October : Isolated heavy
SHWB & Sikkim
14 October: Isolated heavy rainfall.
15 October: Isolated heavy to very heavy rainfall.
Jharkhand
13 & 14 October: Isolated heavy to very heavy rainfall.
Bihar
14 & 15 October: Isolated heavy to very heavy rainfall.</td></tr>
<tr><td>11.10.13/ 0830</td><td>Commencement of rainfall over coastal Odisha, changed to 11th night, Interior Odisha from 12th evening and West Bengal 12th night. Others remained same</td></tr>
<tr><td>12.10.13/ 0830</td><td>Isolated heavy falls over north Chhattisgarh and Jharkhand, next 48 hrs</td></tr>
<tr><td>13.10.13/ 0830</td><td>Isolated heavy to very heavy falls would occur over Bihar, Sub-Himalayan West Bengal & Sikkim during next 48 hours.</td></tr>
<tr><td>14.10.13/ 0830</td><td>Isolated heavy to very heavy falls would occur over Bihar including Kosi and Gandak river catchments during next 24 hour and over Sub-Himalayan West Bengal & Sikkim including Teesta river catchment during next 48 hours. Isolated heavy falls over north Jharkhand during next 24 hours.</td></tr>
</table>

Table 4.14. Verification of Gale Wind Forecast

<table>
<tr><th>Date/ Time(IST)</th><th>Forecast Wind</th><th>Observed Wind</th></tr>
<tr><td colspan="3">Andaman and Nicobar Islands</td></tr>
<tr><td>08.10.13/ 0830</td><td>Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail over Andaman Nicobar Islands and adjoining sea areas during next 48 hours. Sea condition will be rough to very rough along and off Nicobar Islands during this period.</td><td rowspan="3">Observed maximum wind is about 50-60 kmph</td></tr>
<tr><td>09.10.13/ 0830</td><td>Squally/Gale winds speed reaching 60-70 kmph gusting to 80 kmph would prevail over Andaman Nicobar Islands and adjoining sea areas during next 48 hours. Sea condition will be very rough to high along and off Andaman and Nicobar Islands during next 24 hrs.</td></tr>
<tr><td>09.10.13/ 1730</td><td>Squally winds speed reaching 50-60kmph gusting to 70 kmph would prevail over Andaman Nicobar Islands and adjoining sea areas during next 24 hours. Sea condition will be very rough along and</td></tr>
</table>

	off Andaman and Nicobar Islands during next 24 hrs.	
	East Coast	
10.10.13/ 0830	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would commence along and off Odisha and north Andhra Pradesh coast from 11th morning. It would increase in intensity with gale wind speed reaching 175-185 kmph along and off coastal districts of north coastal Andhra Pradesh and south Odisha at the time of landfall.	Observed maximum wind is about 115 Knots (200-210 gusting to 220 kmph)
11.10.13/ 0830	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Odisha and north Andhra Pradesh coast during next 12 hrs. It would increase in intensity thereafter with gale wind speed reaching 210-220 kmph along and off coastal districts of north coastal Andhra Pradesh and south Odisha at the time of landfall.	

Table 4.15. Verification of Storm Surge Forecast issued by IMD

Date/Time(IST)	Forecast Surge	Observed Surge
10.10.13/1730	Storm surge with height of around 1.5-2.0 m above astronomical tide would inundate low lying areas of Ganjam, Khurda, Puri and Jagatsinghpur districts of Odisha and Srikakulam district of Andhra Pradesh during landfall.	2-2.5 metres with coastal inundation upto 500 meter to one km in low lying areas of Ganjam district
11.10.13/1730	Storm surge with height of 3.0 to 3.5 mt. above astronomical tide would inundate low lying areas of Ganjam, Khurda, Puri and Jagatsinghpur districts of Odisha and Srikakulam district of Andhra Pradesh during landfall.	
12.10.13/1730	Storm surge with height of 3.0 to 3.5 metre. above astronomical tide would inundate low lying areas of Ganjam, Khurda, Puri and Jagatsinghpur districts of Odisha and Srikakulam district of Andhra Pradesh during landfall.	

4.3.5 Deep Depression over the Arabian Sea (8-11 November, 2013)

4.3.5.1 Landfall point &time forecast errors

On the first bulletin issued at 0900 UTC of 08 November (64 hrs before the landfall of deep depression over Somalia), it was predicted that the system would intensify into a depression and cross Somalia coast on 10 November around 1200 UTC.

The landfall point forecast error was about 4 km for 24 hr lead period and about 50 km for both 36 and 48 hr lead periods (Table 4.16). Hence, the landfall point could be well predicted 48 hrs in advance.

The average track forecast error is shown in Table 4.15. It was 54 km, 93 km and 163 km respectively for 12, 24 and 48 hrs forecast period. This error is significantly less than the average forecast errors in last five years. Considering the intensity forecast error, the realized wind speed at the time of landfall was about 30 knots as estimated by satellite observations and it was same as the predicted value. There was no observation available over Somalia to estimate the intensity at the time of landfall. Considering average absolute error (AE) and root mean square error in wind forecast, they were about 5-10 knots for all forecast times of 12 to 48 hrs (Table 4.16)

Table 4.15 Operational Landfall point &time forecast errors

Leads Period (hrs)	Landfall point and time forecast Error in Km	
	Landfall point error (km) (Forecast landfall point- Actual landfall point)	Landfall time error in hrs (Forecast landfall time- Actual landfall time)
12	04	+1.5
24	04	-4.5
36	53	-11.5
48	54	-09.5

Table 4.16 Operational average track and intensity forecast error

Lead Period (hrs)	Average track forecast error (km)	Intensity forecast error (knots)	
		Absolute error	Root mean square error
12	54	4.9	5.1
24	93	3.8	7.2
36	163	2.7	7.5
48	163	1.6	3.1

4.3.6 Depression over the Bay of Bengal (13 – 17 November 2013

4.3.6.1 Rainfall forecast

The heavy rainfall warning issued by IMD along with the actual heavy rainfall is given in Table 4.17.

Table 4.17 Heavy rainfall warning issued by IMD, New Delhi

Date & time	Warning issued	24 hr heavy rainfall realised at 0300UTC of date
13th November 2013 0300 UTC	**Isolated extremely heavy rainfall -** north coastal Tamil Nadu and south coastal Andhra Pradesh commencing from 15th November **Heavy to very heavy rainfall**-at a few places over north coastal Tamil Nadu and south coastal Andhra Pradesh commencing from 15th November 2013.	**16th November, 2013** **Isolated Heavy rainfall-** Tamil Nadu & Puduchery. **17th November, 2013** **Isolated heavy rainfall-** Coastal Andhra Pradesh. **Heavy to very heavy at a few places-** Tamil Nadu & puduchery. **18th November, 2013** **Isolated heavy-** south coastal Andhra Pradesh & Kerala
14th November 2013 0300 UTC	**Isolated extremely heavy rainfall** – north coastal Tamil Nadu, Puducherry and south coastal Andhra Pradesh from 15th November 2013 night and over north Tamil Nadu on 16th & 17th November. **Heavy to very heavy rainfall** - at a few places north coastal Tamil Nadu, Puducherry and south coastal Andhra Pradesh from 15thNovember 2013 night and at a few places over north Tamil Nadu on 16th & 17th November. **Isolated heavy to very heavy rainfall** – over south coastal Andhra Pradesh, Rayalaseema and south Tamil Nadu on 16th and 17th ..	
15th November 2013 0300 UTC	**Isolated extremely heavy rainfall –** north coastal Tamil Nadu, Puducherry and south coastal Andhra Pradesh from tonight and north Tamil Nadu on 16th & 17th November. **Heavy to very heavy rainfall at a few places –** north coastal Tamil Nadu, Puducherry and south coasta l Andhra Pradesh from tonight and north Tamil Nadu on 16th & 17th November. **Isolated heavy rainfall-** over south coastal Tamil Nadu. **Isolated heavy to very heavy rainfall-** south coastal Andhra Pradesh, Rayalaseema and south Tamil Nadu on 16th and 17th	
16th November 2013 0300 UTC	**Isolated extremely heavy rainfall-** north Tamil Nadu and Puducherry during next 48 hours. **Heavy to very heavy rainfall at a few places-** north Tamil Nadu and Puducherry during next 48 hours. **Isolated heavy to very heavy rainfall-** south coastal Andhra Pradesh and Rayalaseema during next 48 hours.	

	Isolated heavy falls- over south Tamilnadu and south interior Karnataka during next 48 hrs.	

4.3.7 Severe Cyclonic Storm 'Helen' over Bay of Bengal (19-23 Nov 2013)

4.3.7.1 Track forecast error

In the first bulletin issued in the early morning of 19th November 2013 (three days in advance of landfall), when the system was a depression over west-central Bay of Bengal, it was predicted that the system would intensify into a deep depression and move towards Andhra Pradesh coast during next 72 hrs. In the fifth bulletin issued on 19th November it was predicted that the system would intensify into a cyclonic storm. In the seventh bulletin issued on 20th November (early morning), it was predicted that the system would further intensify into a severe cyclonic storm and move west-northwestwards for some time, then west-southwestward and cross Andhra Pradesh coast with a wind speed of 90-100 kmph.

The average track forecast error is shown in Table 4.18. It was 98 & 237 km respectively for 24 and 48 hrs. forecast respectively against the long period average of 133 & 254 km based on the period of 2008-2012.

Table.4.18. Operational average track forecast error of IMD of 'HELEN'

Lead Period	**Track Forecast Error (km)**	**Long period average (2008-2012)**
12	46.7 (11)	75.4
24	97.6 (09)	132.6
36	165.9 (07)	190.2
48	236.5 (05)	253.6
60	317.1 (03)	308.9

Due to short life of the system forecast could not be issued 72 hrs in advance or beyond.

Table 4.19. Operational Track Forecast Skill (%)

Lead period (hrs)	**Track forecast skill**	**Long period skill (2008-2012)**
12	37.7	23.1
24	36.6	34.8
36	24.3	35.1
48	14.5	41.8
60	6.4	47.4

The track forecast skill was about 37% and 15% for 24 and 48 hrs forecast respectively (Table 4.19).

4.3.6.2 Landfall forecast error

The landfall point forecast errors were 16,12, and 129 km respectively for 12, 24, and 36 hrs respectively before landfall (Table 4.20). The landfall time error was within ±3 hrs for the same period.

Table.4.20. Operational Landfall forecast errors of IMD for SCS 'HELEN'

Lead Period	Landfall point and time forecast error (Difference of forecast landfall point and time and actual landfall point and time			
	Landfall point Error (km)	Landfall Time Error (hrs)	Long period average landfall point error(km) during 2008-12	Long period average landfall time error(hrs) during 2008-12
12	16	+ ½	41.6	2.5
24	12	+3 ½	90.8	5.5
36	129	-2 ½	102.7	8.5
48	188	-7 ½	95.8	7.3
60	184	-8 ½	67.7	2.2

4.3.6.3 Intensity forecast error

The intensity forecast errors (average absolute error (AAE) and root mean square error (RMSE)) of IMD for severe cyclonic storm, Helen are shown in Table 4.21. The AAE was about 3, 4 & 9 knots against the long period average of 7,10 & 13 knots based on the period of 2008-2012 for 12, 24 & 36 hr forecasts The RMSE was about 4,9 and 14 knots against the long period average of 10,13 and 16 knots for the same period .

Table.4.21. Operational average intensity forecast error of IMD of 'Helen'

Lead Period	Intensity Forecast Error (knots)		Long period Average (2008-2012):Absolute Error (knots)	Long period Average (2008-2012): RMS Error (knots)
	Absolute error	Root mean square error		
12	2.8 (11)	3.9	7.3	9.9
24	4.0 (09)	9.0	10.4	13.5
36	9.5 (07)	14.0	12.7	16.1
48	12.8 (05)	15.0	13.4	17.8
60	12.6 (03)	16.8	13.4	15.3

Table 4.22. Operational Intensity Forecast skill (%)

Lead period (hrs)	Skill in term of Absolute Error (%)	Skill in term of RMS Error (%)
12	70.5	70.5
24	72.2	51.3
36	60.9	54.1
48	57.3	62.2
60	58.0	58.7

4.3.6.3 Heavy Rainfall Warning

The heavy rainfall warning issued by IMD alongwith the actual heavy rainfall is given in Table 2.23.

Table 2.23: Heavy rainfall warning and realised rainfall due to SCS 'HELEN'

Date & time	Warning issued : Heavy rainfall	24 hr heavy rainfall realised at 0300UTC of
19/11/2013 0300 UTC	Isolated heavy to very heavy rainfall would occur over coastal Andhra Pradesh and north coastal Tamil Nadu commencing from 20st November 2013 night.	**21st November** **Isolated heavy rainfall-** Tamil Nadu & Puducherry **22nd November** **Isolated heavy rainfall –** Coastal Andhra Pradesh, Tamil Nadu & Puducherry and Kerala **23rd November** **Isolated Heavy to very heavy rainfall -** Coastal Andhra Pradesh **24th November** **Heavy to very heavy rainfall-** Tamil Nadu & Pudicherry and South interior Karnataka **Isolated heavy rainfall-** Telengana, coastal Karnataka & Kerala
20/11/2013 0300 UTC	Isolated extremely heavy falls (25cm or more) would occur over south coastal Andhra Pradesh on 21st and 22nd November. Isolated heavy to very heavy falls would occur over Rayalseema and adjoining north Tamil Nadu on 22nd November.	
21/11/2013 0300 UTC	Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall (25cm or more) would occur over coastal Andhra Pradesh during next 48 hrs commencing from 21st November 2013 night. Isolated heavy to very heavy falls would occur over Rayalseema and Telangana on 22nd and 23rd November.	
22/11/2013 0300 UTC	Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall (25cm or more) would occur over north coastal Andhra Pradesh and adjoining Guntur, Krishna, West Godavari districts of south coastal Andhra Pradesh during next 36 hrs. Isolated heavy to very heavy falls would occur over remaining districts of south coastal Andhra Pradesh, Rayalseema and isolated heavy to very heavy falls over Telangana during next 48 hrs.	

4.3.6.4 Gale Wind Warning

The gale wind forecast alongwith actual wind are presented in table 4.24.

Table 4.24 Gale wind warning and realised wind due to SCS 'HELEN'

Date & Time of Issue	Wind forecast issued	Actual wind (kmph)
19.11.2013 0300 UTC	45-55 kmph gusting to 65 kmph along and off Andhra Pradesh coast commencing from 21st November 2013.	80 – 90 kmph gusting to 100 kmph at the time of landfall along the coastal districts

19.11.2013 0600 UTC	45-55 kmph gusting to 65 kmph along and off Andhra Pradesh coast commencing from 21st November 2013.	nearer to landfall point.
19.11.2013 1500 UTC	55-65 kmph gusting to 75 kmph along and off Andhra Pradesh coast commencing from 20st November 2013. It would gradually increase to 80-90 gusting to 100 kmph at the time of landfall.	
20.11.2013 0300 UTC	55-65 kmph gusting to 75 kmph along and off Andhra Pradesh coast commencing from 20st November 2013. It would gradually increase to 100-110 gusting to 120 kmph at the time of landfall	
21.11.2013 0300 UTC	55-65 kmph gusting to 75 kmph along and off Andhra Pradesh coast commencing from 21st November 2013. It would gradually increase to 100-110 gusting to 120 kmph at the time of landfall over Guntur, Krishna, east and west Godavari districts. 45-55 kmph gusting to 65 kmph along and off remaining parts of Andhra Pradesh coasts commencing from 21st evening and reach upto 60-70 kmph at the time of landfall.	
22.11.2013 0300 UTC	Gale winds speed reaching 100-110, gusting to 120 kmph over Prakasham, Guntur, Krishna, east & west Godavari & Vishakhapatnam districts. Squally winds speed reaching 55-65 kmph gusting to 75 kmph would prevail along and off Andhra Pradesh coasts.	

4.3.6.5 Storm surge forecast.

Table 2.25 Storm surge warning and realised surge due to SCS 'HELEN'

20.11.2013 0600 UTC	Storm Surge of about 1 to 1.5 mt. height above astronomical tide near low lying areas of Andhra Pradesh at the time of landfall	No storm surge report has been received.
20.11.2013 0600 UTC	Storm Surge of about 1 to 1.5 mt. height above astronomical tide near low lying areas of Andhra Pradesh at the time of landfall	
22.11.2013	No warning	
23.11.2013	No warning	

4.3.7. Very Severe Cyclonic Storm VSCS 'Lehar'(23-28 November, 2013)

4.3.7.1 Track forecast error

In the first bulletin issued in the evening of 23rd November 2013 (five days in advance of landfall), when the system was a depression over south Andaman sea, it was predicted that the system would intensify into a cyclonic storm and move northwestward and cross Andaman & Nicobar Islands between Hurt Bay and Long island, close to Port Blair as a cyclonic storm. In the third bulletin issued in the morning of 24th November 2013, it was predicted that the system would intensify into a very severe cyclonic storm and move towards Andhra Pradesh coast.

The average track forecast error and skill is shown in Table 4.26 and Table 4.27 respectively. The track forecast error was 92,133 and 140 km respectively for 24, 48 and 72 hrs. forecast period against the long period average of 133, 254 and 376 km for the *per*iod of 2008-2012.

Table 4.26. Operational track forecast error of LEHAR

Lead period (hrs)	Track Forecast Error in km	Long period average (2008-2012)
12	56.9 (18)	75.4
24	92.4 (16)	132.6
36	111.3 (14)	190.2
48	132.9 (12)	253.6
60	141.0 (10)	308.9
72	139.7 (08)	376.1
84	134.4 (06)	-
96	142.7 (04)	-
108	169.2 (02)	-
120	-	-

Table 4.27. Operational Track Forecast Skill (%)

Lead period (hrs)	Track forecast skill	Long period skill (2008-2012)
12	47.0	23.1
24	53.7	34.8
36	62.1	35.1
48	63.0	41.8
60	75.3	47.4
72	77.8	50.0
84	82.0	-
96	81.7	-
108	85.0	-
120	-	-

The track forecast skill was about 54%, 63% and 78% for 24, 48 and 72 hrs forecast respectively. They were significantly higher than long period average (Table 4.27).

4.3.7.2 Landfall forecast error

Considering the landfall forecast error, the landfall on Andhra Pradesh coast, near Machilipatnam was predicted in the fourth bulletin itself. The landfall point forecast errors 5 days before the landfall was about 162 km. It was 20, 83, and 156 km for 24, 48 and 72 hrs forecast period before landfall respectively.

Table.4.28. Operational Landfall forecast error of LEHAR

Lead	Landfall point and time forecast error (Difference of forecast

Period	landfall point and time and actual landfall point and time)			
	Landfall point Error (km) (Forecast landfall point-Actual landfall point)	Landfall Time Error (Forecast landfall time-Actual landfall time) (hrs)	Long period average landfall point error(km) during 2008-2012	Long period average landfall time error(hrs) during 2008-2012
12	50	-½	41.6	2.5
24	20	+5 ½	90.8	5.5
36	52	+½	102.7	8.5
48	83	+2 ½	95.8	7.3
60	156	+½	67.7	2.2
72	156	-2 ½	134.8	1.2
84	156	-2 ½	-	-
96	156	-1	-	-
108	162	-1½ hr	-	-

4.3.7.3 Intensity forecast error

The intensity forecast error (average absolute error (AAE) and root mean square error (RMSE)) of IMD for very severe cyclonic storm, Lehar are shown in Table 4.29. The AAE was about 18, 29 & 41 knots against the long period average of 10, 13 and 19 knots based on the period of 2008-2012. The RMSE was about 25, 38 and 47 knots against the long period average of 13, 18 and 24 knots. Hence, both the AAE and RMSE are above the long period average. It is due to the rapid weakening of the cyclone on 27th November which could not be predicted well. Considering the skill in intensity forecast compared to persistence, there was positive skill for all forecast times except 12 & 24 hrs forecast. The poor skill in 12 & 24 hrs forecast is mainly due to sudden weakening of the cyclone on 27th November over the sea.

Table 4.29. Operational average intensity forecast error of LEHAR

Lead Period	Intensity Forecast Error (knots)		Long period Average (2008-2012):Absolute Error (knots)	Long period Average (2008-2012): RMS Error (knots)
	Absolute error	Root mean square error		
12	10.2	13.4	7.3	9.9
24	18.4	24.5	10.4	13.5
36	25.5	33.1	12.7	16.1
48	29.2	38.0	13.4	17.8
60	32.4	39.3	13.4	15.3
72	41.0	47.3	19.0	24.0
84	47.0	49.6	-	-
96	48.5	54.3	-	-
108	34.5	36.9	-	-
120	-	-	-	-

Table 4.30. Operational Intensity Forecast skill (%)

Lead period (hrs)	Skill in term of Absolute Error (%)	Skill in term of RMS Error (%)
12	-14.3	-22.3
24	-27.5	-14.0
36	2.5	07.5
48	0.9	09.4
60	10.1	14.4
72	17.8	15.0
84	25.9	27.5
96	33.0	33.2
108	54.7	54.7
120	--	

4.3.7.4 Gale and squally wind forecast

The warning for gale and squally wind issued by IMD along with the actual wind is given in Table 4.31.

Table 4.31: Gale and squally wind forecast verification

<table>
<tr><th>Date & time</th><th>Warning issued</th><th>Realised wind</th></tr>
<tr><td>23rd November 1200 UTC</td><td>Squally winds - Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Andaman & Nicobar island. The wind speed would gradually increase and become 80-90 kmph gusting to 100kmph from 24th evening along and off this coast.</td><td rowspan="3">Port Blear reported 120 kmph at the time of landfall.
Maximum surface wind speed was about 45-55 kmph at the time of landfall near Machilipatnam.</td></tr>
<tr><td>24th November 0300 UTC</td><td>Squally winds speed reaching 50-60 kmph gusting to 70 kmph would prevail along and off Andaman & Nicobar Islands. The wind speed would gradually increase and become 80-90 kmph gusting to 100 kmph from 24th evening along and off this coast.</td></tr>
<tr><td>25th November 0300 UTC</td><td>Gale winds speed reaching 80-90 kmph gusting to 100 kmph would prevail along and off Andaman & Nicobar Islands during next 6 hrs and gradually decrease thereafter.</td></tr>
</table>

26th November 0300 UTC	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would commence along and off Andhra Pradesh and south Odisha coasts from 27th evening. It would increase in intensity with gale wind speed reaching 170-180 kmph gusting to 200 kmph along and off coastal districts of Krishna, west & east Godavari and Vishakhapatnam districts and 120-130 kmph gusting to 140 kmph over Vizianagarm, Srikakulam and Guntur districts of coastal Andhra Pradesh at the time of landfall. Squally winds speed reaching 55-65 kmph gusting to 75 kmph would prevail along and off remaining districts of Andhra Pradesh and south Odisha at the time of landfall.	
27th November 0300 UTC	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would commence along and off Andhra Pradesh from 27th evening. It would increase in intensity with gale wind speed reaching 150-160 kmph gusting to 170 kmph along and off coastal districts of Guntur, Krishna, west & east Godavari and Vishakhapatnam districts of Andhra Pradesh and Yanam district of Puducherry and 100-110 kmph gusting to 120 kmph over Vizianagaram and Prakasham districts of coastal Andhra Pradesh at the time of landfall. Squally winds speed reaching 55-65 kmph gusting to 75 kmph would prevail along and off remaining districts of Andhra Pradesh at the time of landfall. Squally winds speed reaching 40-50 kmph gusting to 60kmph would prevail along and off south coastal Odisha on 28th Nov 2013.	
27th November 1200 UTC	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Andhra Pradesh during next 24 hours. It would increase in intensity with gale wind speed reaching 70-80 kmph gusting to 90 kmph along and off coastal districts of Guntur, Krishna, west & east Godavari and adjoining areas of Vishakhapatnam districts of Andhra Pradesh and Yanam district of Puducherry at the time of landfall.	
28th November 0300 UTC	Squally winds speed reaching 50-60 kmph gusting to 70 kmph would prevail along and off Andhra Pradesh during next 12 hours.	

4.3.7.5 Rainfall forecast

The heavy rainfall warning issued by IMD along with the actual heavy rainfall is given in Table 4.32.

Table 4.32: Heavy rainfall forecast verification

<table>
<tr><th>Date & time</th><th>Warning issued</th><th>24 hr heavy rainfall realised at 0300UTC of date</th></tr>
<tr><td>23rd November 1200 UTC</td><td>Heavy to very heavy rainfall at a few places with isolated extremely heavy falls (25 cm or more) would occur over Andaman & Nicobar Islands during 48 hrs.</td><td rowspan="6">25th November, 2013
Heavy to very heavy rainfall at a few places – Andaman & Nicobar Island

28th November, 2013

Isolated Heavy rainfall - Kerala

29th November, 2013

Isolated Heavy rainfall – Coastal Andhra Pradesh</td></tr>
<tr><td>24th November 0300 UTC</td><td>Heavy to very heavy rainfall at a few places with isolated extremely heavy falls (25 cm or more) would occur over Andaman & Nicobar Islands during 48 hrs.</td></tr>
<tr><td>25th November 0300 UTC</td><td>Isolated heavy to very heavy rainfall would occur over Andaman & Nicobar Islands during next 24 hrs. and intensity would decrease thereafter.</td></tr>
<tr><td>26th November 0300 UTC</td><td>Heavy to very heavy falls at a few places and isolated extremely heavy falls over north coastal Andhra Pradesh on 28th and isolated heavy rainfall over south Odisha and south coastal Andhra Pradesh.</td></tr>
<tr><td>27th November 0300 UTC</td><td>Heavy to very heavy falls at a few places and isolated extremely heavy falls over coastal Andhra Pradesh and Yanam district of Puducherry on 28th November and isolated heavy to very heavy rainfall over these regions on 29th November 2013. Isolated heavy to very heavy falls would also occur over Telangana on 28th and 29th Nov 2013.</td></tr>
<tr><td>28th November 0300 UTC</td><td>Isolated heavy to very heavy falls would occur over coastal Andhra Pradesh and Yanam district of Puducherry during next 24 hours. Isolated heavy to very heavy falls would also occur over Telangana during next 36 hours.</td></tr>
</table>

4.3.7.6 Storm Surge forecast

Table.4.33. Storm surge forecast verification

Date & time	Storm Surge warning issued	Storm Surge reported
24th November 0300 UTC	Storm surge of about 1 to 1.5 metre height above astronomical tide would inundate the low lying areas of Andaman & Nicobar Islands within 100 km from the landfall point.	No storm surge report has received.
25th November 0300 UTC	Storm surge of about 0.5-1.0 metre height above astronomical tide would inundate the low lying areas of Andaman & Nicobar Islands within 100 km from the landfall point during next six hours and decrease	

	thereafter.	
26th November 0300 UTC	Storm surge of height about 2.0-3.0 metres above astronomical tide would inundate low lying areas of west and east Godavari, Vishakhapatnam and Krishna districts at the time of landfall.	
27th November 0300 UTC	Storm surge of height about 2.0-3.0 metres above astronomical tide would inundate low lying areas of west and east Godavari, Guntur and Krishna districts of Andhra Pradesh and Yanam district of Puducherry and about 1 metre near Visakhapatnam district at the time of landfall.	

4.3.8 Very Severe Cyclonic Storm 'Madi' (06-13 December 2013)

4.3.8.1 Track forecast error and skill

In the first bulletin issued in the 06th December, 2013, when the system was a depression over Southwest Bay of Bengal, it was predicted that the system would intensify into a cyclonic storm and move nearly northward and then recurve north-northeastwards. In the 05th bulletin issued in the early morning of 07th December 2013, it was predicted that the system would intensify into a very severe cyclonic storm.

In the bulletin issued at 1130 UTC based on 0900 UTC observation of 08th December, 2013, it was predicted that the cyclone would recurve southwestwards from 10th night. Whereas the cyclone actually started recurving from 1200 UTC of 10th December, 2013.

Similarly the gradual weakening of the system over the sea after attaining the maximum intensity was predicted at 1930 UTC based on 1800 UTC observation maintaining weakening from 1800 UTC of 09th December, 2013. The cyclone actually started weakening from 1200 UTC of 09th December, 2013.

The average track forecast error is shown in Table 4.34. It was 89, 150 and 239 respectively for 24, 48 and 72 hrs. forecast against the long period average of 133, 254 and 376 km based on the period of 2008-2012 respectively.

Table 4.34 Operational track forecast error of 'MADI'

Lead Period (hrs)	Track Forecast Error in km	Long period average (2008-2012)
12	49.5 (21)	75.4
24	88.5 (19)	132.6
36	115.4 (17)	190.2
48	150.0 (17)	253.6
60	196.4 (15)	308.9
72	231.2 (13)	376.1
84	272.2 (11)	-
96	313.4 (9)	-
108	438.0 (7)	-
120	462.6 (4)	-

Table 4.35. Operational Track Forecast Skill (%)

Lead period (hrs)	Track forecast skill	Long period skill (2008-2012)
12	56.1	23.1
24	57.7	34.8
36	64.6	35.1
48	69.5	41.8
60	67.0	47.4
72	65.0	50.0
84	61.1	-
96	54.9	-
108	28.1	-
120	12.3	-

The track forecast skill was about 58%, 69% and 65% for 24, 48 and 72 hrs forecast respectively. They were significantly higher than long period average (Table 4.35).

4.3.8.2 Intensity forecast error

The intensity forecast error (average absolute error (AAE) and root mean square error (RMSE)) of IMD for very severe cyclonic storm, MADI are shown in Table 4.36. The AAE was about 07, 09 & 07 knots against the long period average of 10,13 and 19 knots based on the period of 2008-2012. The RMSE was about 08, 10 and 10 knots against the long period average of 13, 18 and 24 knots. Hence, both the AAE and RMSE are below the long period average. The skill of intensity forecast compared to persistence forecast is shown in Table 4.37. The skill varied from 23% for 12 hrs to 89% for 120 hrs forecast.

Table 4.36 Operational average intensity forecast error of 'MADI'

Lead Period	Intensity Forecast Error (knots)		Long period Average (2008-2012):Absolute Error (knots)	Long period Average (2008-2012): RMS Error (knots)
	Absolute error	Root mean square error		
12	5.0 (23)	6.5 (23)	7.3	9.9
24	6.6 (21)	8.1 (21)	10.4	13.5
36	8.8 (19)	10.6 (19)	12.7	16.1
48	8.7 (17)	9.9 (17)	13.4	17.8
60	7.5 (15)	8.9 (15)	13.4	15.3
72	7.3 (13)	9.8 (13)	19.0	24.0
84	9.0 (11)	11.8 (11)	-	-
96	11.3 (09)	13.0 (09)	-	-
108	14.8 (07)	15.2 (07)	-	-
120	14.2 (05)	14.4 (05)	-	-

Table 4.37. Operational Intensity Forecast skill (%)

Lead period (hrs)	Skill in term of Absolute Error (%)	Skill in term of RMS Error (%)
12	23.1	16.5
24	45.5	44.9
36	53.2	53.3
48	67.9	68.9
60	80.8	80.1
72	84.9	83.7
84	87.3	85.5
96	88.0	87.6
108	87.7	88.3
120	89.1	89.7

4.3.8.3 Rainfall forecast

The heavy rainfall warning issued by IMD along with the actual heavy rainfall is given in Table 4.38.

Table 4.38. Verification of heavy rainfall warning issued by IMD

<table>
<tr><th>Date & time</th><th>Warning issued</th><th>24 hr heavy rainfall realised at 0300UTC of date</th></tr>
<tr><td>06th December 0300 UTC</td><td>Isolated heavy falls r Andaman and Nicobar Island during next 72 hours.</td><td rowspan="7">07th December- Nil

08TH December, 2013
Isolated Heavy rainfall- Andaman & Nicobar

09TH December, 2013
Isolated Heavy rainfall- Andaman & Nicobar
10th , 11th & 12th December – Nil

13th December, 2013

Isolated heavy rainfall - Tamil Nadu</td></tr>
<tr><td>07th December 0300 UTC</td><td>NIL</td></tr>
<tr><td>08th December 0300 UTC</td><td>NIL</td></tr>
<tr><td>09th December 0300 UTC</td><td>NIL</td></tr>
<tr><td>10th December 0300 UTC</td><td>NIL</td></tr>
<tr><td>11th December 0300 UTC</td><td>Isolated places over coastal Tamil Nadu and Puducherry during next 48 hours.</td></tr>
<tr><td>12th December 0000 UTC</td><td>Isolated places over coastal Tamil Nadu and Puducherry during next 48 hours.</td></tr>
</table>

13th December 0000 UTC	Isolated places over Lakshadweep during next 24 hours.	& Puducherry **14th December – Nil**

4.3.8.4 Squally wind forecast

The Squally wind forecast issued by IMD along with the actual Squally wind is given in Table 4.39

Table 4.39. Verification of Squally wind warning issued by IMD

Date & time	**Warning issued**	**Realised wind (kmph)**
12th December 0900 UTC	Squally wind speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Tamil Nadu and Puducherry coasts during next 24 hrs.	South coastal Tamil Nadu experienced squally wind of 40 – 50 kmph at the time of landfall. Tondi: 46 kmph
12th December 1200 UTC	Squally wind speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Tamil Nadu and Puducherry coasts during next 24 hrs.	
12th December 1800 UTC	Squally wind speed reaching 45-55 kmph gusting to 65 kmph would prevail along and off Tamil Nadu and Puducherry coasts during next 12 hrs.	
13th December 0000 UTC	Strong surface wind speed reaching 40-50 kmph gusting to 60 kmph would prevail over Lakshadweep area and along off Kerala coast during next 24 hrs.	

4.3.8.5 Storm surge forecast

No storm surge was predicted due to this system and no surge was also reported along the Tamil Nadu and Puducherry coast.

4.4. Annual average error

The annual average errors for 2013 are shown in following Tables (Table 4.40—41) and figures. It all indicates that the error has decreased and skill has increased over the years. However, the rate of improvement is higher in case of track forecast compared to intensity forecast.

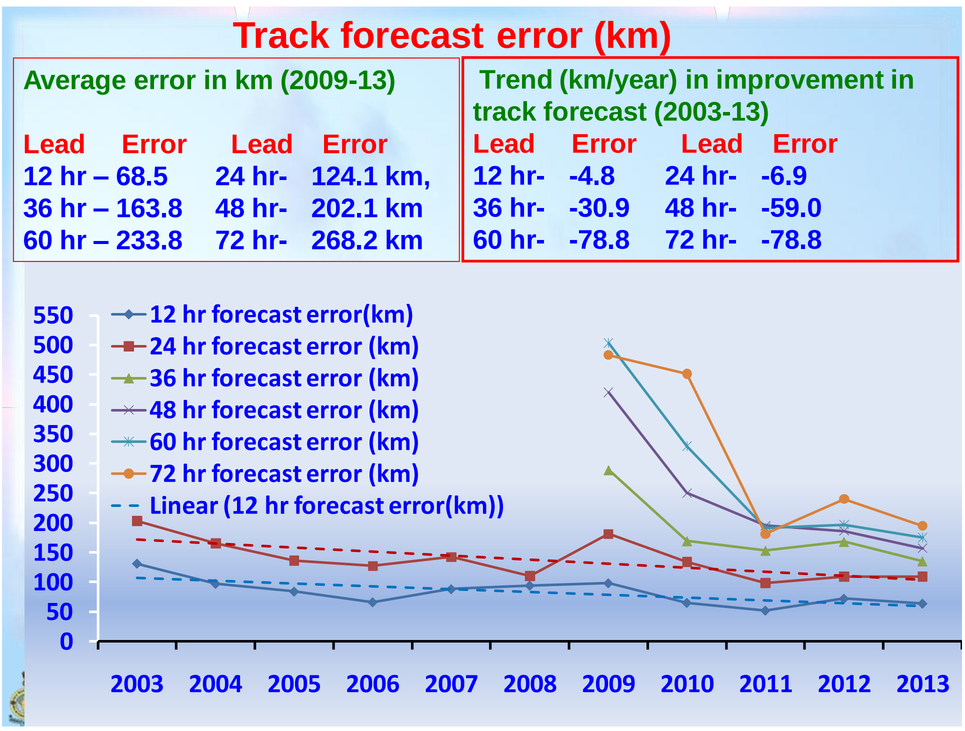
Table 4.40 Annual Average track forecast error (km) and skill (%) during 2013

Lead Period (Hours)	**Annual Track Forecast Error (km)**	**Annual Track Forecast Skill (%)**	**No. of Forecasts Verified**
12	63.7	39.1	94
24	109.0	41.6	84
36	135.1	53.5	72
48	156.9	62.5	65
60	175.0	67.3	55

72	194.7	70.9	44
84	205.1	72.7	34
96	251.3	71.7	26
108	304.9	67.8	18
120	296.4	73.4	11

Table 4.41 Annual average intensity forecast error (knots) and skill (%) during 2013

Lead Period (Hours)	Absolute Error (AE) (knots)	Root Mean Square Error (RMSE) (knots)	Skill(%) in terms of reduction in AE	Skill(%) in terms if reduction in RMSE	No. of Forecasts Verified
12	6.2	8.2	26.4	28.4	94
24	10.1	13.9	34.6	31.8	84
36	13.5	17.2	46.6	44.8	72
48	14.9	18.4	54.0	55.6	65
60	15.6	18.9	67.0	66.8	55
72	16.2	19.5	64.8	66.9	44
84	18.5	22.4	61.3	61.4	34
96	16.1	19.5	72.1	72.5	26
108	14.1	15.0	80.4	81.5	18
120	13.2	14.3	87.5	87.3	11



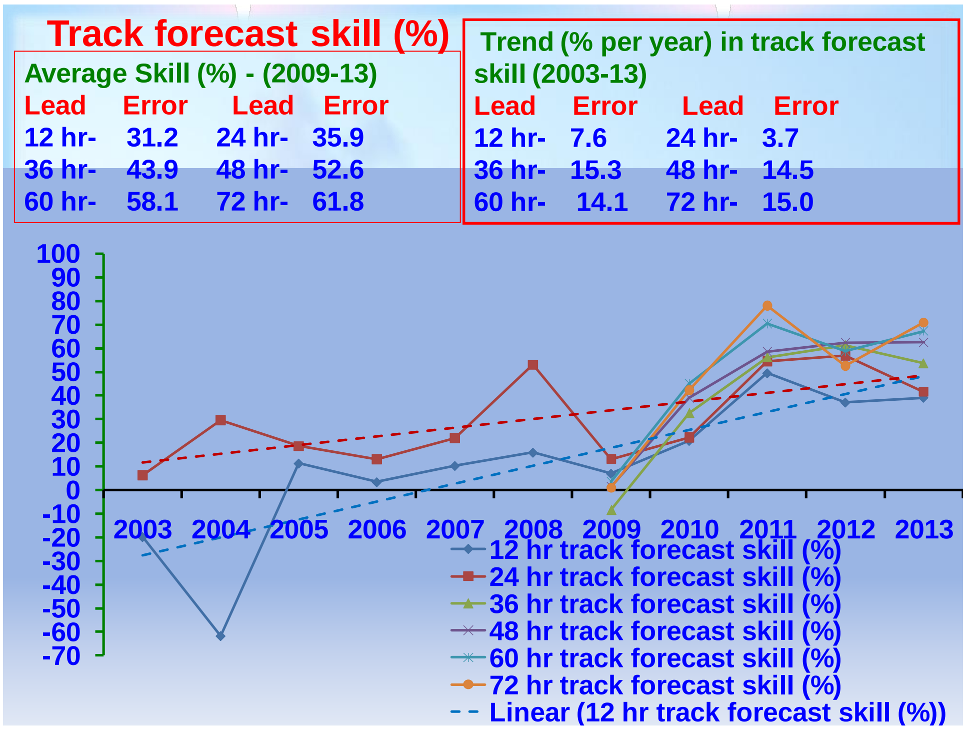
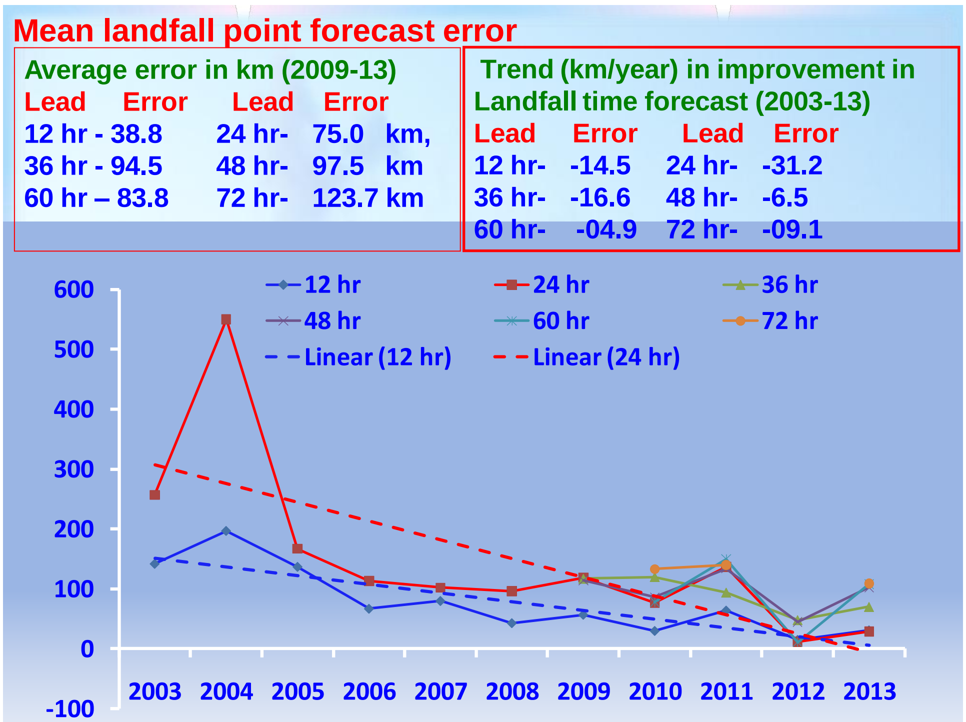


Fig. 4.1. IMD's annual mean track forecast error and skill during 2003- 2013



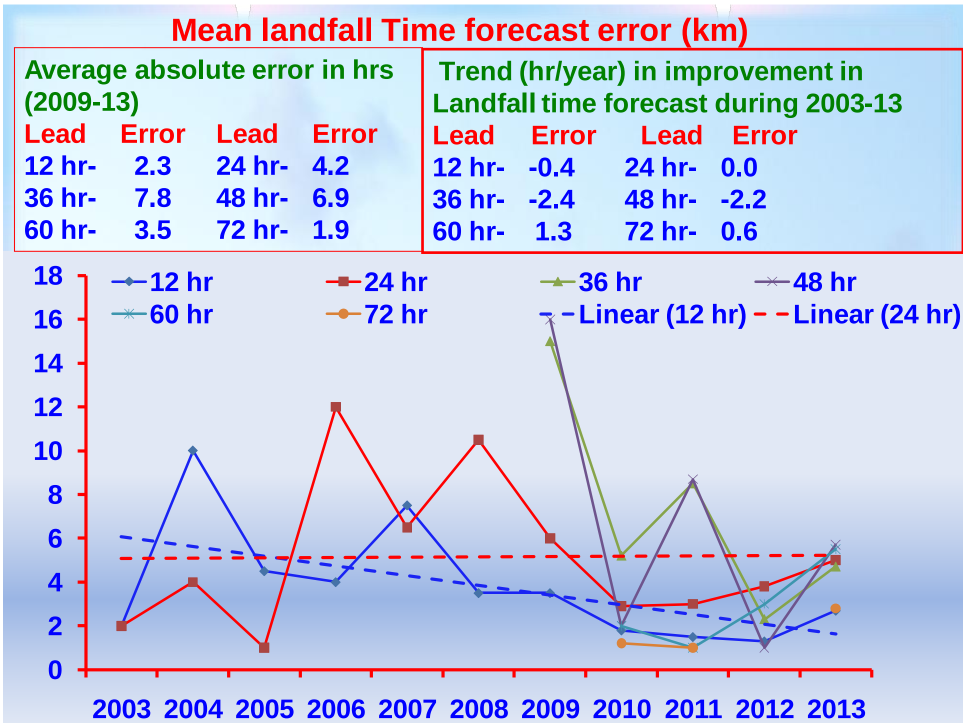
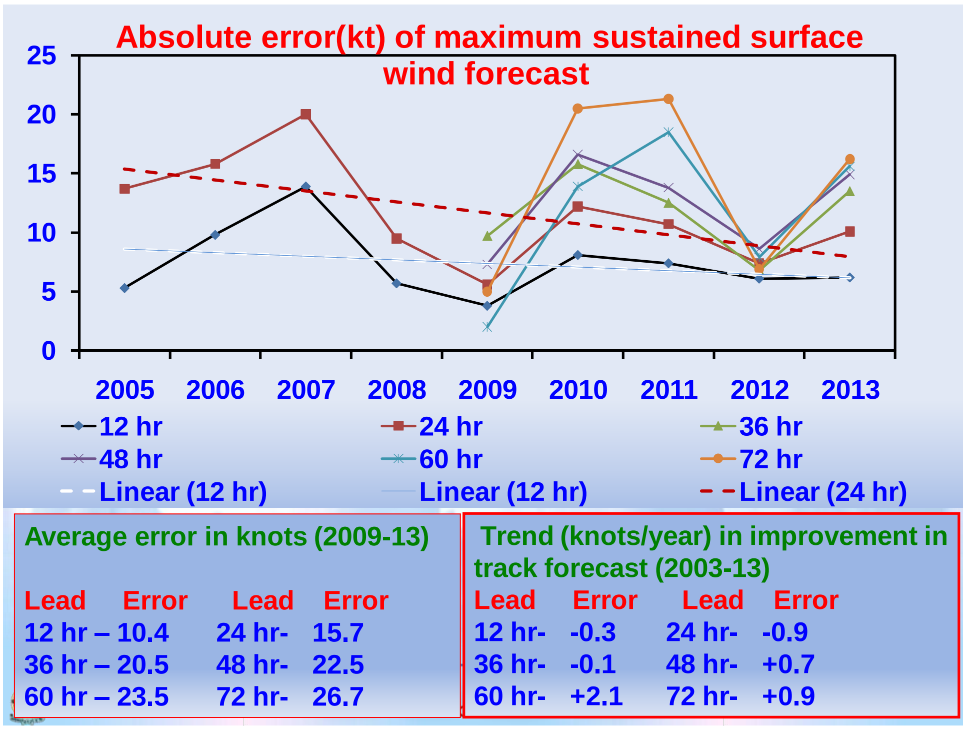


Fig. 4.2. Annual mean landfall point and time forecast error of IMD' operational forecast during 2003-2013



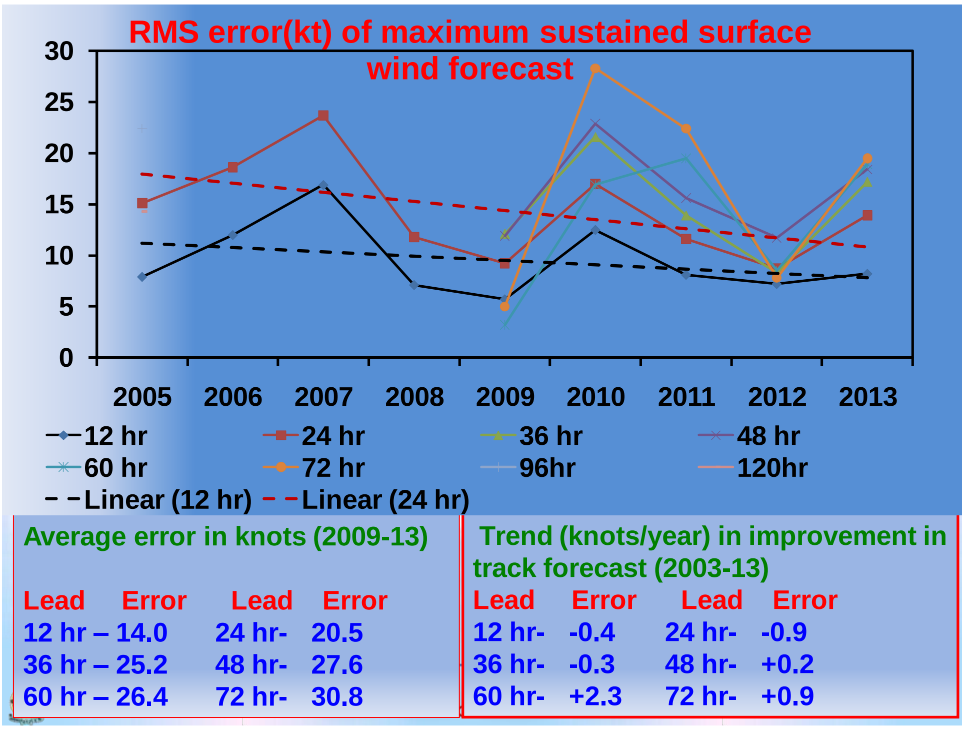


Fig. 4.3 IMD's annual mean operational absolute error and RMS error of maximum sustained wind during 2003-1013

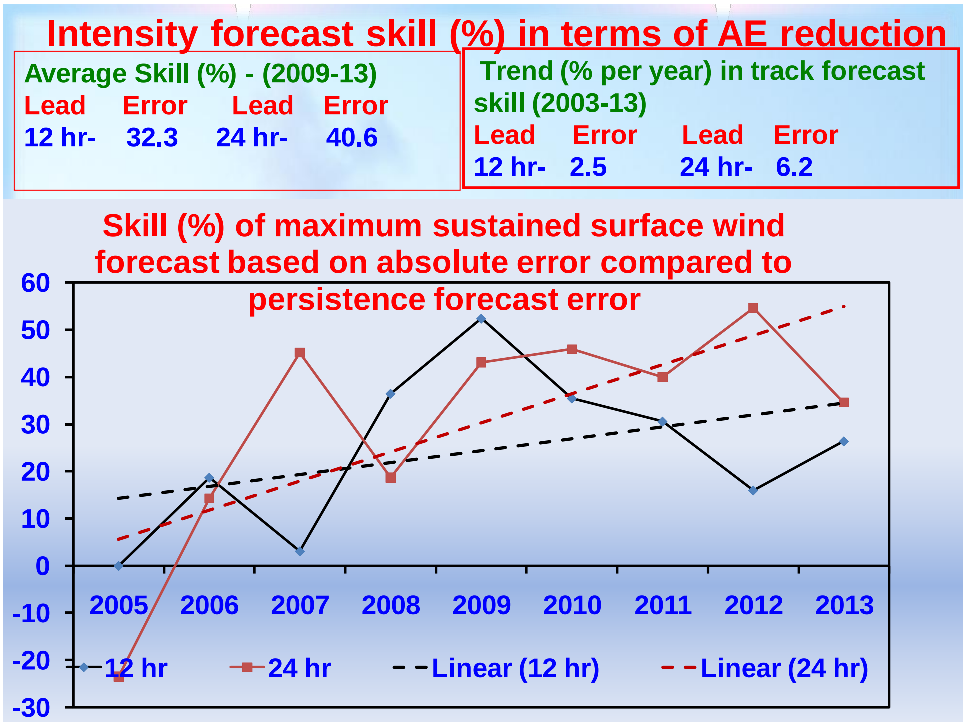


Fig.4.4. IMD's annual mean operational intensity (Maximum sustained wind) forecast skill in terms of absolute error (AE) reduction during 2005-2013

Damaged cellular phone in Berhampur on 13th Oct. 2013

Truck was overturned by strong wind on 13th Oct. 2013

DAMAGE DUE TO VSCS 'PHAILIN'(08-14 OCT. 2013)