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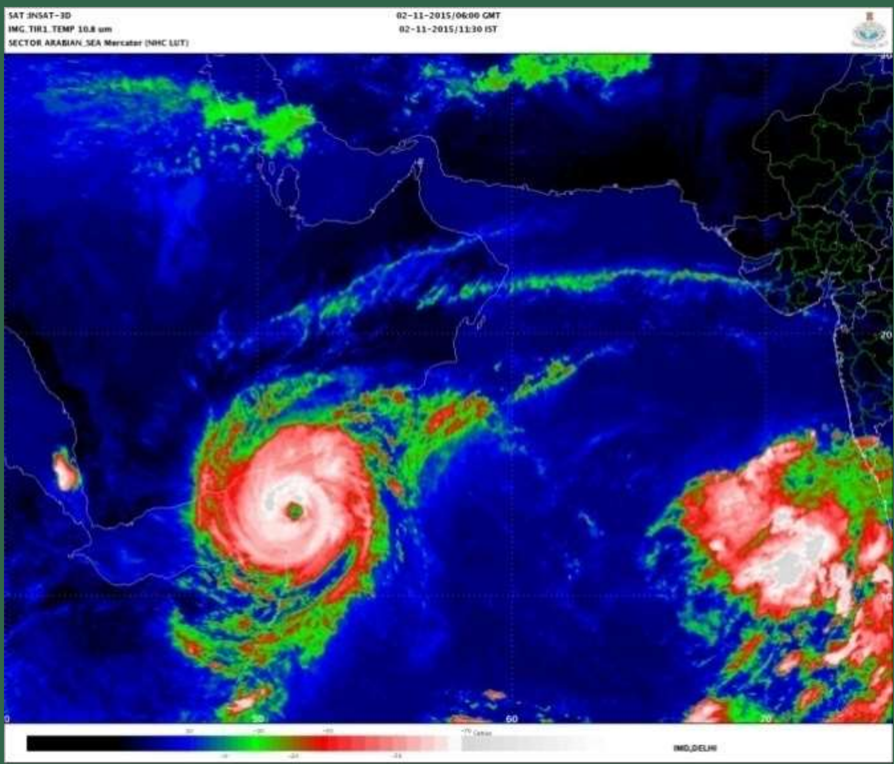
REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2015



SATELLITE IMAGERY OF EXTREMELY SEVERE CYCLONIC STORM, “CHAPALA"

RSMC-TROPICAL CYCLONES, NEW DELHI

APRIL 2016

WMO

INDIA METEOROLOGICAL DEPARTMENT

RSMC- TROPICAL CYCLONES, NEW DELHI

APRIL 2016

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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 2015. The special emphasis has been given on the features associated with genesis, intensification, movement, landfall and associated adverse weather like heavy rain, strong wind and storm surge. The performance of the forecasts issued by RSMC, New Delhi with respect to tropical cyclones are verified and discussed. Also the performance of various dynamical and statistical models for cyclone forecasting has been evaluated and discussed.

CONTENTS

INTRODUCTION

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

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

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

CHAPTER- I

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

1.1 Area of Responsibility

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

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

1.2 Naming of tropical cyclones over north Indian Ocean:

The WMO/ESCAP Panel on Tropical Cyclones at its twenty-seventh Session held in 2000 in Muscat, Sultanate of Oman agreed in principle to assign names to the tropical cyclones in the Bay of Bengal and Arabian Sea. After long deliberations among the member countries, the naming of the tropical cyclones over north Indian Ocean commenced from September 2004, by RSMC New Delhi. The first name was ‘ONIL’ which developed over the Arabian Sea (30 September to 03 October, 2004). According to approved principle, a list of 64 names in eight columns has been prepared. The name has been contributed by Panel members. The RSMC tropical cyclones New Delhi gives a tropical cyclone an identification name from this name list. The Panel member’s name is listed alphabetically country wise in each column. The names are used sequentially column wise. The first name starts from the first row of column one and continues sequentially to the last row in column eight. The names are not rotated every few years unlike that over Atlantic and Eastern Pacific lists. Out of 64 approved names, 42 names have been utilized till the end of year 2015.

1.3 Observational System

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

1.3.1 Surface Observatories

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

As a routine, a large number of ship observations over Indian seas from about 50 ships per day, both Indian and International are also received and are assimilated in the analysis.

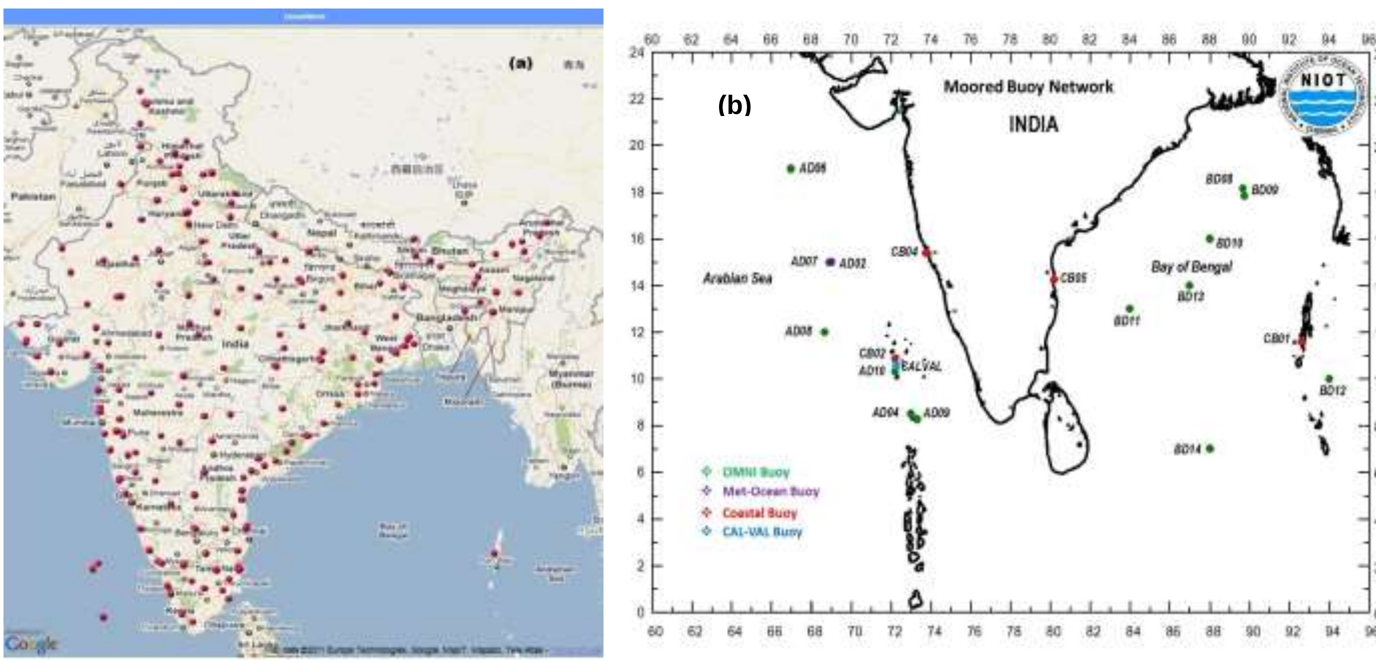


Fig.1.2. (a) The surface Observatory Network of IMD (b) Buoy network of NIOT

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

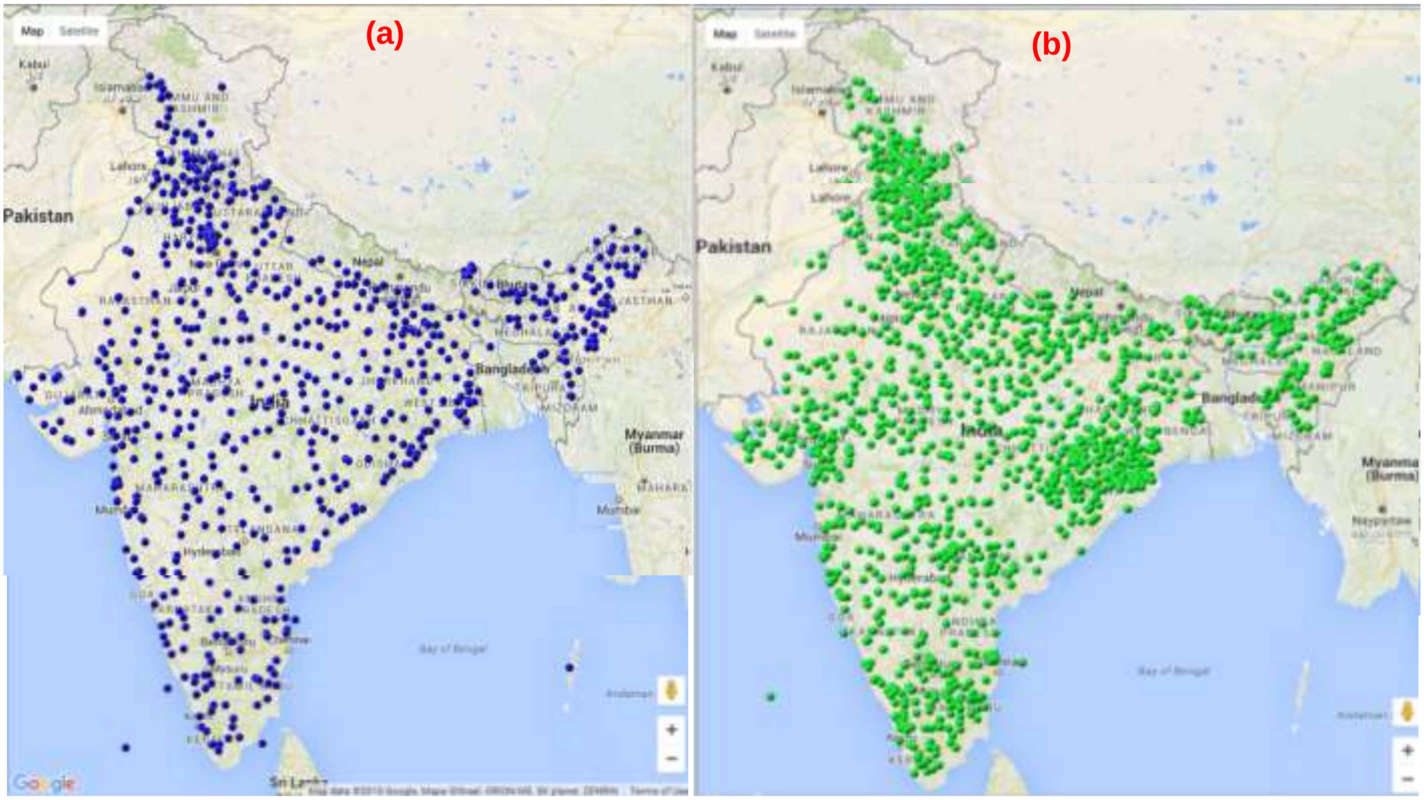


Fig. 1.3 (a) Network of 675 AWS and (b) 1289 ARG installed.

1.3.2 Upper Air Observatories

There are at present 62 Pilot Balloon Observatories, 39 Radiosonde/ Radio wind observatories and 02 Radiosonde Observatory. Among the 37 Radiosonde/Radiowind observatories, 17 stations are GPS based stations, 8 with Sameer instruments, 7 with IMS-1500 instruments and 5 with RSGE instruments. The pilot balloon observation network and RS/RW network of IMD is shown in fig 1.4

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

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

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

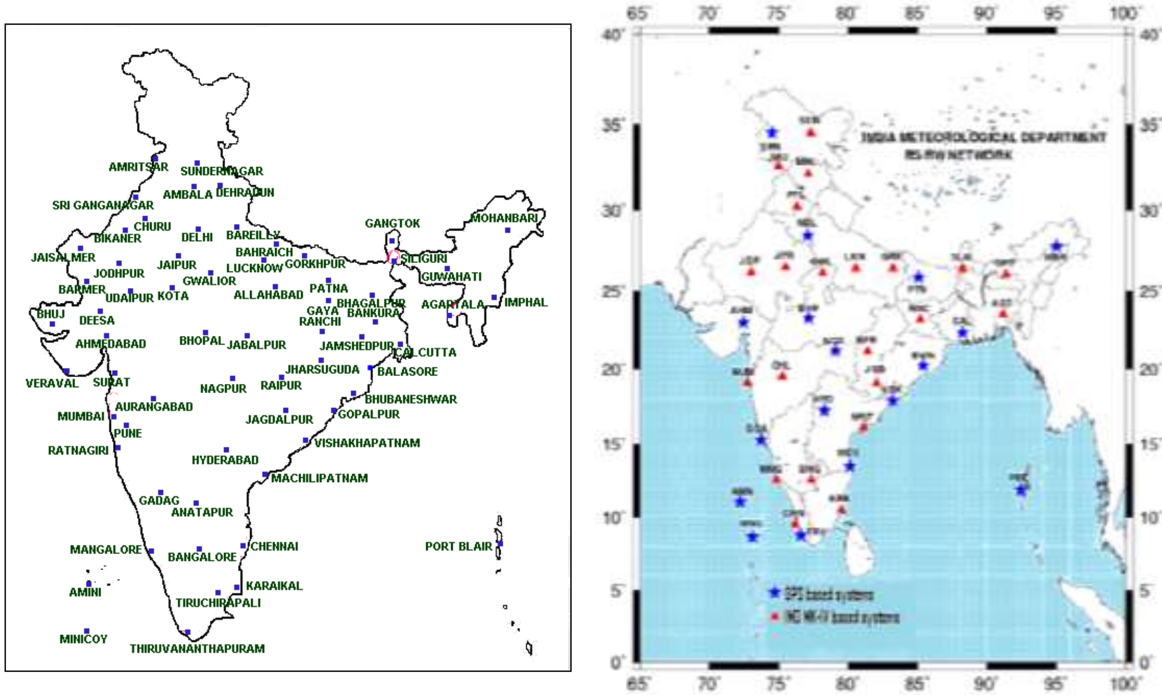


Fig.1.4 (a) Network of Pilot Balloon Observatories and (b) Network of Radiosonde/ Radio wind observatories

1.3.3 Radars

1.3.3.1 Current status

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

S-band DWRs are installed at Agartala, Bhopal, Chennai, Hyderabad, Kolkata, Lucknow, Machilipatnam, Mohanbari, Nagpur, New Delhi, Patna, Patiala, Sriharikota and Visakhapatnam. C-band Polarimetric DWRs are installed at Jaipur and New Delhi. Recently one X-Band transportable radar has been installed at Srinagar. Five Nos. of DWRs are being installed at Gopalpur, Paradip, Goa, Karaikal and Kochi

X-band weather radars are installed at Ahmedabad, Bhubaneswar, Guwahati, Kolkata, Mangalore, Ranchi and are being phased out.

Conventional radar provides information only on reflectivity whereas DWRs provide information on reflectivity, velocity and spectral width.

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

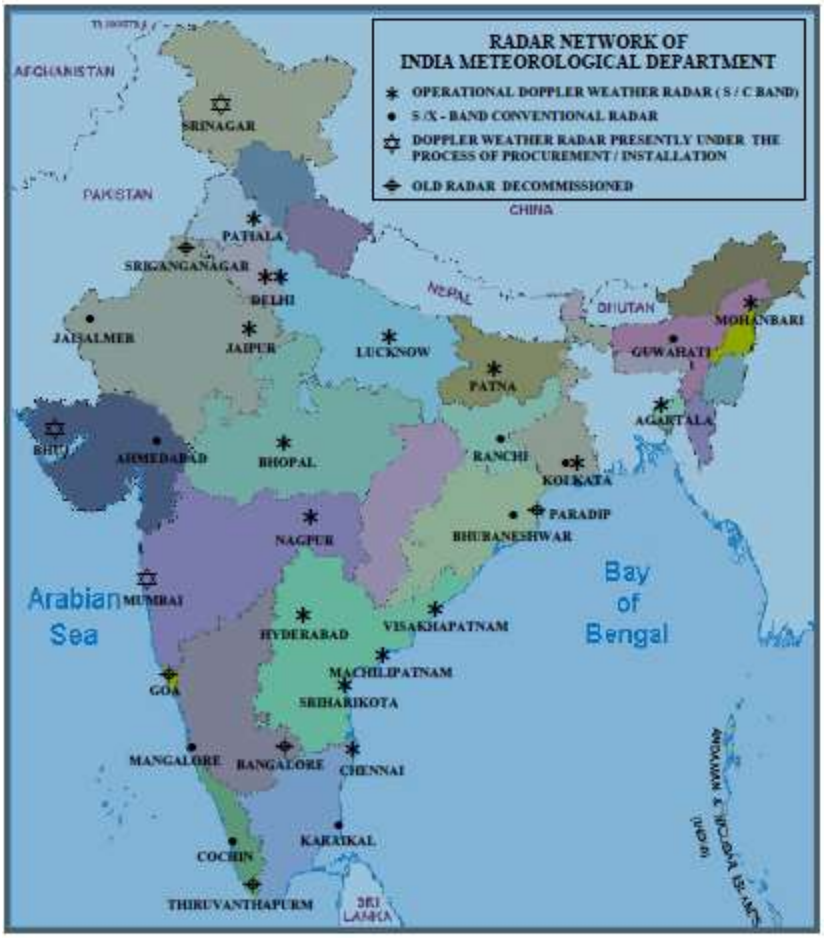


Fig. 1.4(b) Network of Radar

1.3.3.2 Future Plan:

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

1.3.4 Satellite Monitoring

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 was launched on 26 July 2013. Kalpana-1 and INSAT-3A both have payload of Very High Resolution Radiometer (VHRR) for imaging the earth in three channels viz. Visible (0.55-0.75 µm), Infra-Red (10.5-12.5µm) and Water vapour (5.7-7.1µm) having resolution of 2X2 km in visible and 8X8 km in Water vapour (WV) and Infra-red (IR) channels. In addition, the INSAT-3A has a three channel Charge Coupled Device (CCD) payload for imaging the earth in Visible (0.62- 0.69um), Near IR (0.77-0.86µm) and Short Wave IR (1.55-1.77µm) bands of Spectrum.

The Resolution of CCD payload in all the three short wave (SW) channels is 1KmX 1 Km. INSAT-3D has an advanced imager with six imagery channels **{**Visible (0.55-0.75 µm), Short wave Infra-Red (SWIR) (1.55-1.70 µm), Medium Infra-Red (MIR) (3.80-4.00 µm), Thermal Infra-Red-1(TIR-1) (10.2-11.3 µm), TIR-2 (11.5-12.5 µm), & WV (6.50-7.10 µm)**}** and a nineteen channel sounder (18 IR & 1 Visible) for derivation of atmospheric temperature and moisture profiles. It provides 1 km. resolution imagery in visible band, 4 km resolution in IR band and 8 km in WV channel.

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

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

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

At present Dvorak technique is used but manually applied. Recently efforts have been made for automation of this technique. Automated Dvorak technique version (8.2.1) is running in experimental mode at Satellite 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.

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

1.4 Analysis and Prediction

1.4.1 Analysis and Prediction system

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

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

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

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

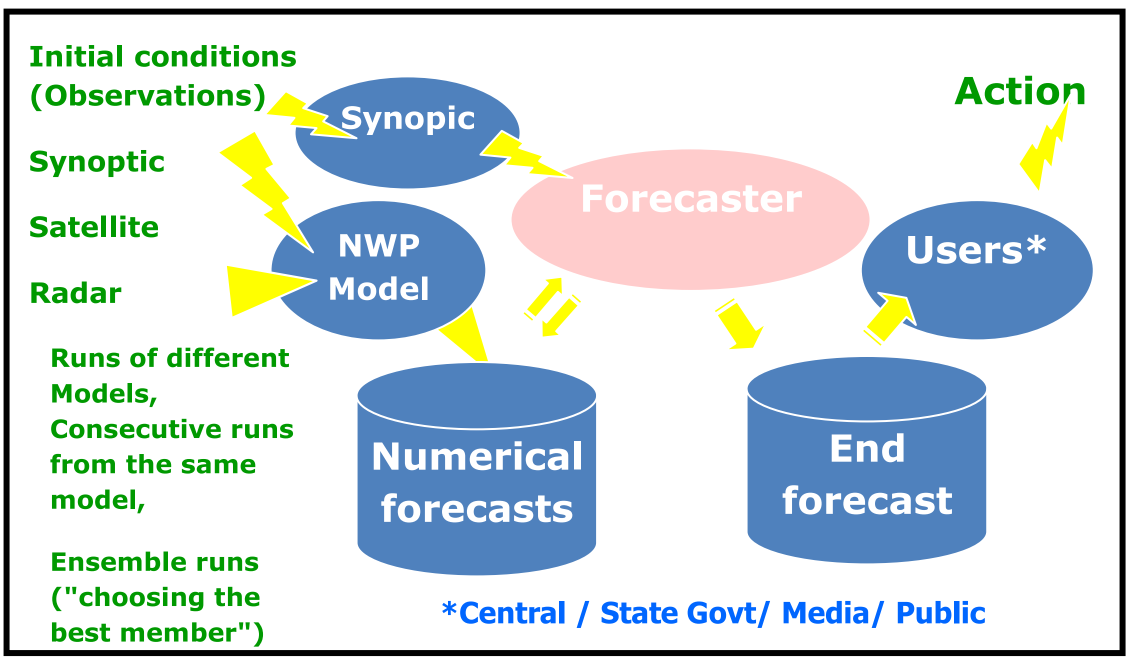


Fig.1.5. Strategy adopted for cyclone analysis and forecasting

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

- Analysis of all synoptic, satellite and NWP model products for genesis, intensity and track monitoring and prediction
- Preparation of past and forecast tracks up to 120 hrs

- Depiction of uncertainty in track forecast
- Preparation of quadrant wind radii forecast up to 120 hrs.

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

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

Cloud imageries from Geostationary Meteorological Satellites INSAT-3A, METSAT (KALPANA-1) and INSAT-3D are the main sources of information for the analysis of tropical cyclones over the data-sparse region of north Indian Ocean. Data from scatteometry based satellites and Ocean buoys also provide vital information. Ship observations are also used critically during the cyclonic disturbance period. When the system comes closer to the coastline, the system location and intensity are determined based on hourly observations from Radar as well as from coastal observatories. The AWS stations along coast are also very useful as they provide hourly observations on real time basis. The WVW and CMV in addition to the conventional wind vectors observed by Radio Wind (RW) instruments are very useful for monitoring and prediction of cyclonic disturbance, especially over the Sea region. The direction and speed of the movement of a tropical cyclone are determined primarily from the three hourly displacement vectors of the center of the cyclone. 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 2015

1.5.1 Global Forecast System

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

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

1.5.2 Regional Forecast System

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

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

The mesoscale forecast system Weather Research and Forecast WRFDA (version 3.2) with 3DVAR data assimilation is being operated daily twice to generate mesoscale analysis at 9 km horizontal resolution 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 9 km and 3 km and 45 Eta levels in the vertical. The model mother domain covers the area between lat. 23ºS to 46ºN long 40ºE to 120ºE and child covers whole India. The performance of the model is found to be reasonably skilful for cyclone genesis and track prediction. At ten other regional Centers, very high resolution mesoscale models (WRF at 3 km resolution) are also operational with their respective regional setup/configurations.

1.5.2.2 Hurricane WRF Model (HWRF)

Recently under Indo-US joint collaborative program, IMD adapted Hurricane-WRF model for Tropical Cyclone track and intensity forecast for North Indian Ocean region for its operational requirements. The basic version of the model HWRFV (3.7+) which was operational at EMC, NCEP, USA was ported on IITM ADITYA HPCS machine with nested domain of 27 km, 9 km and 3 km horizontal resolution and 61 vertical levels with outer domain covering the area of 216X432, 106X204 and innermost domain 198X354 with Center of the system adjusted to the Center of the observed cyclonic storm. The outer domain covers most of the North Indian and the inner domain mainly covering the cyclonic vortex which moves along the movement of the system. The model has special features such as vortex initialization, coupled with Ocean model to take into account the changes in SST during the model integration, tracker and diagnostic software to provide the graphic and text information on track and intensity prediction for real-time operational requirement. Model has full physics configuration with cloud microphysics of eta-HWRF scheme (Rogers et al., 2001), radiation physics for short wave and long wave (GFDL schemes), surface layer (GFDL) and surface physics (GFDL slab model), planetary boundary layer physics (Hong and Pan, 1996) and cumulus physics (New simplified Arakawa-Schubert - Han and Pan, 2011).

As part of model validation, case studies were undertaken to test the ability of the model for the Cyclonic storms formed during the year 2010 and model forecasts are produced up to 5 days from the 2011 cyclone season as an experimental forecast in real-time. In these runs only the atmospheric model (HWRF) was tested. The Ocean Model (POM-TC) and Ocean coupler requires the customization of Ocean Model for Indian Seas. In this regards, IMD is working in collaboration with INCOIS, Hyderabad which is running the Ocean Models (POM)/Hybrid co-ordinate ocean model (HYCOM) to support in porting the Ocean Model with Indian Ocean climatology and real time data of SST over Indian Seas. The model is run on real time six hourly basis (started from cyclone season 2015) based on 00, 06, 12 and 18 UTC initial conditions to provide 6 hourly track and intensity forecasts along with surface wind and rain swaths valid up to 126 hours. The model uses IMD GFS-T574L64 analysis/forecast as first guess.

1.5.3 Dynamical Statistical models

The Dynamical Statistical models include (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) Predicting decaying intensity after the landfall.

1.5.3.1 Genesis Potential Parameter (GPP)

A cyclone genesis parameter, termed the genesis potential parameter (GPP), for the North Indian Ocean is developed (Kotal et al, 2009). The parameter is defined as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability, and the inverse of vertical wind shear. The parameter is operationally used for distinction between non-developing and developing systems at their early development stages with threshold of T3.0 at GPP value of 8.0 or more. The composite GPP value is found to be around three to five times greater for developing systems than for non-developing systems. The analysis of the parameter at early development stage of T1.5 is found to provide a useful predictive signal for intensification of the system.

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

1.5.3.2 Multi-model ensemble (MME) technique

The multi model ensemble (MME) technique (Kotal and Roy Bhowmik, 2011) is based on a statistical linear regression approach. The predictors selected for the ensemble technique are forecasts latitude and longitude positions at 12-hour interval up to 120-hour of five operational NWP models. In the MME method, forecast latitude and longitude position of the member models are linearly regressed against the observed (track) latitude and longitude position for each forecast time at 12-hours intervals for the forecast up to 120-hour. The outputs at 12 hours forecast intervals of these models are first post-processed using GRIB decoder. The 12 hourly predicted cyclone tracks are then determined from the respective mean sea level pressure fields using a cyclone tracking software. Multiple linear regression technique is used to generate weights (regression coefficients) for each model for each forecast hour (12hr, 24hr, 36 hr, 48hr, 60hr, 72hr,84hr, 96hr, 108hr and 120 hrs) based on the past data. These coefficients are then used as weights for the ensemble forecasts. A collective bias correction is applied in the MME by applying multiple linear regression based minimization principle for the member models GFS(IMD), GFS(NCEP), ECMWF, UKMO and JMA. ECMWF data are available at 24h intervals. Therefore, 12h, 36h, 60h, 84h, 108h forecast positions are computed based on linear interpolation. All these NWP products are routinely made available in real time on the IMD web site: ***www.rsmcnewdelhi.imd.gov.in.***

1.5.3.3 Statistical Dynamical model for Cyclone Intensity Prediction (SCIP)

A statistical-dynamical model (SCIP) (Kotal et al, 2008) has been implemented for real time forecasting of 12 hourly intensity up to 120 hours. The model parameters are derived based on model analysis fields of past cyclones. The parameters selected as predictors are: Initial storm intensity, Intensity changes during past 12 hours, Storm motion speed, Initial storm latitude position, Vertical wind shear averaged along the storm track, Vorticity at 850 hPa, Divergence at 200 hPa and Sea Surface Temperature (SST). For the real-time forecasting, model parameters are derived based on the forecast fields of IMD-GFS model. The method is found to provide useful guidance for the operational cyclone forecasting.

1.5.3.4 Rapid Intensification (RI) Index

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

1.5.3.5 Decay of Intensity after the landfall

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

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

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

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

1.6 Bulletins and Products Generated By RSMC, New Delhi

RSMC, New Delhi prepares and disseminates the following bulletins.

1.6.1 Tropical Weather Outlook

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

1.6.2 Special Tropical Weather Outlook

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

1.6.3 Tropical Cyclone Advisories

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

1.6.4 Storm Surge Guidance

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

1.6.5 Maritime forecast bulletins

Under Global Maritime Distress and Safety System (GMDSS) Scheme, India has been designated as one of the 16 services in the world for issuing Sea area bulletins for vessels on high seas 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. Fleet Forecasts for Indian seas are also issued for Indian Navy twice a day with validity period of twelve hours.

Port Warnings & fishermen warnings are also issued all along the Indian coast as and when the coast is likely to be affected due to disturbances in seas.

1.6.6 Tropical Cyclone Advisories for Aviation

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

1.6.7 National bulletin

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

1.6.8 Cone of uncertainty forecast

The Cone of uncertainty (COU) represents the probable position of a CD/ TC's circulation Center, and is made by drawing a set of circles centered at each forecast point—06, 12, 18, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hours for a five-day forecast. The radius of each circle is equal to the average official track forecast errors of 10, 20, 30, 45 60, 80, 100, 120, 135, 150, 165, 180 and 195 nautical miles for 06, 12, 18, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hr forecasts respectively. The radii of circle to construct cone of uncertainty have been changed based on the average error of 2009-2013. The new radii have been introduced with effect from cyclone, Hudhud in October, 2014. An example of this product is shown in Fig. 1.6

1.6.9 Wind forecast for different quadrants

The forecast of radius of maximum sustained wind in four quadrants of a cyclone commenced with effect from cyclone, GIRI during October 2010. In this forecast, the radius of 28, 34, 50 and 64 knot winds are given for various forecast periods like +06, +12, +18, +24, +36, +48, +60, … 120 hrs. A typical graphical presentation of this forecast is shown in Fig.1.7. This quadrant wind forecast is issued as bulletin from the deep depression stage onwards to various users through global telecommunication system. It is also uploaded on RSM, New Delhi website in both textual and graphics form.

1.6.10 TC Vital

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

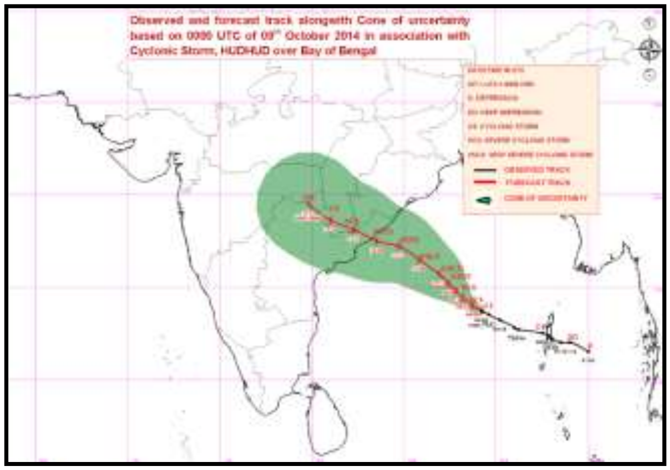


Fig.1.6. A typical example of observed and forecast track of Cyclonic Storm HUDHUD which later on became a VSCS.

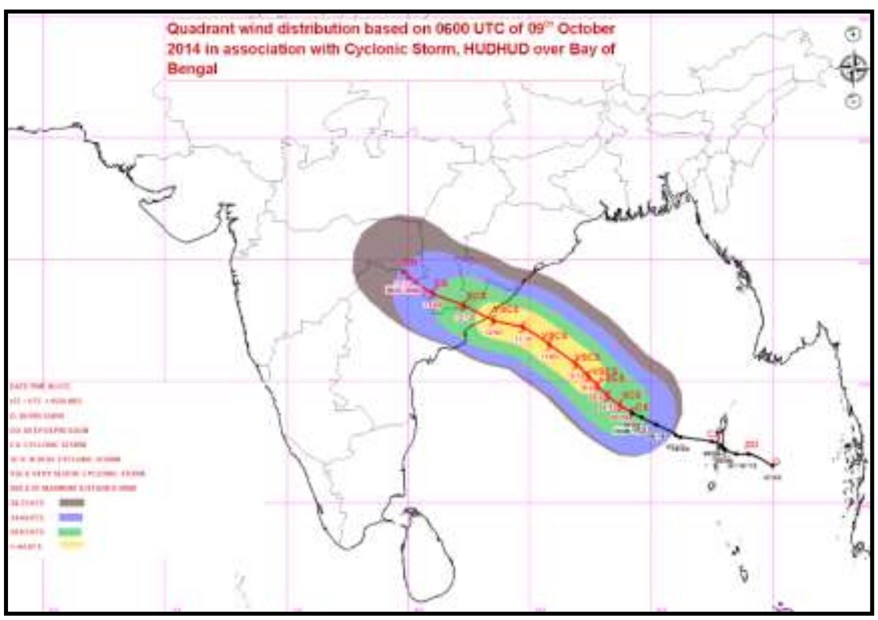


Fig.1.7. A typical graphical presentation of cyclone wind forecast during VSCS HUDHUD

1.6 Cyclone Warning Dissemination System

Cyclone warnings are disseminated to various users through telephone, fax, email SMS, Global Telecom System (GTS), WMO Information System (WIS), All India Radio, FM & community radio, Television and other print & electronic media, press conference & press release. These warnings/advisories are also put in the website **(www.rsmcnewdelhi.imd.gov.in)** of IMD. Another means to transmit warning is IVRS (Interactive Voice Response system).It is functioning with effect from July, 2000.The requests for weather information and forecasts from general public are automatically answered by this system One can access current weather and forecast for major Indian cities by dialing Toll free number 1800 180 1717. Presently a centralized IVRS is catering the weather information of major cities. India Meteorological Department has taken various initiatives in recent years for improvement in dissemination of weather forecast and warning services based on latest tools and technologies. Since 2009 IMD has started SMS based weather and alert dissemination system through AMSS (Transmet) at RTH New Delhi. To further enhance this initiative, India Meteorological Department has taken the leverage of Digital India Programme to utilize "Mobile Seva" of Department of Electronics and Information Technology (DeitY), Ministry of Communication and Information Technology; Govt. of India for SMS based Warnings /Weather information dissemination for wide range of users. The SMS based cyclone alert to the register users including public was inaugurated on 25th December, 2014. Global Maritime Distress and Safety System (GMDSS) message is also put in RSMC, New Delhi website (URL: www.rsmcnewdelhi.imd.gov.in) as well as transmitted through GTS. The WIS Portal –GISC New Delhi is another system for cyclone warning dissemination. The user can access the warning messages through the -URL: http://www.wis.imd.gov.in. IMD has also started issuing of NAVTEX bulletins for coastal region along east as well as west coast of India for operation of lightships and fishermen from 30th March, 2015. In addition to the above network, for quick dissemination of warning against impending disaster from approaching cyclones, IMD has installed specially designed receivers within the vulnerable coastal areas for transmission of warnings to the concerned officials and people using broadcast capacity of INSAT satellite. This is a direct broadcast service of cyclone warning in the regional languages meant for the areas affected or likely to be affected by the cyclone. Since the existing 252 Cyclone Warning Dissemination System (CWDS) stations and 101 digital CWDS have become obsolete and many of these systems have stopped working and were beyond repair, IMD and ISRO jointly decided to replace all these CWDS systems by new 500 numbers of Direct Telecom Hub (DTH) based Disaster Warning Dissemination Systems (DWDS) for issuing warning to cyclone prone areas. Till 2015, 178 numbers of DTH based DWDS systems have been installed in Tamil Nadu, Pondicherry and Andhra Pradesh. The IMD's Area Cyclone Warning Centers (ACWCs) at Chennai, Mumbai & Kolkata and Cyclone Warning Center (CWCs) at Bhubaneswar, Visakhapatnam & Ahmedabad are responsible for originating and disseminating the cyclone warnings through this system. The DTH based DWDS system can disseminate the warning messages in real time to multiple receiving locations spread over large coastal areas. This service is unique in the world and will help the public in general and the administration, in particular, during the cyclone.

The SMS based alert/warnings are issued to registered famers through Kisan portal of Govt. of India (Ministry of Agriculture) and to registered fishermen through Indian National Centre for Ocean Information Sciences (INCOIS), Hyderabad also.

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 monitoring and prediction of tropical cyclone.

The project is operated during 15 October to 30 November every year. During 15 Oct- 30 Nov. 2015, several national institutions participated for joint observational, communicational & NWP activities, like during 2008-2014. There was improved observational campaign with the observation from Buoys, Scatterometry based satellite and microwave imageries products. There was intense observation period for 12 days during the field phase 2015 in association with the systems over Bay of Bengal and Arabian Sea. The daily reports were prepared during this period to find out the characteristics of genesis, intensification and movement of the systems as well as environmental features over the NIO. The detailed report on implementation of FDP-2015 is available in RSMC, New Delhi website (www.rsmcnewdelhi.gov.in)

CHAPTER-II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2015.

During the year 2015, 12 cyclonic disturbances developed over north Indian Ocean including two Extremely Severe Cyclonic Storm (ESCS) and one Cyclonic Storm (CS) and two deep deression over Arabian Sea where as one cyclonic storm, one deep deression and one depression over Bay of Bengal. Four land depression (D) also formed during 2015. Considering season-wise distribution, out of 12 disturbances, eight during monsoon and three during post-monsoon season. Salient features of cyclonic disturbances during 2015 are given below.

i. There was one cyclone over the Bay of Bengal and three over the Arabian Sea against the long period average of 5 per year over the entire north Indian Ocean including about four over Bay of Bengal and one over Arabian Sea. Thus the cyclonic activity was subdued in the Bay of Bengal during the year 2015. However, the frequency of very severe cyclonic storms was near normal (two)
ii. Though there were four cyclones, none of thse crossed Indian coast. CS Ashobaa dissipated over Sea, CS Komen crossed Bangladesh coast and Chapala & Megh crossed Yemen coast
iii. Velocity Flux, Accumulated cyclone energy and Power Distribution Index of the period 2015 are 56.25, 33.92 and 26.34 against long period average based on the data of 1990-2013 and 21.17, 13.09 and 9.67 respectively.
iv. The total duration of cyclonic disturbances during 2015 was 44.5 days against the long period average of 29.4 days based on data of 1990-2013.

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

(a) Cyclonic Storm, 'ASHOBAA' over the Arabian Sea(07-12 June 2015)

The Cyclonic Storm 'ASHOBAA' (07-12 June 2015) developed over eastcentral Arabian Sea from monsoon onset vortex in the morning of 5th June 2015. It gradually moved northwards and became a low pressure area over southeast and adjoining eastcentral Arabian Sea in the morning of 6th June. It concentrated into a Depression (D) in the morning of the 7th June over eastcentral Arabian Sea. Moving nearly north-northwestwards and it intensified into a Deep Depression (DD) in the early hours of 8th June over eastcentral Arabian Sea. It further intensified into the Cyclonic Storm (CS) 'ASHOBAA' in the morning of of 8th June. It gradually intensified till the night of 10th June. Thereafter, while moving west-southwestwards from forenoon of 10th June to morning of 11th June, it encountered high vertical wind shear and low ocean thermal energy and started weakening. It slowly moved westwards over a colder oceanic region and weakened into a deep depression in the night of 11th June. Due to adverse environmental conditions, interaction with land surface and dry air intrusion from western side, it further weakened into a depression in the morning of 12th June and into a well marked low pressure area over northwest Arabian Sea and adjoining Oman coast in the evening of 12th June.

The salient features of this system are as follows.

i. CS 'ASHOBAA' developed over eastcentral Arabian Sea during the onset phase of monsoon.
ii. It had a unique track, as it moved initially northwards, then north-northwestwards and finally west-southwestwards towards Oman coast.
iii. It dissipated over northwest Arabian Sea off Oman coast before landfall.
iv. The numerical weather prediction (NWP) and dynamical statistical models provided reasonable guidance with respect to its genesis, track and intensity, though there was large divergence in model guidance with respect to track, intensity and landfall.

(b) Cyclonic Storm (CS) Komen over the Bay of Bengal (26 July-02 August 2015)

The cyclonic storm (CS), KOMEN over the Bay of Bengal (BoB) developed from a low pressure area which lay over northeast BoB and adjoining Bangladesh & Gangetic West Bengal on 25th July evening and concentrated into a depression over the same area in the morning of 26th July. It followed a semi-circular track over northeast Bay of Bengal and then crossed Bangladesh coast between Hatia and Sandwip near lat. 22.5^0N and long. 91.4^0E during 1400 and 1500 UTC of 30th July. After landfall, it moved initially north-northwestwards, then westwards and west-southwestwards across Bangladesh, Gangetic West Bengal and Jharkhand. It weakened gradually into a well marked low pressure area over Jharkhand and adjoining north Odisha and north Chhattisgarh at 1200 UTC of 02nd August.

The salient features of this cyclone are as follows.

i. It was the fourth system during the monsoon month of July which intensified into a CS during the satellite era (1965-2015). Of the three systems before CS Komen, the CS in July 1972 & 1973 and the CS in July 1989 crossed Odisha and Andhra Pradesh coast respectively.
ii. The CS Komen had a unique track, as it developed near Bangladesh coast, followed a semi-circular track over the northeast Bay of Bengal and finally moved northward to cross Bangladesh coast.

(c) Extremely Severe Cyclonic Storm (ESCS) Chapala over the Arabian Sea (28 October - 04 November 2015)

An Extremely Severe Cyclonic Storm (ESCS) 'Chapala' formed from a low pressure area over southeast Arabian Sea (AS) which concentrated into a depression in the morning of 28th October. It moved north-northwestwards and intensified into a deep depression in the same evening. It further intensified into a cyclonic storm in the early hours of 29th over eastcentral Arabian Sea. It then moved west-northwestwards, further intensified into a severe cyclonic storm(SCS) in the evening and a very severe cyclonic(VSCS) storm in the midnight of 29th and into an extremely severe cyclonic storm in the morning of 30th. It then moved mainly westwards, maintained its intensity till 1st November and then started weakening gradually. Moving west-northwestwards, it crossed Yemen coast to the southwest of Riyan (14.1^{0}N/48.65^{0}E) during 0100-0200 UTC of 3rd November as very severe cyclonic storm. It further westwards and weakened into a severe cyclonic storm in the morning, into a cyclonic storm by noon and into deep depression around midnight of 3rd November, it then weakened into a depression in the early morning of 4th and lay as well marked low pressure area over Yemen at 0300 UTC of 4th November. The salient features of this cyclone are as follows.

i. ESCS Chapala is the first severe cyclone to cross Yemen coast after the severe cyclonic storm of May 1960.
ii. The ESCS Chapala had a life period of 7 days , which is above normal (average life period of VSCS/ESCS is 6 days in NIO and 4.7 days in Post monsoon season for VSCS/ESCS)
iii. It had the maximum intensity of 115 kts (215 kmph) and crossed Yemen coast with a speed of 65 knots (120 kmph).
iv. The system had the longest track length after VSCS Phet in 2010. It travelled a distance of about 2248 km during its life period.
v. The Accumulated Cyclone Energy (ACE) was about 18.29 X 10^4 $knot^2$ (the mean for the period (1990-2013) in the post monsoon season over Arabian Sea is 0.8 X 10^4 $knot^2$), which is same as VSCS, Phet over Arabian Sea in 2010.
vi. The Power Dissipation Index was 17.92 X 10^6 $knot^3$ which is also same as that of VSCS Phet in 2010 (the mean for the period (1990-2013) in the post monsoon season is 0.4 X 10^6 $knot^3$.
vii. The system rapidly intensified from 29th morning to 30th afternoon, when the speed increased from 35 kts at 0000 UTC of 29th Oct to 90 kts at 0900 UTC of 30th Oct.
viii. Though the system moved over to colder Gulf of Aden, experienced dry air intrusion and interacted with the land surface, it did not weaken rapidly due to low vertical wind shear around the centre and in the forward sector of the system.
ix. There was large divergence and hence higher than normal errors in NWP models for prediction of its track and intensity especially, the landfall over Yemen.
x. RSMC New Delhi predicted genesis on 25th October, 3 days in advance and its intensification to ESCS one day in advance on 29th October 2015. The forecast of

landfall over Yemen and adjoining Oman coast was issued on the day of genesis i.e., 28th Oct., 6 days advance and landfall over Yemen was issued on 31 Oct. with a lead period of 5 days. Every 3 hourly Tropical Cyclone Advisory were issued to WMO/ESCAP panel countries including Oman and Yemen & Somalia.

(d) Extremely Severe Cyclonic Storm, 'Megh' over the Arabian Sea (05-10 November 2015)

A depression formed over the eastcentral Arabian Sea (AS) at 0000 UTC of 5th November from a low level circulation over Lakshadweep and neighbourhood. It moved westwards/west-southwestwards and intensified into a cyclonic storm (CS) at 1200 UTC of 5th November. It continued its west-southwestward movement and intensified into a severe cyclonic storm (SCS) at 0600 UTC of 7th, into a very severe cyclonic storm (VSCS) at 1500 UTC of 7th and rapidly intensified into an extremely severe cyclonic storm (ESCS) at 0300 UTC of 8th. Maintaining its peak intensity for a short period of about 6 hrs, it weakened gradually into a VSCS at 0000 UTC of 9th. From 0600 UTC of 9th, it exhibited west-northwestward movement, weakened rapidly into an SCS at 2100 UTC of 9th, into a CS at 0300 UTC of 10th and deep depression (DD) at 0600 UTC of 10th. It recurved northeastwards from 0300 UTC of 10th and crossed Yemen coast near latitude 13.4°N and longitude 46.1°E around 0900 UTC 10th as a DD. Continuing its northeastwards movement, it weakened into a depression at 1500 UTC of 10th and into a well marked low pressure area over Yemen and neighborhood at 1800 UTC of 10th.

The salient features of the system are as follows.

i. ESCS Megh occurred just after a week of formation of ESCS, Chapala over Arabian Sea. Also, ESCS Megh has been the first back to back cyclone after Chapala that reached Gulf of Aden and crossed Yemen within a week.

ii. ESCS Megh was the second ESCS after Chapala crossing Yemen coast in the satellite era. Chapala crossed Yemen coast close to the southwest of Riyan near 14.1^{0}N/48.65^{0}E during 0100-0200 UTC as a VSCS (with maximum sustained wind speed (MSW) of 65 knots) and Megh crossed Yemen coast near 13.4°N/46.1°E around 0900 UTC as a DD (with MSW of 30 knots).

iii. Unlike Chapala, ESCS Megh was a small core system with a pin hole eye.

iv. Megh maintained the intensity of ESCS for 18 hours (08/03-08/21) unlike Chapala which maintained the intensity of ESCS for 78 hours (30/03-02/09). The peak intensity in Megh was 95 knots for a period of 3 hours (08/06-08/09) against 115 knots for a period of 15 hours (30/09-31/00) in case of Chapala.

v. Lowest estimated central pressure (ECP) was 964 hPa with a pressure drop of 44 hPa unlike Chapala where it was 940 hPa with a pressure drop of 66 hPa.

vi. Like Chapala, ESCS Megh also experienced rapid intensification on 0000 UTC of 7th when its MSW increased from 45 knots to 85 knots at 0000 UTC of 8th (rise in wind speed 40 knots in 24 hours). During same period the ECP fell from 994 hPa to 974 hPa (20 hPa fall in 24 hours).

vii. ESCS Megh experienced rapid weakening over Gulf of Aden from 1800 UTC of 9th (MSW 65 knots) to 0600 UTC of 10th (MSW 35 knots), i.e. Megh experienced a fall in MSW by 30 knots in 12 hours.

viii. The ESCS Megh moved west to west-southwestwards throughout its life period till landfall over Yemen. While, ESCS Chapala moved initially north-northwestwards and then west-southwestwards to Yemen.

ix. Both ESCS Chapala and Megh could intensify upto the stage of ESCS under favourable environmental conditions, mainly low vertical wind shear (5-10 knots) around the system centre and the forward sector of the storm.

x. The system had the longest track length after VSCS Phet in 2010, as it travelled a distance of about 2307 km during its life period.

xi. The Accumulated Cyclone Energy (ACE) was about 8.2 X 10^4 $knot^2$ which is also the maximum after VSCS Phet in 2010 and ESCS Chapala in 2015 over the Arabian Sea.

xii. The Power Dissipation Index was 6.07 X 10^6 $knot^3$ which is the maximum after VSCS Phet in 2010 and ESCS Chapala in 2015 over the Arabian Sea.

xiii. The ESCS Megh had a life period of 5.7 days against long period average of 4.7 days in post-monsoon season for VSCS/ESCS over Arabian Sea)

xiv. The westward movement of the cyclone away from the Indian coasts was predicted from the first bulletin itself i.e. on 5th November 2015 (0300 UTC). Every three hourly Tropical Cyclone Advisories were issued to WMO/ESCAP member countries, Yemen and Somalia.

xv. The NWP and dynamical statistical models provided reasonable guidance with respect to its genesis and track. However, most of the NWP and dynamical statistical models except HWRF could not predict the landfall and rapid intensification/ weakening of ESCS Megh.

Details of the cyclonic disturbances formed over the north Indian Ocean and adjoining land areas are given in Table 2.1-2.3. The tracks of these disturbances are shown in Fig. 2.1

Table 2.1 Brief statistics of cyclonic disturbances over NIO and adjoining land areas during 2015:

1.	Cyclonic Storm, ASHOBAA, over Arabian Sea (07-12 June, 2015)
2.	Depression over Bay of Bengal (20-21 June, 2015)
3.	Deep depression over Arabian Sea (22-24 June, 2015)
4.	Land Depression (10-12 July, 2015)
5.	Land Deep Depression (27 - 30 July, 2015)
6.	Cyclonic Storm, KOMEN, over Bay of Bengal (26 Jul – 2 Aug 2015)
7.	Land Depression (4 August, 2015)
8.	Land Deep Depression (16 -19 September, 2015)
9.	Deep depression over Arabian Sea (09-12 October, 2015)
10.	Extremely Severe Cyclonic Storm, CHAPALA, over Arabian Sea (28 October-04 November 2015)
11.	Extremely Severe Cyclonic Storm, MEGH, over Arabian Sea (05 – 10 November, 2015)
12.	Deep depression over Bay of Bengal (08-10 November, 2015)

Table 2.2 Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2015

S. No.	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
1	Cyclonic Storm (CS) ASHOBAA over the Arabian Sea (07-12 June, 2015)	07th Jun-2015, 0300 UTC over east central Arabian Sea (14.5/68.5).	Weakened into a well-marked low pressure over northwest Arabian Sea and adjoining Oman coast at 1200 UTC on 12th Jun-2015	990 hPa at 0600 UTC on 09th Jun-2015 near (20.3/64.6)	45 knots at 1800 UTC of 09th June, 2015	T 3.0
2	Depression over Bay of Bengal (20-22 June, 2015)	20th Jun-2015, 0300 UTC over northwest and adjoining west central Bay of	Crossed Odisha coast between Gopalpur and Puri (19.7/85)	990 hPa at 0300 UTC 20th Jun-2015 near (18.0/86.0)	25 knots at 0300 UTC of 20th June, 2015	T 1.5

		Bengal (18.0/86.0)	between 2000-2100 UTC on 20th Jun-2015			
3	Deep Depression over Arabian Sea (22– 25 June, 2015)	22nd Jun-2015, 0300 UTC over northeast and adjoining Arabian Sea (20.0/67.0).	Crossed South Gujarat coast near Diu (21.0/71.3) between 0900 -1000 UTC on 23rd June 2015	988 hPa at 0300 UTC 23rd June, 2015 near (20.5/70.5)	30 knots at 0300 UTC of 23rd June, 2015	T 2.0
4	Land Depression (10-12 July, 2015)	10th Jul, 2015, 0300 UTC over Jharkhand and neighbourhood (23.1/85.1)	Weakened into a well-marked low pressure area over northwest Uttar Pradesh and adjoining Haryana at 1200 UTC on 12th July, 2015	994 hPa at 0900 UTC 10th Jul, 2015 near (23.3/84.0)	25 knots at 0300 UTC 10th Jul, 2015	-
5	Land Deep Depression (27-30 July, 2015)	27th Jul-2015, 1200 UTC over southwest Rajasthan and adjoining Gujarat (26.7/71.8).	Weakened into a well-marked low pressure area over west Rajasthan and neighbor-hood at 0300 UTC on 30th July, 2015.	994 hPa at 1200 UTC 27th Jul-2015 near (26.2/71.8)	30 knots at 0300 UTC 28th Jul-2015	-

6	Cyclonic Storm, KOMEN Over bay of Bengal (26 July –2 August, 2015)	26th Jul-2015, 0000 UTC over northeast Bay of Bengal and adjoining coastal area of Bangladesh & Gangetic West Bengal (22.0/90.8).	Crossed Bangladesh coast (near lat. 91.4^{0}E) between 1400-1500 UTC of 30th July	986 hPa at 1800 UTC 29th Jul, 2015 near (21.6/91.4)	40 knots at 0600 UTC 30-Jul-2015	T 2.5
7	Land Depression (4-5 August, 2015)	04th Aug-2015, 0300 UTC over East Madhya Pradesh and adjoining Chhattisgarh (22.7/80.5)	Weakened into a well-marked low pressure area over southwest Madhya Pradesh and neighbor-hood at 0000 UTC on 5th August, 2015.	998 hPa at 0300 UTC 04th Aug, 2015 near (22.7/80.5)	25 knots at 0300 UTC 04th Aug, 2015	-
8	Land Deep Depression (16 - 19 September, 2015)	16th Sep-2015, 0300 UTC over south Odisha and neighbourhood (19.6/83.5)	Weakened into a well-marked low pressure area over north Madhya Maharashtra and adjoining areas of southwest Madhya Pradesh and Gujarat region at 0300 UTC on 19th September, 2015	996 hPa at 1200 UTC 17th Sep, 2015 near (20.5/79.0)	30 knots at 0300 UTC 17th Sep, 2015	-
9	Deep depression (DD) over Arabian sea (09-12 October 2015)	09th Oct-2015, 0000 UTC over eastcentral Arabian Sea (14.0/70.3)	Weakened into a Well-marked low pressure area over	1000 hPa at 0600 UTC 10th Oct, 2015 near (15.1/69.4)	30 knots at 1800 UTC 09-Oct-2015	T 2.0

			eastcentral Arabian Sea at 0300 UTC on 12th October, 2015			
10	Extremely severe cyclonic storm CHAPALA over Arabian sea (28 October to 04 November, 2015)	28th Oct-2015, 0300 UTC over west central Arabian Sea (11.5/65.0).	Crossed Yemen coast to the southwest of Riyan (14.1/48.65) between 0100-0200 UTC of 3rd November, 2015	940 hPa at 0900 UTC 30th Oct, 2015 near (14.2/60.8)	115 knots at 0900 UTC 30th Oct, 2015 near	T 6.0
11	Extremely severe cyclonic storm MEGH over Arabian sea (05-10 November, 2015)	05th Nov., 2015, 0000 UTC over westcentral and adjoining southwest Arabian Sea (14.1/66.0)	Crossed Yemen coast (13.4/46.1) at 0900 UTC of 10th November, 2015	964 hPa at 0600 UTC 08th Nov., 2015 near (12.7/54.9)	95 knots at 0600 UTC 08th Nov., 2015	T 5.0
12	Deep Depression over Bay of Bengal (08-10 November, 2015)	08th Nov., 2015, 0300 UTC over southwest Bay of Bengal (10.7/83.7)	Crossed north Tamil Nadu coast close to Marakanam, north of Puducherry (12.2/80.0) at around 1400 UTC on 9th November, 2015	996 hPa at 0600 UTC 09th Nov., 2015 near (11.7/80.1)	30 knots at 1800 UTC 08th Nov., 2015	T 2.0

Table 2.3 Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2015

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.	ESCS										↔	↔	
7.	Land Dep.							↔ ↔	↔	↔			

↔ Peak intensity of the system

B) Life time of cyclonic disturbances during 2015 at different stages of intensity

S.No.	Type	Life Time in (Days)
1	D	20 days 03 hours
2.	DD	09 days 03 hours
3.	CS	07 days 12 hours
4.	SCS	01 days 03 hours
5.	VSCS	02 days 06 hours
6.	ESCS	04 days 09 hours
7	SuCS	-
	Total Life Time in(Days)	44 days 12 hours

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

CI No.≥	**.≥1.5**	**.≥2.0**	**.≥2.5**	**.≥3.0**	**.≥3.5**	**.≥4.0**	**.≥4.5**	**.≥5.0**	**≥5.5**	**≥6.0**
No of Disturbances	12	9	4	3	2	2	2	2	1	1

D) Basin-wise distribution of cyclonic distribution

Basin	Number of cyclonic disturbances
Bay of Bengal	3
Arabian Sea	5
Land depression	4

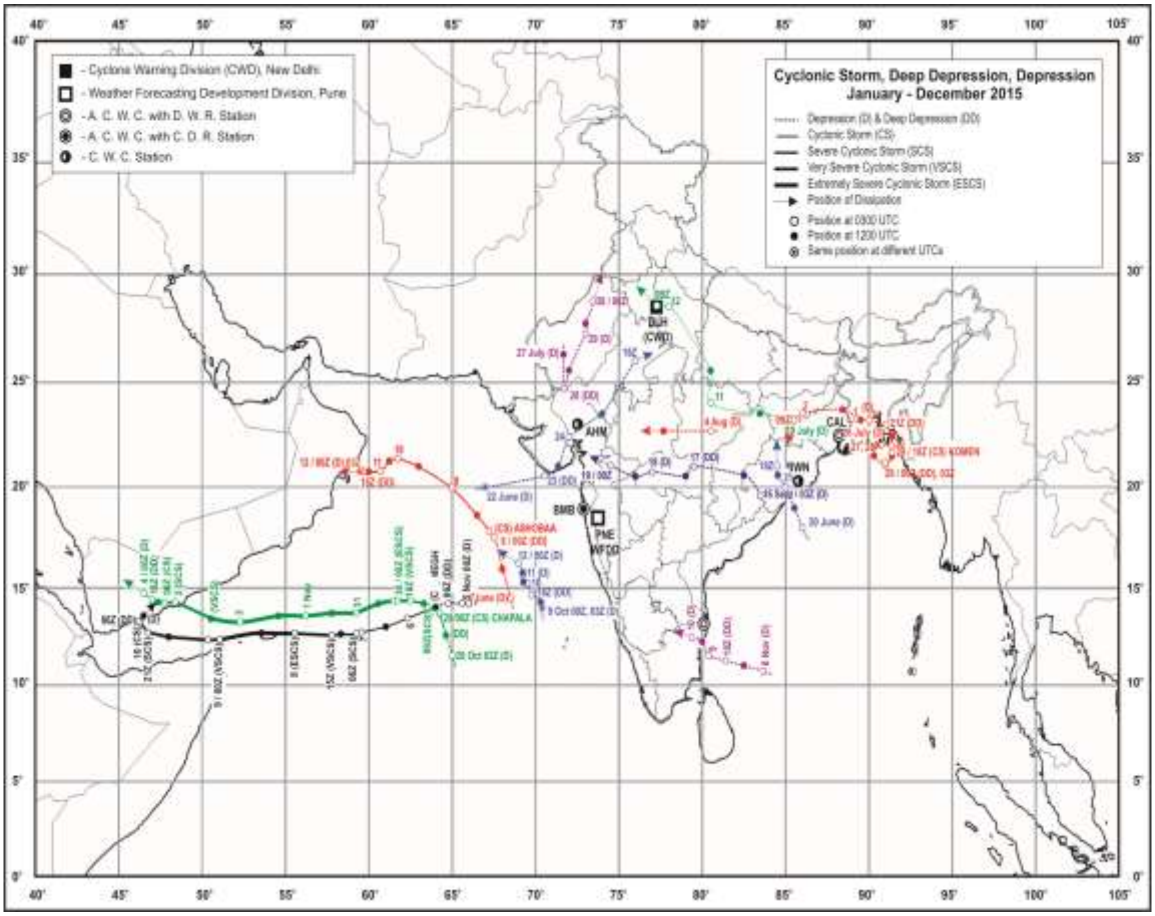


Fig. 2.1 Tracks of the cyclonic disturbances over the north Indian Ocean and adjoining land regions during the year, 2015

2.1 Cyclonic Storm, 'ASHOBAA' over the Arabian Sea(07-12 June 2015)

2.1.1 Introduction

The Cyclonic Storm 'ASHOBAA' (07-12 June 2015) developed over eastcentral Arabian Sea from monsoon onset vortex in the morning of 5th June 2015. It gradually moved northwards and became a low pressure area over southeast and adjoining eastcentral Arabian Sea in the morning of 6th June. It concentrated into a Depression (D) in the morning of the 7th June over eastcentral Arabian Sea. Moving nearly north-

northwestwards and it intensified into a Deep Depression (DD) in the early hours of 8th June over eastcentral Arabian Sea. It further intensified into the Cyclonic Storm (CS) 'ASHOBAA' in the morning of of 8th June. It gradually intensified till the night of 10th June. Thereafter, while moving west-southwestwards from forenoon of 10th June to morning of 11th June, it encountered high vertical wind shear and low ocean thermal energy and started weakening. It slowly moved westwards over a colder oceanic region and weakened into a deep depression in the night of 11th June. Due to adverse environmental conditions, interaction with land surface and dry air intrusion from western side, it further weakened into a depression in the morning of 12th June and into a well marked low pressure area over northwest Arabian Sea and adjoining Oman coast in the evening of 12th June.

The salient features of this system are as follows.

i. CS 'ASHOBAA' developed over eastcentral Arabian Sea during the onset phase of monsoon.
ii. It had a unique track, as it moved initially northwards, then north-northwestwards and finally west-southwestwards towards Oman coast.
iii. It dissipated over northwest Arabian Sea off Oman coast before landfall.
iv. The NWP and dynamical statistical models provided reasonable guidance with respect to its genesis, track and intensity, though there was large divergence in model guidance with respect to track, intensity and landfall.

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.

2.1.2 Monitoring of CS ASHOBAA

The CS 'ASHOBAA' was monitored & predicted continuously since its inception by the IMD. The forecast of its genesis on 7th June, its track, intensity, point & time of landfall were predicted with sufficient lead time.

At the genesis stage, the system was monitored mainly with satellite observations, supported by meteorological buoys and coastal and island observations. Various national and international NWP models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models, dynamical statistical models for genesis and intensity were utilized to predict the genesis, track and intensity of the storm. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation.

2.1.3 Brief life history

2.1.3.1 Genesis

The CS 'ASHOBAA' (07-12 June 2015) developed over eastcentral Arabian Sea from monsoon onset vortex. In association with the southwest monsoon onset over Kerala, a cyclonic circulation in lower levels developed over southeast Arabian Sea on 5th June. It gradually moved northwards and concentrated into a low pressure area over southeast and adjoining eastcentral Arabian Sea on 6th morning. As per satellite imagery, broken low and medium clouds with embedded intense to very intense convection lay over Arabian Sea between latitude 9.0˚N & 19.0˚N and longitude 61.0˚E & 74.0˚E in association with the system. The convective clouds remained fragmented in the embedded broad scale cyclonic circulation. The lowest cloud top tempereature was -70˚C. The buoy and Ascat observations suggested the associated maximum sustained surface winds of about 10-20 kts. Estimated central pressure was about 1005 hPa. The sea surface temperature was 29-30˚C, ocean thermal energy was about 80-100 KJ/cm^2, low level convergence was (10-15)$x10^{-5}$ s^{-1}, upper level divergence was about (10-20)$x10^{-5}$ s^{-1}, the low level relative vorticity was about (5-10)$x10^{-5}$ s^{-1}, vertcal wind shear was low to moderate(10-20 knots). Upper tropospheric ridge lay along 20˚N and middle tropospheric ridge was near about 16˚N. There was trough in westerlies in middle troposphere to the west of the system. Under these conditions, the low pressure area moved slowly northwards/north-northwestwards and concentrated into a depression over eastcentral Arabian Sea and lay centred at 0300 UTC of 7th June near 14.5^0N/68.5^0E about 700 km southwest of Mumbai. The intensity of the system as per the Dvorak's technique was T1.5. Intense to very intense convection lay over the area between 6.0^0N & 19.5^0N and longitude 63.0^0E & 74.0^0E. Lowest CTT was -70^0C.

2.1.3.2 Intensification and Movement

On 7th June, as the depression lay over eastcentral Arabian Sea, it experienced the ocean thermal energy of about 100-120 KJ/cm^2 with SST of $30\text{-}32^0$C. Compared to previous day, the low level convergence, upper level divergence and low level relative vorticity increased and were about 15-20x $10^{-5}s^{-1}$, 20-30 x $10^{-5}s^{-1}$ and 10-20 x $10^{-5}s^{-1}$ respectively. The vertical wind shear was moderate (10-20 kts). The Madden Julian lay over Phase-2 with amplitude>1. All these environmental and large scale features were favourable for the intensification of the system. The upper tropospheric ridge at 200 hPa level ran along 20^0N. However, there was a trough in westerlies in the middle troposphere to the west of the system. As a result, though the system was far south of upper tropospheric ridge (5.5^0), its westward component was restricted and the system moved nearly north-northwestwards and intensified into a deep depression at 0000 UTC of 8th June over eastcentral Arabian Sea near 17.5^0N/67.5^0E about 600 km west-southwest of Mumbai. It further intensified into the cyclonic storm (CS) 'ASHOBAA' at 0300 UTC of 8th June near 17.9^0N/67.2^0E. As per

Dvorak's technique, the intensity was T2.5 and maximum sustained wind (MSW) was 35 Kts. It continued to move north-northwestwards till 0900 UTC of 8th June and then moved northwestwards till 0600 UTC of 9th June. Thereafter, it moved west-northwestwards till 0600 UTC of 10th June and then west-southwestwards till 0000 UTC of 11th June. Finally, it moved westwards on 11th and 12th June. The maximum intensity of T3.0 (45Kts) was maintained till 2100 UTC of 10th June. From the night of 10th June, the lower level convergence, divergence and relative vorticity decreased slightly. The vertical wind shear was moderate near the system centre and was high to the south. As the system moved west-southwestwards from 0600 UTC of 10th June to 0000 UTC of 11th June, it encountered the high vertical wind shear. Further, the ocean thermal energy was less than 50 KJ/cm^2 near the system centre. As a result the intensity of CS'ASHOBAA' decreased from T3.0 (45Kts) at 2100 UTC of 10th June to T2.5 (35Kts) at 0600 UTC of 11th June. On 11th June, as the system moved very slowly westwards over a colder oceanic region, alongwith the adverse environmental conditions like moderate to high vertical wind shear, interaction with land surface and dry air intrusion from western side, it further weakened into a deep depression at 1800 UTC of 11th June near 20.8^0N/59.7^0E. It further weakened into a depression at 0000UTC of 12th June near 20.8^0N/59.5^0E and into a well marked low pressure area over northwest Arabian Sea and adjoining Oman coast at 1200 UTC of 12th June. The system moved west-northwestwards on 9th June as the trough in the middle latitude westerlies moved away eastwards. During 10th to 12th June, the upper tropospheric ridge at 200 hPa level ran along $22\text{-}24^0$ N with an anticyclone located to the northeast of the system centre and another to the northwest. While the anticyclonic circulation in the northeast influenced the system to move northwestwards, the anticyclonic circulation in the northwest tried to restrict movement towards north and rather pushed the system towards southwest. As a result, the system moved slowly westwards during 10-12th June. The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.1.1.

Table 2.1.1 Best track positions and other parameters of the Cyclonic Storm, 'ASHOBAA' over the Arabian Sea during 07-12 June, 2015

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
07/06/2015	0300	14.5/68.5	1.5	1004	25	3	D
	0600	15.0/68.2	1.5	1004	25	3	D
	1200	16.0/68.0	1.5	1003	25	4	D
	1800	16.5/68.0	1.5	1003	25	4	D
08/06/2015	0000	17.5/67.5	2.0	996	30	5	DD

	0300	17.9/67.2	2.5	994	35	7	CS
	0600	17.9/67.2	2.5	994	35	7	CS
	0900	18.5/66.7	2.5	994	35	7	CS
	1200	18.6/66.5	2.5	994	35	7	CS
	1500	18.8/66.2	2.5	994	35	7	CS
	1800	19.2/65.7	2.5	994	35	7	CS
	2100	19.5/65.3	2.5	994	35	7	CS
09/06/2015	0000	20.0/65.0	2.5	992	35	8	CS
	0300	20.0/65.0	2.5	992	35	8	CS
	0600	20.3/64.6	2.5	990	35	10	CS
	0900	20.5/63.8	3.0	990	40	10	CS
	1200	21.0/63.0	3.0	990	40	10	CS
	1500	21.2/62.5	3.0	990	40	10	CS
	1800	21.2/62.5	3.0	990	45	10	CS
	2100	21.3/62.3	3.0	990	45	10	CS
10/06/2015	0000	21.3/62.1	3.0	990	45	10	CS
	0300	21.3/61.8	3.0	990	45	10	CS
	0600	21.3/61.5	3.0	990	45	10	CS
	0900	21.2/61.1	3.0	990	45	10	CS
	1200	21.2/61.1	3.0	990	45	10	CS
	1500	20.9/60.8	3.0	990	45	10	CS
	1800	20.9/60.8	3.0	992	45	10	CS
	2100	20.9/60.8	3.0	992	45	10	CS
11/06/2015	0000	20.8/60.8	2.5	994	40	10	CS
	0300	20.8/60.8	2.5	994	40	10	CS
	0600	20.8/60.5	2.5	994	35	10	CS
	0900	20.8/60.3	2.5	994	35	10	CS
	1200	20.8/60.0	2.5	994	35	10	CS
	1500	20.8/59.7	2.5	994	35	10	CS
	1800	20.8/59.7	2.0	996	30	6	DD
12/06/2015	0000	20.8/59.5	1.5	996	25	4	D
	0300	20.8/59.5	1.5	996	25	4	D
	0600	20.8/59.5	1.5	996	25	4	D
	1200	Well marked low pressure area over northwest Arabian Sea and adjoining Oman coast					

2.1.4 Features observed through satellite

Satellite monitoring of the cyclone was mainly done by using half hourly Kalpana-1, INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 and MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical satellite INSAT-3D imageries of CS ASHOBAA representing the life cycle of the cyclone are shown in Fig. 2.1.1(a&b). IMD-GFS analysis of mean sea level (MSLP) and wind at 10m, 850 hPa, 500 hPa & 200 hPa levels are shown in Fig. 2.1.2 (a-f)

Intensity estimation using Dvorak's technique suggested that the system attained an intensity of T 1.5 on 07th June 2015 / 0300 UTC. Associated broken low and medium clouds embedded with intense to very intense convection was seen over the area between 6.0^0 N & 19.5^0 N latitudes and 63.0^0 E & 74.0^0 E longitudes and convection was seen over $13\text{-}21^0$N and $61\text{-}69^0$E. The lowest CTT was about -93^0 C. On 9th / 0900 UTC, the system intensified to T 3.0. It showed curved band pattern and covered Lakshadweep. The lowest CTT was about -70^0C. At 1200 UTC of 7th, the system intensity was T1.5 and associated broken low and medium clouds embedded with intense to very intense convection was seen over the area between latitude 6.0^0 N & 21.5^0 N, longitude 60.0^0 E & 74.0^0 E, coastal Karnataka, extreme north Kerala and Lakshadweep. The lowest CTT was about -90^0 C. At 0000 UTC of 8th, the system attained intensity of T2.0 corresponding to deep depression and at 0300 UTC of 08th, the intensity was T 2.5 corresponding to cyclonic storm. Intense to very intense 0.6 of 10 degree log spiral. Intense to very intense convection was seen over $17.0\text{-}22.0^0$ N and to the west of 66.0^0 E. The system continued to show curved band pattern until 10th /0000 UTC and the lowest CTT was about -92^0 C. At 1200 UTC of 10th, the system maintained the intensity of T 3.0 and convection showed central dense overcast pattern. However, a slight decrease in the compactness of the system was observed at 1800 UTC of 10th, convection showed sign of disorganisation and the lowest CTT was -73^0 C. On 11th / 0000 UTC, the intensity of the system decreased to T 2.5. Convection was disorganised and the major convective clouds were observed in the southern sector. Areas of intense convection were over $18.5\text{-}22^0$ N and to the west of 62.5^0 E. At 0600 UTC of 11th, the major convective clouds were observed in the southern sector was elongated from northeast to southwest direction. At 1800 UTC of 11th, the intensity of the system further decreased to T 2.0. Areas of intense to very intense convection were between $18\text{-}24^0$ N and to the west of 62.5^0 E and Oman. The lowest CTT was -64^0 C. On 12th / 0000 UTC, the intensity of the system became T 1.5. Convection was disorganised with convective clouds sheared to the southwest of the system centre. Moderate to intense convection was seen over $18\text{-}23.5^0$ N and the west of 61.5^0 E and Oman. Enhanced IR imageries depicting the growth of the system to T 1.5, T 2.0, T 2.5, T 3.0 and its weakening to T 2.5, T 2.0 and T 1.5 are presented in Fig.3. The system further weakened with intensity becoming T1.0 at 1200 UTC of 12th June 2015 corresponding to a well marked low pressure area. It moved over Oman on 13th June as a low level cyclonic circulation.

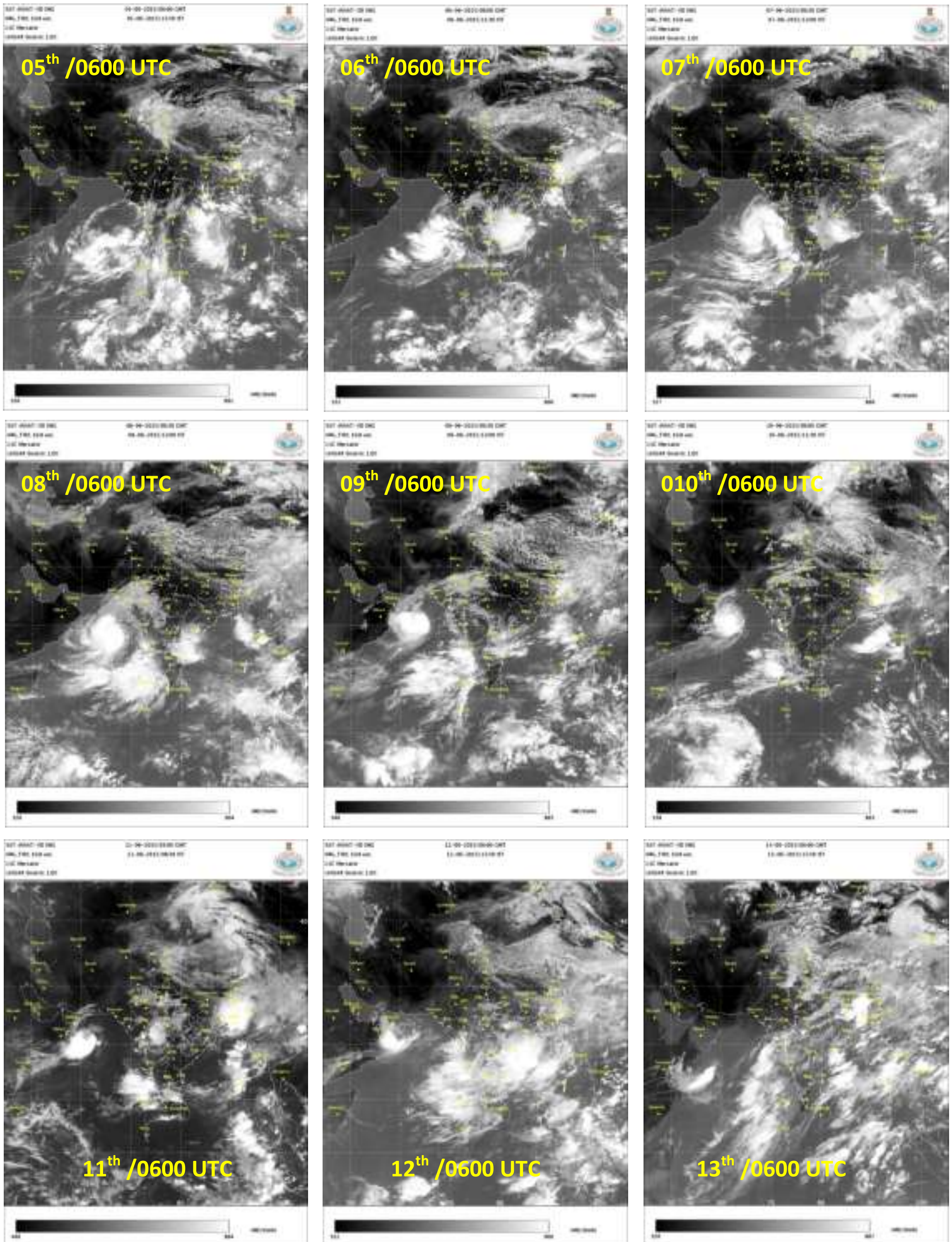


Fig.2.1.1(a) INSAT-3D IR imageries based on 0600 UTC of 05-13 June

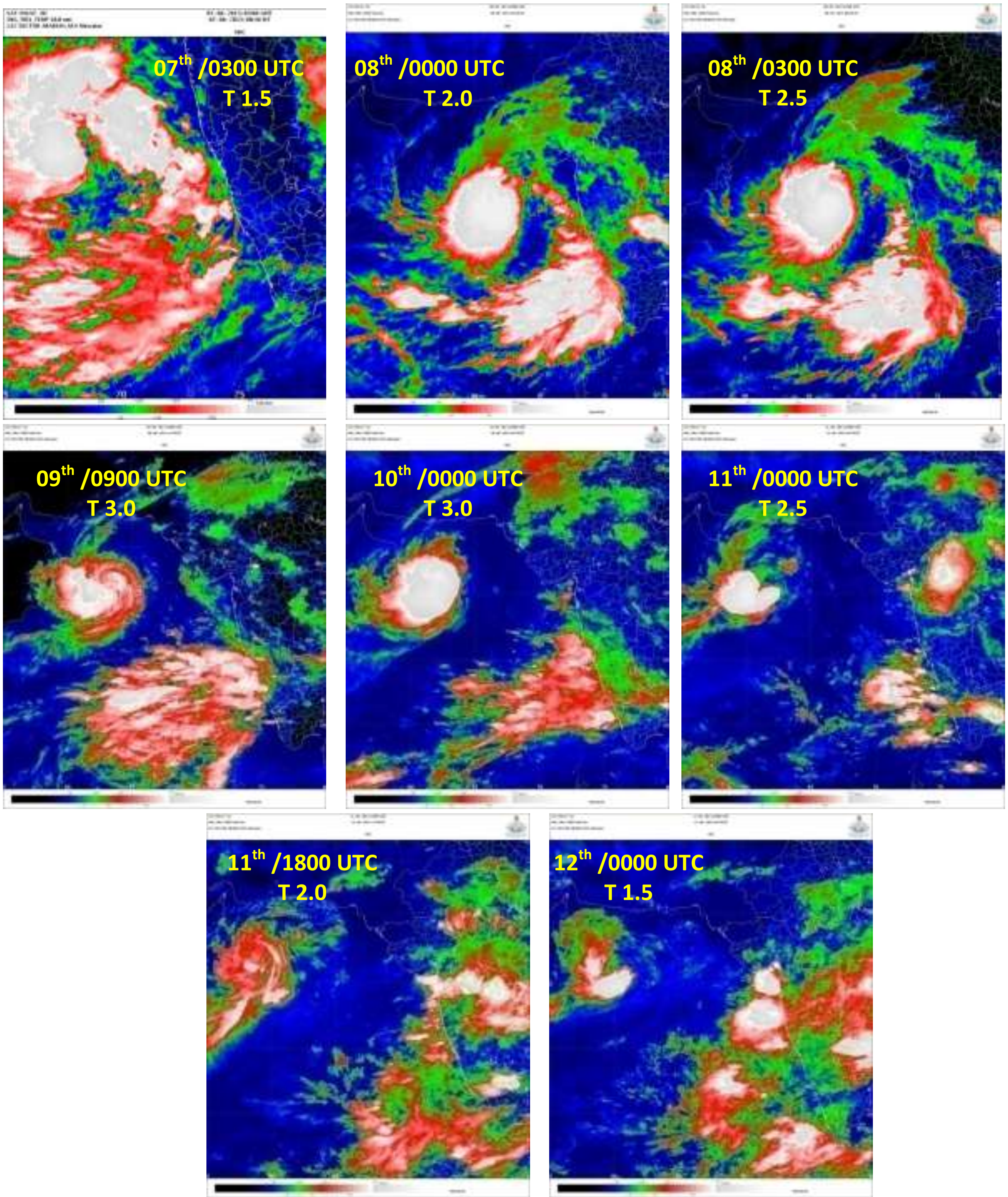


Fig.2.1.1(b) INSAT-3D IR imageries based on 07/0300, 08/0000, 08/0300, 09/0900, 10/0000, 11/0000, 11/1800 and 12/0000 UTC of June 2015

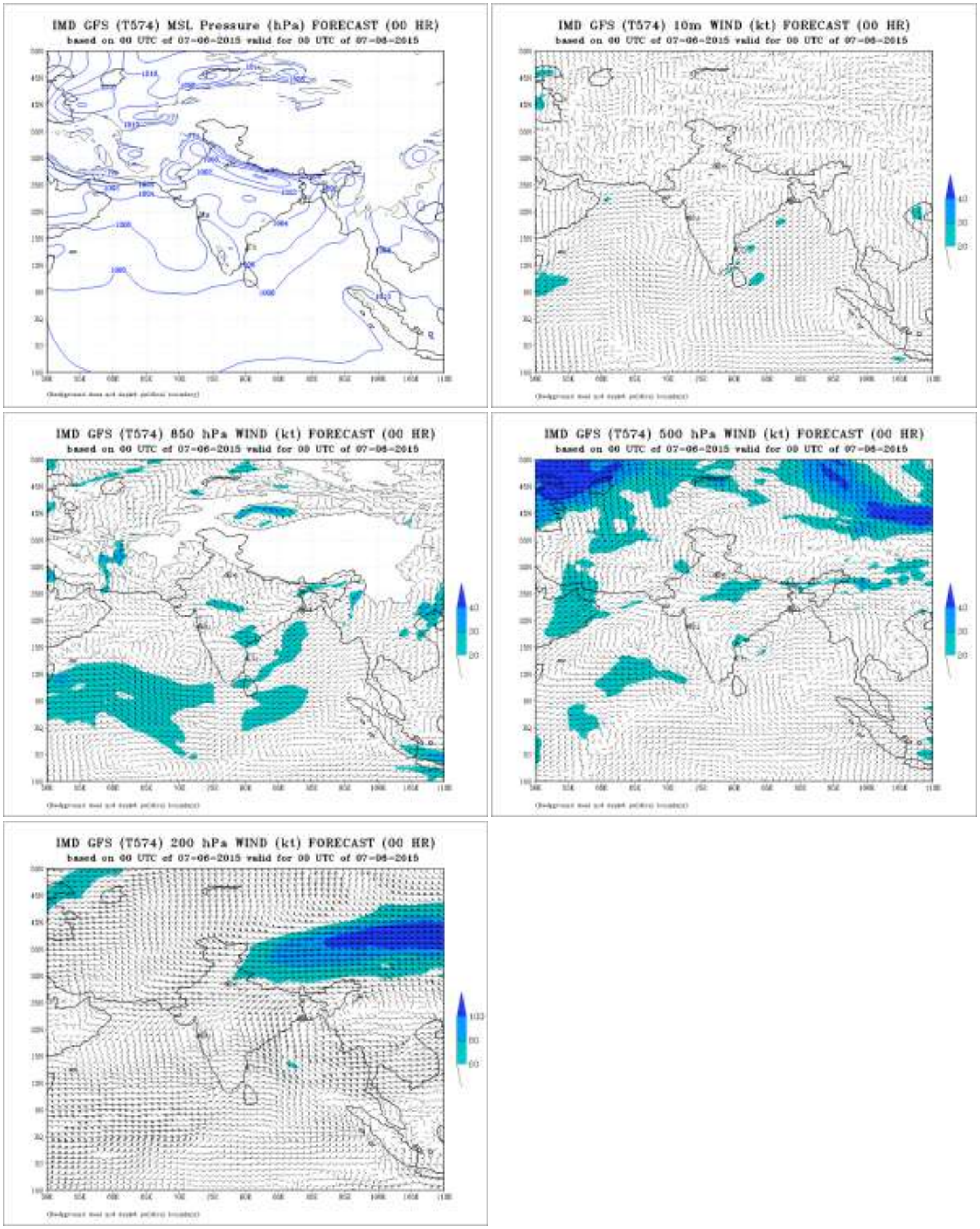


Fig.2.1.2(a) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 7th June 2015

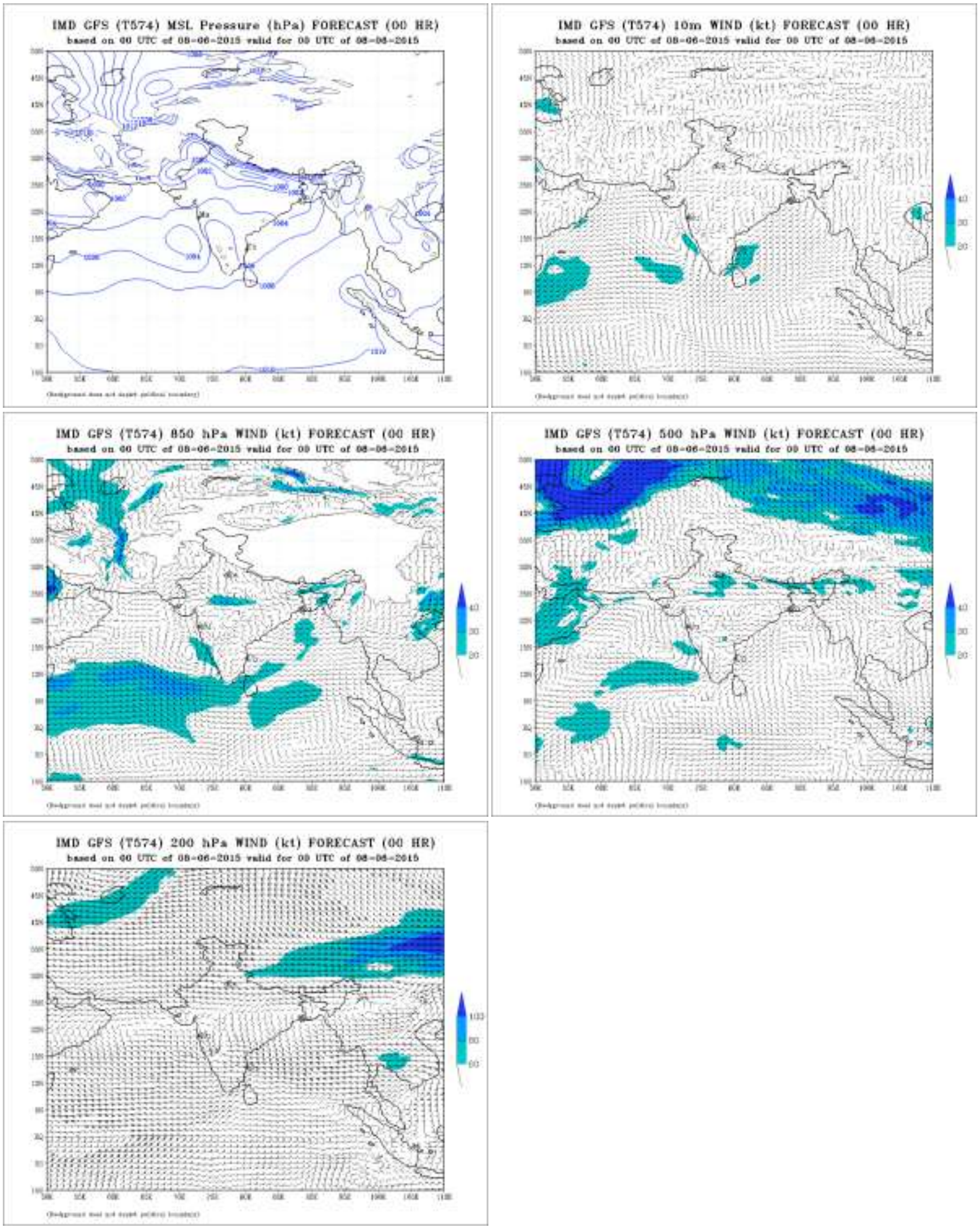


Fig.2.1.2(b) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 8th June 2015

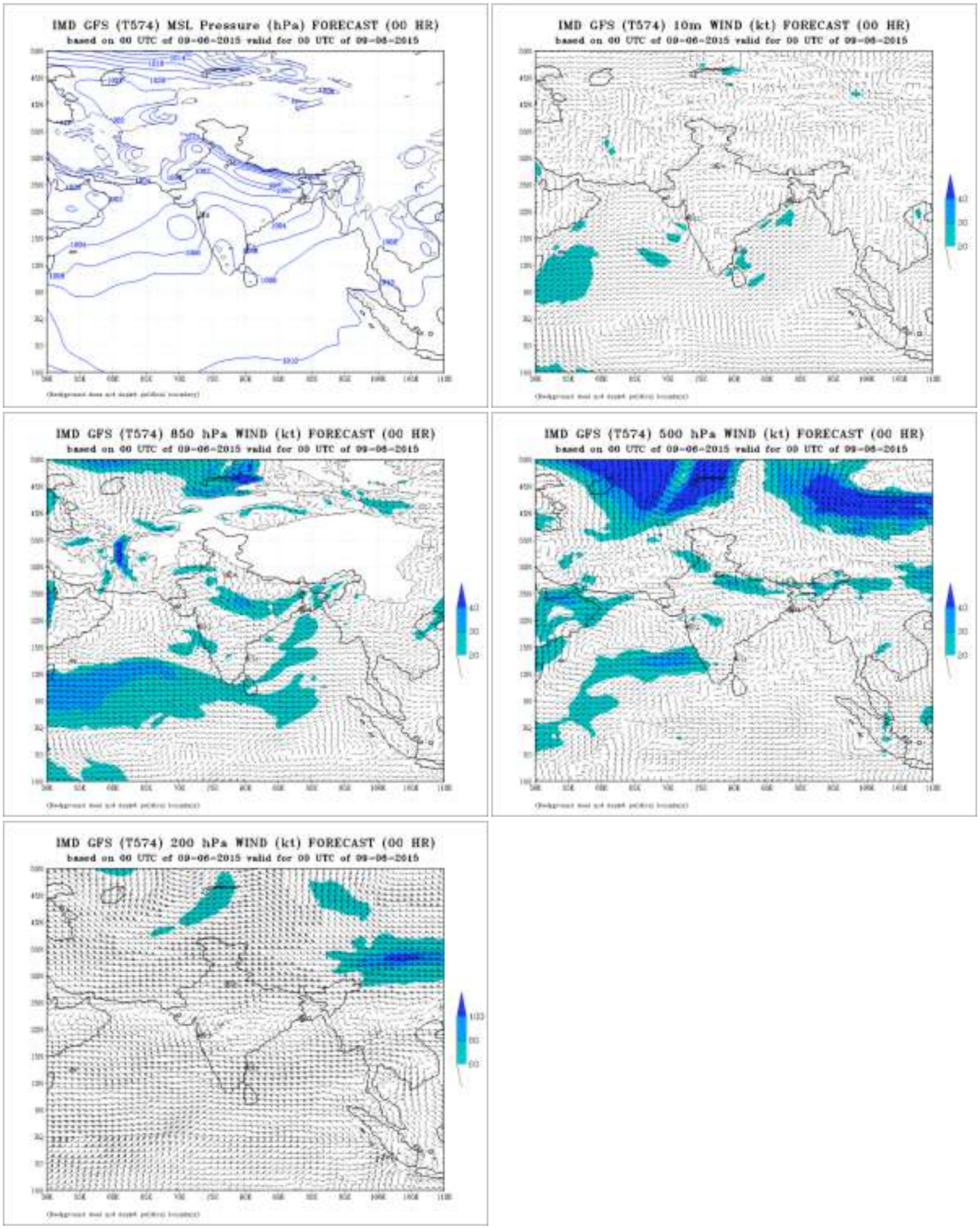


Fig.2.1.2(c) IMD GFS MSLP, 10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 9th June 2015

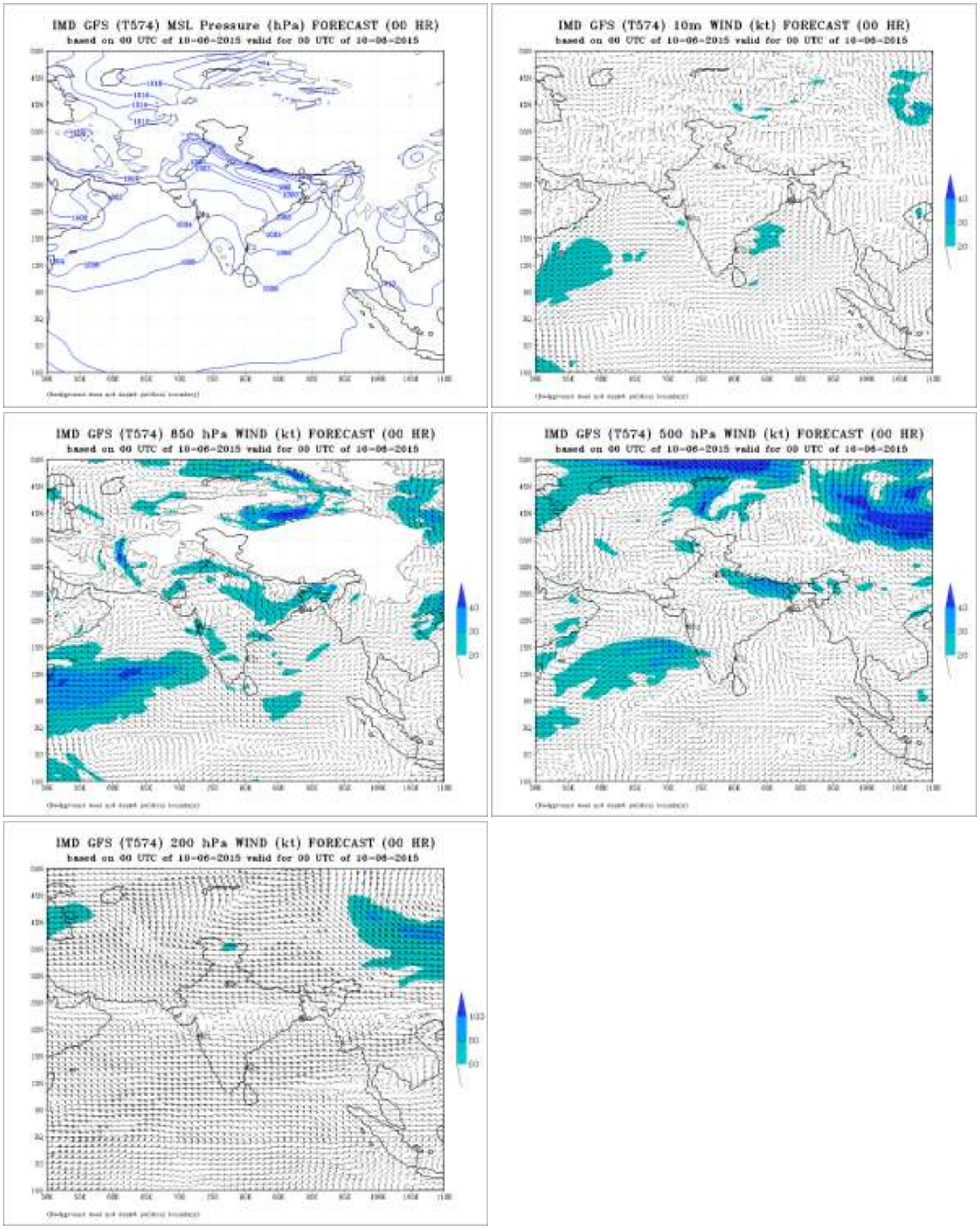


Fig.2.1.2(d) IMD GFS MSLP, 10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 10th June 2015

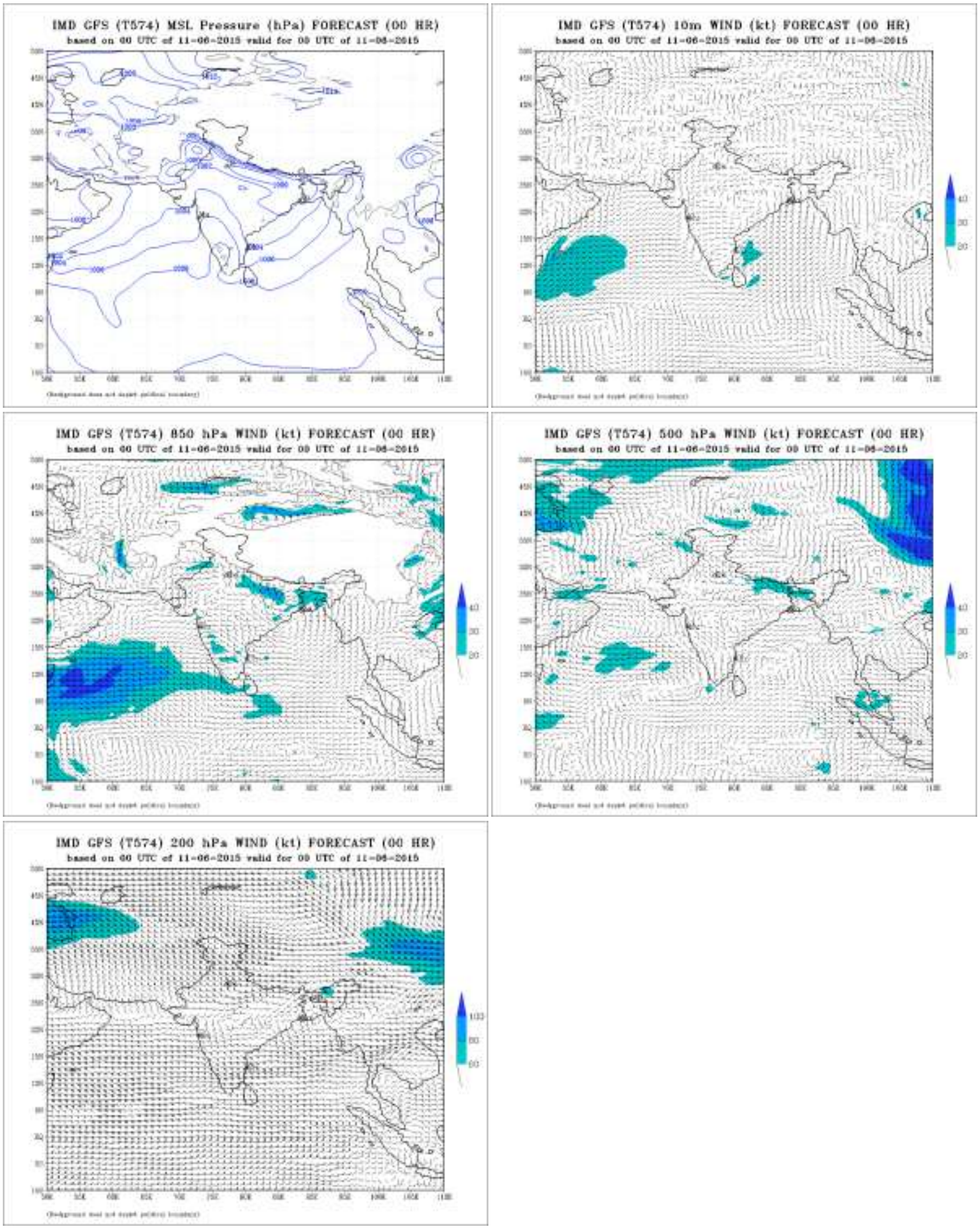


Fig.2.1.2(e) IMD GFS MSLP, 10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 11th June 2015

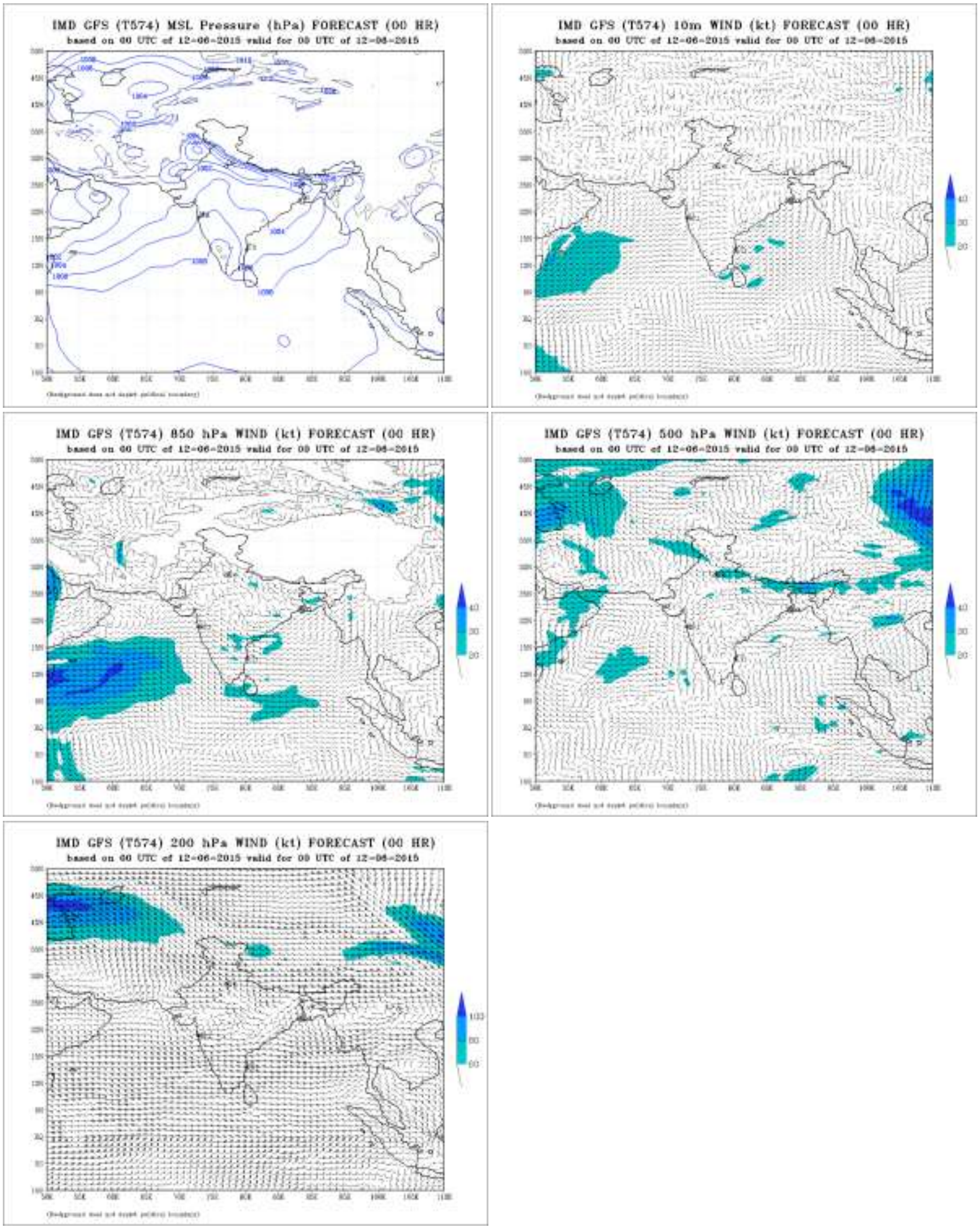


Fig.2.1.2(f) IMD GFS MSLP, 10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 12th June 2015

2.2 Depression over northwest and adjoining west central Bay of Bengal (20– 22 Jun 2015)

2.2.1 Introduction

A Depression formed over northwest Bay of Bengal on 20th June morning & crossed Odisha coast between Gopalpur and Puri in the early hours of 21st June 2015. It moved north-westwards across Odisha on 21.06.2015 and weakened into a well marked low pressure area on 22.06.2015 over interior Odisha & adjoining Jharkhand and Chattisgarh. It caused good rainfall activity over central & adjoining north India as well as peninsular India. It also helped in advancing southwest monsoon over central & east India.

2.2.2 Brief life history

2.2.2.1 Genesis

A cyclonic circulation between 4.5 & 5.8 kms a.s.l. formed over west central Bay of Bengal off south Odisha - north Andhra Pradesh coasts on 16th. Under its influence, a low pressure area formed over westcentral Bay of Bengal off Andhra Pradesh coast on 17th June 2015. It gradually moved northwards and became well marked low pressure area over westcentral and adjoining northwest Bay of Bengal off north Andhra Pradesh and south Odisha coast on 19th morning. It concentrated into a depression over northwest and adjoining west central Bay of Bengal and lay centred near Lat. 18.0°N / Long. 86.0°E, about 200 kms south of Puri at 0300 UTC of 20th

The genesis occurred under the favourable conditions like lower level convergence, upper level divergence and increase in relative vorticity at lower levels.

2.2.2.2 Intensification and movement

As the depression lay close to the coast and vertical wind shear being high, it did not intensify further. The upper tropospheric ridge ran along 24°N and the upper tropospheric winds were southeasterly. As a result, the depression moved northwestwards and lay centred near Lat. 18.5°N / Long. 85.5°E, about 150 kms south-southwest of Puri at 1200 UTC of 20th. It continued to move northwestwards and crossed Odisha coast between Gopalpur and Puri around 0100 UTC of 21st and lay over coastal Odisha, centred near Lat. 20.0°N / Long. 85.0°E, about 90 kms southeast of Phulbani at 0300 UTC of 21st. It moved slightly northwestwards and lay centered over interior Odisha, near Lat. 20.5°N / Long. 84.5°E, about 110 kms southeast of Sambalpur at 1200 UTC of 21st. Further moving northwestwards, it weakened into a well marked low pressure area in the morning hours of 22nd and lay over Odisha and adjoining areas of Jharkhand & Chhattisgarh

The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.2.1.The typical satellite imageries are shown in Fig. 2.2.1. IMD GFS analysis of mean sea level pressure (MSLP) and wind at 10metre, 850 hpa, 500 hpa and 200 hpa levels are shown in Fig. 2.2.2(a-c).

Table 2.2.1 Best track positions and other parameters of the Depression over the Bay of Bengal during 20-22 June, 2015

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
20/06/2015	0300	18.0/86.0	1.5	990	25	4	D
	0600	18.5/86.0	1.5	990	25	4	D
	1200	19.0/85.5	1.5	990	25	4	D
	1800	19.2/85.4	1.5	990	25	4	D
	The system crossed Odisha coast between Gopalpur and Puri during 2000-2100 UTC						
21/06/2015	0000	19.7/85.0	-	992	25	3	D
	0300	20.0/85.0	-	992	25	3	D
	0600	20.0/84.5		992	25	3	D
	1200	20.5/84.5	-	992	25	3	D
	1800	21.0/84.5	-	992	25	3	D
22/06/2015	0000	The system weakened into a well-marked low pressure area over interior Odisha and adjoining Jharkhand and Chhattisgarh at 0000 UTC					

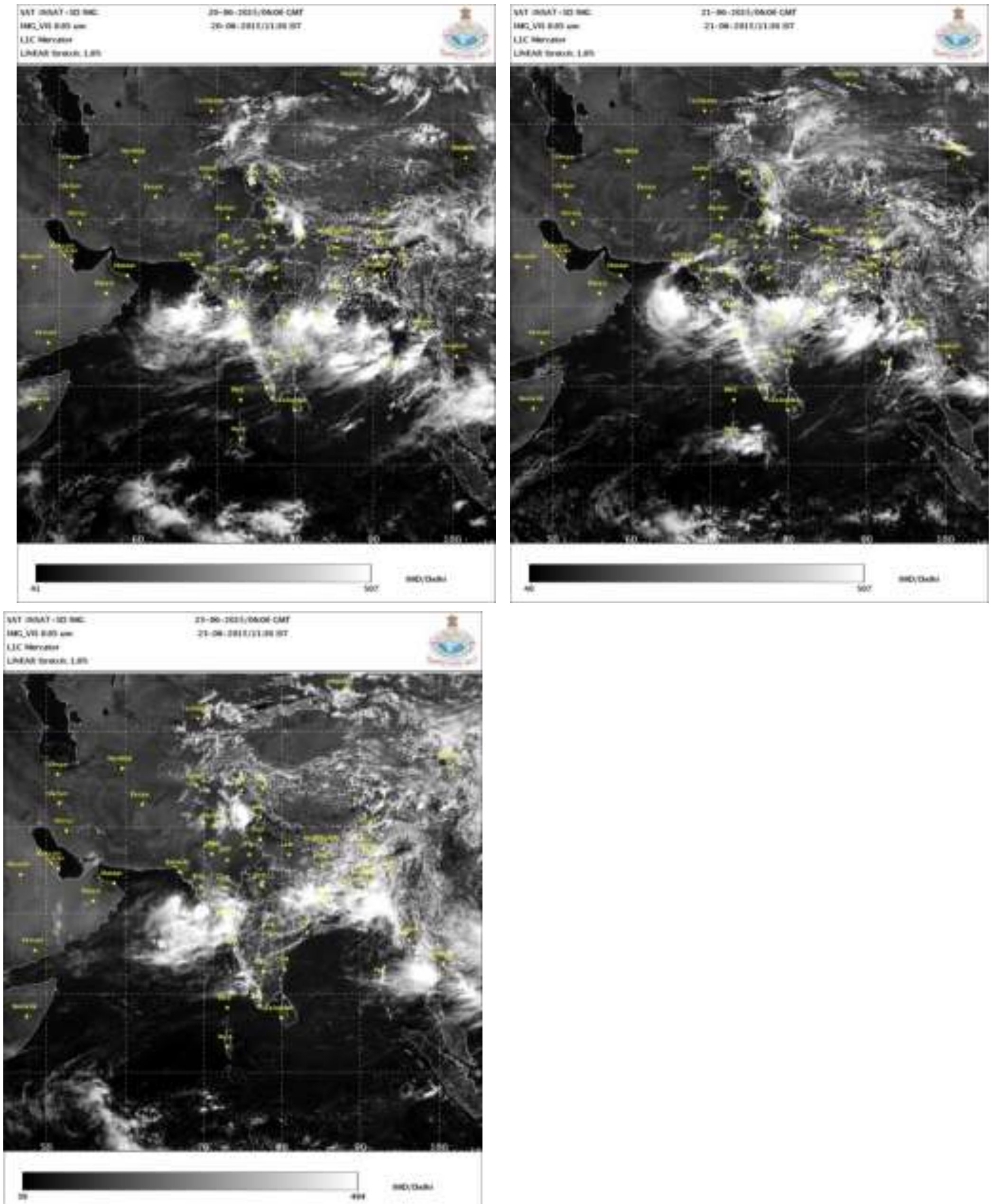


Fig.2.2.1 Typical INSAT 3D imageries of depression at 0600 UTC during 20-22 June, 2015

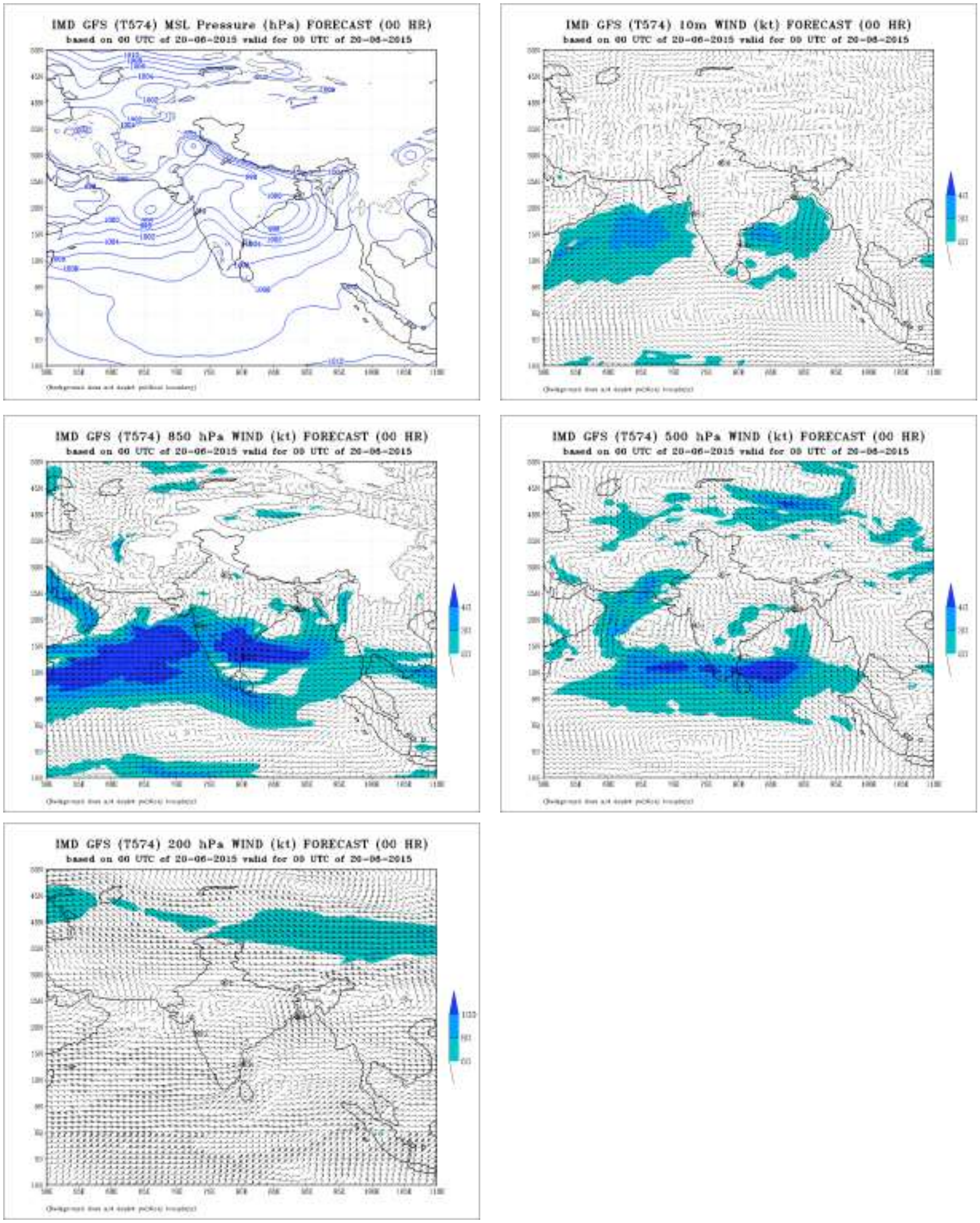


Fig.2.2.2(a) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 20th June 2015

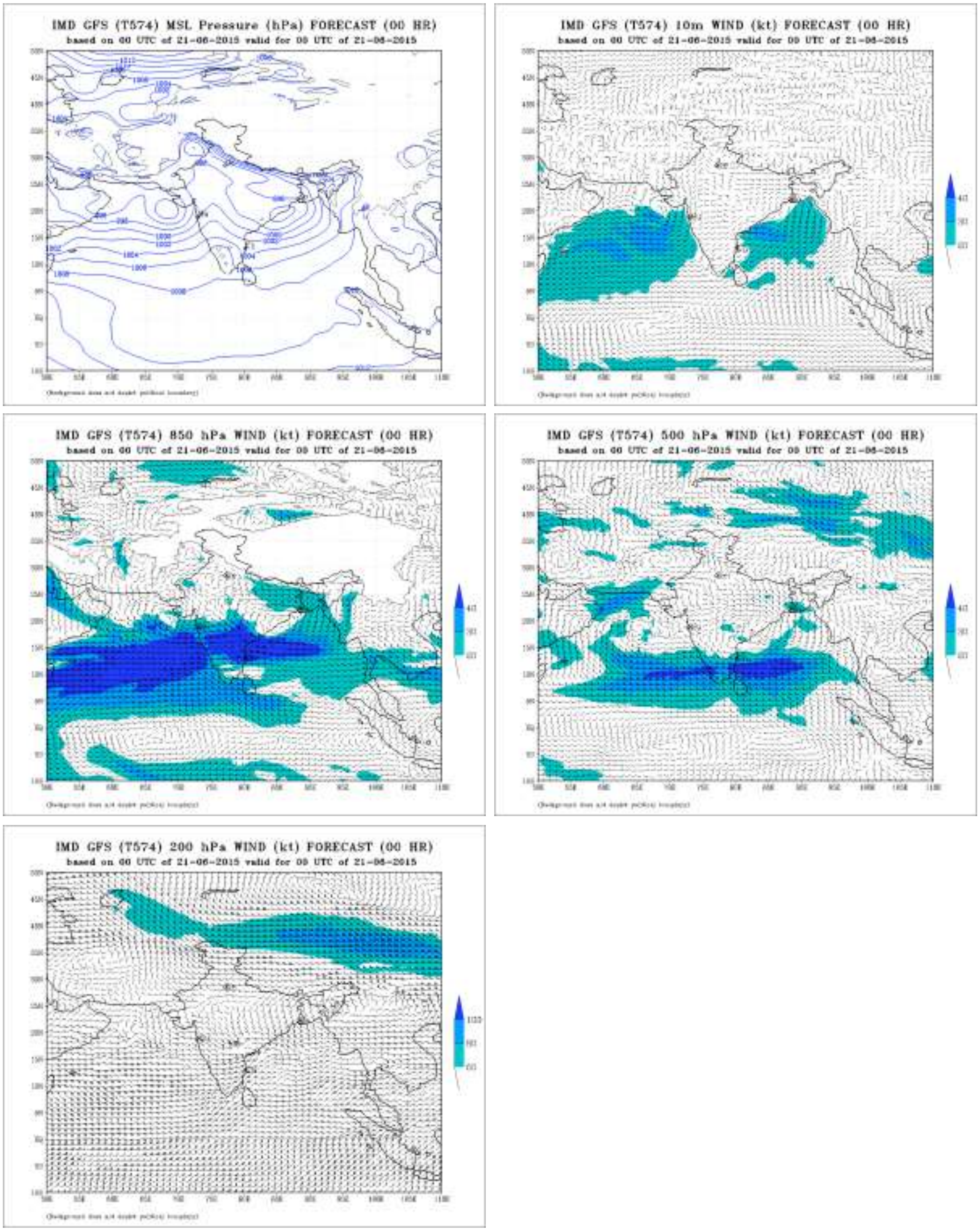


Fig. 2.2.2 (b) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 21th June 2015

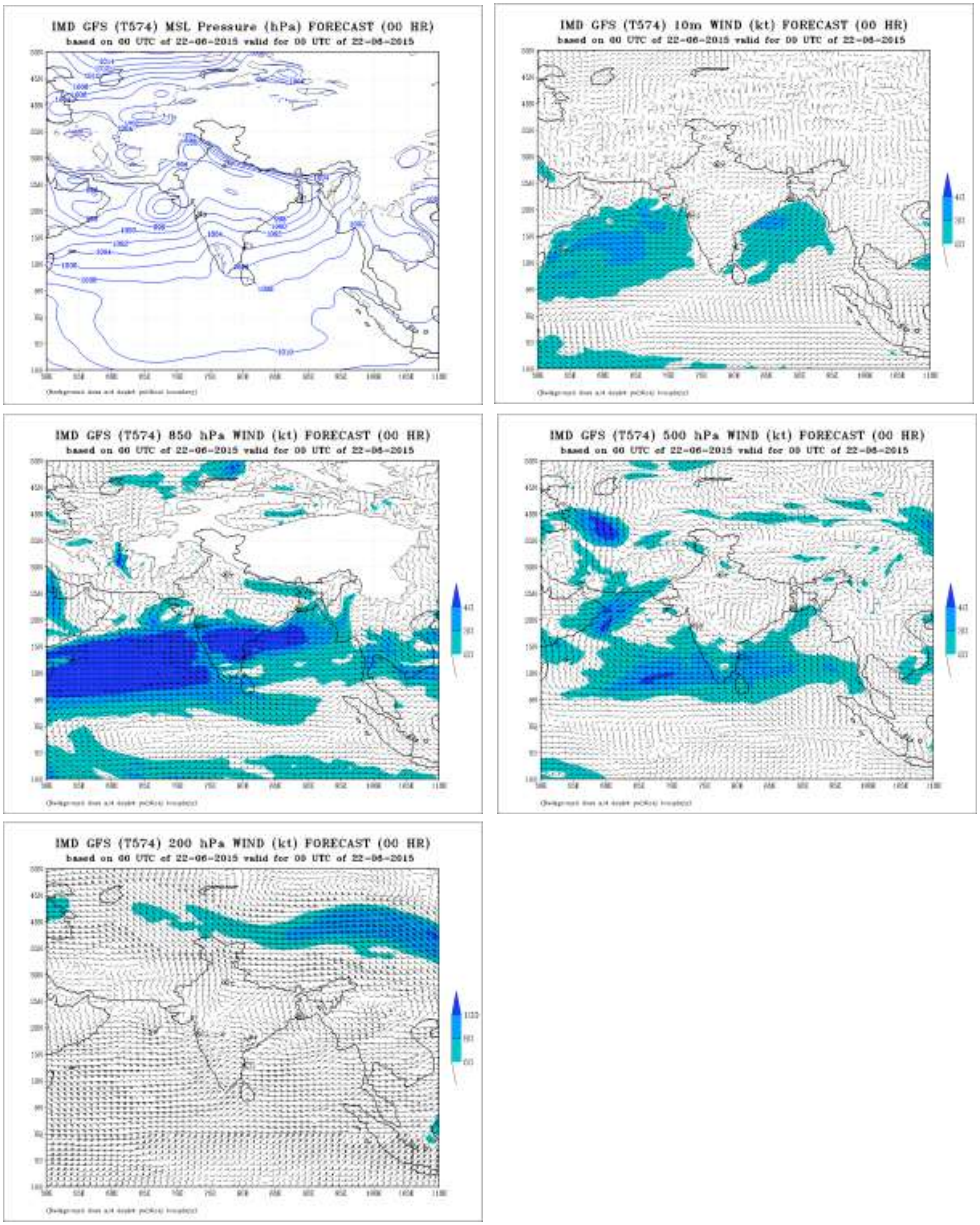


Fig. 2.2.2 (c) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 22nd June 2015

2.2.3 Realized Weather:

The cumulative 24-hour rainfall (>=7cm) ending at 0300 UTC of 21st to 24th June 2015 in association with the system are given below:

21 JUN 2015:

ODISHA: Nawarangpur & Malkangiri-21 each, R.Udaigiri-16, Junagarh, Jeypore, Dharmagarh Arg, Mahendragarh & Gudari-13 each, Gopalpur & Jaipatna-11 each, Digapahandi Arg, Mohana, Bissem-Cuttack & Madhabarida-10 each, Nuagada Arg, Chhatrapur & Berhampur-9 each, Purushottampur, Aska, Kashipur & Koraput-8 each.

CHHATTISGARH: Jagdalpur-15, Narayanpur-10, Deobhog-9, Bhanupratappur-7.

COASTAL ANDHRA PRADESH: Ichchapuram-20, Sompeta-12, Kalingapatnam-11, Mandasa, Cheepurupalle, Garividi & Ranastalam-9 each and Palasa-8.

TELANGANA: Eturnagaram & Shayampet-18 each, Khanapur, Parkal, Gundala & Gudur-17 each, Venkatapuram & Venkatapur-16 each, Chennaraopet,Govindaraopet, Kaleswaram, Mulakalapalle, Mulugu(Arg), Atmakur, Yellandu and Narsampet-15 each, Mogullapalle & Palawancha-14 each, Pinapaka, Bhupalpalle & Mahabubabad-13 each, Manuguru & Nallabelly-12 each, Adilabad, Bayyaram, Tekulapalle, Dummugudem & Chennur each , Kothagudem, Hasanparthy, Julurpad, Huzurabad, Sultanabad and Chandrugonda-10 each, Hanamkonda, Aswapuram, Manthani, Enkuru, Dornakal and Garla-9 each, Karimnagar, Koida, Parvathagiri, Dharmasagar, Julapalle, Sirpur (T), Ramgundam, Pegadapalle & Bheemadevarpalle-8 each, Burgampadu, Boath, Dharmapuri, Utnur, Thollada, Asifabad-7 each.

VIDARBHA: Chandrapur-20, Etapalli-19, Ahiri-16, Sironcha-15, Korpana-14, Mulchera-13, Chamorshi-12, Ashti-11, Joiti-11, Pandherikawara-9, Gadchiroli-9, Wani-7, Gondpipri-7, Chimur-7, Hinganghat-7, Bhadravati-7, Kuhi-7

22 JUN 2015

COASTAL ANDHRA PRADESH: Nil

ODISHA: Rairakhol-23, Dunguripalli-15, Birmaharajpur Arg-13, Loisingha Arg, Salebhatta Arg and Jujumura Arg-11 each, Khairamal, Sorada, Ullunda Arg, Patnagarh, Daspalla and Tarva Arg-10 each, Binika, Rajkishorenagar, Nawana, Komna and Nuagada Arg-9 each, Madhabarida & Bhanjnagar-8 each and Odagaon Arg & Korei Arg-7 each.

TELANGANA: Utnur-9, Adilabad & Sirpur-8 each

JHARKHAND: Raidih-8, Palkot-7,

VIDARBHA: Kurkheda-18, Sironcha-14, Nagpur Aerodrome, Joiti & Dhanora-11 each, Mulchera, Chamorshi, Ahiri & Bhadravati-10 each, Gadchiroli & Ballarpur-9 each, Saoli, Aheri (Arg), Darwha, Ramtek & Pandherikawara-8 each and Korpana, Chimur, Rajura, Sindewahi, Desaiganj, Gondpipri, Mul, Narkheda, Chandrapur, Manora & Karanjalad-7 each.

CHHATTISGARH: Bhanupratappur-16, Sarangarh-15, Kanker-13, Raipur-11, Mahasamund, Saraipali & Mana-Raipur-Ap-10 each, Rajnandgaon-9, Bemetara-8, Dondilohara & Kawardha-7 each.

23.06.2015:

JHARKHAND: Amrapara-11, Jarmindi-11, Moharo, Panchet, Maithon, Goregaon, Bhandara, Sakoli & Amgaon -8 each, Raidih-7

VIDARBHA: Mohadi-11, Kalmeshwar-10, Sakoli (Arg), Hingna, Korchi, Mauda, Perseoni & Salekasa-7 each.

CHHATTISGARH: Sarangarh-11, Bilaspur, Rajnandgaon & Saraipali-8 each, Mahasamund & Dongargarh-7 each.

ODISHA: Hirakud-10, Kuchinda & Ambabhona-9 each, Sambalpur & Burla Arg-8 each, Bhawanipatna, Pallahara & Atabira Arg-7 each.

24.06.2015:

JHARKHAND: Maheshpur-10, Amrapara-9, Chakradharpur-8

ODISHA: Tensa-13, Karanjia and Lahunipara-7 each.

CHHATTISGARH: Berla-7

2.3 Deep Depression over northeast and adjoining eastcentral Arabian Sea (22nd – 24th June 2015)

2.3.1 Introduction

A depression formed over northeast Arabian Sea off Gujarat coast on 22nd June 2015 morning and intensified into deep depression in the morning of 23rd. It moved northeastward & crossed south Gujarat coast close to Diu in the afternoon of 23nd June 2015. It then moved northeastward across Gujarat & weakened into a well marked low pressure area on 25th morning over northwest Madhya Pradesh & adjoining south Uttar Pradesh. Under its influence monsoon was active to vigorous over Gujarat state leading to flood condition over some regions. It also helped in advancing monsoon over west, central & northwest India.

2.3.2 Brief History

2.3.2.1 Genesis

Under the influence of strong monsoon conditions, an upper air cyclonic circulation formed between 1.5 & 4.5 kms a.s.l over northeast (NE) Arabian Sea off Gujarat coast during 18th – 20th June 2015. Under its influence, a low pressure area formed over NE Arabian Sea off Gujarat coast on 21st June 2015. It became well-marked low pressure area in the same evening over NE and adjoining eastcentral (EC) Arabian Sea. It concentrated into a depression and lay centred at 0300 UTC of 22nd June 2015 over NE and adjoining EC Arabian Sea near latitude 20.0°N and longitude 67.0°E, about 320 km southwest of Porbandar.

2.3.2.2 Intensification and movement

The low level relative vorticity, low level convergence and upper level divergence in association with the system increased during 21st and 22nd June. However, the vertical wind shear was moderate to high around the system centre. The Madden-Julian Oscillation (MJO) index was transiting from phase 4 to phase 5 with amplitude greater than one. The sea surface temperature (SST) was about 30°C near the system centre. The ocean thermal energy was 50-60 kJ/cm^2 around the system centre and it significantly decreased towards the west. Under these conditions, the depression moved eastnortheastwards, intensified into a Deep Depression over northeast Arabian Sea off south Gujarat coast and lay centred near Lat. 20.5°N / Long. 70.5°E, about 50 kms west-southwest of Diu at 0300 UTC of 23rd. It moved east-northeastwards and crossed south Gujarat coast near Diu between 0900 and 1000 UTC of 23rd and lay over Saurashtra centred near Lat. 21.0°N / Long. 71.3°E, about 65 kms south-southeast of Amreli at 1200 UTC of 23rd. It moved northeastwards and lay over Saurashtra & adjoining Gujarat Region centered near Lat. 22.4°N / Long. 72.0°E, about 85 kms southwest of Ahmedabad at 0300 UTC of 24th. It then moved east northeastwards and weakened into a Depression at 0900 UTC of 24th over Gujarat region and neighbourhood near Lat. 22.7°N / Long. 73.3°E, about 80 km southeast of Ahmedabad and 40 km north of Vadodara. Further moving east northeastwards, it lay centred at 1200 UTC of 24th, near Lat. 23.0°N / Long. 73.8°E, over Gujarat region and adjoining areas of west Madhya Pradesh and south Rajasthan, about 50 km northwest of Dohad (Gujarat) and 130 km west southwest of Ratlam (west Madhya Pradesh). It weakened into a well marked low pressure area over northwest Madhya Pradesh and neighbourhood in the morning hours of 25th

The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.3.1. The typical satellite imageries are shown in Fig. 2.3.1. IMD GFS analysis of mean sea level pressure (MSLP) and wind at 10metre, 850 hpa, 500 hpa and 200 hpa levels are shown in Fig. 2.3.2(a-c).

Table 2.3.1 Best track positions and other parameters of the Deep Depression over the Arabian Sea during 22-25 June, 2015

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
22/06/2015	0300	20.0/67.0	1.5	990	25	4	D
	0600	20.0/67.0	1.5	990	25	4	D
	1200	20.0/67.0	1.5	990	25	4	D
	1800	20.2/68.5	1.5	990	25	4	D
23/06/2015	0000	20.5/69.5	1.5	988	25	4	D
	0300	20.5/70.5	2.0	988	30	6	DD
	0600	21.0/71.0	2.0	988	30	6	DD
	The system crossed South Gujarat coast near Diu between 0900 -1000 UTC						
	1200	21.0/71.3	-	990	30	5	DD
	1800	21.6/71.4	-	990	30	5	DD
24/06/2015	0000	22.2/71.5	-	990	30	4	DD
	0300	22.4/72.0	-	990	30	4	DD
	0600	22.8/72.7	-	990	30	3	DD
	1200	23.5/74.0	-	992	25	3	D
	1800	26.0/76.0	-	994	25	3	D
25/06/2015	0000	The system weakened into a well-marked low pressure area over northwest Madhya Pradesh and neighbourhood					

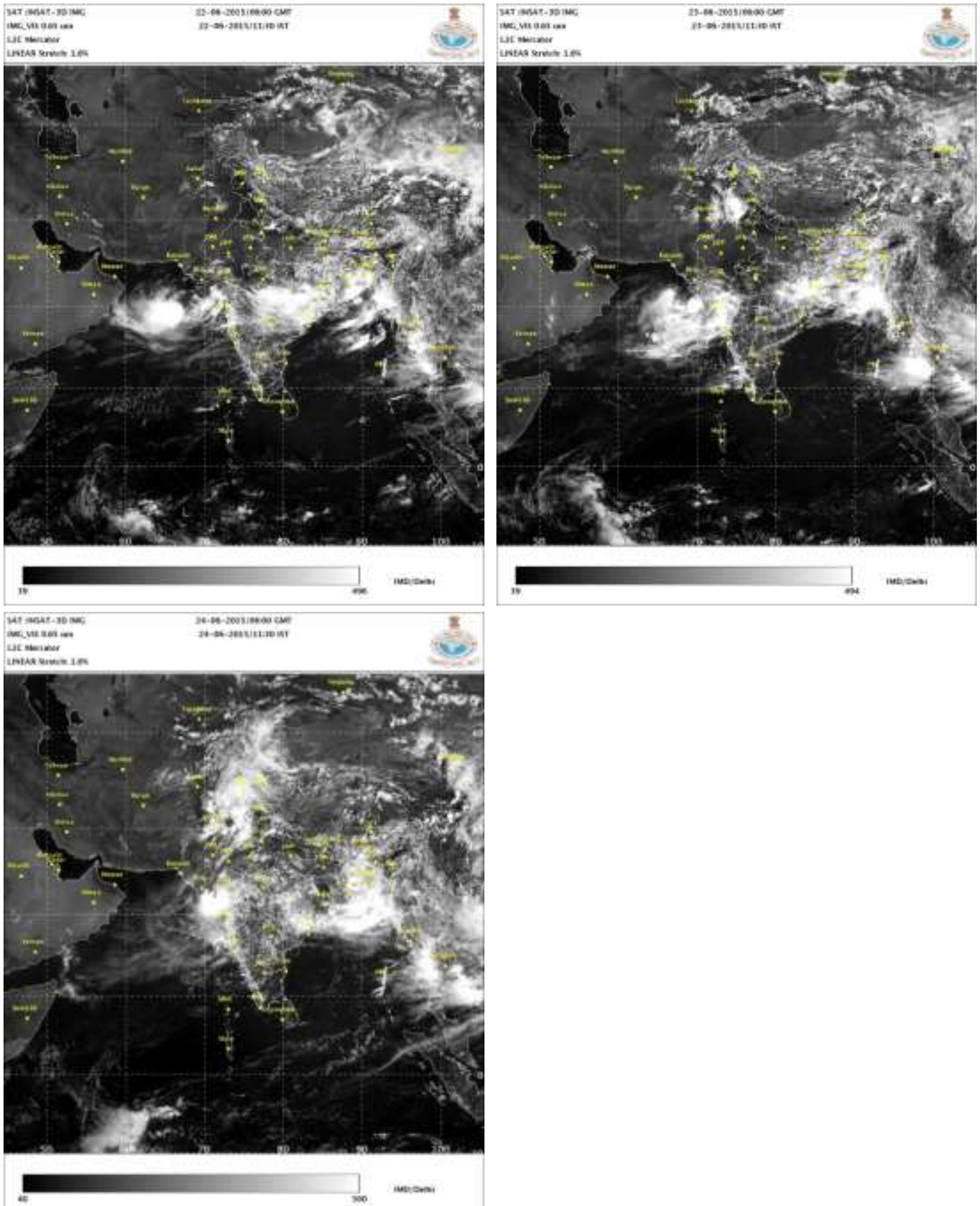


Fig.2.3.1 Typical INSAT 3D imageries of depression at 0600 UTC during 22-24 June, 2015

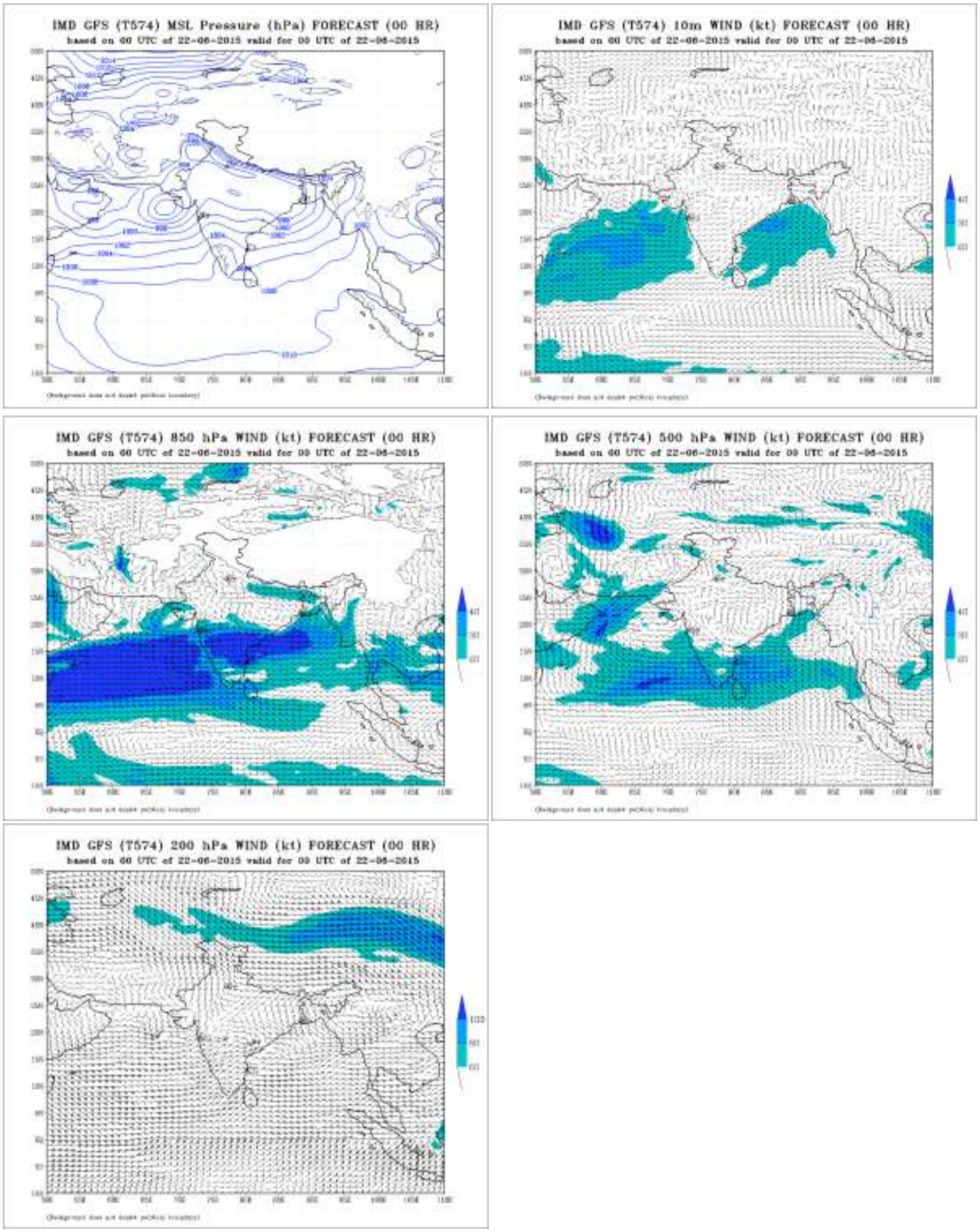


Fig. 2.3.2 (a) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 22nd June 2015

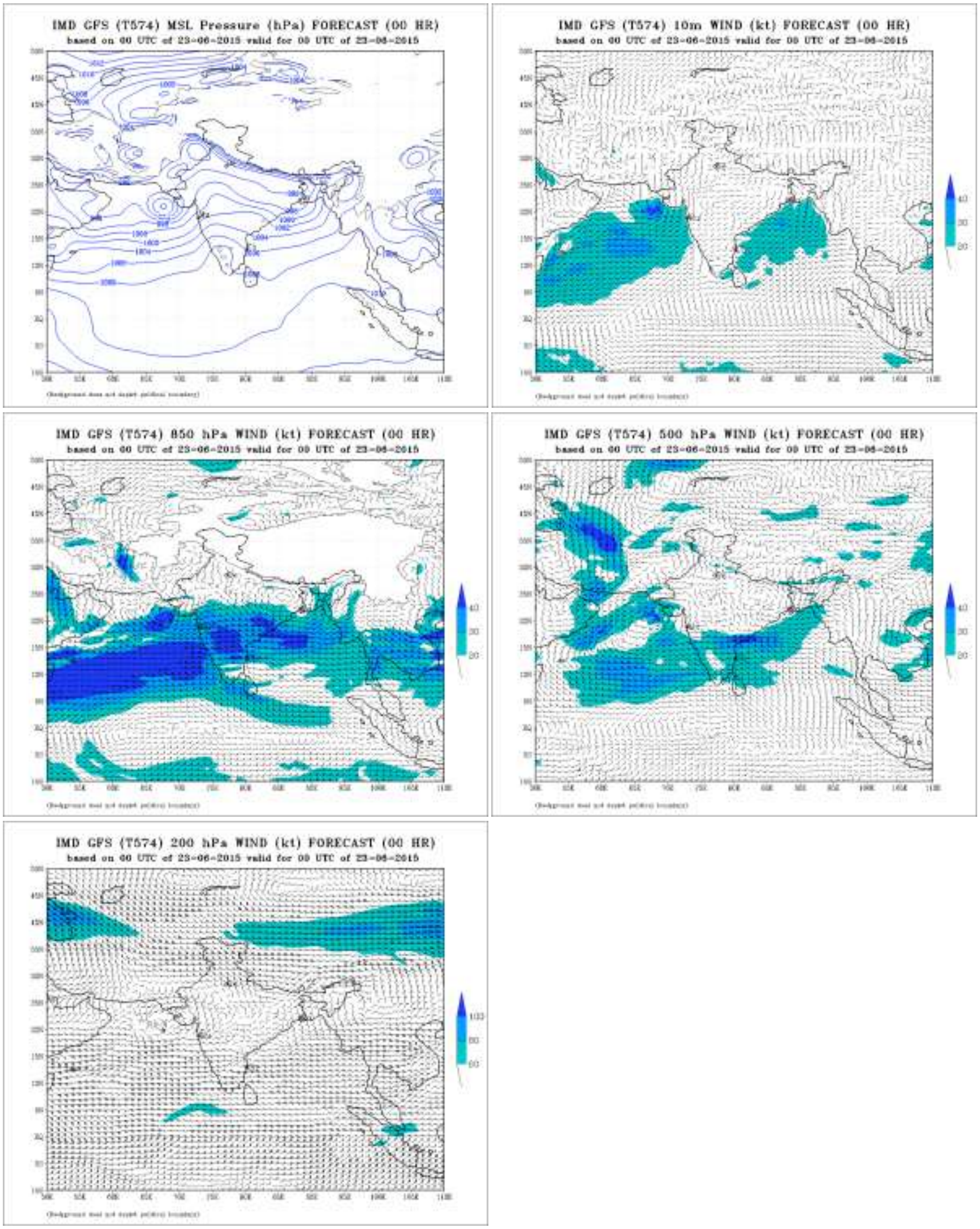


Fig. 2.3.2 (b) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 23rd June 2015

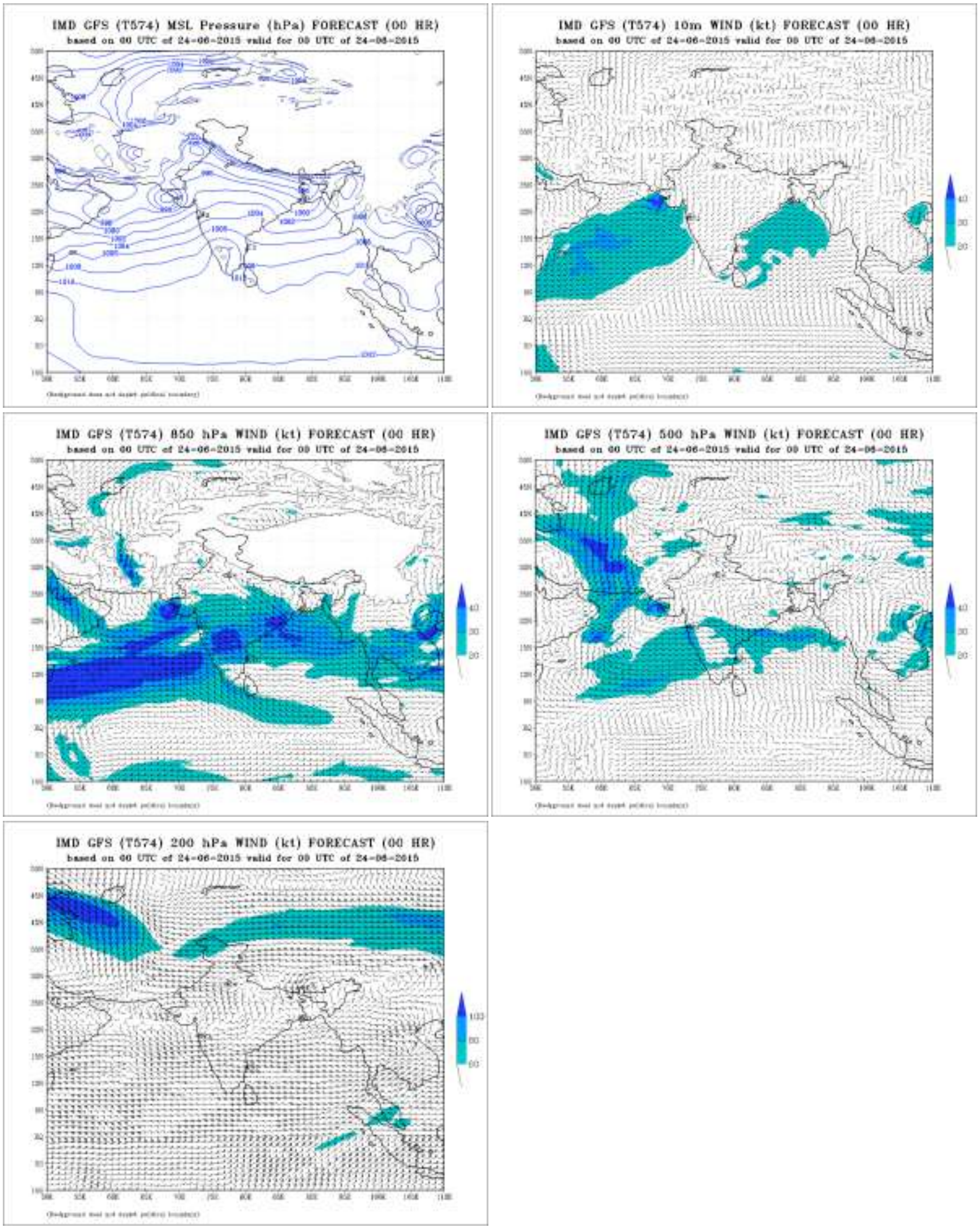


Fig. 2.3.2 (c) IMD GFS MSLP,10 meter wind, winds at 850, 500 & 200 hPa levels analysis based on 24th June 2015

2.3.3 Realised Weather

Heavy to very heavy rainfall rainfall occurred over Gujarat state, rajasthan and west Madhya Pradesh with extremely heavy rainfall over Saurashtra and Kutch.This system caused damage to life and property in Gujarat. Death toll crossed 81.Chief amounts of 24 hrs. Rainfall (7 cm or more) ending at 0300 UTC from 22nd to 24th June 2015 are given below:

22.06.2015

Gujarat region: - Khedbrahma and Umergam 9each; Nanipalson-7

East Rajastan: Devel-12; Dungarpur Tehsil-11; Bhungra-7

West Madhya Pradesh: Indore, Multai, Indore - AWS and Shegaon 7 each

East Madhya Pradesh: Bichhia 7

23.06.2015

Gujarat region: Choryasi-17; Olpad-16; Kamrej-14; Valod, Surat and Jalalpor 10 each; Valsad and Nanipalson 9 each; Umergam and Vyara 8 each; Navsari and Umerpada 7 each

Saurashtra & Kutch: Diu -12; Ghogha-11; Jafrabad-10; Talaja and Una 9 each; Mangrol (J), Dwarka and Rajula 7 each

East Rajastan: Rajsamand-9; Chabra-8

West Madhya Pradesh: Sehore – AWS-15; - Susner-12; Budhni, Depalpur, Tarana, Narsingarh, Badnagar and Khilchipur 9 each; - Agar-8; Sonkatch, Nalkheda, Hoshangabad and Khategaon 7 each

East Madhya Pradesh: - Dindori –-22; - Lanji-9.

24.06.2015

East Rajastan: - Shahabad-10

Gujarat Region: Dhandhuka ARG, Dhandhuka and Ranpur 8 each; Madhbun and Nanipalson 7 each

Saurashtra & Kutch: Una-32; Malia-27; - Kodinar-23; Talala-22; Rajula and Diu 19 each; Rajkot-17; Jafrabad-13; Mangrol (J), Khambha and Tankara 12 each; Keshod, Savarkundla, Veraval and Ranavav 11 each; Mahuva, Gondal and Sutrapada 10 each; Botad, Palitana, Chotila and Vanthali 9 each; Khambhalia, Junagadh, Kotdasangani, Mendarda and Porbandar AP 7 each

East Rajastan: - Shahabad- 10.

East Madhya Pradesh: - Chahtarpur – AWS-12; Rajnagar-8

<u>25.06.2015:</u>

JHARKHAND: Tilaiya-21, Hunterganj-11, Barhi-10

<u>26.06.2015:</u>

JHARKHAND: Rajmahal-9, Maheshpur-7 and Hiranpur-7

2.4 Land Depression over Jharkhand and nighbourhood (10-12 July 2015)

2.4.1 Introduction

A depression formed over Jharkhand & neighbourhood in the morning of on 10th June, 2015 It moved westnorthwestwards initially and then weswardsand northwestwards to reach west Uttar Pradesh and adjoining parts of Haryana in the afternoon of 12th and weakened in the same evening. The salient features of the depression given below.

2.4.2 Brief History

2.4.2.1 Genesis

A cyclonic circulation extending upto mid-tropospheric levels lay over north Bay of Bengal and neighbourhood on 5th, over coastal areas of west Bengal and neighbourhood on 6th and over north Bay of Bengal and neighbourhood on 7th. Under its influence, a low pressure area formed over north Bay of Bengal and adjoining coastal areas of Bangla Desh and West Bengal with associated cyclonic circulation extending upto 5.8 kms a.s.l. on 8th. It lay over northern parts of Gangetic West Bengal and adjoining areas of Bihar and Jharkhand with the associated cyclonic circulation extending upto 5.8 kms a.s.l. on 9th. It lay over Jharkhand and adjoining areas of Gangetic West Bengal & Bihar on the same evening It rapidly concentrated into a Depression and lay over Jharkhand and neighbourhood centered near Lat. 23.1°N / Long. 85.1°E, about 30 kms southwest of Ranchi at 0300 UTC on 10th.

2.4.2.2 Intensification and movement

The depression moved west-northwestwards and lay over north Chhattisgarh and adjoining areas of Jharkhand centered near Lat. 23.5°N / Long. 83.5°E, about 60 Kms northeast of Ambikapur at 1200 UTC of same evening. It continued to move west-northwestwards and lay over northeast Madhya Pradesh and adjoining southeast Uttar Pradesh centered near Lat. 24.0°N / Long. 80.5°E, about 55 kms south-southwest of Satna at 0300 UTC of 11th. It moved northwestwards and lay centred over central parts of south Uttar Pradesh and adjoining north Madhya Pradesh near Lat. 25.5°N / Long. 80.5°E about 80 kms northeast of Khajuraho and 125 kms southwest of Fursatganj at 1200 UTC of 11th. It further moved northwestwards and lay over west Uttar Pradesh and adjoining areas of Haryana centred near Lat. 28.5°N / Long. 78.0°E, about 55 kms east of Delhi at 0300 UTC of 12th and over Haryana and neighbourhood, near Lat. 28.5°N / Long. 77.3°E, close to Delhi at 0900 UTC of 12th. It moved northwestwards and weakened into a well marked low pressure area over northwest Uttar Pradesh and adjoining areas of Haryana on the same evening.

The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.4.1. The typical satellite imagery are shown in Fig.

2.4.1. IMD GFS analysis of mean sea level pressure (MSLP) and wind at 850 hpa, 500 hpa and 200 hpa levels are shown in Fig. 2.4.2(a-c).

Table 2.4.1 Best track positions and other parameters of the Land Depression over Jharkhand and neighbourhood during 10-12 July, 2015

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
10/07/2015	0300	23.1/85.1	-	996	25	4	D
	0600	23.1/85.0	-	996	25	4	D
	0900	23.3/84.0	-	994	25	4	D
	1200	23.5/83.5	-	994	25	4	D
	1500	23.5/82.5	-	996	25	4	D
	1800	23.6/82.3	-	996	25	4	D
	2100	23.8/81.0	-	996	25	4	D
11/07/2015	0000	24.0/80.5	-	995	25	4	D
	0300	24.0/80.5	-	996	25	4	D
	0600	24.5/80.5	-	996	25	4	D
	0900	24.5/80.5	-	996	25	4	D
	1200	25.5/80.5	-	996	25	4	D
	1500	26.0/80.0	-	996	25	4	D
	1800	26.5/79.5	-	998	25	4	D
	2100	26.0/78.5	-	998	25	4	D
12/07/2015	0000	27.5/78.3	-	998	25	4	D
	0300	28.5/78.0	-	998	25	3	D
	0600	28.5/77.5	-	998	25	3	D
	0900	28.5/77.3	-	998	25	3	D
	1200	Weakened into a well marked low pressure area over northwest Uttar Pradesh and adjoining areas of Haryana in the evening.					

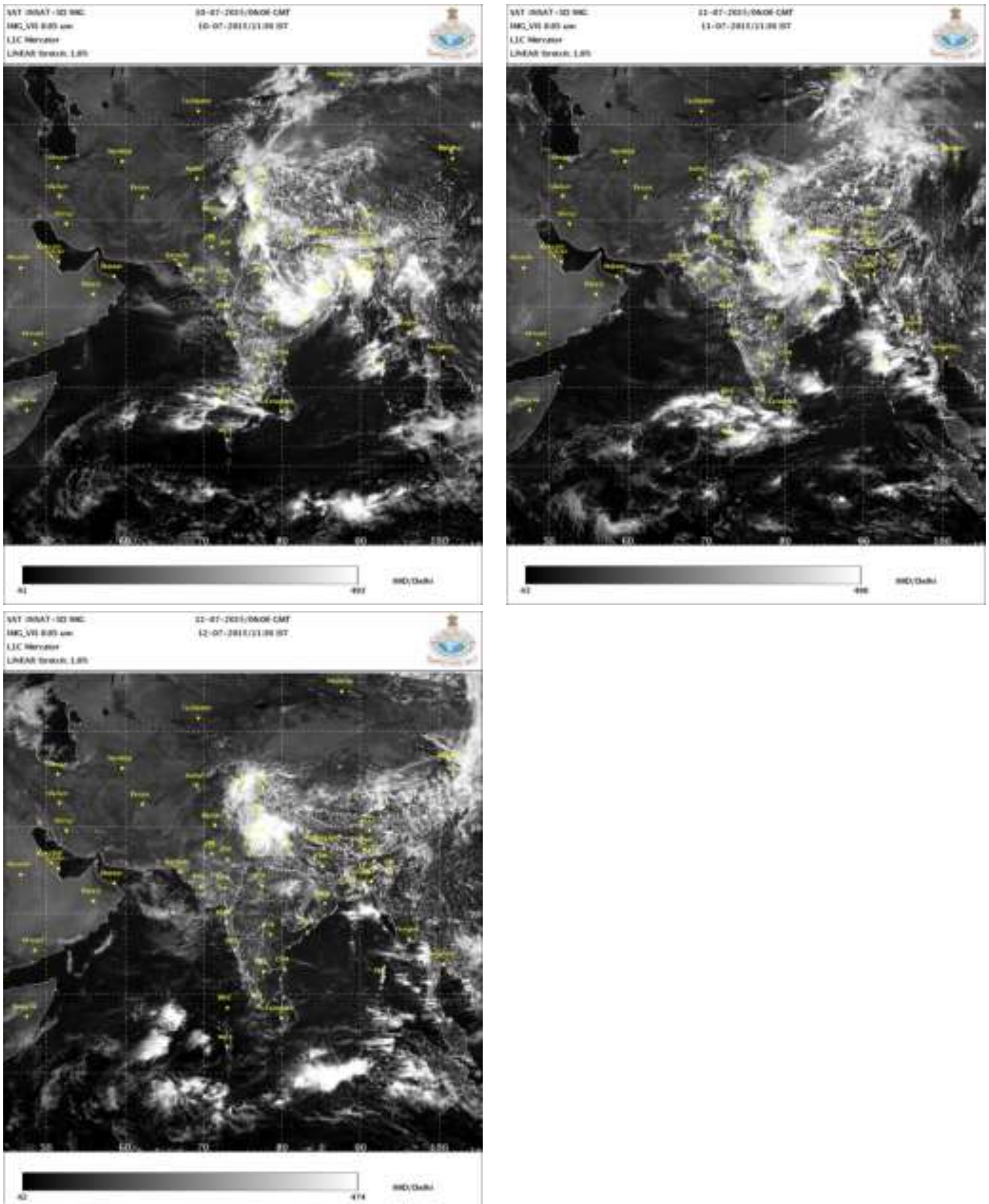


Fig.2.4.1 Typical INSAT 3D imageries of depression at 0600 UTC during 10-12 July, 2015

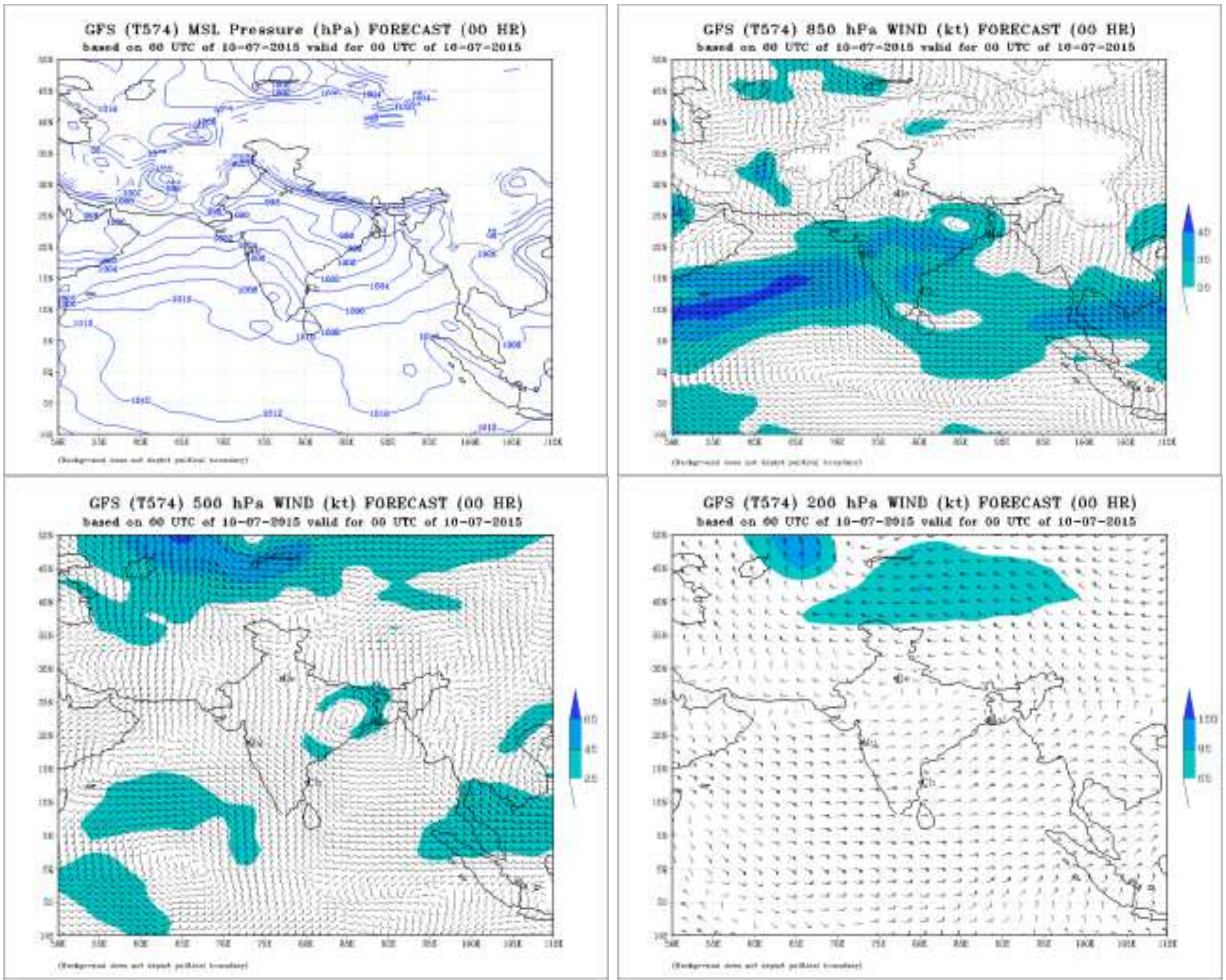


Fig. 2.4.2 (a) GFS MSLP winds at 850, 500 & 200 hPa levels analysis based on 10th July, 2015

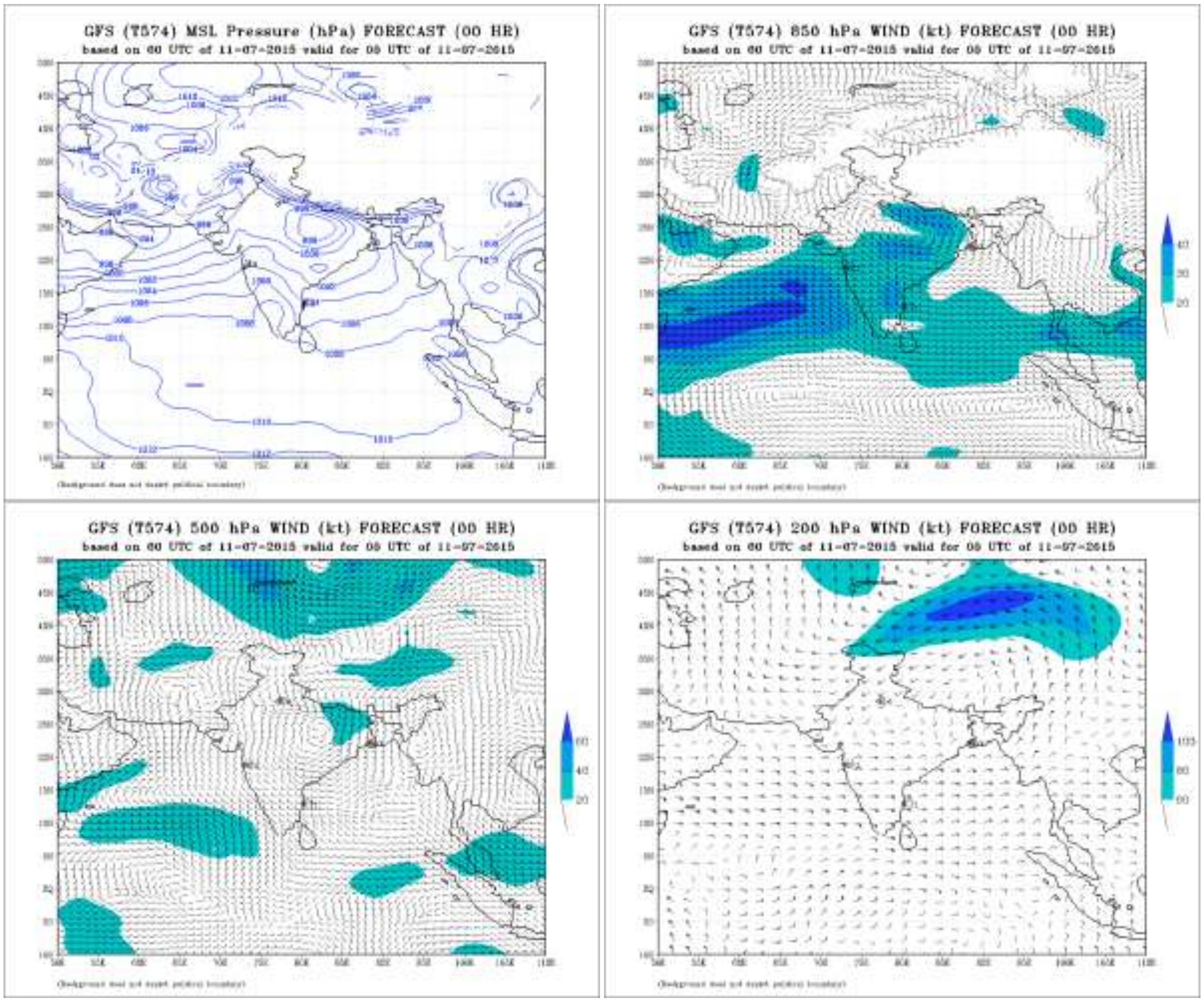


Fig. 2.4.2 (b) GFS MSLP winds at 850, 500 & 200 hPa levels analysis based on 11th July, 2015

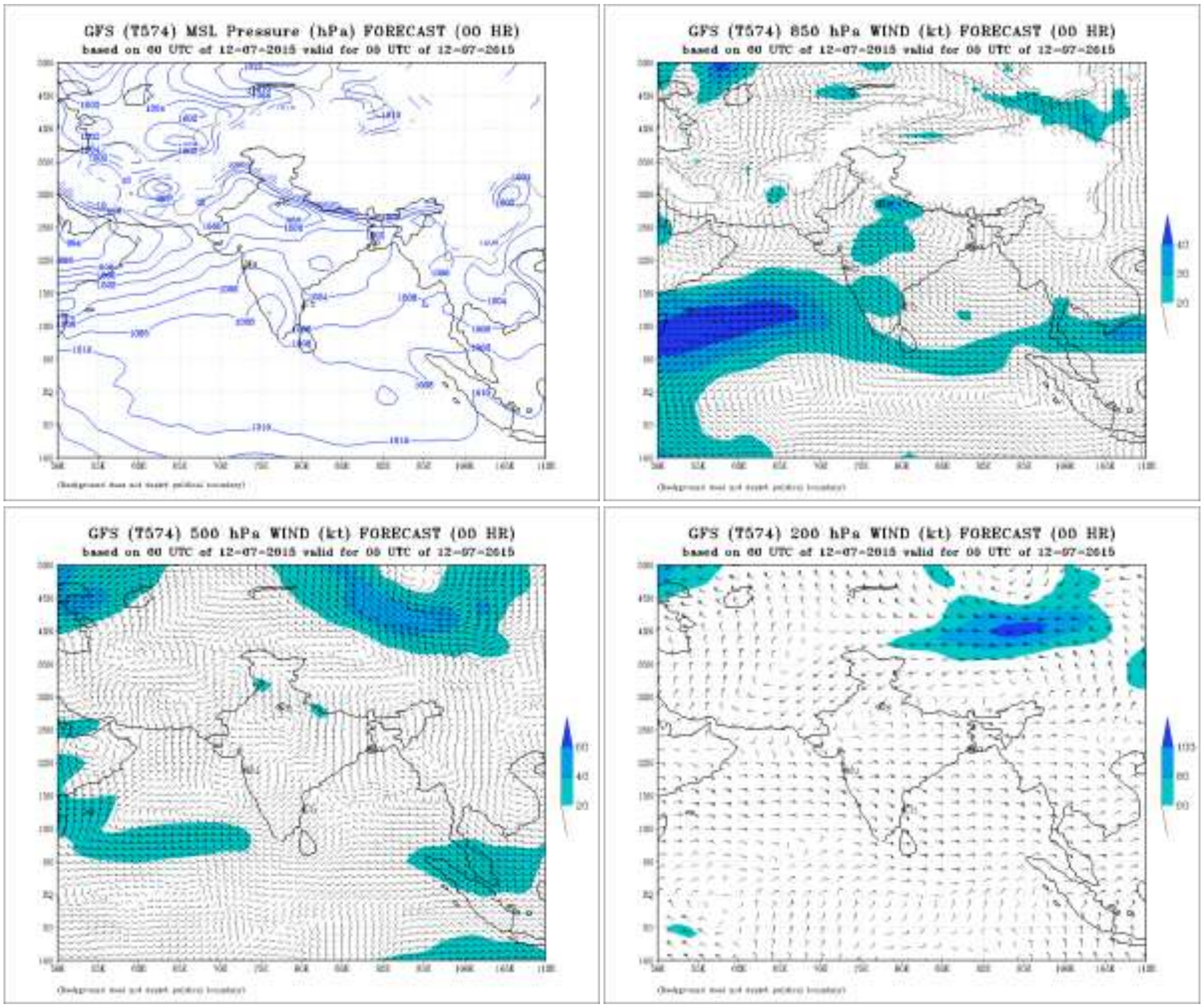


Fig. 2.4.2 (c) GFS MSLP winds at 850, 500 & 200 hPa levels analysis based on 12th July, 2015

2.4.3 Realised Weather

Active to vigorous monsoon condition prevailed over Gangetic West Bengal, Odisha, Jharkhand, Uttar Pradesh, Madhya Pradesh and Chhattisgarh with extremely heavy rainfall at isolated places over Gangetic West Bengal, Odisha and Jharkhand.

Chief amounts of 24 hrs rainfall (7 cm or more) ending at 0300 UTC from 10th -12th July are given below:

<u>10.7.2015</u>

Gangetic West Bengal : Deganga-26; Bongaon 25-; Katwa and Durgachak 23 each; Sonamukhi ARG and Baruipur 20 each; Tilpara Barrage-17; Salar, Kolkata AP and Bolpur 16 each; Suri CWC and Diamond Harbour 15 each; Bashirhat, Kolkata and Chinsura 14 each; Purihansa, Basirhat, Nandigram, Kandi and Harinkhola 13 each; Sriniketan 12; Burdwan, Shekhampore ARG, Kalna, Tusuma, Kandi and Dhaniakhali ARG 11 each; Contai, Amtala, Ranaghat, Dhaniakhali, Contai and Bagati (Magra) 10 each; Rajnagar, Labpur, Kharidwar, Kalyani Smo, Mangalkote and Bankura CWC 9 each; Krishnanagar, Berhampore, Barrackpur IAF, Manteswar, Digha, Phulberia and Purulia 8 each; Narayanpur, Simula, Burdawan, Sagardighi, Manmothnagar, Hatwara, Bankura and Jiaganj 7 each

Odisha: Tensa 15; Lahunipara 13; Gurundia ARG-12; Jamankira and Banaigarh AWS 11 each; Kuchinda, Barkote, Laikera and Deogarh 9 each; Nawapara, Rairakhol, Kirmira ARG, Soro and Keiri AWS 8 eachKhariar, Pallahara, Atabira ARG, Bonth, Patnagarh, Bijepur, Joda ARG, Komna, Lakhanpur ARG and Birmaharajpur ARG ; 7 each

Jharkhand: Palkot-13; Mandar-12; Ranchi AP-11; Messenjore-10; Moharo, Dumka and Deoghar 9 each; Torpa and Simdega 8 each; Nimdih, Kolebira, Dumri, Jarmindi and Amrapara 7 each

West Uttar Pradesh: Bijnor-11; Baheri-10; Sahaswan-9; Garotha and Jalaun 8 each.

West Madhya Pradesh: Chachoda-14; Seodha (Seondha) and Udaipura 9 each Pachmarhi and Mungaoli 8 each; Salwani / Silvani-7

East Madhya Pradesh: Kareli-15; Malanjkhand-11; Gadarwara 9; Chindwara – AWS-7

ChhattisgarhAmbikapur:-8; Gandai and Gharghoda 7 each.

<u>11.7.2015</u>

Gangetic West Bengal : Bolpur and Pingla 16 each; Sriniketan and Mangalkote 14 each; Burdawan-13; Khirpai and Shekhampore ARG 11 each; Burdwan-9; Manteswar-8 ; Dhaniakhali ARG and Amta 7-each

Odisha: 26 - Sundargarh; 25 - Balisankara ARG; 22 - Hemgiri; 16 - Bargaon; 15 - Bamra ARG; 13 - Lakhanpur ARG and Laikera each; 12 - Jharsuguda AP; 11 - Kirmira ARG, Deogaon and Kolabira ARG each; 9 - Kuchinda; 8 - Salepur ARG, Burla ARG and Akhuapada each; 7 – Rajgangpur

Jharkhand: Kolebira-39; Mohanpur-13; Raidih-12; Simdega-9; Pakuria-7; Daltonganj and Palkot 6 each; Mandar-5

East Uttar Pradesh: Ankinghat-10; Rasoolabad, Chhibramau, Kannauj and Hasanganj 7 each.

West Uttar Pradesh: Narora and Mathura CWC 14 each; Nakur-12; Maudaha-9; Gunnaur 8

West Madhya Pradesh: Biaora-18; Rajgarh-15; Narsingarh, Kolaras, Morena - AWS and Sabalgarh 9 each; Udaipura-8-; - Isagarh-7

East Madhya Pradesh: Gadarwara and Maihar 10 each; Ajaigarh, Nagode and Kotma 7 each

Chhattisgarh: Raigarh-17; Janakpur-12; Janjgir and Pathalgaon 9 each; Manendragarh, Korba and Jashpurnagar 8 each; Baikunthpur, Gharghoda and Bilaspur 7 each

<u>12.7.2015</u>

Jharkhand: Dumka- 9

East Uttar Pradesh: Hardoi-17; Shahabad-16; Muhammadi and Sandila 15 each; Neemsar-12; Jaunpur Tehsil and Nawabganj Tehsil 11 each; Bara Banki and Malihabad 10 each; Bhatpurwaghat and Sidhauli 9 each; Sultanpur CWC, Sultanpur, Biswan, Sawayajpur, Lucknow AP and Hasanganj 8 each; Sitapur, Misrikh, Varanasi city, Shahganj, Kannauj, Handia, Elgin Bridge and Hardoi Teh 7 each

West Uttar Pradesh: Moradabad-15; Shajanpur and Shahjahapur 14 each; Sahaswan and Amroha 13 each; Pawayan, Bareilly and Bareilly Tehsil 12 each; Bareilly CWC-11; Bilari-10; Kasganj-8; Narora, Harpur, Bisalpur, Gunnaur, Shahjahanpur T and Garotha 7 each

West Madhya Pradesh: Gwalior and Dabra 19 each; Biaora-9; Gohad, Khilchipur and Rajgarh 8 each; Narsingarh and Isagarh 7 each

13.7.2015

EAST UTTAR PRADESH: Neemsar-14, Dalmau CWC-7

WEST UTTAR PRADESH: Moradabad CWC-11

2.5 Land Deep depression over southwest Rajasthan and adjoining Gujarat (27 -30 July. 2015)

2.5.1 Introduction

A depression formed over southwest Rajasthan and neighbourhood in the evening if of 27th July, 2015 It intensified into a deep depression in the morning of 28th . It weakened into a depression in the morning of 29th and into a Well Marked Low Pressure Area on 30th. The salient featurure of this Depression is:

It caused heavy to very heavy with extremely heavy rainfall at isolated places of Rajastan, Gujarat State and west Madhya Pradesh.

2.5.2 Brief Hostory

2.5.2.1 Genesis

A low pressure area formed over northwest Madhya Pradesh and adjoining east Rajasthan on 24th and persisted there on 25th. It lay as a well marked low pressure area over east Rajasthan and neighbourhood on 26th and over central parts of Rajasthan and neighbourhood on the same evening. It lay over southwest Rajasthan and neighbourhood on 27th. Associated cyclonic circulation extending upto 5.8 kms a.s.l. persisted during 24th - 27th. The well marked low pressure area concentrated into a Depression and lay over southwest Rajasthan & neighbourhood centred near Lat.26.2°N/Long.71.8°E, about 100 kms east-southeast of Jaisalmer (Rajasthan) at 1200 UTC on 27th evening.

2.5.2.2 Intensification and movement

The dererssion intensified into a Deep Depression and lay over southwest Rajasthan and adjoining Gujarat centred near Lat.24.8°N/Long.71.8°E, about 110 kms east-southeast of Barmer (Rajasthan) at 0300 UTC on 28th. It remained over the same region and lay centred near Lat.25.5°N/Long.72.0°E, about 70 kms south-southeast of Barmer (Rajasthan) at 1200

UTC on 28th. It moved north-northeastwards and weakened into a Depression and lay over west Rajasthan, centered near Lat.27.2°N/Long.73.0°E, about 40 kms south-southwest of Bikaner (Rajasthan) at 0300 UTC on 29th. It moved northeastwards and lay over the same region centred near Lat.27.7°N/Long.73.4°E about 30 kms south-southeast of Bikaner (Rajasthan) at 1200 UTC of 29th July. It moved northwards and lay over west Rajasthan and neighbourhood centered near Lat. 28.7°N / Long. 73.4°E, about 80 kms north-northeast of Bikaner (Rajasthan) at 0000 UTC on 30th. It further moved north-northeastwards and weakened into a well marked low pressure area over the same region on 30th. It lay as a low pressure area over northwest Rajasthan and neighbourhood on 30th evening. It persisted over the same region on 31st July. over central Pakistan and adjoining west Rajasthan on 1st & 2nd Aug. and over central Pakistan and adjoining northwest Rajasthan on 3rd. It became less marked on 4th. Associated cyclonic circulation extending upto mid tropospheric levels during 30th July -3rd August. It became less marked 4th.

The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.5.1. The typical satellite imageries are shown in Fig. 2.5.1. IMD GFS analysis of mean sea level pressure (MSLP) and wind at 10metre, 850 hpa, 500 hpa and 200 hpa levels are shown in Fig. 2.5.2(a-d).

Table 2.5.1 Best track positions and other parameters of the Land Deep Depression over southwest Rajasthan and neighbourhood during 27-30 July, 2015

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
27/07/2015	1200	26.2/71.8	-	994	25	4	D
	1500	26.0/71.8	-	994	25	4	D
	1800	25.8/71.8	-	996	25	4	D
	2100	26.1/71.8	-	996	25	4	D
28/07/2015	0000	26.2/71.8	-	994	25	4	D
	0300	24.8/71.8	-	994	30	5	DD
	0600	24.8/71.8	-	994	30	5	DD
	0900	24.8/71.8	-	994	30	5	DD
	1200	25.5/72.0	-	994	30	5	DD
	1500	25.6/72.1	-	996	30	5	DD
	1800	25.8/72.1	-	996	30	5	DD
	2100	25.9/72.3	-	996	25	5	DD
29/07/2015	0000	26.5/72.5	-	996	25	5	DD
	0300	27.2/73.0	-	996	25	4	D
	0600	27.2/73.0	-	996	25	4	D

	0900	27.2/73.0	-	996	25	4	D
	1200	27.7/73.0	-	998	25	4	D
	1500	27.9/73.0	-	998	25	4	D
	1800	27.9/73.1	-	998	25	3	D
	2100	28.0/73.1	-	998	25	3	D
30/07/2015	0000	28.7/73.4	-	998	25	3	D
	0300	It further moved north-northeastwards and weakened into a well marked low pressure area over west Rajasthan and neighbourhood.					

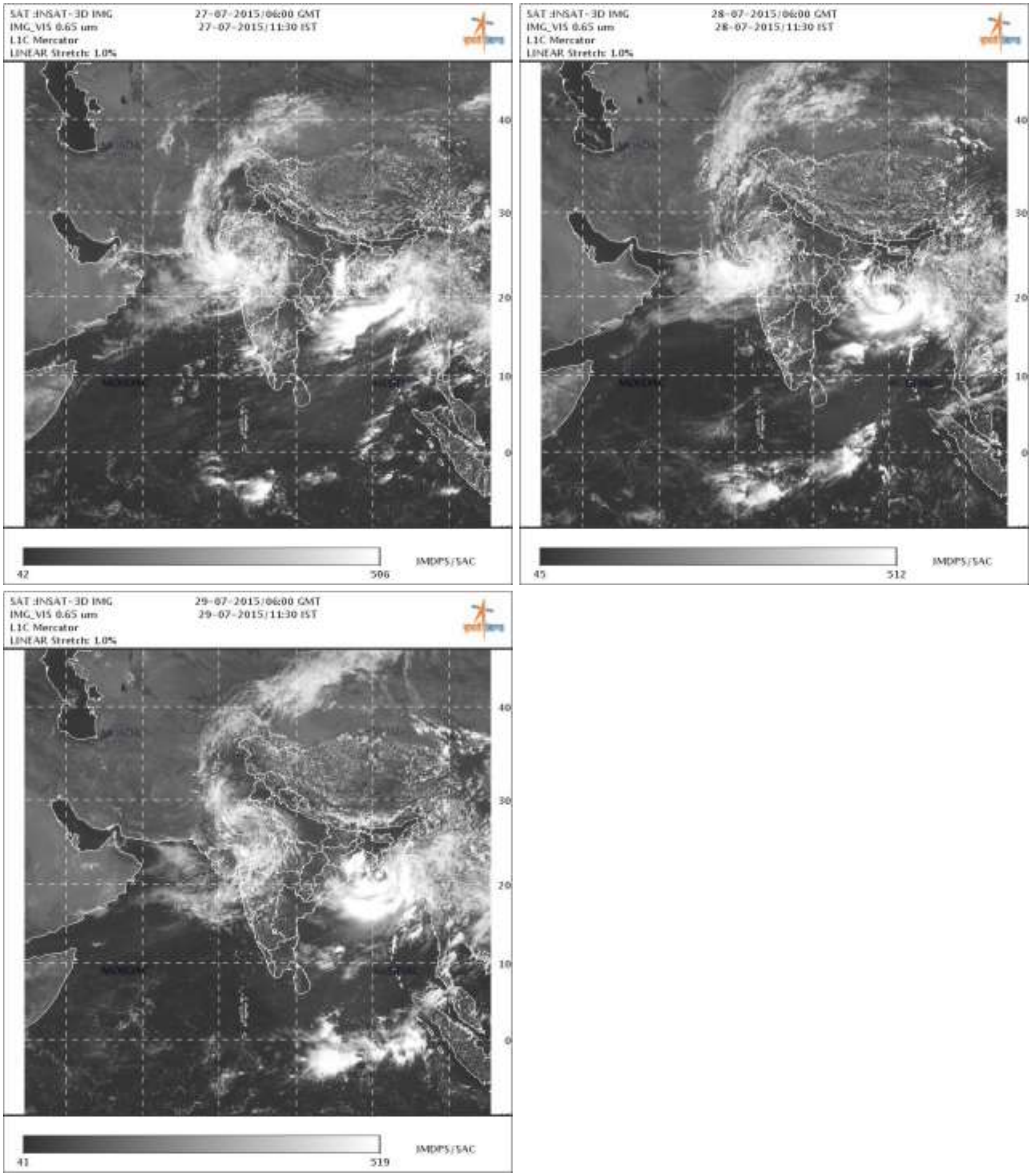


Fig. 2.5.1 Typical INSAT 3D imageries of depression at 1200 UTC 27th and 0600 UTC 0f 28th and 29th July, 2015

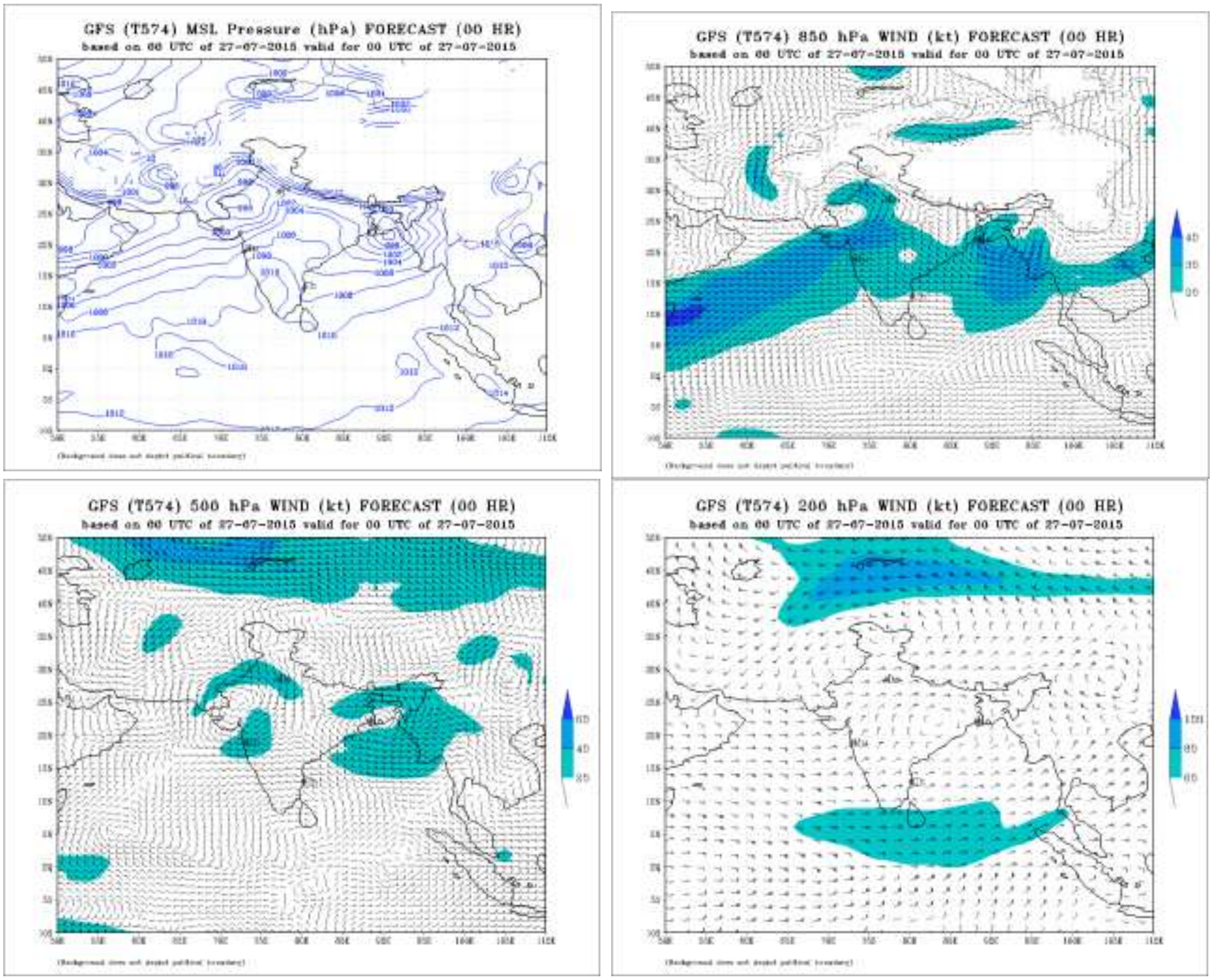


Fig. 2.5.2 (a) GFS MSLP, winds at 850, 500 & 200 hPa levels analysis based on 27th July, 2015

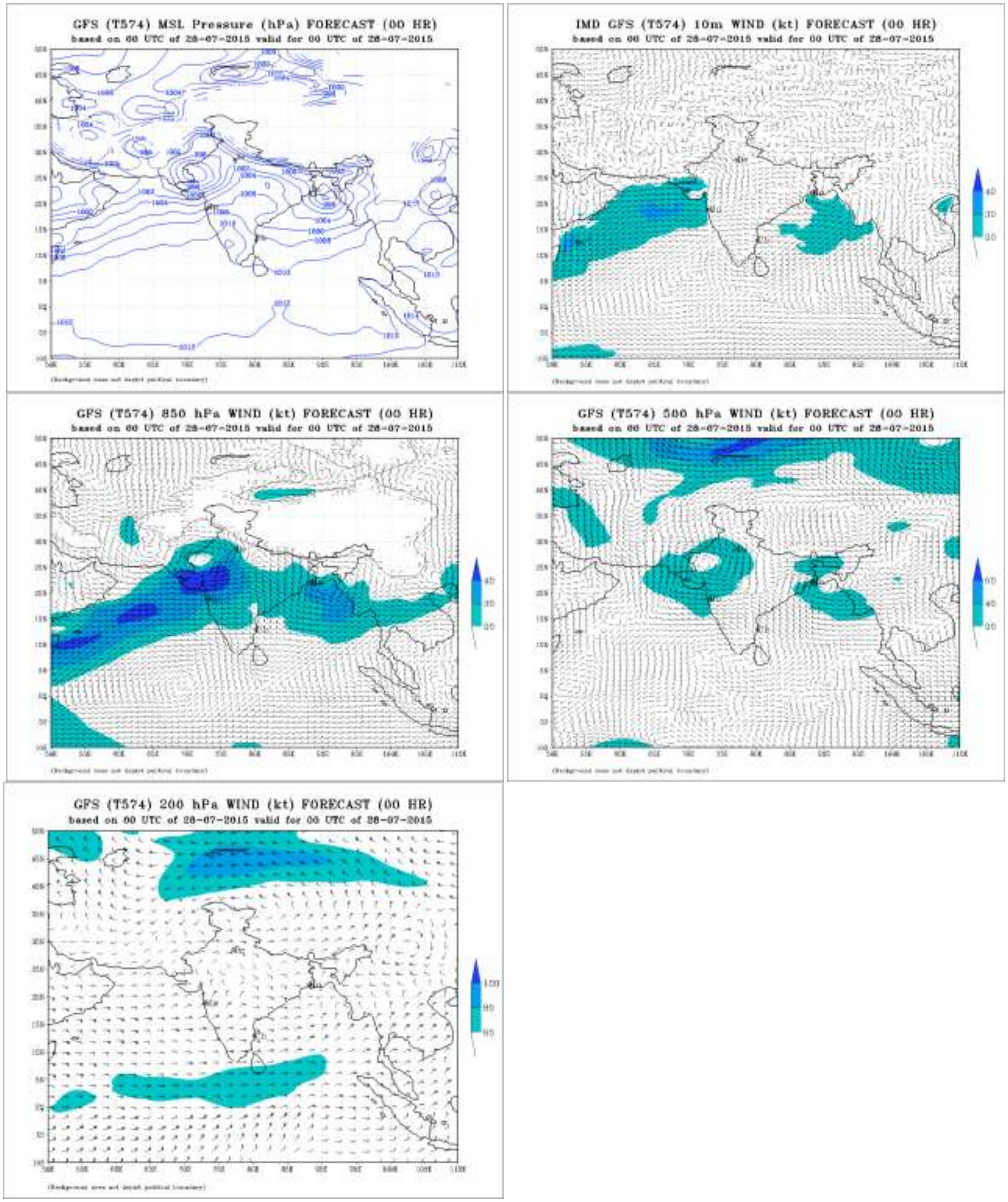


Fig. 2.5.2 (b) GFS MSLP, 10 metre wind, winds at 850, 500 & 200 hPa levels analysis based on 28th July, 2015

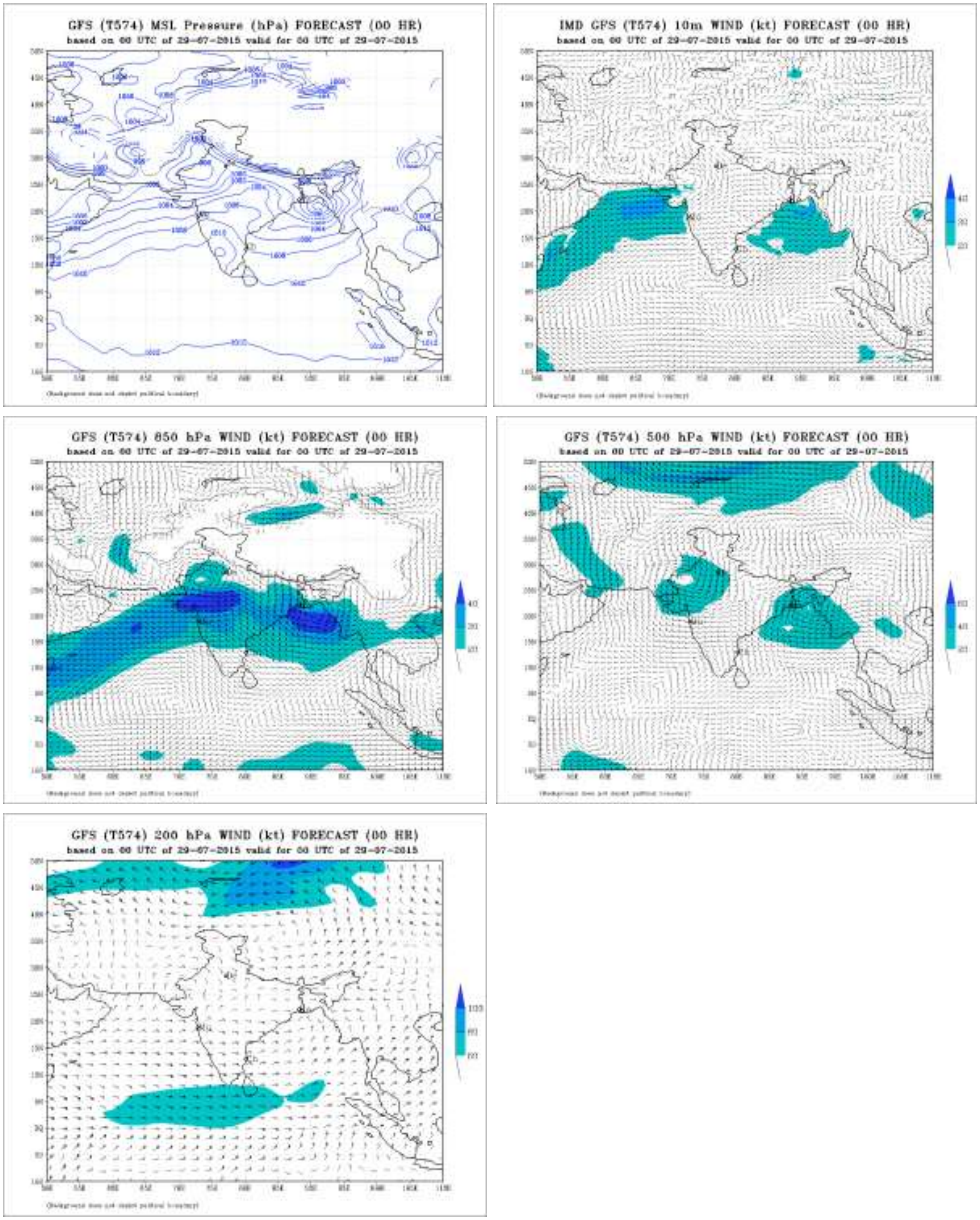


Fig. 2.5.2 (c) GFS MSLP, 10 metre wind, winds at 850, 500 & 200 hPa levels analysis based on 29th July, 2015

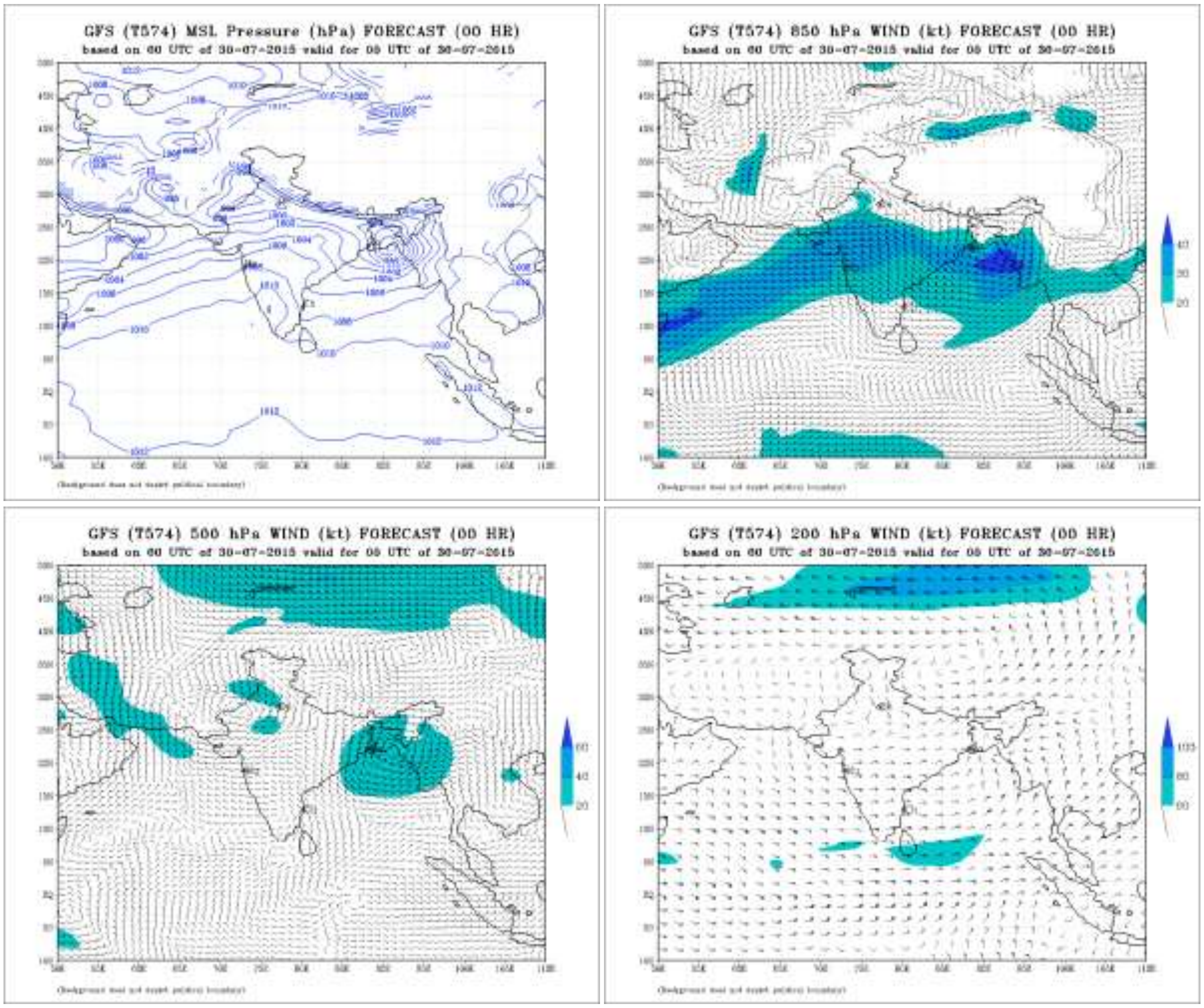


Fig. 2.5.2 (d) GFS MSLP, winds at 850, 500 & 200 hPa levels analysis based on 30th July, 2015

2.5.3 Realised Weather

Active to vigorous monsoon conditions prevailed over Rajastan, Gujarat State and west Madhya Pradesh. This deep depression caused heavy to very heavy rainfall at a few places with extremely heavy rainfall at isolated places of Rajastan, Gujarat State and west Madhya Pradesh.

Chief amounts of 24 hrs. rainfall (7 cm or more) ending at 0300 UTC from 27th to 30th are given below:

27.7.2015

West Rajastan: Gudamalani-33; Raniwada-32; Jaswantpura-29; Bhinmal-22; Bagoda-18; Bali and Chotan 17 each; Sinderi and Sanchore 15 each; Dorimanna and Desuri 13 each; Erinpura Rd. and Sumerpur 12 each; Sayla-11; Bilara-9; Pachpadra, Sedwa and Ramsar 7 each.

East Rajastan: Mount Abu-45; Abu Road-24 -; Reodar-21; Arthuna-19; Sirohi-15; Galiakot-12; Danpur, Bijoliya, Nayanagar / Beawar, Veja and Bhainsroadgarh 11 each; Chikali, Sheoganj and Kesarpura 10 each; Pindwara, Kanva, Bagidora, Shergarh, Kumbhalgarh, Sallopat, Dungarpur Tehsil and Aspur 9 each; Dhambola, Garhi, Sabla, Sagwara, Sajjangarh, Chambal / R.B.Dam and Nimbahera 8 each; Gangrar, Khushalgarh, Kotda, Ladpura, Bari -Sadri, Kota AP, Loharia and Chittorgarh 7 each.

West Madhya Pradesh: Jawad-11; Alirajpur - AWS and Sailana 8 each; Nimach, Manasa, Ratlam, Ratlam - AWS and Jabot 7 each.

Gujarat region: Dadiapada ARG and Dhanera 19 each; Vapi-18; Mansa-17; Dahegam, Vijapur and Kankrej 16 each; Valia, Siddhpur and Silvassa 15 each; Dantiwada, Danta and Mangrol 14 each; Vadgam, Himatanagar, Patan, Unjha, Amirgadh, Dharampur, Godhra and Palanpur 13 each; Kaprada, Mahesana, Dangs (Ahwa), Kamrej and Deodar 12 each; Dharoi Colony, Bhiloda, Tharad, Umerpada, Anand and Pardi 11 each; Kalol (G), Jambughoda, Kadana, Daman, Wanakbori, Malpur, Umergam, Khedbrahma, Balasinor, Valsad, Deesa, Olpad, Madhubun and Kapadvanj 10 each; Quant, Tilakwada ARG, Viramgam, Sagbara, Wav, Dhansura, Gandhinagar and Kadi 9 each; Radhanpur, Talod, Karjan, Lunawada, Bavla, Khanpur, Bhabhar, Chhota Udepur, Gandevi ARG, Kamrej ARG, Kathalal and Dediapada 8 each; Chhota ARG, Santrampur, Ahmedabad, Detroj, Vansda, Becharaji, Morva Hadaf, Shahera, Tilakwada, Bodeli, Fatepura, Sinor, Rajpipala, Meghraj, Nanipalson, Bardoli and Umreth 7 each.

Saurashtra & Kutch: Junagadh-19-; Jodia-17; Dasada-15; Bhesan-14; Junagarh AWS-13; Morbi, Vanthali and Visavadar 12 each; Manavadar-11; Kotdasangani-10; Tankara-9 -; Amreli-8 -; Bhuj AP and Kharaghoda 7 each.

28.7.015

West Rajastan: Sanchore-24; Raniwada-19; Jalore and Bagoda 18 each; Jaswantpura-16; Gudamalani and Sedwa 9 each; Bhinmal.- 7

East Rajastan: Mount Abu-33; Abu Road-13; Reodar-12 ; Kotda-11; Veja-10; Galiakot and Dungarpur Tehsil 8 each; Gogunda, Ganeshpur and Bari -Sadri 7 each.

West Madhya Pradesh: Thandla and Petlawad 10 each; Bhabhra-9; Sailana, Jhabua - AWS and Khachrod 8 each; Ratlam- 7

Gujarat region: Dhanera-43; Wav-42; Deesa-40; Bhabhar-35; Kankrej-34; Tharad and Dantiwada-33 each; Radhanpur-32; Deodar-25; Palanpur-22; Umerpada and Patan 21 each; Santalpur-20 ; Dharoi Colony19; Siddhpur, Unjha and Vadgam 18 each; Mahesana and Becharaji 16 each; Amirgadh and Vapi 15 each; Dangs (Ahwa), Idar, Gandhinagar, Chanasma, Quant and Vansda 14 each; - Danta and Talod 13 each; Silvassa, Ghandinagar AWS, Detroj, Himatanagar, Petlad and Satlasana 12 each; Vadali, Kadi, Dadiapada ARG, Anand, Khedbrahma, Bodeli, Dharampur, Kaprada and Vijapur 11 each; Kheralu, Mansa, Mangrol and Prantij 10 each; Visnagar, Nandod, Sanand, Chikhli, Jetpur Pavi, Kalol (G), Mandal, Umergam, Mc Ahmedabad ARG, Dahegam, Khambhat, Ahmedabad, Rajpipala, Sami and Pardi 9 each; Harij, Dohad, Chhota Udepur and Dhansura 8 each; Naswadi, Vadnagar, Shahera, Gandevi ARG, Tilakwada, Sankheda, Borsad, Daman, Sagbara, Kamrej, Jambughoda, Godhra and Madhbun 7 each.

Saurashtra & Kutch: Nakhatrana-31; Bhuj AP-25; Anjar and Rapar 23 each; Morbi and Kandla Airport 19 each; Tankara-18; New Kandla-17; Bhachau-15; Gandhidham-14; Jodia and MaliaMiana 13 each; Lakhpat, Lalpur and Mundra 12 each; Dasada, Halvad and Dhrangadhra 11 each; Jamnagar IAF, Dhrol ARG, Lakhtar, Chotila, Targhadia AWS and Surendranagar 7 each.

29.7.2015

West Rajastan: Sanchore and Sedwa 15 each; Marwar Junction-9; Erinpura Rd., Bali, Sumerpur and Pali 7-each.

East Rajastan: Abu Road-41; Mount Abu3-2; Kotda-30; Jhadol-19; Devel-18; Girva, Udaipur AP and Gogunda 12 each; Mavli and Veja 10 each; Kherwara and Galiakot 9 each; Udaipur, Dungarpur Tehsil, Bhungra, Chikali, Dhambola, Kanva and Arthuna 8 each; Tatgarh, Sarara, Pindwara, Sheoganj, Shergarh and Salumber 7 each.

Gujarat region: Vadgam-49; Deesa-36 ; Palanpur-32; Amirgadh-31; Dhanera-30; Siddhpur-28; Mahesana, Patan and Dharoi Colony 27each; Danta and Unjha 25 each; Kadi-23; Idar-21; Radhanpur and Vijaynagar 20 each; Prantij-19; Mansa and Bhabhar 18 each; Vijapur, Deodar and Khedbrahma 17-each; Kalol (G) and Vadali 16 each; Sanand, Himatanagar, Mandal and Harij 15 each; Kheralu-14; Dahegam, Chanasma, Talod and Viramgam 13 each; Dhansura, Detroj and Umerpada 12 each; Vadnagar, Gandhinagar and Visnagar 11 each; Sami, Kathalal, Mahemdavad, Ghandinagar AWS, Modasa and Mc Ahmedabad ARG 10 each; Satlasana, Ahmedabad and Meghraj 9 each; Dascroi 8; Dholka, Lunawada, Kapadvanj, Wanakbori, Dholka ARG, Mahuva, Bayad, Chhota Udepur and Matar 7 each.

Saurashtra & Kutch: Bhachau-33; Morbi-23; MaliaMiana and Rapar 21 each; Dasada-19 ; Nakhatrana-17; Anjar-14 ; Dhrangadhra and Bhuj AP 13-each; Halvad and Kharaghoda 11 each; Gandhidham and Vanthali 9 each; Mundra, Lakhpat, Lalpur, New Kandla and Tankara 8 each; Kandla Airport and Mangrol (J) 7 each.

30.7.2015

West Rajastan: Marwar Junction and Pali 10 each; Bhinmal, Nokh, Dorimanna and Jaswantpura 9 each; Sojat-8; Bagoda, Phalodi Tehsil, Bhopalgarh and Ramgarh 7 each.

East Rajastan: Mount Abu-12; Sirohi-10 ; Bhim, Dungarpur Tehsil and Tatgarh 9 each; Pindwara-8 ; Abu Road, Deogarh, Asind and Hurda 7 each.

Gujarat region: Deodar-14; Vadali-10; Amirgadh, Idar and Bhiloda 9 each; Santalpur, Siddhpur, Khedbrahma, Palanpur and Harij 8 each; Vijaynagar and Unjha 7 each.

31.7.2015

West Rajastan: Nagaur Tehsil-13, Ladnoo-11, Khivensar, Nokha, Phalodi, Sujangarh and 8 each, Kolayat Magra, Jayal and Srivijaynagar-7 each

EAST RAJASTHAN: Vijaynagar and Ramgarhshekhatan-7 each

2.6 Cyclonic Storm Komen over the Bay of Bengal (26 July-02 August 2015)

2.6.1 Introduction

The cyclonic storm, KOMEN over the Bay of Bengal developed from a low pressure area which lay over northeast BoB and adjoining Bangladesh & Gangetic West Bengal on 25th July evening and concentrated into a depression over the same area in the morning of 26^{th} July. It followed a semi-circular track over northeast Bay of Bengal and then crossed Bangladesh coast between Hatia and Sandwip near lat. 22.5^0N and long. 91.4^0E during 1400 and 1500 UTC of 30^{th} July. After landfall, it moved initially north-northwestwards, then westwards and west-southwestwards across Bangladesh, Gangetic West Bengal and Jharkhand. It weakened gradually into a well marked low pressure area over Jharkhand and adjoining north Odisha and north Chhattisgarh at 1200 UTC of 02^{nd} August.

The salient features of this cyclone are as follows.

i. It was the fourth system during the monsoon month of July which intensified into a CS during the satellite era (1965-2015). Of the three systems before CS Komen, the CS in July 1972 & 1973 and the CS in July 1989 crossed Odisha and Andhra Pradesh coast respectively.
ii. The CS Komen had a unique track, as it developed near Bangladesh coast, followed a semi-circular track over the northeast Bay of Bengal and finally moved northward to cross Bangladesh 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.

2.6.2 Monitoring of CS, KOMEN

The CS KOMEN was monitored & predicted continuously since its inception by the India Meteorological Department (IMD). The forecast of its genesis (formation of Depression) on 26^{th} July., its track, intensity, point & time of landfall, as well as associated adverse weather like heavy rain, gale wind & storm surge were predicted well with sufficient lead time which helped the disaster managers to maximize the management of cyclone.

At the genesis stage, which occurred close to Bangladesh coast, the system was monitored mainly with surface observations from India, Bangladesh and Myanmar, supported by meteorological buoys and scatterometer based surface wind observations from satellite. As the system entered into the northeast Bay of Bengal moving southward away from the coast, it was monitored additionally by satellite observations 29th July early morning. It was also tracked by the Doppler Weather Radar (DWR) at Khepupara and Cox's Bazar (Bangladesh) throughout its life period.

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

2.6. 3. Brief life history

2.6.3.1. Genesis

Under the influence of active monsoon conditions, a low pressure area formed over northeast BoB and adjoining Bangladesh & Gangetic West Bengal on 25th evening. It persisted over the same region and concentrated into a depression at 0300 UTC of 26th July near lat 22.0^{0}N and long. 90.8^{0}E, close to Bangladesh coast.

The winds were stronger in southern sector (25-30 knots) under the influence of southwest monsoon current and were about 15-20 knots in northern sector. The vertical wind shear was low (5-10 knots) around the system centre. The low level relative vorticity was about 100-150 x 10^{-5} second^{-1} and low level convergence was 40 x 10^{-5} second^{-1}. The upper level divergence was 40 x 10^{-5} second^{-1}. The region of maxima in low level vorticity, low level convergence and upper level divergence lay to the southeast of system centre. As a result, maximum convection in association with the system lay to the southeast of the system centre.

2.6.3.2. Track and intensification

Best track parameters of cyclonic storm, KOMEN over BoB (26th July-2nd August, 2015) are given in Table 2.6.1. The observed track of the system is also shown in Fig.2.1

The environmental features as mentioned in the previous section continued during 26-30th July favouring the intensification of the system to a CS, Komen. However, it could not intensify further, as it interacted with the land surface and the Ocean thermal energy was less than 50 KJ/cm^{2}, though the sea surface temperature was about 31^{0}C. The large scale feature like Madden Julian Oscillation index lay over phase 2 (west equatorial Indian Ocean with amplitude less than 1 and hence it was not favourable for intensification. There was a cyclonic circulation to the north-northeast of the CS. It helped in dry air intrusion in the CS field which inhibited further intensification.

The Depression moved slowly westwards and lay centred at 1200 UTC of 26th July near lat. 22.0^{0}N and long. 90.5^{0}E. It remained stationary there till 0300 UTC of 28th and then moved slowly southwestwards and lay centred at 1200 UTC of 28th July near lat. 21.5^0N and long. 90.2^0E. It then moved southeastwards, intensified into a Deep Depression and lay centred at 0000 UTC of 29th July near lat. 21.0^0N and long. 91.0^0E. The Deep Depression moved east-northeastwards initially and then north-northeastwards till 1200 UTC of 29th July. It then moved nearly northward, intensified into a CS, KOMEN and lay centred at 1800 UTC of 29th July near lat. 21.6^0N and long. 91.4^0E. It continued to move nearly northwards and crossed Bangladesh coast between Hatia and Sandwip (near lat. 22.5^0N and long. 91.4^0E) during 1400 and 1500 UTC of 30th July. After the landfall it moved north-northwestwards and gradually weakened into a Deep Depression at 2100 UTC of 30th July over Bangladesh near lat. 23.0^0N and long. 91.0^0E, it then moved west-northwestwards and further weakened into a Depression at 1200 UTC of 31st July and lay centred over Bangladesh and adjoining Gangetic West Bengal near lat. 23.1^0N and long. 89.5^0E. It continued its west-northwestward movement till 1200 UTC of 1st August and then moved initially westwards and then west-southwestwards and weakened into a well marked low pressure area over Jharkhand and adjoining north Odisha and north Chhattisgarh at 1200 UTC of 02nd August.

The system was steered by the low to middle level monsoon circulation leading to a semi-circular path till 29th July. Thereafter, the anti-cyclonic circulation to the east of the system centre located over Myanmar and adjoining Bangladesh helped in providing northward steering current. As a result the CS, Komen moved nearly northward on 30th July till landfall. After that the system was steered by the Tibetan anti-cyclonic circulation and hence moved westwards. The anti-cyclonic circulation to the west of the system centre limited the translational speed of the cyclone towards the west on 31st July and further pushed the system west-southwestwards on 2nd August.

During the initial period of the CS, Komen, there was a deep depression over Gujarat, which moved north-northwestwards across Rajasthan and weakened gradually, while the depression over northeast Bay of Bengal moved south-southeastward and strengthened gradually. It needs therefore further investigation to find out the interaction, if any, between the deep depression over Gujarat/ Rajasthan and the deep depression over northeast Bay of Bengal.

Table 2.6.1 Best track parameters of cyclonic storm, KOMEN over the Bay of Bengal during 26 July- 2 August, 2015

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
26/07/2015	0000	22.0/90.8	1.5	994	20	3	D
	0300	22.0/90.8	1.5	994	20	3	D
	0600	22.0/90.5	1.5	994	20	3	D
	1200	22.0/90.5	1.5	994	20	3	D
	1800	22.0/90.5	1.5	994	20	3	D
27/07/2015	0000	22.0/90.5	1.5	994	20	3	D
	0300	22.0/90.5	1.5	994	25	4	D
	0600	22.0/90.5	1.5	994	25	4	D
	1200	22.0/90.5	1.5	994	25	4	D
	1800	22.0/90.5	1.5	994	25	4	D
28/07/2015	0000	22.0/90.5	1.5	994	25	4	D
	0300	22.0/90.5	1.5	994	25	4	D
	0600	21.8/90.3	1.5	994	25	4	D
	1200	21.5/90.2	1.5	994	25	4	D
	1800	21.3/90.6	1.5	992	25	4	D
29/07/2015	0000	21.0/91.0	2.0	990	30	5	DD
	0300	21.1/91.0	2.0	990	30	5	DD
	0600	21.2/91.1	2.0	990	30	5	DD
	1200	21.5/91.4	2.0	988	30	6	DD
	1800	21.6/91.4	2.5	986	35	7	CS
30/07/2015	0000	21.7/91.4	2.5	986	35	7	CS
	0300	22.0/91.4	2.5	986	35	7	CS
	0600	22.2/91.4	2.5	986	40	8	CS
	0900	22.3/91.4	2.5	986	40	8	CS
	1200	22.4/91.4	2.5	988	35	7	CS
	Crossed Bangladesh coast near longitude 91.4^{0}E during 1400-1500 UTC						
	1500	22.6/91.3	-	988	35	7	CS
	1800	22.8/91.1	-	988	35	7	CS
	2100	23.0/91.0	-	988	30	6	DD
31/07/2015	0000	23.1/90.0	-	990	30	5	DD

	0300	23.1/90.0	-	990	30	5	DD
	0600	23.1/89.8	-	992	30	5	DD
	1200	23.1/89.5	-	994	25	4	D
	1800	23.1/89.4	-	994	25	4	D
01/08/2015	0000	23.2/89.2	-	994	20	4	D
	0300	23.2/89.2	-	994	20	4	D
	0600	23.5/88.8	-	994	20	4	D
	1200	23.8/88.4	-	994	20	4	D
	1800	23.8/87.5	-	994	20	4	D
02/08/2015	0000	23.8/86.7	-	996	20	3	D
	0300	23.5/86.0	-	996	20	3	D
	0600	23.3/85.7	-	996	20	3	D
	0900	23.1/85.5	-	996	20	3	D
	1200	Well Marked Low over Jharkhand and adjoining north Odisha and north Chhattisgarh					

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

The MSW in association with a cyclone affecting Indian coasts is defined as the average surface wind speed over a period of 3 minutes measured at a height of 10 meters. The MSW is either estimated by the remotely sensed observations or recorded by the surface based instruments. As the CS, Komen developed over northeast Bay of Bengal and crossed Bangladesh coast near long. 91.4^0E, the surface observations as well as radar and satellite observations played crucial role in determining the MSW. The highest MSW has been estimated as 40 knots. However, Teknaf (Bangladesh) reported 55 knots (in the southeastern sector of the CS, Komen) in the early hours of 30^{th} July for a short period. It reported 76 kmph (40 kts) at 0600 UTC of 30th July. Maungdaw (48061) and Sittwe (47062) which lay to the southeast of the centre of the cyclonic storm reported maximum wind of 67 kt at 2300 UTC and 58 kt at 0400 UTC of 30th July respectively which may be due to the squall in association with the .cyclonic storm.

The lowest estimated central pressure has been 986 hPa. The MSLP of about 986.5 hPa has been reported from southeastern coast of Bangladesh, when the CS was moving northward close to that coast.

2.6.4 Climatological aspects

Climatologically, during the monsoon month of July, low pressure systems (LPS) forming over the BoB do not intensify into tropical cyclones as the mean area of formation lies over the head Bay of Bengal which is very close to land and the mean vertical wind shear is quite high. During the satellite era of last 50 years period (1965-2015) over BOB, only three LPS intensified into cyclones. The tracks of these three cyclones are shown in Fig. 2.6.1. All these three systems crossed coast as a CS. All the three systems, intensified into CS and maintained the intensity of CS for a short duration of time for about a day, tracked along the climatological track of west-northwest to northwestwards towards Odisha and north Andhra Pradesh coasts before landfall.

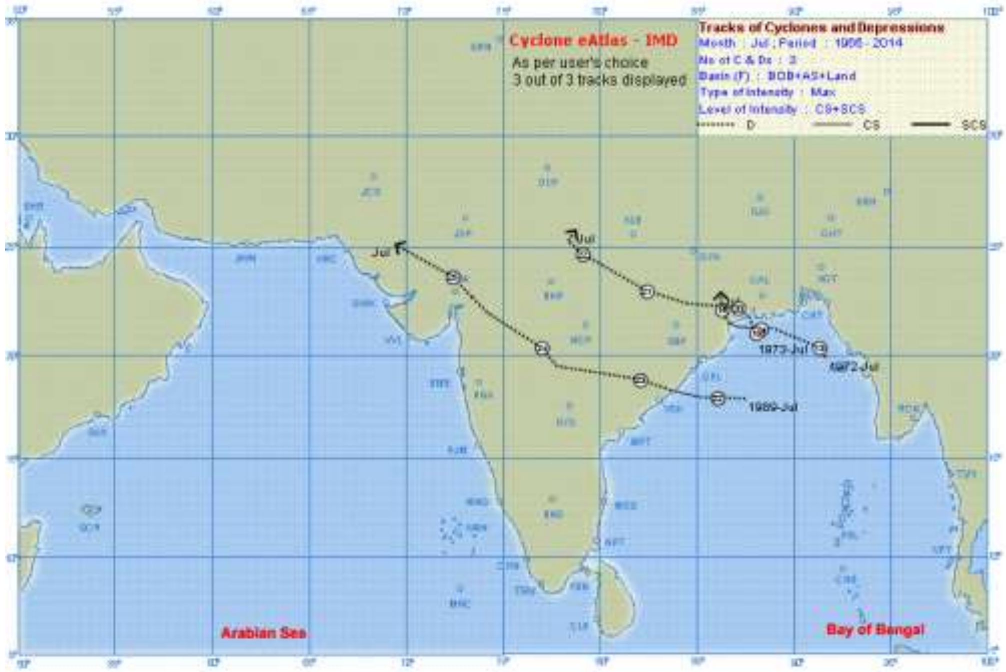


Fig. 2.6.1 Tracks of tropical cyclones over BOB during the month of July in the period 1965-2015

2.6.5 Features observed through satellite

Half hourly Kalpana-1 and INSAT-3D imageries were utilised for monitoring of CS, Komen. Satellite imageries of international geostationary satellites Meteosat-7 and MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical satellite INSAT-3D imageries (visible, IR, IRBD and enhanced colour imageries) of CS Komen representing the life cycle of the cyclone are shown in Fig.2.6.2- 2.6.5

According to INSAT-3D imageries and products, the system was seen as a low level cyclonic circulation on 26th July when the system was declared as a depression based on synoptic observations. It got organized on 27th and acquired shear pattern with T 1.0 at 27/0300 UTC and the intensity was increased to T 1.5 at 28/0300 UTC. The distance between centre and cloud mass imagery was 100 km and the cloud mass was sheared to the southeast of the centre of low level circulation. The intensity was upgraded to T2.5 at 29/2100 UTC corresponding to 35 knots. At 31/0300 UTC, it indicated that the storm was over land.

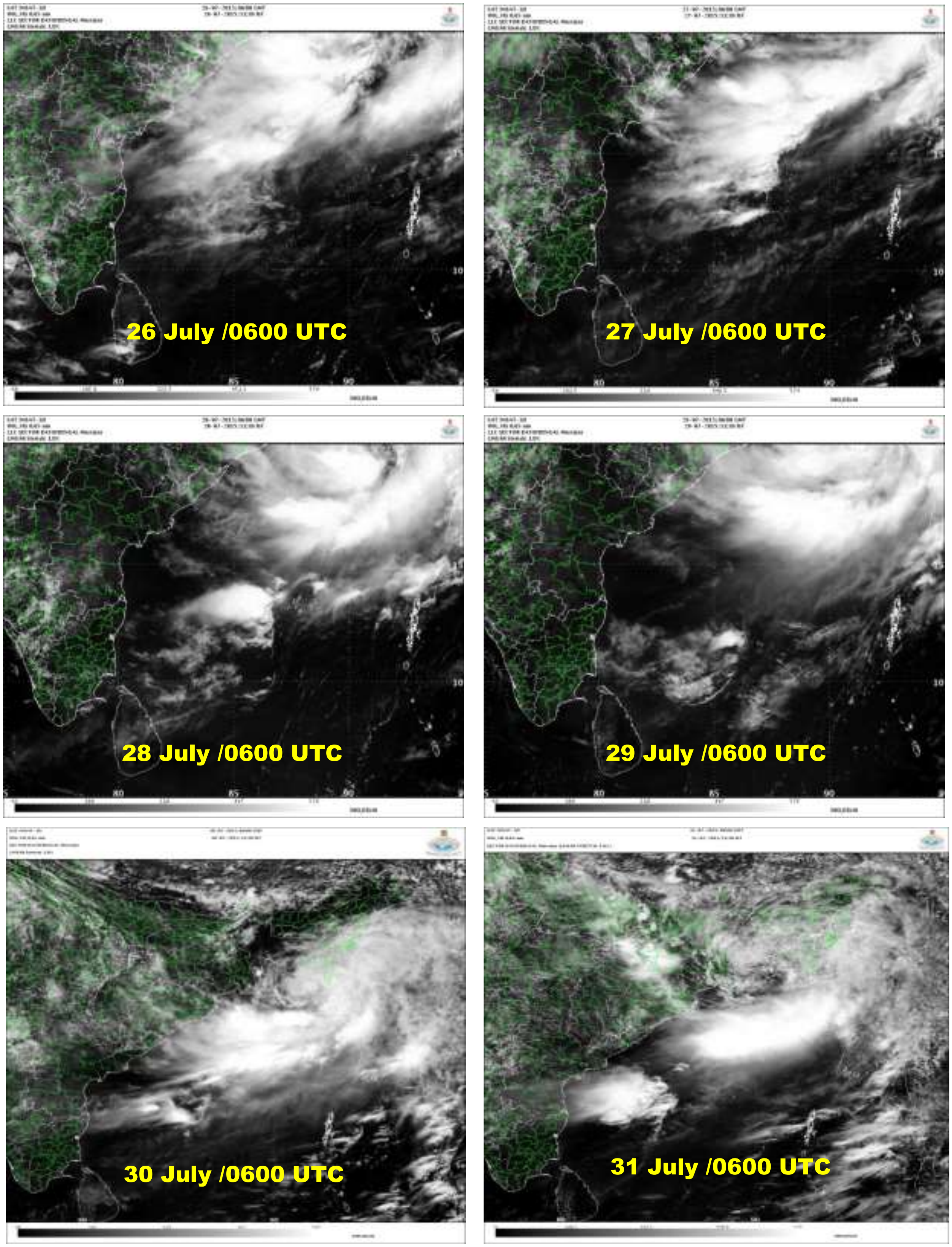


Fig2.6.2 (a)INSAT-3D Visible imageries of CS Komen over Bay of Bengal during 26 July – 31July 2015

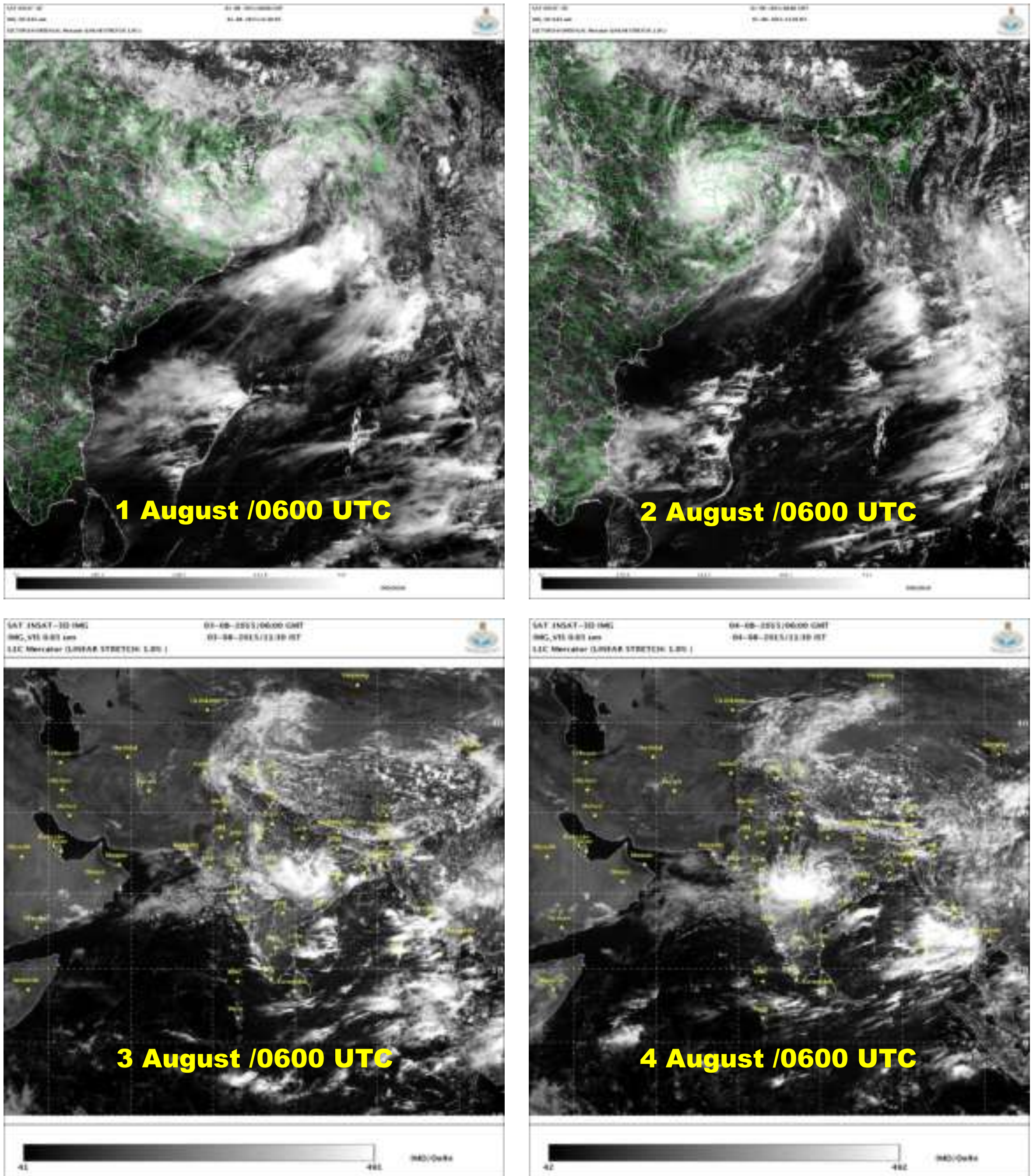


Fig2.6.2 (a) contd.INSAT-3D Visible imageries of CS Komen over Bay of Bengal during 01 August – 04 August 2015

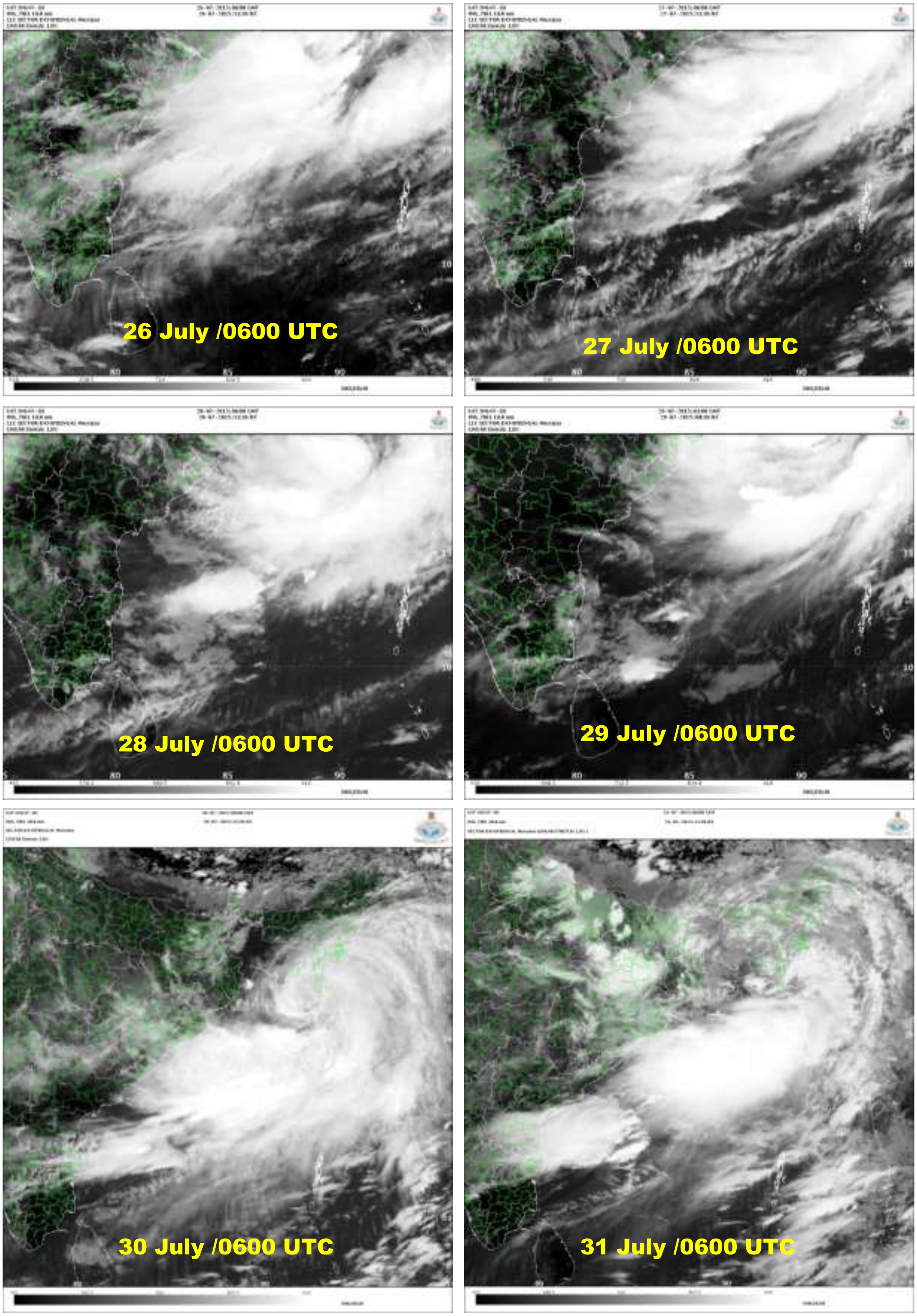


Fig. 2.6.3 (a) INSAT-3D IR imageries of CS Komen over Bay of Bengal during 26 July – 31 July 2015

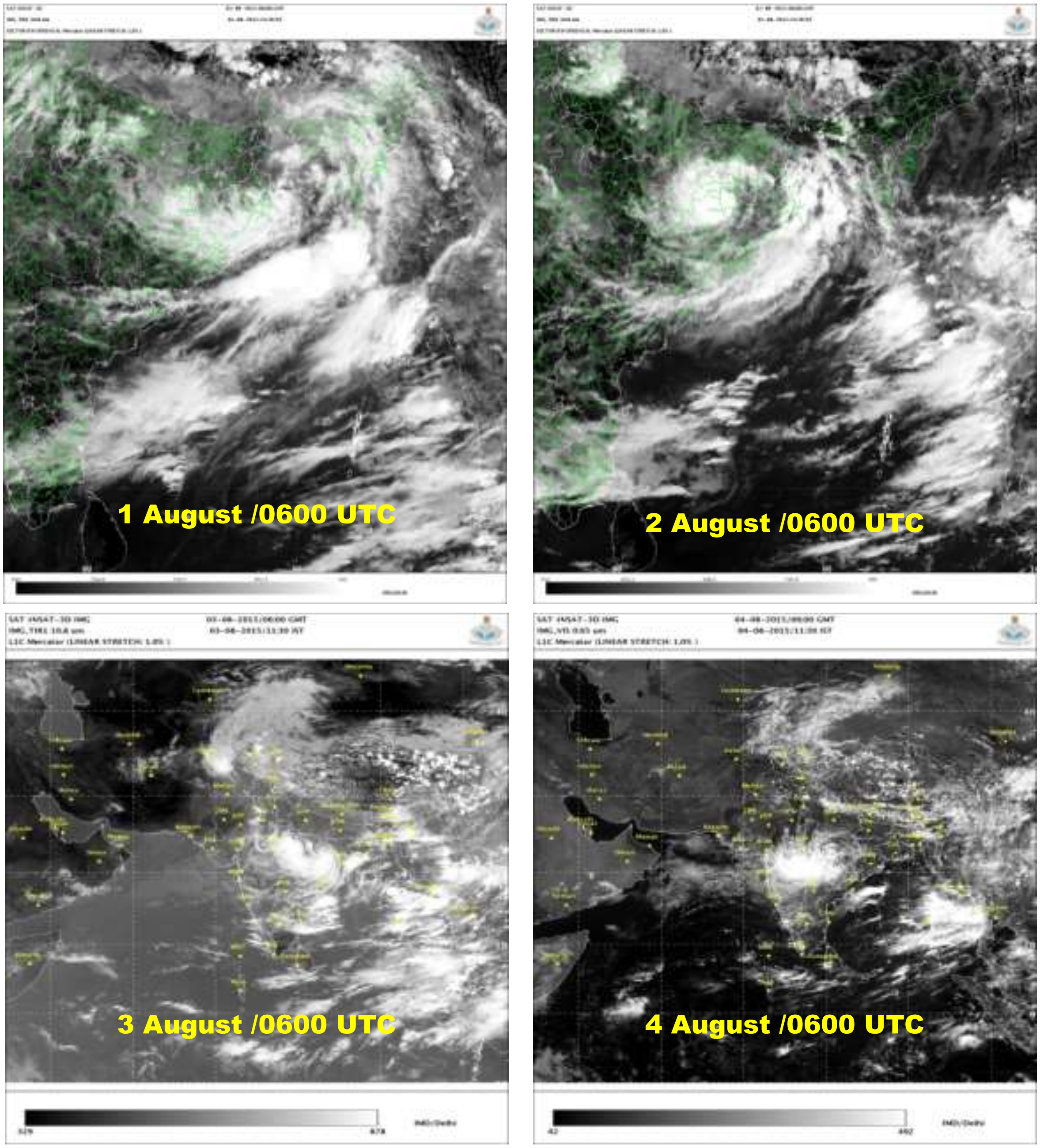


Fig. 2.6.3 (b) contd. INSAT-3D IR imageries of CS Komen over Bay of Bengal during 26 July – 4 August 2015

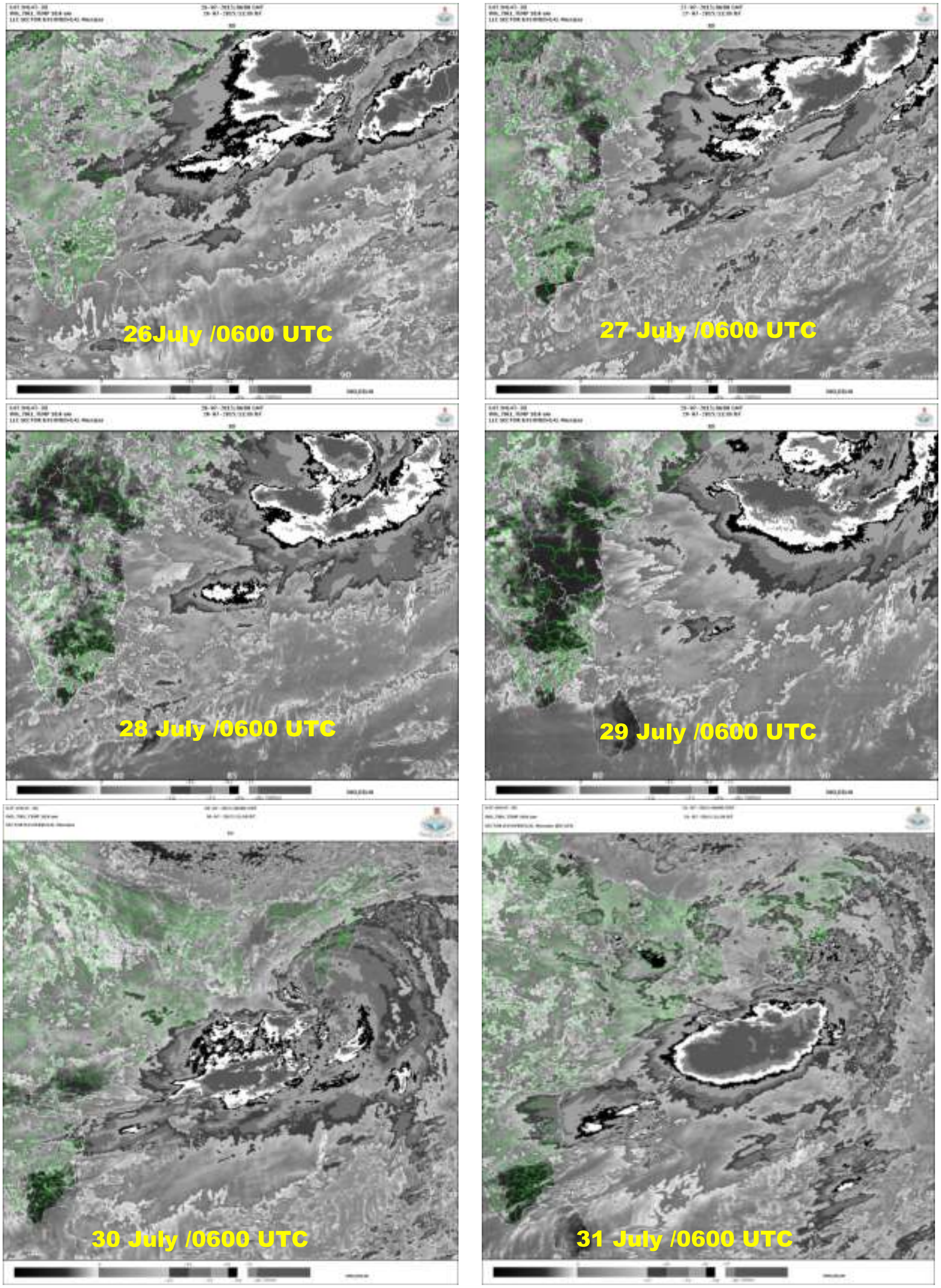


Fig. 2.6.4 (a) INSAT-3D enhanced IR imageries of CS Komen over Bay of Bengal during 26 July – 4 August 2015

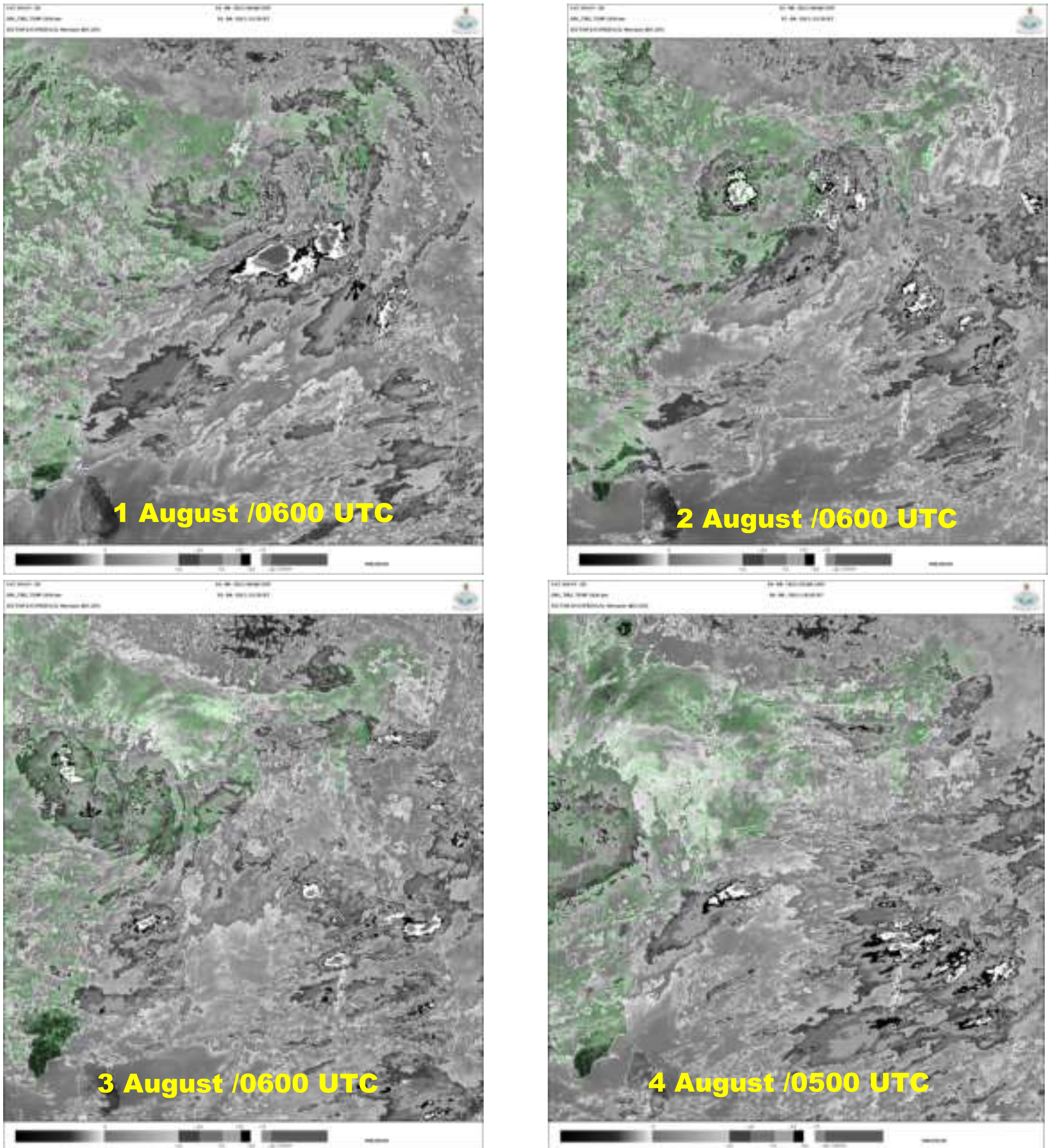


Fig. 2.6.4 (b) contd. INSAT 3D enhanced IR imageries of CS Komen over Bay of Bengal during 26 July – 4 August 2015

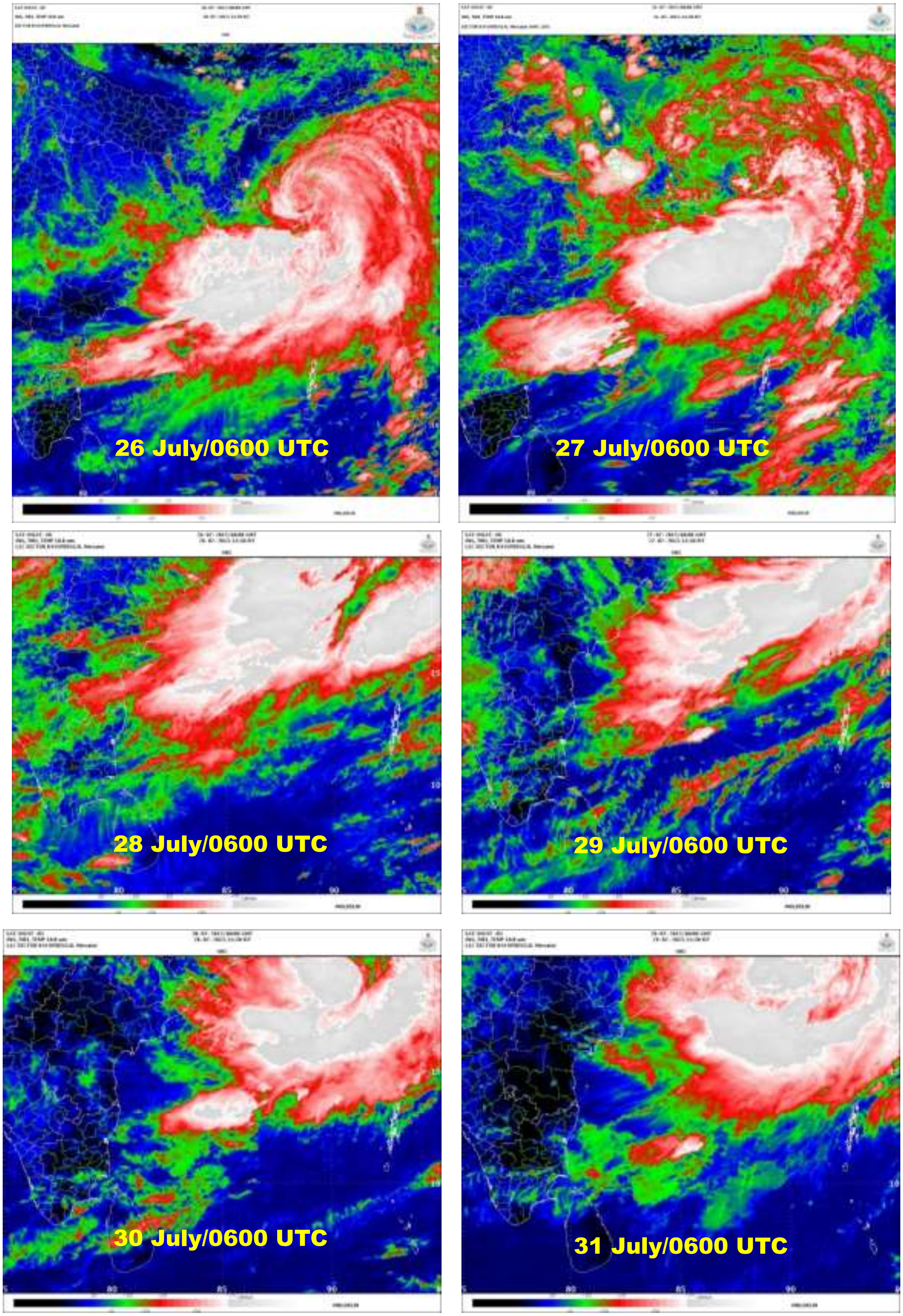


Fig. 2.6.5 (a) Enhanced colour INSAT-3D imageries of CS Komen over Bay of Bengal during 26–31 July 2015

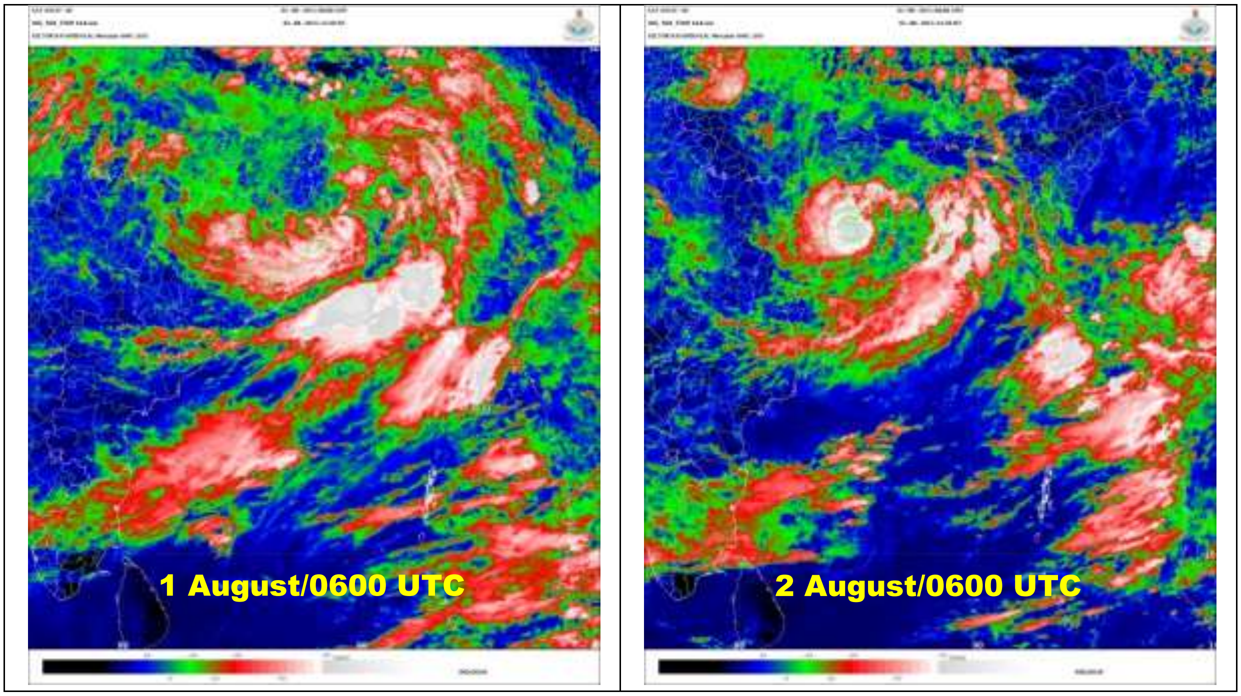


Fig. 2.6.5 (b) contd. Enhanced colour INSAT-3D imageries of CS Komen over Bay of Bengal during 1–2 August 2015

2.6.6. Features observed through Radar

On 29th and 30th, when the system was well within the radar range of DWRs at Cox's Bazar and Khepupara (Bangladesh), it was tracked continuously by these radars. The system showed spiral band structure with an ill-defined eye. The DWR observations from Khepupara and Cox's Bazar indicated well defined circulation with strong banding feature in southern semi circle similar to the features observed through satellite. There was weak banding in the northern sector, as long as the CS over the Sea. When the system was over the sea, maximum convection was observed in the southeastern sector. However, as the system approached the coast and after coastal crossing, convection shifted to the southwestern sector. Fig.2.6.6 shows the Constant Altitude Plan Position Indicator (CAPPI) imageries of (a) Cox's Bazar (at about 14 & 17 UTC of 29th and 10 and 12 UTC of 30th) and (b) Khepupara radars (at about 0530 and 15 UTC of 29th and 1130 UTC of 30th).

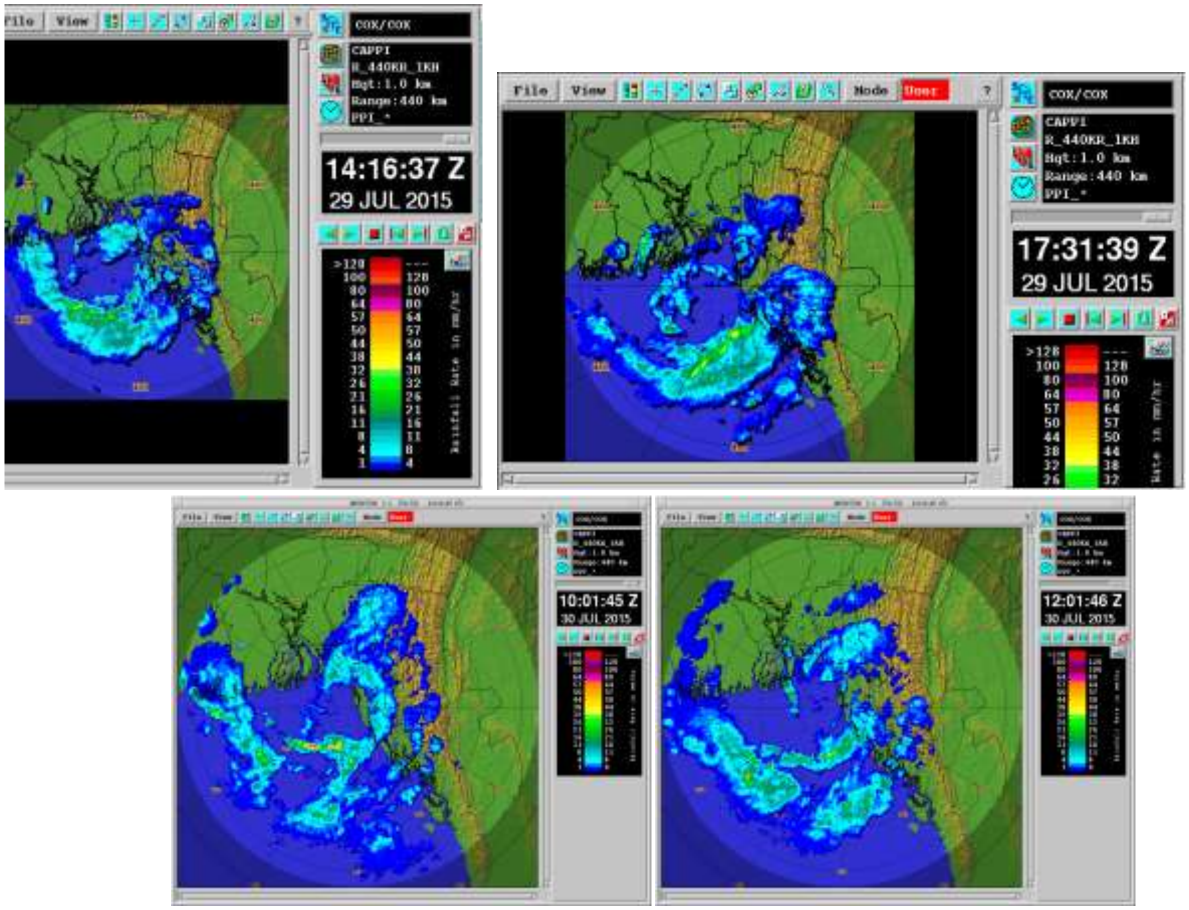


Fig. 2.6.6 (a) CAPPI imageries of Cox's Bazar (Bangladesh) at about 1416 & 1730 UTC of 29th and 1000 and 1200 UTC of 30th

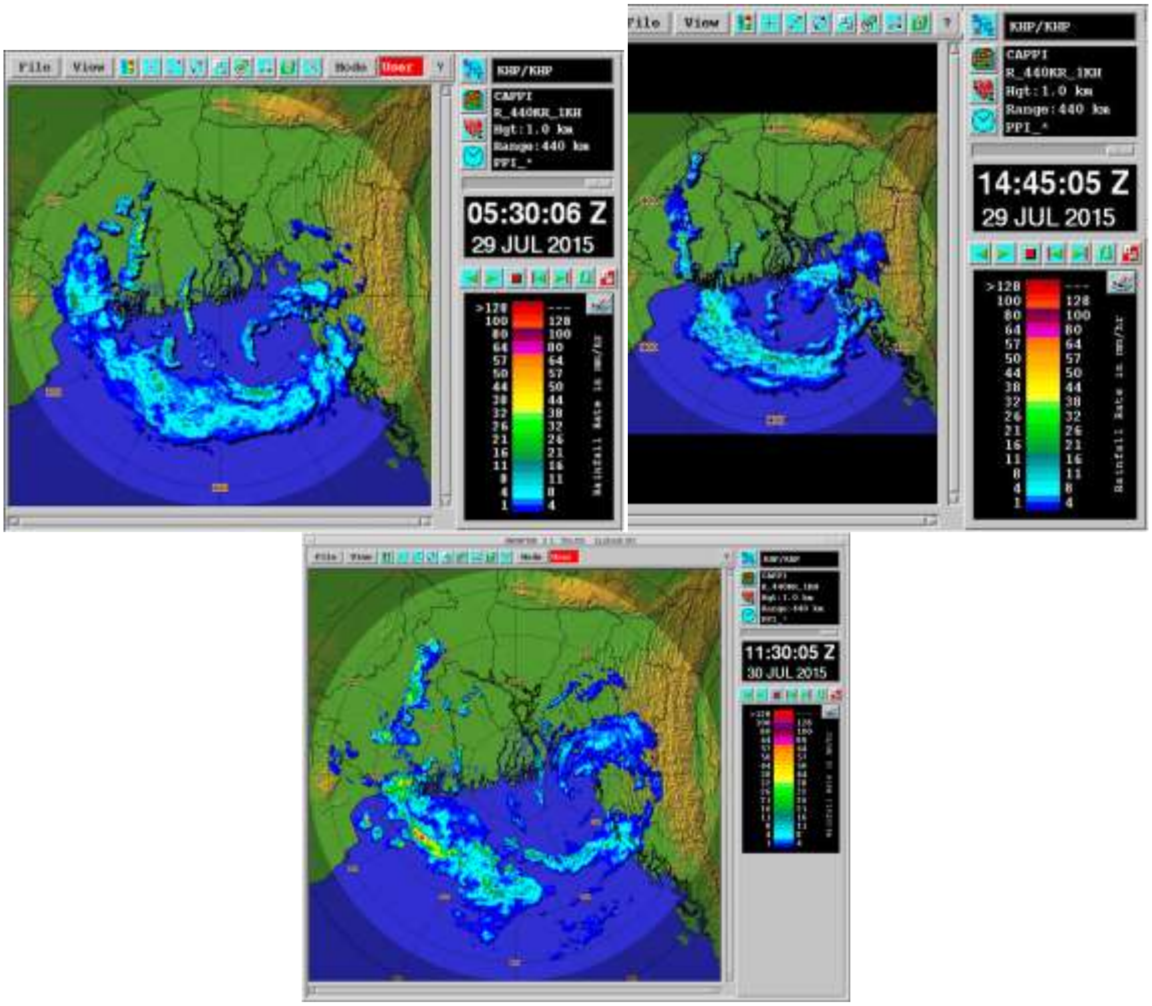


Fig.. 2.6.6 (b) CAPPI imageries of Khepupara (Bangladesh) at about 0530 & 1445 UTC of 29th and 1130 UTC of 30th

2.6.7. Dynamical features

To analyse the dynamical features, the IMD-GFS model analyses based on the initial conditions of 0000 UTC of 27-31 July are shown in Fig 2.6.7(a-c). It is observed that the model could very well simulate the genesis and intensification though there was under-estimation of the intensity. Further it could simulate the track well and establish the interaction between the depression over Rajasthan and CS, Komen over the Bay of Bengal. It could simulate the gradual north-northwest movement and later the northeastward movement of the Depression over Rajasthan along with gradual initial intensification and weakening in the later stage during the period of 27-31 July 2015. During the same period, the opposite trend in intensification and movement of CS, Komen could also be simulated by the model. Further, the model could simulate the higher wind speed in the southern sector and relatively less wind in the northern sector of Komen, while it was over the sea. However, the unique track showing the semi-circular movement over the Bay of Bengal could not be simulated very well. Further, the model could not simulate the cyclonic circulation lying to the northeast of the system centre on 29th and 30th July, which helped in dry air incursion into the system and hence limited its further intensification. It also failed to simulate the anti-cyclonic circulation in middle and upper tropospheric level over Myanmar and Bangladesh which helped in steering the system northward on 30th July.

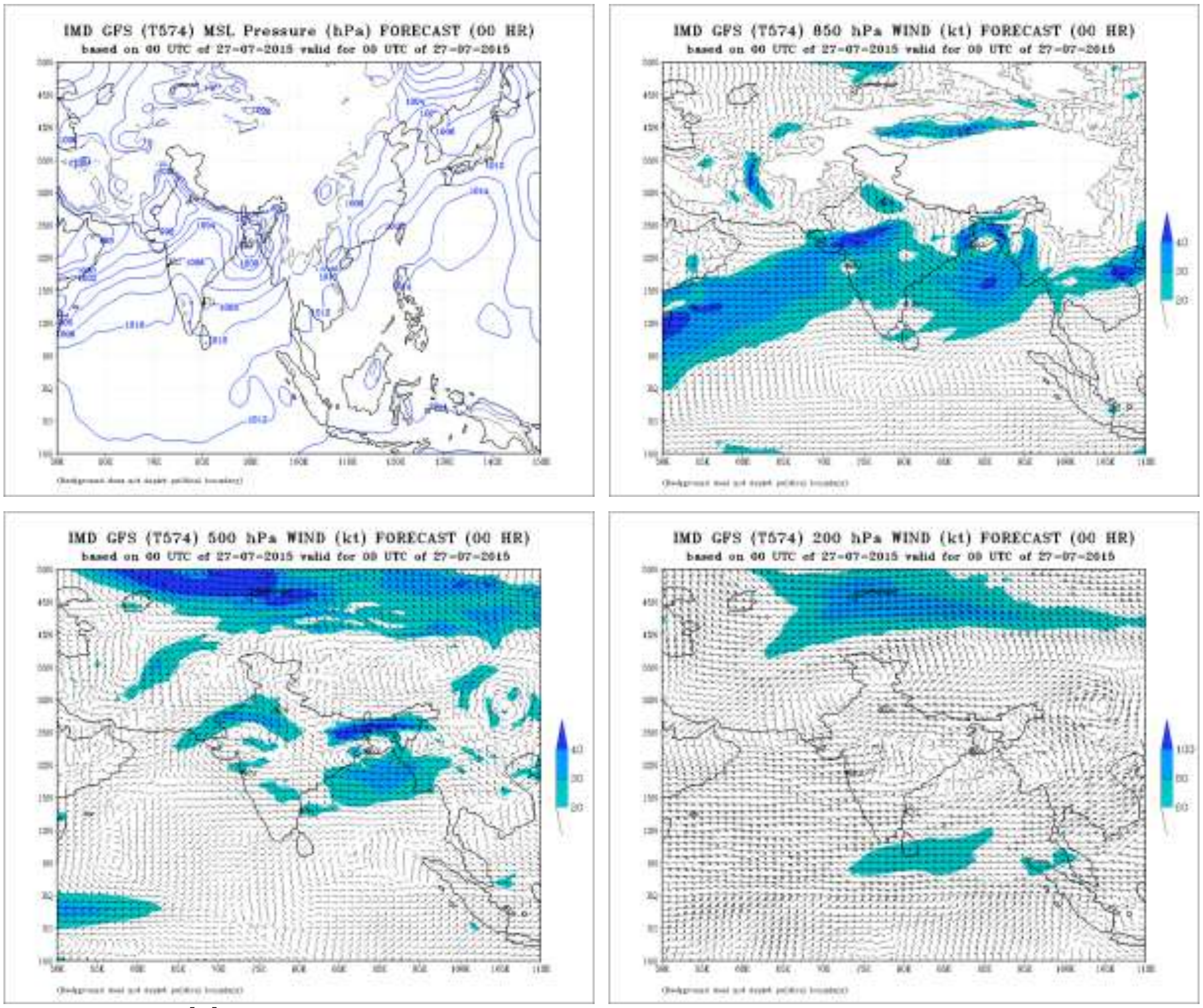


Fig 2.6.7 (a) IMD-GFS analyses of MSLP, winds at (a) 850 hPa, (b) 500 hPa and (c) 200 hPa levels based on 0000 UTC of 27th July, 2015

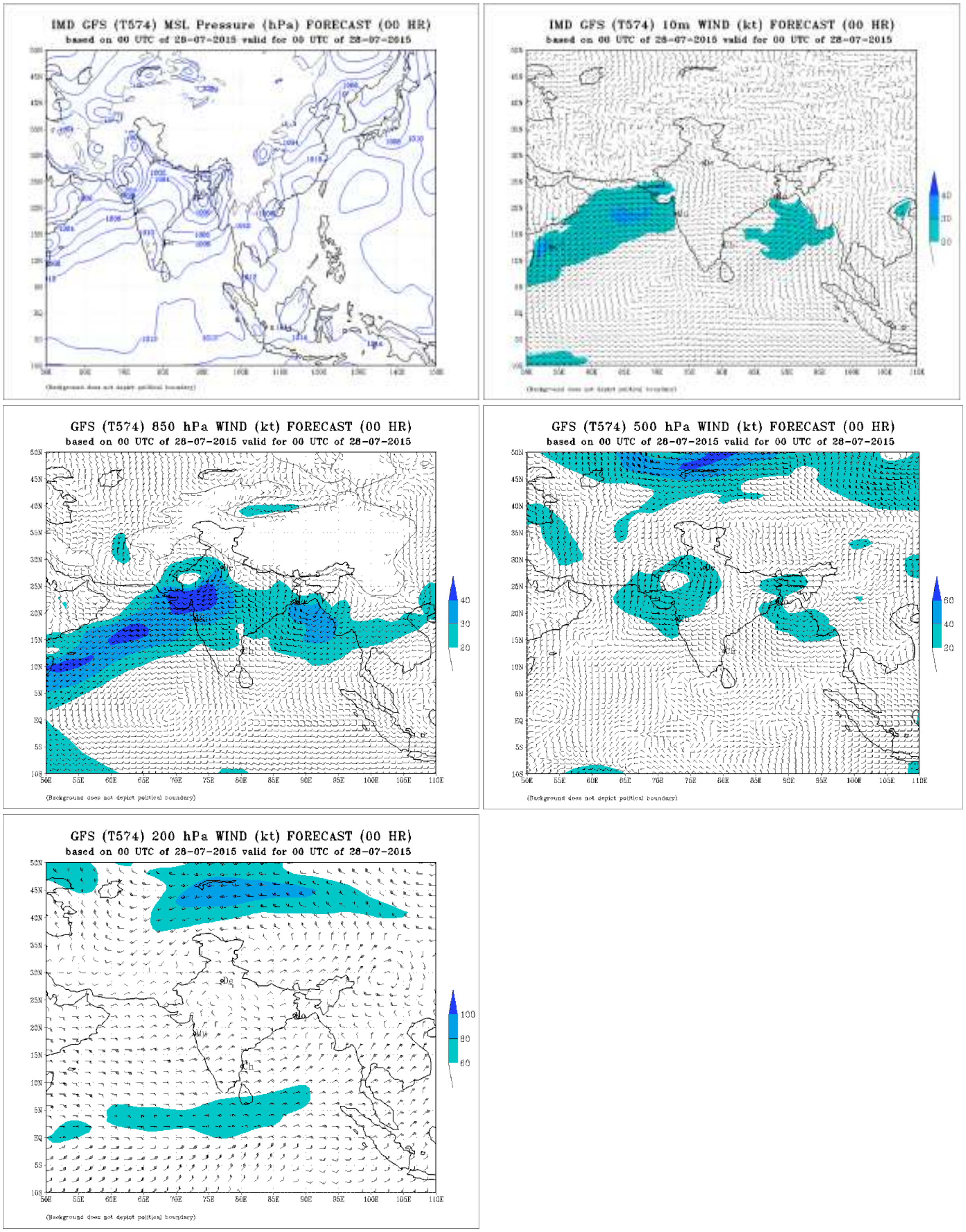


Fig 2.6.7 (b) IMD-GFS analyses of MSLP, 10 metre wind, winds at (a) 850 hPa, (b) 500 hPa and (c) 200 hPa levels based on 0000 UTC of 28th July, 2015

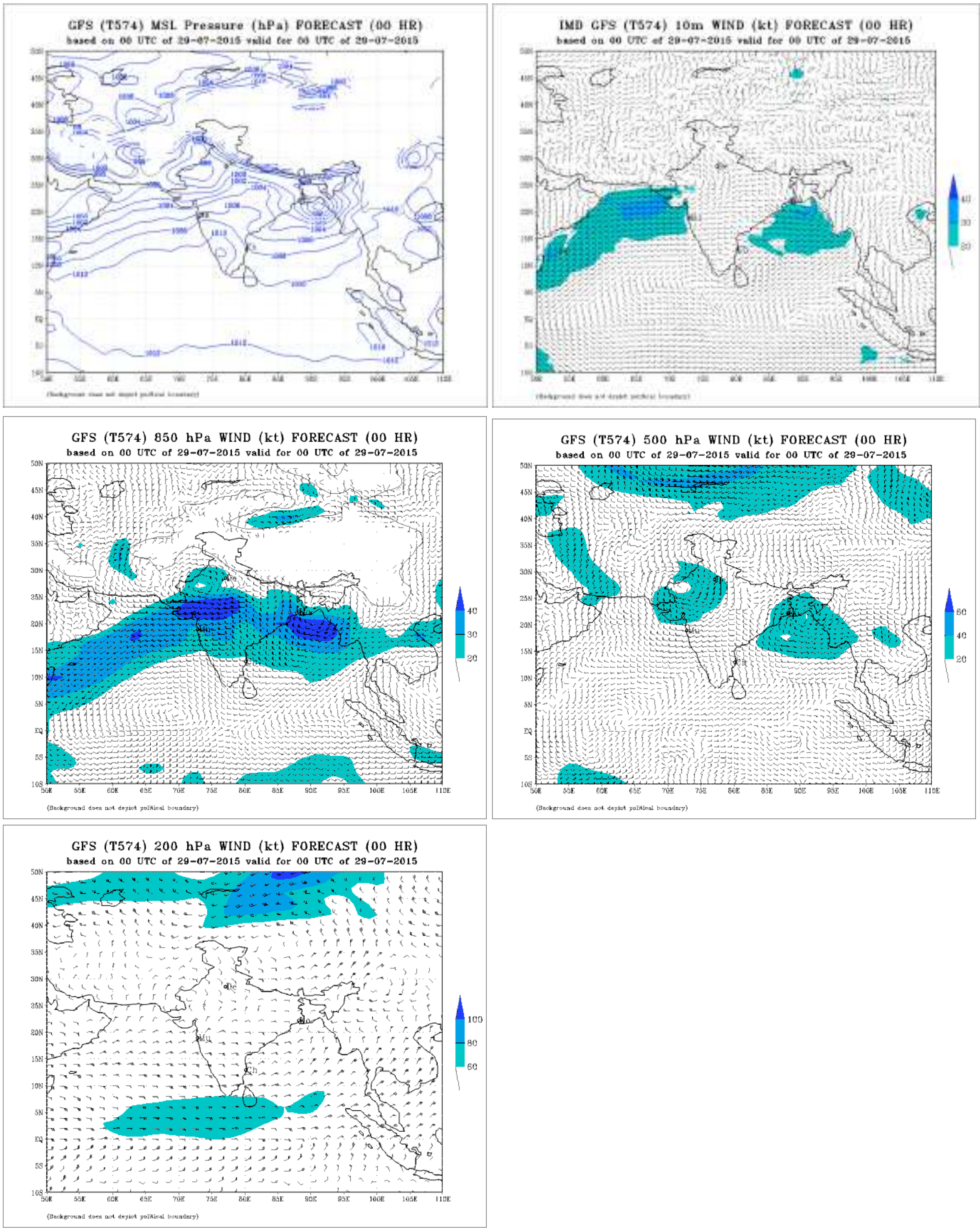


Fig 2.6.7 (c) IMD-GFS analyses of (a) MSLP, 10 metre wind and winds at (b) 850 hPa ,(c) 500 hPa & (d) 200 hPa levels based on 0000 UTC of 29th July, 2015

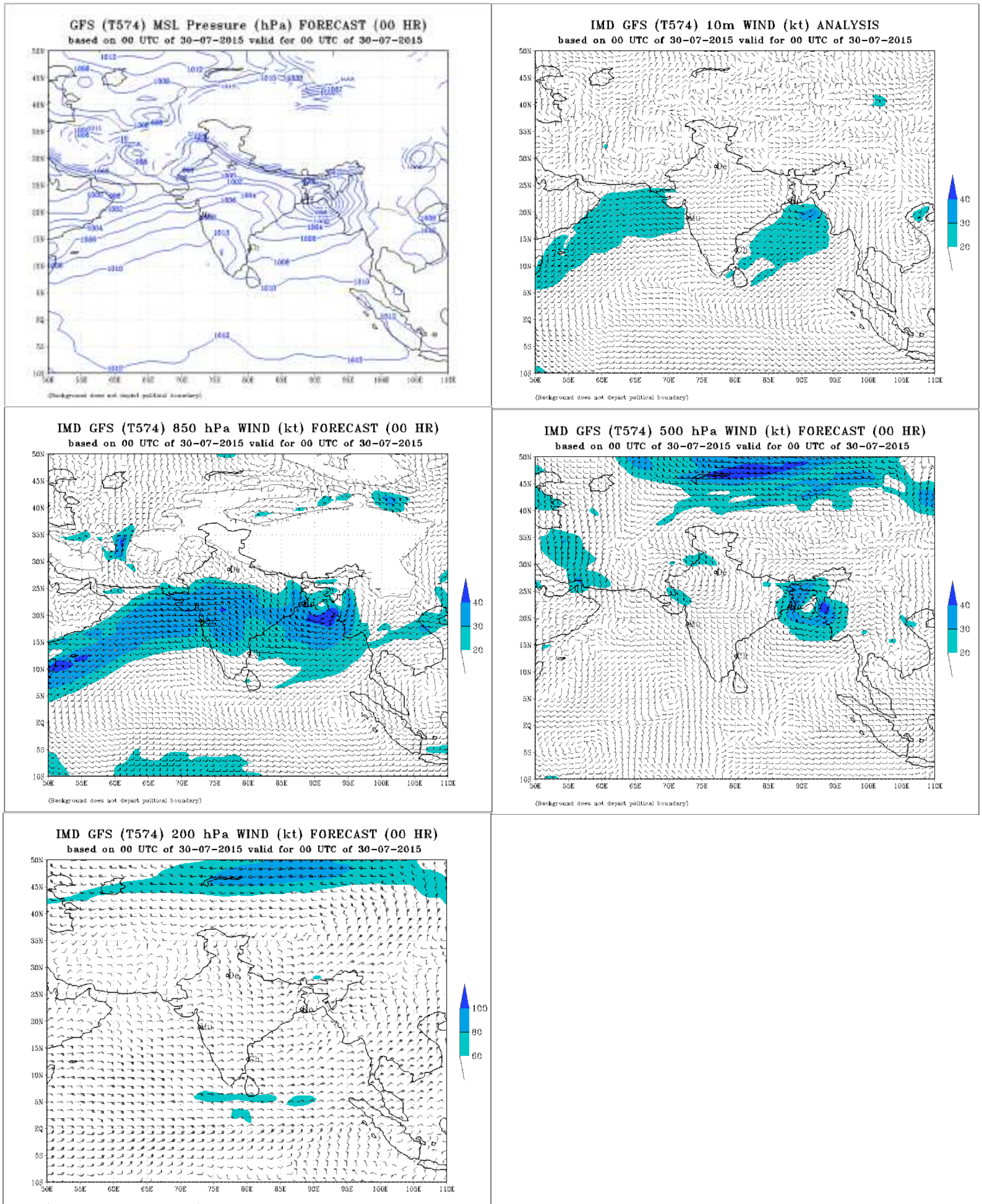


Fig 2.6.7 (d) IMD-GFS analysis of (a) MSLP, (b) 10m wind, winds at (c) 850 hPa,(d) 500 hPa & (e) 200 hPa levels and based on 0000 UTC of 30th July, 2015

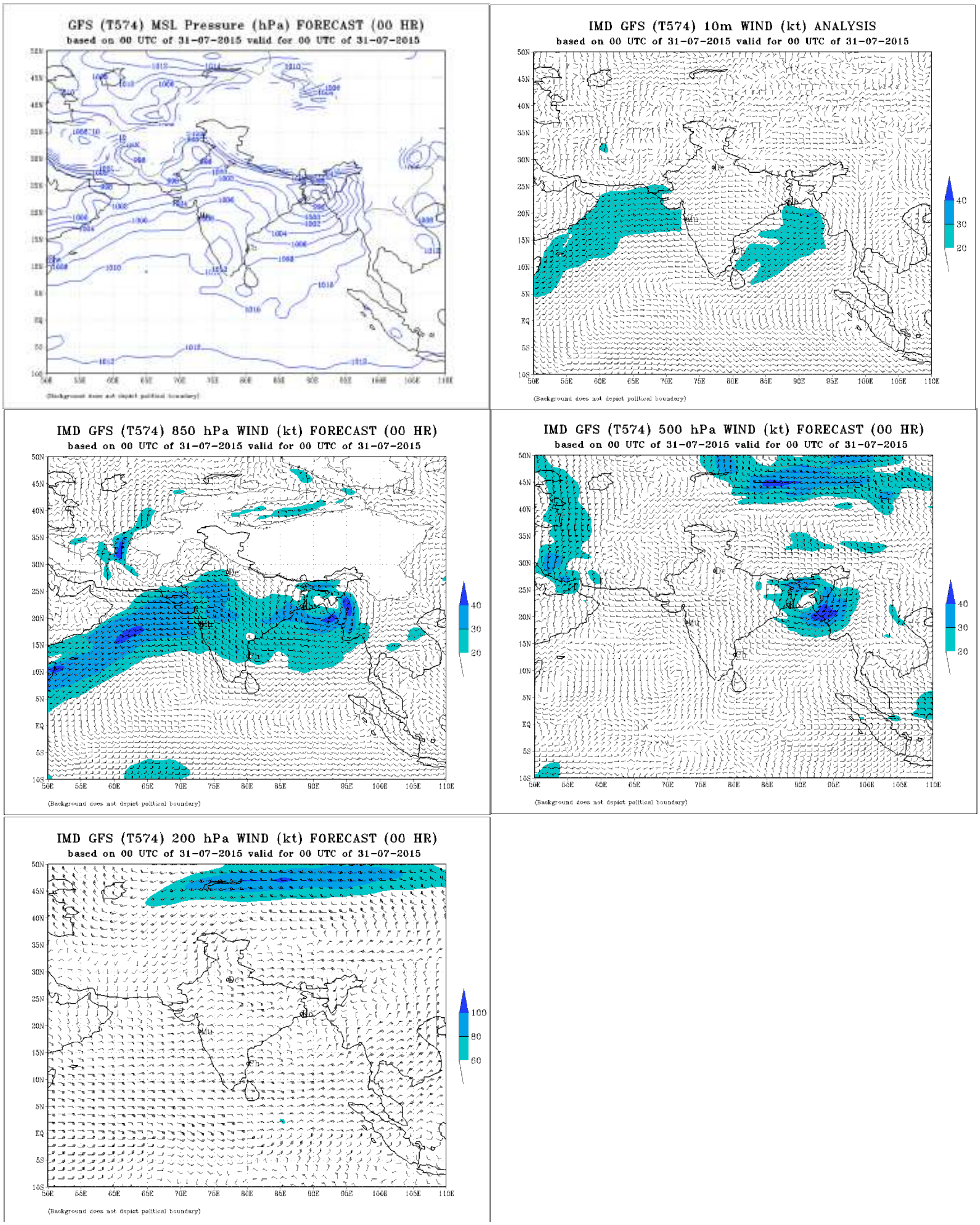


Fig 2.6.7 (e) IMD-GFS analysis of (a) MSLP, (b) 10m wind, winds at (c) 850 hPa, (d) 500 hPa & 200 hPa levels and based on 0000 UTC of 31st July, 2015

2.6.8. Realized Weather:

2.6.8.1 Heavy rainfall due to KOMEN:

The CS Komen caused heavy to very heavy rainfall in Myanmar during 26-31 July and heavy rainfall in Bangladesh during 28 - 30 July 2015.

The Cyclonic storm also caused isolated heavy to very heavy rainfall over Odisha, Gangetic West Bengal, Jharkhand, Nagaland, Manipur, Mizoram, Tripura, Assam, Meghalaya, Arunachal Pradesh, East Madhya Pradesh and Chhattisgarh. The chief amounts of past 24 hr rainfall realised (≥ 7 cm) ending at 0300 UTC of date during the period of CS KOMEN are furnished below:

(Description of rainfall terminologies: Heavy: 64.5 to 124.4 mm; Very Heavy: 124.5 to 244.4 mm and Extremely Heavy: ≥244.5 mm) as well as spatial distribution [Isolated (ISOL): (1-25% of stations reporting rainfall); Scattered (SCT / A few places) : 26-50% of stations reporting rainfall; Fairly Widespread (FWS/ Many places): 51-75% of stations reporting rainfall; Widespread (WS/ Most places): 76-100% of stations reporting rainfall during the last 24 hours ending at 0300 UTC of every day).

26th July, 2015: (Rainfall in centimeter)

India

Nagaland, Manipur, Mizoram & Tripura: Bungtlang (ARG)-11, Chhuarllung (ARG)-9

Gangetic West Bengal: Dhaniakhali ARG-10, Canning-9, Uluberia, Kansabati Dam & Harinkhola-8 each and Bagati-7.

Odisha: Mandira Dam-9, Khandapara-9, Kuchinda-8 and Danagadi ARG & Panposh-7 each.

Bihar: Dehri-10.

Myanmar

Ann 21, Maungdaw 19, Sittwe & Myauk U 18 each, Kyauktaw 17, Paletwa 15, Kyaukpyu 14, Thandwe & Mawlamyine 12 each, Taungkok, Khayan & Kyeikkhame 11 each, Thaton, Myaungmya & Ngathyinechang 9 each, Pinlaung 8, Mudon, Shwegyin, Hakha, Nyaung Lay Bin & Phyarpon 7 each.

27 July 2015

India

Nagaland, Manipur, Mizoram & Tripura: Sabroom-9 And Bungtlang (Arg)-7

Gangetic West Bengal: Bankura (CWC)-14, Kansabati Dam, Phulberia & Bankura-10 each and Kharidwar-9.

Odisha: Lahunipara-17, Jamankira-15, Deogarh-12, Banaigarh AWS & Keiri AWS-11 each, Tensa & Rengali-10 each, Naktideul, Reamal, Chendipada, Barkote & Chandanpur-9 each, Batagaon, Karanjia, Kujanga ARG & Kaniha ARG-8 each and Marsaghai ARG, Swam-Patna, Joda ARG, Ghatagaon, Chandbali, Pallahara & Rairakhol-7 each.

Jharkhand: Nimdih & Chandil-8 each and Jamshedpur-7.

Myanmar

Myauk U 30, Sittwe & Kyauktaw 20 each, Maungdaw & Khayan 18 each, Gwa 16, Thandwe 15, Paletwa 14, Hakha 13, Launglon & Taungkok 10 each, Kyeikkhame & Kyopinkauk 9, Hpa-An, Yay, Kyaukpyu, Belin, Kalay & Gangaw 8 each and Phyu 7.

28th July, 2015:

India

Gangetic West Bengal: Purihansa-24, Tusuma-13, Purulia-12, Simula-11, Kharidwar-9 and Phulberia-7.

Odisha: Tiring-23, Rairangpur-21, Balikuda ARG-19, Tirtol ARG-18, Dhamnagar ARG, Paradeep CWR, Binjharpur ARG & Salepur ARG-17 each, Kujanga ARG, Marsaghai ARG & Korei ARG-16 each, Kendrapara, Raghunathpur ARG, Garadapur ARG, Jagatsinghpur AWS, Swam-Patna, Banki ARG, Pattamundai, Jajpur & Jenapur-15 each, Joshipur & Karanjia-14 Each, Nawana, Derabis ARG, Bonth & Chandanpur-13 each, Bari ARG, Mahanga ARG, Danagadi ARG & Daitari-12 each , Bhuban ARG & Anandpur-11 each, Thakurmunda-10, Alipingal, Tihidi ARG, Hindol, Kantapada ARG & Ghatagaon-9 each, Mandira Dam, Betanati ARG, Sukinda & Kakatpur-8 each and Kaniha ARG, Rajkanika & Bangiriposi-7 each.

Jharkhand: Jamshedpur AERO-20, Ghatsila-10, Putki & Topchanchi-9 each, Nimdih & Nandadih-8 each and Dumka & Dumri-7 each.

Bihar: Sheikhpura-9

Myanmar

Sittwe 13, Phyu 12, Taungkok 11, Thieinzayet & Thaton 10 each, Hmawbi, Kyopinkauk, Zaungtu, Mudon & Khayan 9 each.

Bangladesh

Noakhali 12, Barisal 10, Teknaf, Chandpur 7.

29th July, 2015:

India

Gangetic West Bengal: Uluberia-21, Tamluk (AWS)-19, Contai-14, Dhaniakhali (ARG)-11, Harinkhola-10, Labpur-9, Narayanpur & Sri Niketan-8 each.

Odisha: Chandanpur-16, Rairangpur & Bhograi-13 each, Bangiriposi-12, Nawana-10, Jaleswar-7.

Jharkhand: Ghatsila-15, Dhanbad-10, Sarath-8, Dumka-7.

Myanmar

Thieinzayet 22, Kyeikkhame & Paletwa 16 each, Thandwe 13, Hmawbi & Phyarpon 11 each, Kabaaye & Loikaw 10 each, Taungkok, Sittwe & Hakha 9 each, Kyaukpyu 8

Bangladesh

Barguna 11, Barisal 10, Teknaf 9, Patuakhali 7.

30th July, 2015:

India

Gangetic West Bengal: Manteswar-20, Harinkhola-19, Salar-11, Amtala, Dhaniakhali ARG & Burdwan (PTO)-9 each, Murarai, Contai, Narayanpur & Mangalkote-8 each and Durgachack-7.

Myanmar

Kyeikkhame 24, Hmawbi 23, Phyu 19, Paletwa, Thieinzayet 17, Kabaaye 15, Loikaw, Pinlaung 14, Phyarpon, Mindat 13, Kyopinkauk 12, Thandwe, Manaung, Myauk U 9, Taunggu(Aviation Met.), Thaton, Shwegyin 8 each, Mingalardon and Mudon 7 each.

Bangladesh

Teknaf 12, Khulna 11, Satkhira 8.

31st July, 2015:

India

Nagaland, Manipur, Mizoram & Tripura: Chhuarllung (ARG)-14, Bungtlang (ARG)-13.

Gangetic West Bengal: Digha & Hetampur-8 each.

Odisha: Bhograi-8.

Jharkhand: Maheshpur-17, Dumka & Jarmindi-15 each, Moharo & Sarath-9 each and Giridih, Topchanchi, Jamtara & Messenjore-7each.

Myanmar

Bago 23, Paletwa 22, Thieinzayet 21, Mindat 20, Kyeikkhame 18, Kabaaye 17, Loikaw 16, Khayan 14, Kyopinkauk, Myauk U, Manaung 11, Mudon 10, Katha 9, Launglon, Myaungmya, Heho 8.

01st August, 2015:

India

Assam & Meghalaya: Cherrapunji (RKM)-15, Cherrapunji-9 and Shillong C.S.O. & Shillong (AWS)-7 each.

Nagaland, Manipur, Mizoram & Tripura: Thoubal (AWS) & Imphal T AERO-9 each.

Gangetic West Bengal: Contai-16, Basirhat (PT)-15, Kolkata (Alipore) & Kolkata (Dum Dum)-13 each, Barrackpur (LAF) & Mohanpur-10 each, Burdwan (PTO), Midnapore (CWC), Midnapore & Canning-9 each, Durgapur & Phulberia-8 each and Hetampur, Dhaniakhali (ARG), Asansol (CWC), Kalyani SMO, Suri (CWC), Tusuma, Panagarh (LAF), Tilpara Barrage, Mangalkote, Mankar & Bankura (CWC)-7 each.

Jharkhand: Dumri-13, Hazaribagh-9, Panki, Kuru & Messenjore-8 each, Daltonganj & Sarath-7 each.

Bihar: Buxar-11, Indrapuri-10, Daudnagar-9, Jalalpur & Bodh Gaya-8 each, Hathwa & Dehri-7 each.

02nd August, 2015:

India

Gangetic West Bengal: Mangalkote-11, Narayanpur & Burdwan (PTO)-9 each, Mankar-8 and Sri Niketan, Murarai, Harinkhola & Bankura (CWC)-7 each.

Odisha: Khairamal-10, Jujumura ARG-8, Kantapada ARG-7.

Jharkhand: Deoghar, Putki and Koner-11 each, Ramgarh, Barkisuriya & Barhi-10 each, Mandar-9, Rajdhanwar, Jarmindi, Pathalgada, Dhanbad, Hindgir & Tenughat-8 each and Lohar-Daga, Moharo, Chatra, Bokaro, Giridih, Papunki, Hazaribagh, Jamtara, Sarath and Jaridih-7 each.

Bihar: Rajauli-8, Nawada -7.

03rd August, 2015:

India

Arunachal Pradesh: Wakra (ARG)-11, Tezu-9, Passighat-7

Odisha: Bargaon-23, Jharsuguda, Rajgangpur& Lakhanpur ARG-19 each, Deogaon, Mandira Dam & Sundargarh-17 each, Kirmira ARG & Ambabhona-16 Each, Laikera-14, Hemgiri-13, Panposh-12, Kolabira ARG-9, Atabira ARG & Balisankara ARG-8 each and Bonth-7.

Jharkhand: Raidih-14, Kurdege-12, Bagodar I-11, Kuru, Hazaribagh & Simdega-10 Each, Daltonganj-8 and Palkot, Lohar-Daga, Torpa & Latehar-7 each.

East Madhya Pradesh: Mandla-AWS-13, Nagode-7.

Chhattisgarh: Raigarh-22, Gharghoda-10, Saraipali-7.

04th August, 2015:

India

East Madhya Pradesh: Amarwara & Balaghat-AWS-15 each, Narsinghpur-AWS-13, Seoni-AWS, Gotegaon & Chindwara-AWS-12 Each, Keolari & Katangi-11 each, Lakhnadon-10, Jabalpur-New—AWS, Gadarwara & Kareli-9 each, Malanjkhand & Deori-8 each and Dindori-AWS-7.

Chhattisgarh: Bemetara-12, Korba-10, Katghora-9, Pali-8, Raigarh-7

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

Rainfall associated with the cyclone when it was out in the sea is also determined based on satellite-gauge merged rainfall dataset generated by IMD and NCMRWF (Mitra et al, 2009) for the North Indian Ocean region from 2013 onwards using the TRMM data. 24-hour accumulated rainfall associated with the CS KOMEN during the period 26 July-04 August as well as the 7-day average rainfall during the same period is furnished in the Fig.2.6.8.

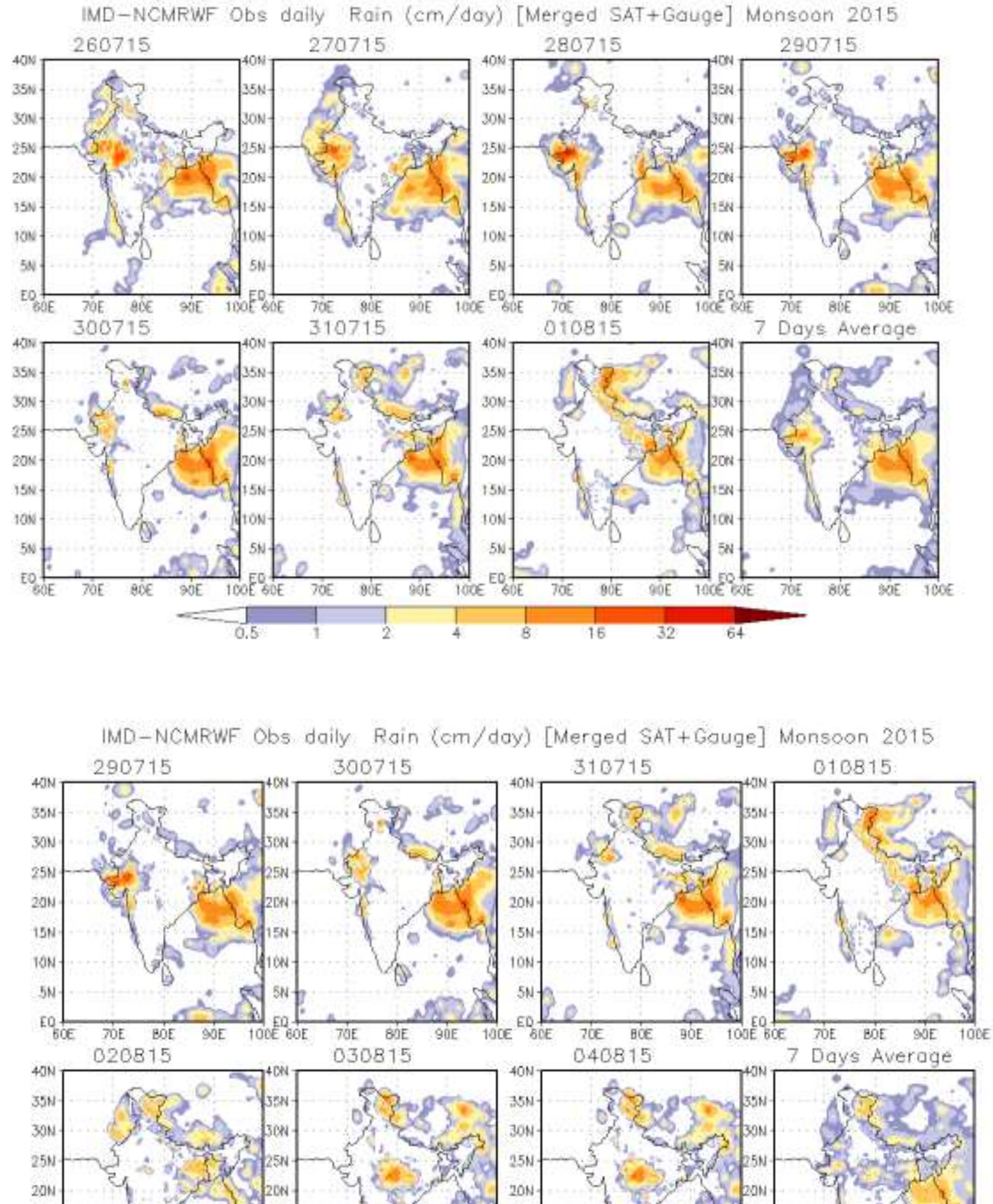


Fig.2.6.8 IMD-NCMRWF (TRMM based) daily merged rainfall (a) during 26 July to 01 Aug & (b) 29 July to 04 Aug 2015 and 07-day average rain during the above periods.

From the figures it is observed that the maximum rainfall occured in the southeastern sector of the system centre when the system was in the sea i.e. during the period 26-30 July. After landfall, the maximum rainfall belt gradually shifted to southwest sector. This shift in the maximum rainfall regime is associated with gradual recurvature of the TC from northward movement over the sea to northwestward and west-northwestward movement after landfall. This spatial pattern of rainfall distribution was in expected lines as it has occurred in a similar fashion in earlier cases also.

2.6.8.2 Gale Wind

Maximum gale wind of 100 kmph prevailed over Teknaf (Bangladesh) on 29th July night when the CS was lying over northeast BoB close to southeastern coast of Bangladesh. However, the wind speed at the time of landfall was about 60-70 kmph along Bangladesh coast.

2.6.8.3 Storm Surge

RSMC New Delhi predicted that tidal wave (storm surge + astronomical tide) of about 2 meters would inundate low lying areas of Bangladesh coast around the time of landfall as the coastal inundation model of Bangladesh did not predict any significant storm surge and the tidal wave was expected to be about 2 meters.

2.6.9. Damage due to Cyclone 'KOMEN'

Damage in West Bengal

The details of the damages in West Bengal due to KOMEN are given below in Table 2.6.2.

Table -2.6.2 Damages associated with CS KOMEN

S No.	Specification	
1	Districts Affected	12
2	Block Affected (Nos.)	233
3	Municipality	53
4	Corporation	2
5	Gram Panchayat	781
6	Village Affected(Nos.)	16,309
7	People affected	61,29,965
8	Loss of human Loss	83
9	Loss of livestock	10,088
10.	Housing	
11	Number of Affected houses (no.)	41269
	(i) completely damaged	1,07,808
	(ii) partially damaged	3,68,238

Damage in Odisha

No damage was reported in Odisha.

Damage in Bangladesh

According to press and media reports, rain/floods and lightning claimed 6 lives in Bangladesh and about 88900 houses were damaged partially.

Damage in Myanmar

According to press and media reports, 2 persons died and 2 were injured. 86 houses and 4 primary schools were damaged

2.7 Land Depression over east Madhya Pradesh and adjoining Chhattisgarh (4th Aug, 2015)

2.7.1 Introduction

A depression formed over Madhya Pradesh and adjoining Chhatisgarh from the remnant of cyclonic storm Komen in the morning of 4th August 4th August , 2015. It moved westward and weakened into a wellmarked Low pressure Area in the early morning of 5th August

2.7.2 Brief History

2.7.2 .1 Genesis

The remnant of the cyclonic storm 'KOMEN', as a well marked low pressure area lay over Jharkhand and adjoining areas of north Odisha and north Chhattisgarh on 2nd. It moved southwestwards and lay over north Chhattisgarh and adjoining north Odisha and Jharkhand with an associated cyclonic circulation extending upto mid tropospheric levels upto 3rd and over north Chhattisgarh and adjoining southwest Bihar, southeast Uttar Pradesh and east Madhya Pradesh on 4th evening. It intensified into a Depression and lay over east Madhya Pradesh and adjoining Chhattisgarh centred near Lat. 22.7°N and Long. 80.5°E, about 75 kms southeast of Jabalpur at 0300 UTC on 4th.

2.7.2 .2 Intensification and movement

It moved westwards and lay over central parts of Madhya Pradesh centred near Lat. 22.7°N and Long. 77.8°E, close to Hoshangabad at 1200 UTC on 4th. It weakened into a well marked low pressure area and lay over southwest Madhya Pradesh and neighbourhood at 0000 UTC on 5th. It lay over central parts of Madhya Pradesh with an associated cyclonic circulation extends upto mid tropospheric levels on 5th. It weakened into a low pressure area over the same region at 0900 UTC on 5th and persisted there upto same evening. It became less marked on 6th. However the associated cyclonic circulation lay over east Madhya Pradesh and neighbourhood and extending between 1.5 & 5.8 kms a.s.l. on 6th and over north Chhattisgarh and neighbourhood and extending upto 3.1 kms a.s.l. during 7th - 10th. It became less marked on 11th. The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.7.1. The typical satellite imagery are shown in Fig. 2.7.1. IMD GFS analysis of mean sea level pressure (MSLP) and wind at 10metre, 850 hpa, 500 hpa and 200 hpa levels are shown in Fig. 2.7.2.

Table 2.7.1 Best track parameters of Land depression over east Madhya Pradesh and adjoining Chhattisgarh during 4-5 August, 2015

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
4/08/2015	0300	22.7/80.5	-	998	25	3	D
	0600	22.7/80.0	-	998	25	3	D
	0900	22.7/79.5	-	998	25	3	D
	1200	22.7/77.8	-	998	25	4	D
	1800	22.7/77.8	-	998	25	4	D
5/08/2015	0000	Weakened into a well marked low pressure area and lay over southwest Madhya Pradesh and neighbourhood.					

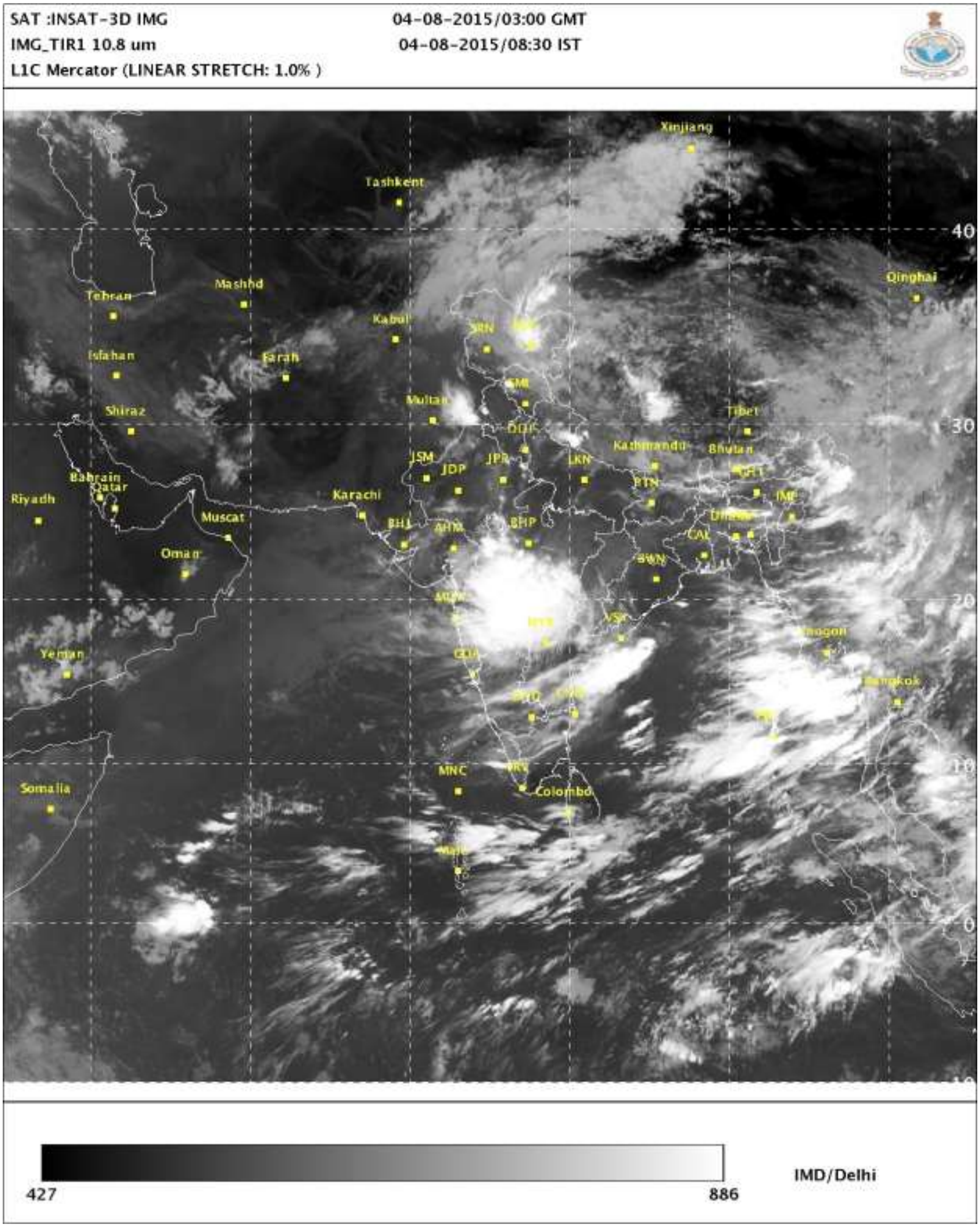


Fig.2.7.1 Typical INSAT-3D IR imageries of Depression over Madhya Pradesh at 0300 UTC of 4th August, 2015

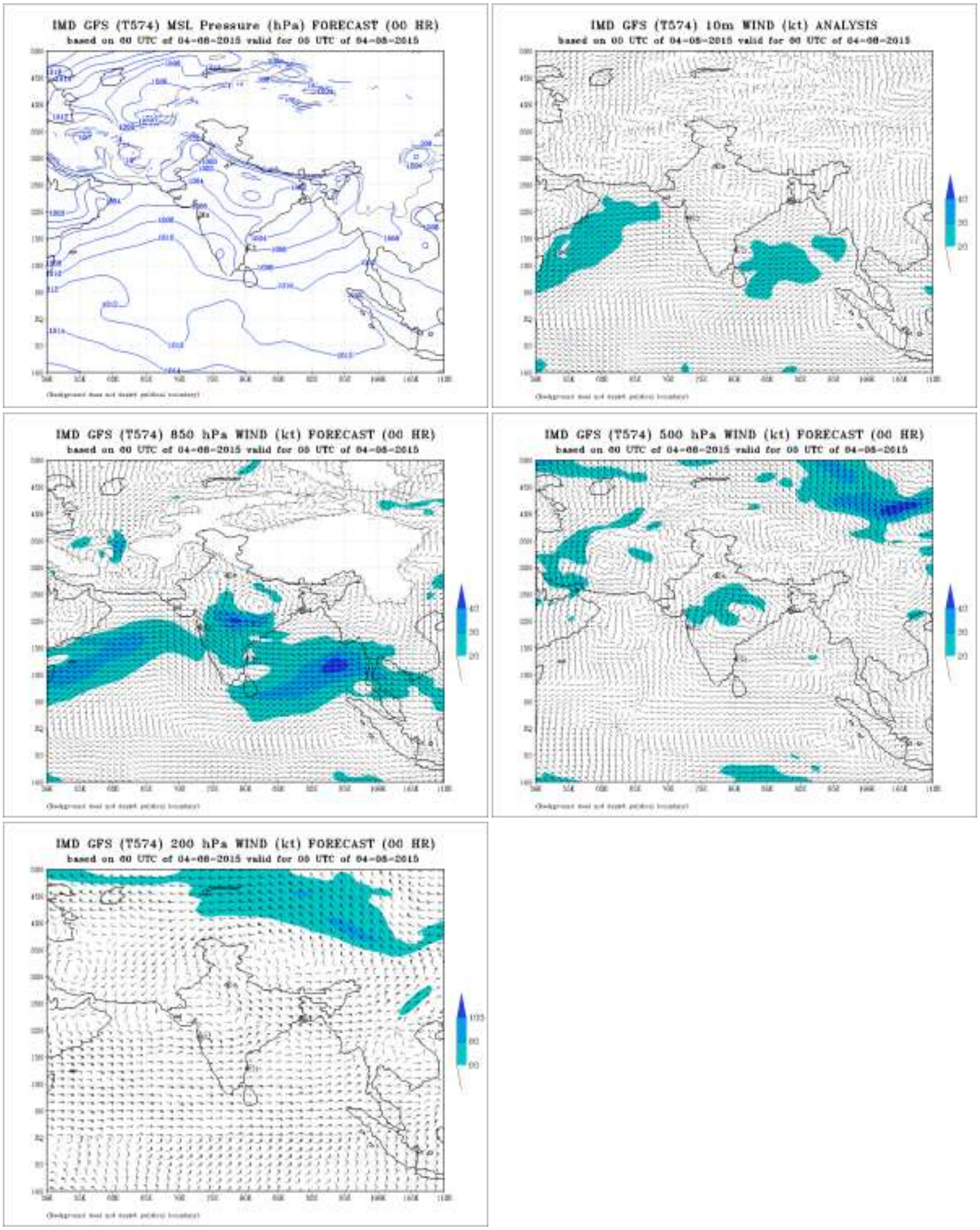


Fig.2.7.2 IMD-GFS analysis of (a) MSLP, (b) 10m wind, winds at (c) 850 hPa,(d) 500 hPa & (e) 200 hPa levels and based on 0000 UTC of 4th August, 2015

2.7.3 Realised Weather

Active monsoon conditions with heavy to very heavy rainfall at isolated places prevailed over Madhya Pradesh, Vidarbha and Chhattisgarh.

Chief amounts of 24 hrs. rainfall (7 cm or more) ending at 0300 UTC from 4th August are given below:

4.8.2015

Madhya Pradesh: Pachmarhi-21; Betul, Betul - AWS, Udaipura and Sardarpur 10 each; Bhainsdehi- 9; Chanderi, Chicholi and Kolaras 8 each; Pichhore and Multai 7 each

East Madhya Pradesh: Amarwara and Balaghat - AWS 15 each; Narsingpur-13, Seoni, Seoni - AWS, Gotegaon and Chindwara - AWS 12 each; Keolari and Katangi 11 each; Lakhnadon, Mandla - AWS and Bichhia 10 each; Jabalpur, Gadarwara and Kareli 9 each; Malanjkhand, Deori, Nainpur and Patan 8-each; Dindori – AWS-7

Vidarbha: Nil.

Chhattisgarh: - Bemetara-12; Korba-10; Katghora-9; Pali-8; Raigarh; Gandai -7 each.

5.8.2015

EAST MADHYA PRADESH: chindwara-AWS-7

WEST MADHYA PRADESH: Khandwa-Aws-29, Khirkiya-Arg-29, Sonkatch-23, Depalpur-21, Nepanagar-20, Harsud-Arg-20, Atner-19, Indore-Aws-19, Bhikangaon-19, Badnagar-17, Gautampura-17, Mhow-17, Khaknar-17, Thikri-16, Chicholi-15, Badnawar-15, Bhainsdehi-14, Bagli-13, Harda-Aws, Burhanpur, Betul-Aws, Maheshwar, Dhar-Aws, Kasarwad-12 Each, Barwaha, Sardarpur, Multai, Dewas-Aws And Pandhana- 11 Each, Shegaon-10, Khargone-Aws-9, Tonkhurd-8, Pachmarhi, Nalchha, Sendhwa(Med), Ujjain-Aws And Manawar-7 Each

2.8 Land Deep depression over south Odisha and neighbourhood (16-19 September)

2.8.1 Introduction

A depression formed over south Odisha and neighbourhood around the noon of 16th September, 2015. It further intensified into a deep deression over Vidarbha & adjoining areas of south Chhatisgarh in the morning of 17th. It weakened into a depression on 18th & well marked low pressure area in the morning of 19th. The salient features are fiven below.

2.8.2 Brief History

2.8.2.1 Genesis

A cyclonic circulation extending upto upper tropospheric level lay over west-central Bay of Bengal & neighbourhood on 7th -11th. Under its influence, a low pressure area formed over west-central & adjoining northwest Bay of Bengal on12th and persistsed over the same area on 13th -14th. It lay as a well marked low pressure area over west-central & adjoining northwest Bay of Bengal off north Andhra Pradesh - south Odisha coasts on 15th and over south Odisha & neighbourhood on 16th. Associated cyclonic circulation extending upto 7.6 km a. s. l. during 12th - 16th. The well marked low pressure area over south Odisha & neighbourhood concentrated into a depression and lay centered at 0600 UTC of 16th Sept. 2015 over south Odisha and neighbourhood near Lat 20.3°N/ Long.83.0°E, about 40 kms northwest of Titilagarh and 160 kms southeast of Raipur

2.8.2.2 Intensification and movement

The depression moved west-northwestwards and lay centered at 1200 UTC of 16th Sept. 2015 over south Odisha and adjoining Chattisgarh near Lat.20.5°N/Long.82.5°E about 70 kms northwest of Titlagarh and 130 kms southeast of Raipur. It continued to move west-northwestwards and intensified into a Deep Depression and lay centered over Vidarbha and adjoining areas of south Chhattisgarh near Lat.21.0°N/ Long.79.5°E about 50 kms east-southeast of Nagpur at 0300 UTC on 17th. It moved nearly westwards and lay centred over Vidarbha & neighbourhood near Lat.20.5°N/ Long.79.0°E about 50 kms east of Wardha at 1200 UTC on 17th. It further moved nearly westwards and weakened into a Depression and lay centred over Vidarbha & neighbourhood near Lat.20.7°N/ Long.77.0°E close to Akola at 0300 UTC on 18th. It moved nearly westwards and lay centred over west Vidarbha & neighbourhood near Lat.20.5° N/ Long.76.0° E close to Buldhana at 1200 UTC on 18th. It nearly moved west-northwestwards and lay centred over north Madhya Maharashtra & neighbourhood near Lat.21.0° N/ Long.74.5° E about 50 kms north of Malegaon and 160 kms southeast of Vadodara, at 0000 UTC of 19th. It further moved westwards and weakened into a well marked low pressure area over north Madhya Maharashtra & adjoining areas of southwest Madhya Pradesh and Gujarat region at 0300 UTC on 19th. It lay over south Gujarat and neighbourhood on 19th evening. It lay as a low pressure area over Saurashtra & neighbourhood on 20^{t}h, over Saurashtra & Kutch and neighbourhood on 21st, over northwest Rajasthan and neighbourhood on 22nd and became less marked on the same evening. However, associated cyclonic circulation lay over Haryana and adjoining Punjab extending between 1.5 & 2.1 kms a.s.l. on 23rd Sept. The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.8.1. The typical satellite imagery are shown in Fig. 2.8.1. IMD GFS analysis of mean sea level pressure (MSLP) and wind at 10metre, 850 hpa, 500 hpa and 200 hpa levels are shown in Fig. 2.8.2(a-d).

Table 2.8.1 Best track parameters of Land Deep Depression over south Odisha and neighbourhood during 16-19 September, 2015

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
16/09/2015	0300	19.6/83.5	-	998	25	3	D
	0600	20.3/83.0	-	998	25	3	D
	0900	20.4/82.7	-	998	25	3	D
	1200	20.5/82.5	-	998	25	4	D
	1500	20.6/82.0	-	998	25	4	D
	1800	20.8/81.9	-	998	25	4	D
	2100	21.0/81.9	-	998	25	4	D
17/09/2015	0000	21.1/81.5	-	998	25	4	D
	0300	21.0/79.5	-	998	30	4	DD
	0600	20.5/79.5	-	998	30	4	DD
	0900	20.0/79.5	-	998	30	4	DD
	1200	20.5/79.0	-	996	30	5	DD
	1500	20.0/77.5	-	996	30	5	DD
	1800	20.0/77.0	-	996	30	5	DD
	2100	20.0/76.4	-	996	30	5	DD
18/09/2015	0000	20.8/77.4	-	996	25	5	DD
	0300	20.7/77.0	-	996	30	4	D
	0600	20.0/77.0	-	998	30	4	D
	0900	20.7/76.5	-	998	25	4	D
	1200	20.5/76.0	-	998	25	4	D
	1500	20.5/75.8	-	998	25	4	D
	1800	20.5/75.5	-	998	25	4	D
	2100	20.8/75.0	-	998	25	4	D
19/09/2015	0000	21.0/74.5	-	998	25	4	D
	0300	It weakened into well marked low pressure area over north Madhya Maharashtra & adjoining areas of southwest Madhya Pradesh and Gujarat region.					

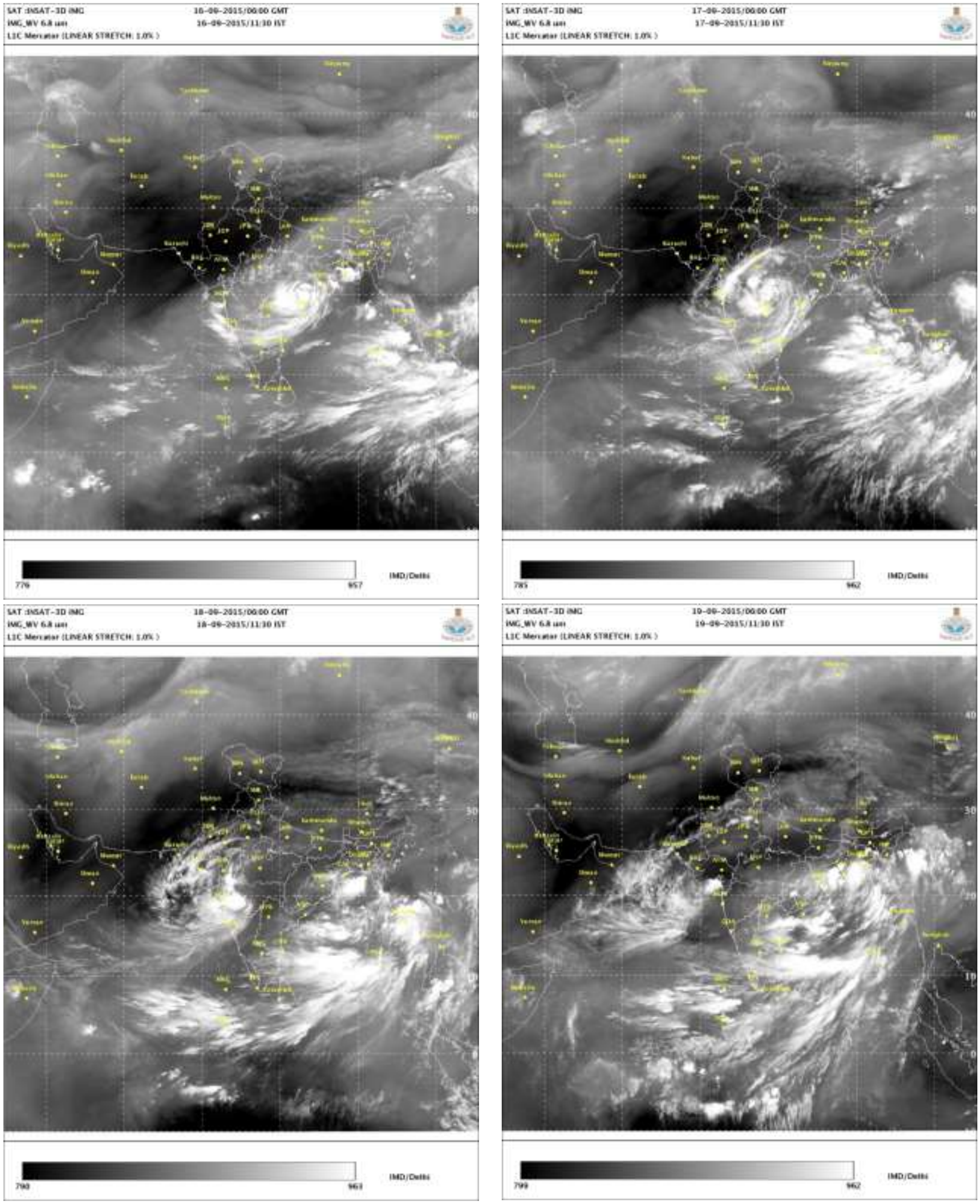


Fig.2.8.1 Typical INSAT-3D IR imageries of Depression over south Odisha at 0600 UTC during 16-19 September, 2015

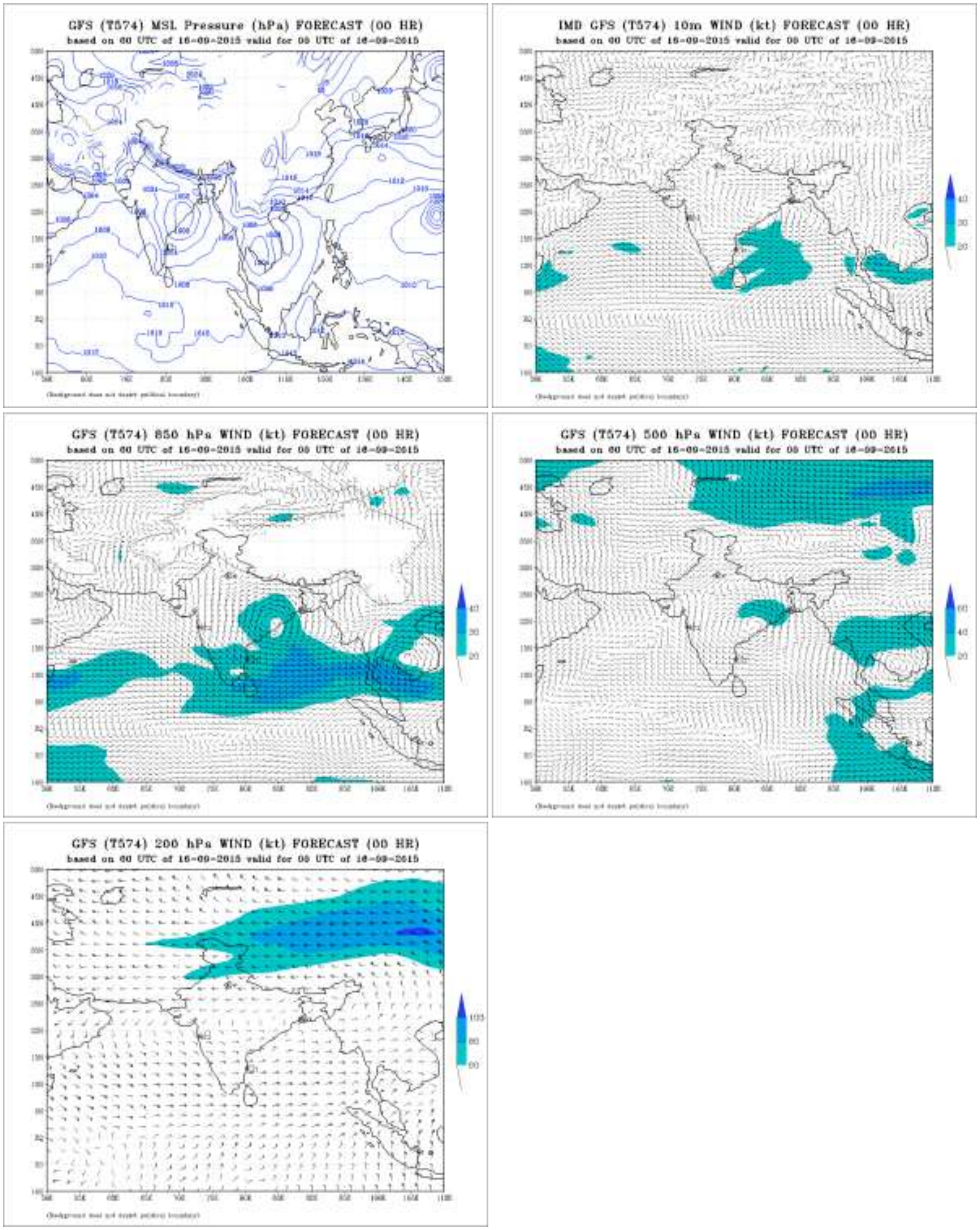


Fig.2.8.2 (a) IMD-GFS analysis of MSLP, 10m wind, winds at 850 hPa, 500 hPa & 200 hPa levels and based on 0000 UTC of 16th September, 2015

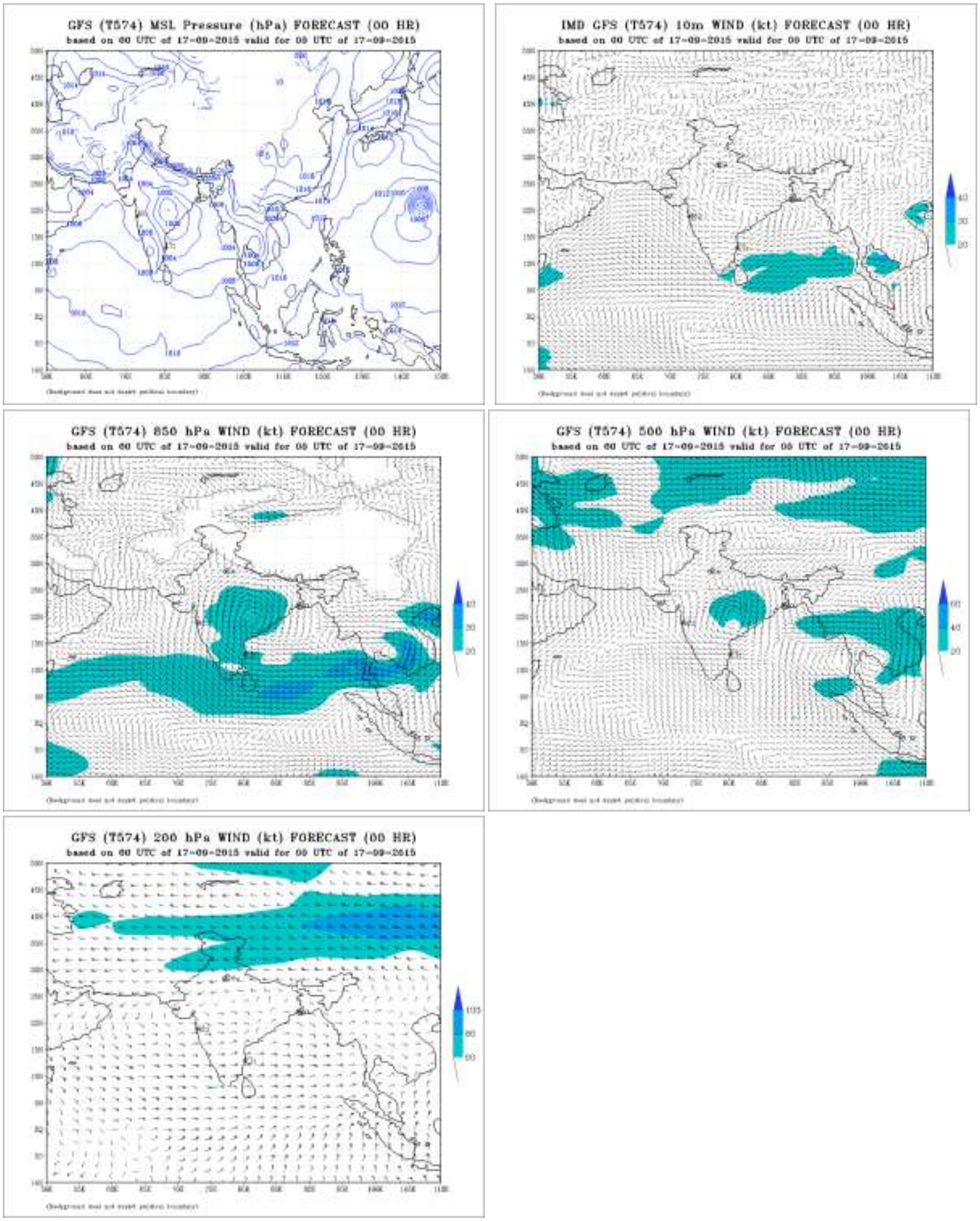


Fig.2.8.2(b) IMD-GFS analysis of MSLP, 10m wind, winds at 850 hPa, 500 hPa & 200 hPa levels and based on 0000 UTC of 17th September, 2015

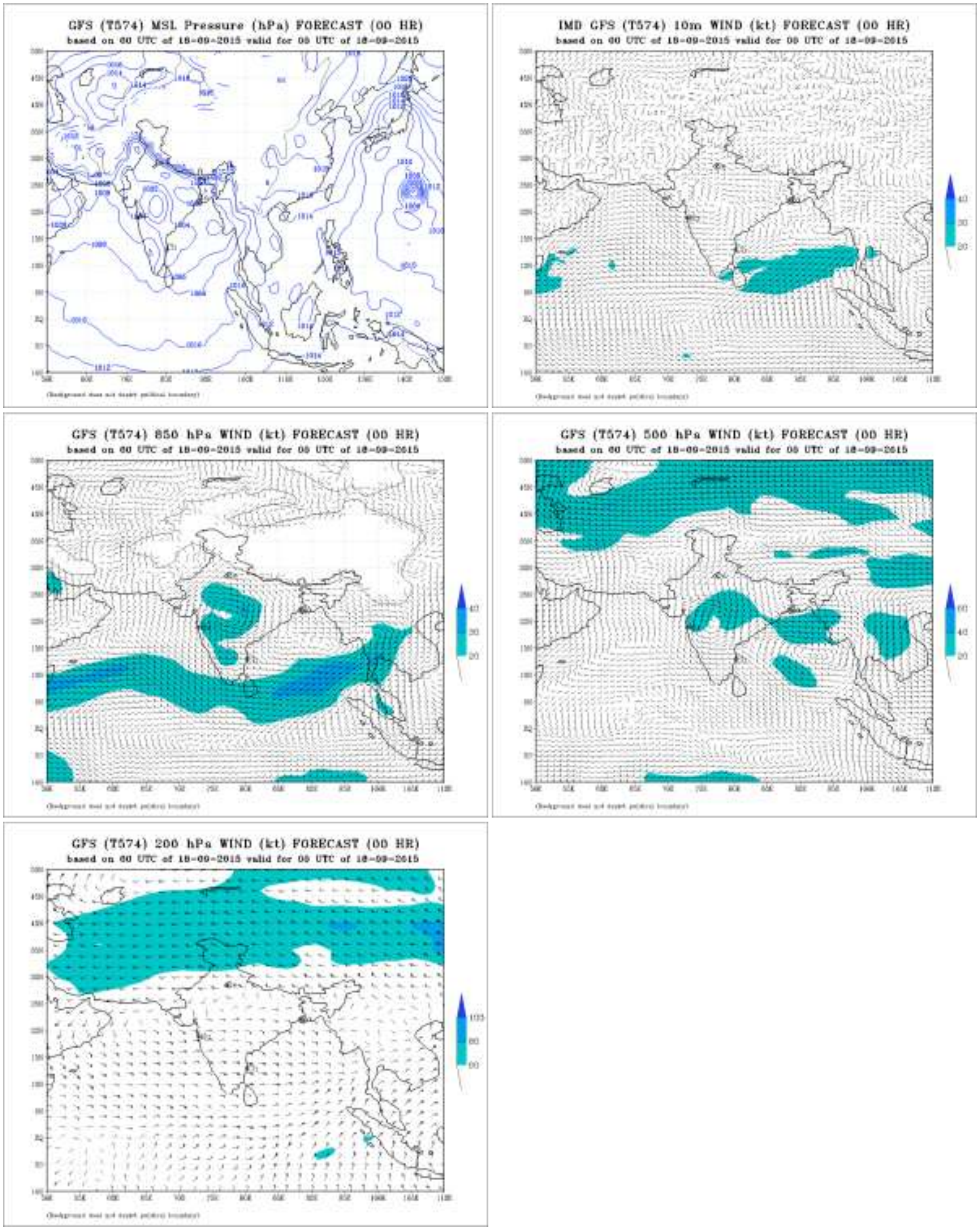


Fig.2.8.2(c) IMD-GFS analysis of MSLP, 10m wind, winds at 850 hPa, 500 hPa & 200 hPa levels and based on 0000 UTC of 18th September, 2015

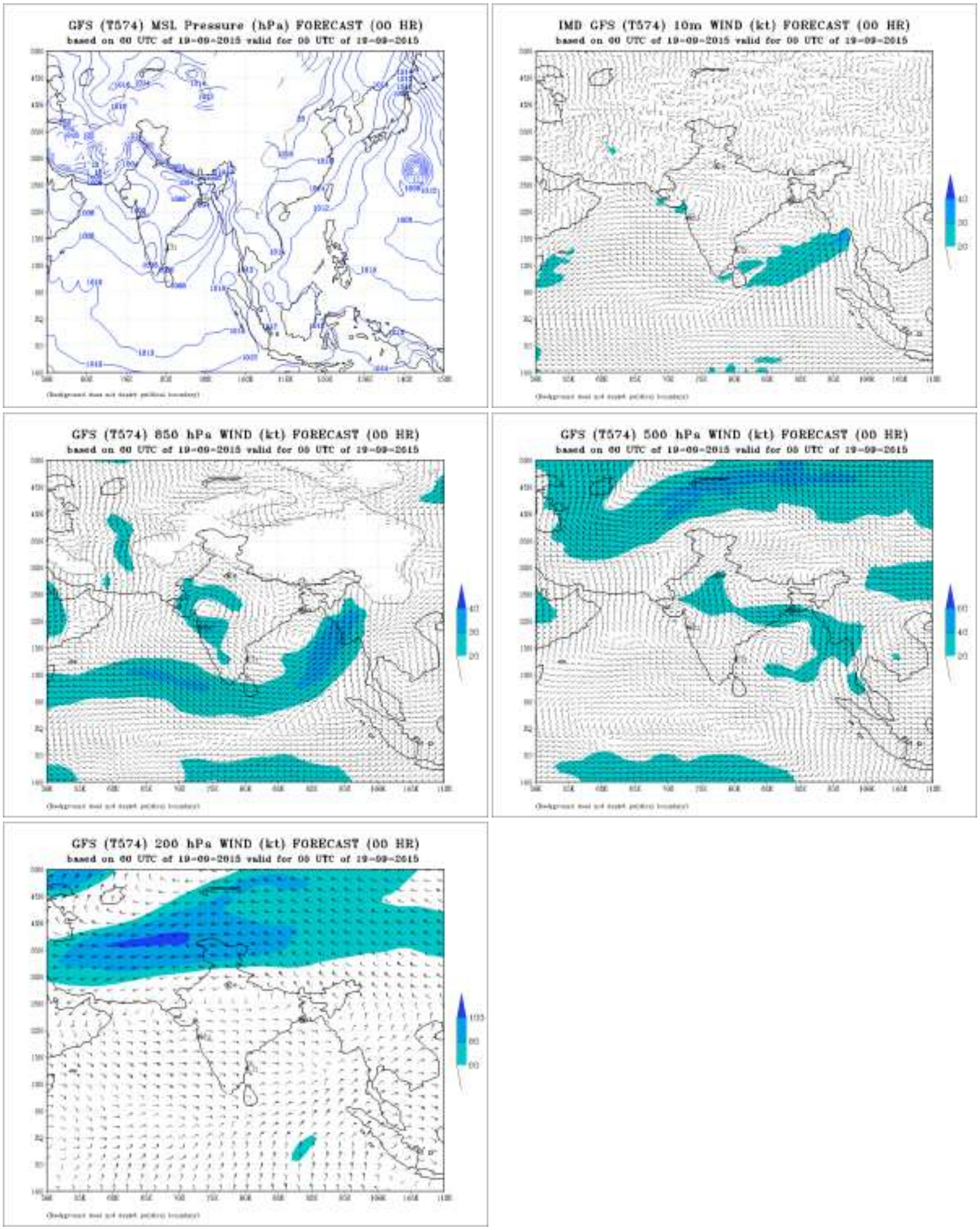


Fig. 2.8.2 (d) IMD-GFS analysis of MSLP, 10m wind, winds at 850 hPa, 500 hPa & 200 hPa levels and based on 0000 UTC of 19th September, 2015

2.8.3 Realised Weather

Active to vigorous monsoon conditions prevailed over Odisha, south Gujarat Region, Maharashtra state and Chhattisgarh. This deep depression caused heavy to very heavy rainfall over Odisha, Maharashtra State and Chhattisgarh with extremely heavy rainfall at isolated places over Odisha and south Gujarat Region.

Chief amounts of 24 hrs. rainfall (7 cm or more) ending at 0300 UTC from 16th to 20th September, 2015 are given below:

16.9.2015

Odisha: Tentulikhunti ARG-28; Muniguda ARG-26; Jaipatna-23; Bhavani P. and Narla ARG 22 each; Jhorigam ARG, Ambadola and Koraput 21 each; Chandahandi ARG and Nawarangpur 19 each; Lanjigarh18; Madanpur Rampur, Kotagarh and Sorada 17 each; Junagarh, Similiguda AWS, Daringibadi, Madhabarida and Bissem -Cuttack 15 each; Jeypore and Kashipur 14 each; Kotraguda and Nuagada ARG 13 each; Gudari, Kesinga ARG, Pottangi and Dabugan ARG 12 each; Raikia ARG, Belaguntha ARG, Bhanjnagar and Tikabali 11 each; Kalinga10; Mohana, Belgaon, Titlagarh, Dharmagarh ARG, Khariar, Kaptipada ARG, Umarkote, Tikarpara, Kosagumda and Rayagada 9 each; R.Udaigiri, Raighar ARG, G Udayagiri AWS, K Nuagaon ARG, Phiringia ARG, Gunupur, Komna and Sinapali ARG 8 each; Balimundali, Boden ARG, Aska, Baliguda, Jagannath Prasad ARG, Barmul, Nayagarh, Ranpur, Bolangir, Daspalla and Udala 7 each;

Konkan & Goa: Ratnagiri11; Canacona 10; Panjim (Goa) and Mapusa each-9; Ponda-8; Sanguem and Malvan 7 each;

Vidarbha: Balapur-9; Chamorshi-7 ; Sadakarjuni-6;

Chhattisgarh: Deobhog-16; Balod-11; Bhanupratappur-9; Dhamtari, Jagdalpur and Kanker 7 each.

17.9.2015

Odisha: Jhorigam ARG-13; Umarkote and Raighar ARG 12 each; Junagarh-10; Boden ARG and Patnagarh 8 each; Belaguntha ARG, Khariar, Malkangiri and Kalinga 7 each;

Konkan & Goa : KarjatAgri and Chiplun 7 each;.

Vidarbha: Sadakarjuni-14; Korpana, Amgaon, Goregaon and Mul 12 each; Deori, Kurkheda, Lakhani, Korchi, Bhadravati and Salekasa 11 each; Bramhapuri, Saoli, Rajura and Desaiganj 10 each; Ahiri, Sakoli and Gondpipri 9 each; Lakhandur, Chamorshi, Gondia AP, Gondia, Chandrapur, Armori and Arjuni Morgaon 8 each; Pauni, Nagbhir and Dhanora 7 each;

Chhattisgarh: Sukma-21; Kanker-17; Mahasamund-14; Dongargarh and Balod 11 each; Ambagarh Chowki, Narayanpur and Bhanupratappur 9 each; Raipur and Kondagaon 8 each; Mana AP, Rajnandgaon, Durg, Deobhog, Pendra and Dondilohara 7 each;

18.9.2015

Marathawada: Sillod-16; Mahur-11; Himayatnagar-10; Bhokardan, Jalna, Hingoli - Hyd, Kallamnuri, Phulambri, Sengaon, Hadgaon and Aurangabad AP 9 each; Partur, Kinwat, Parbhani and Dhalegaon - FMO -8 -each; Soegaon, Kannad, Ambad and Selu 7 each;.

Konkan & Goa: - Sanguem-10; Quepem, Margao, Mulde Agri and Mulde - AWS 7 each

Madhya Maharashtra: Sindkheda-18; Gidhade – FMO-15; Shahada-13; Jalgaon, Jamner and Dahigaon - FMO 12 each; - Shirpur-11; Malegaon and Sinnar 9 each; Pachora and Kalvan 8 each; Nandurbar, Yaval, Erandol and Sakri 7 each;

Vidarbha: - Pandherikawara and Korpana 16 each; Deolgaon Raja and Wani 15 each; Zarizamni-14 -; Maregaon, Sindkhed Raja, Buldhana, Nandgaonkazi and Bhadravati 13 each; 12 - Akot, Darwha, Lonar, Umerkhed, Digras, Joiti, Ner, Mahagaon and Ghatanji each; Buldhana (AWS), Mehkar, Washim and Manora 11 each; Arni, Hinganghat, Yeotmal, Ballarpur, Warora, Washim (AWS) and Wardha 10 each; Kuhi, Ralegaon, Risod, Motala, Chandur Rlwy and Kalamb 9 each; Shegaon, Bhandara (AWS), Amraoti, Mauda, Mangrulpir and Chikhli 8 each; Tiwsa, Akola (AWS), Khamgaon, Malegaon, Chikhalda, Karanjalad, Sangrampur, Samudrapur, Telhara, Chandrapur, Jalgaon Jamod and Selu 7 each;

19.9.2015

Marathwada: Phulambri-10, Aurangabad and Sillod-7each

Konkan & Goa: Karjat Agri-11, Mokhada-10, Bhiwandi, Jawhar, Shahapur, Vikramgad, Matheran and Wada- 7 Each

Madhya Maharashtra: Taloda And Kalvan -15 Each, Junnar and Igatpuri- 13 Each, Vadgaon Maval-12, Surgana-11, Peth, Niphad and Dindori- 10 each, Paud Mulshi, Ambegaon Ghodegaon and Harsul-9 each, Akole, Nashik And Satna Baglan -8 each, Velhe, Nandurbar, Bhadgaon and Kopargaon-7 each

20.9.2015

Konkan & Goa: Mangaon-7

Madhya Maharashtra:SURGANA-9

2.8.4 *Damage*

This system caused flood in Odisha which claimed 2 death and 25,000 affected by rain, landslides and road & rail traffic.

2.9 Deep Depression over the Arabian Sea (09-12 October, 2015)

2.9.1 Introduction

A depression formed over the Arabian Sea on 9th October morning from a low level circulation embedded in the eastwest shear zone passing through eastcentral AS. It moved north-northwestwards and intensified into a deep depression (DD) on 10th morning.

Continuing its north-northwestward movement, it maintained its intensity till 11th morning. It then weakened gradually and dissipated over the sea itself while moving initially northwards and then west-northwestwards.

The salient features of this system are as follows.

i. The DD weakened over the sea due to its slow movement and dry air intrusion from northwest.
ii. India Meteorological Department predicted genesis of the system 72 hrs in advance.
iii. The movement of DD away from the Indian coasts was also predicted well in advance from the first bulletin itself on 9th Oct 2015 (0830 IST). Hence reducing cost towards cyclone preparedness measures including evacuation of coastal regions by Disaster Managers.
iv. No heavy rainfall warning was issued by IMD during the entire life period of the system.
v. The numerical weather prediction (NWP) and dynamical statistical models provided reasonable guidance with respect to its genesis, track and intensity, though there was some divergence in model guidance with respect to track and intensity.

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.

2.9.2 Monitoring of DD

The DD was monitored & predicted continuously since its inception by IMD. The forecast of its genesis on 9th October, its track, intensity, dissipation over sea were predicted with sufficient lead time. Observed tarck of DD over AS during 9th -12th October is shown in fig.1.

At the genesis stage, the system was monitored mainly with satellite observations, supported by meteorological buoys and ships. Various national and international NWP models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models were utilized to predict the genesis, track and intensity of the storm. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation.

2.9.3 Brief life history

2.9.3.1 Genesis

In association with east-west shear zone extending from eastcentral AS to eastcentral Bay of Bengal across south Peninsula, an upper air cyclonic circulation extending upto mid-tropospheric levels lay over eastcentral AS on 6th October. It persisted over the same region on 7th and lay as a low pressure area (LPA) over esatcentral and adjoining southeast AS in the early morning of 8th. It became well marked low (WML) over the same region in the forenoon of 8th. According to satellite imagery, the low level cyclonic circulation (LLCC) which was observed over southeast and adjoining eastcentral AS on 7th moved gradually northwards and intensified into a vortex (T1.0) over eastcentral AS near latitude 12.8^{0}N/longitude 71.3^{0}E at 0300 UTC of 8th. The convection over the area organised during past 24 hours. Lowest cloud top temperature (CTT) near the system centre was about -70^{0}C. The convection pattern was of shear type. The distance between the centre and cloud mass was about 1.5^0. The convective cloud mass was sheared to northwest of the system centre. Ascat observations suggested the associated maximum sustained surface winds of about 25 kts. Winds were higher in the eastern sector due to increased cross equatorial flow. The sea surface temperature was 29-30˚C, ocean thermal energy was about 60-80KJ/cm^2, low level convergence was (5-10)x10^{-5} s^{-1}, upper level divergence was about (20)x10^{-5} s^{-1}, the low level relative vorticity was about (100-150)x10^{-5} s^{-1}, vertical wind shear was low to moderate(10-20 knots) around the system centre. Low level vorticity and upper level divergence increased during past 24 hours. The sub-tropical ridge in the upper tropospheric level lay along 17˚N. Under these conditions, the low pressure area moved slowly north-northwestwards and concentrated into a depression over eastcentral Arabian Sea and lay centred at 0000 UTC of 9th October near 14.0^{0}N/70.3^{0}E, about 410 km west- southwest of Goa and 630 km south-southwest of Mumbai. The intensity of the system as per the Dvorak's technique was T1.5. Intense to very intense convection lay over AS and adjoining Indian Ocean area between 11.0^{0}N & 16.5^{0}N and east of longitude 71.0^{0}E. Similar conditions prevailed leading to further intensification of the system to DD at 0600 UTC of 10th.

To summarise, the genesis of the DD can be attributed to the persistent well defined eastwest shear zone embedded in large scale monsoon circulatio and favourable environmental conditions like warmer SST, moderate wind shear, increased vorticity and upper air divergence.

2.9.3.2 Intensification

The depression moved north-northwestwards very slowly with a speed of about 6 kmphon 9th and it intensified into a DD at 1800 UTC of 9th and lay centered at latitude 14.7^{0}N/ longitude 69.9^{0}E over eastcentral AS, about 430 km west-southwest of Goa and 580 km south-southwest of Mumbai. It intensifed into DD mainly due to moderate wind shear (15-20 knots), warmer SST (29-31^{0}C), higher Ocean thermal energy (60-80 KJ/cm^2) and incursion of warm and moist air from south in association with the eastwest shear zone and cross equatorial flow.

As the system moved further northwards from 0300 to 1800 UTC of 11th, it experienced moderate to high southeasterly wind shear (15-25 knots) leading to further shearing of cloud mass to the northwest. In addition, the dry air intruded towards the system from northwest cutting off the supply of warm and moist air from southeast as observed through animation of total precipitable water (TPW) imageries (fig. 2.9.1a). SST was also low to the west of the system centre. As a result the system weakened into a depression at 0300 UTC of 11th and into a WML at 0300 UTC of 12th. According to satellite imageries the distance between the LLCC and the convection bounadry in the shear pattern increased gradually and the centre was poorly defined in IR imagery on 12th. The depth of convection reduced significantly from 10th to 11th being limited to mid-tropospheric level as observed in the CTT field. (fig 2.9.1.b). It further decreased on 12th and weakened into a low pressure area in the morning of 13th becoming less marked on 14th.

It may also be mentioned here that another low pressure area formed over north BoB in the morning of 7th and became WML on 8th over northeast BoB. It moved northeastwards and lay over Myanmar and adjoining Bangladesh, Mizoram and Tripura on 9th morning. Though both the systems developed in association with same eastwest shear zone, their interaction if any, needs to be further investigated. The observed track of the system is shown in Fig.2.1. The best track parameters of the systems are presented in Table 2.9.1.

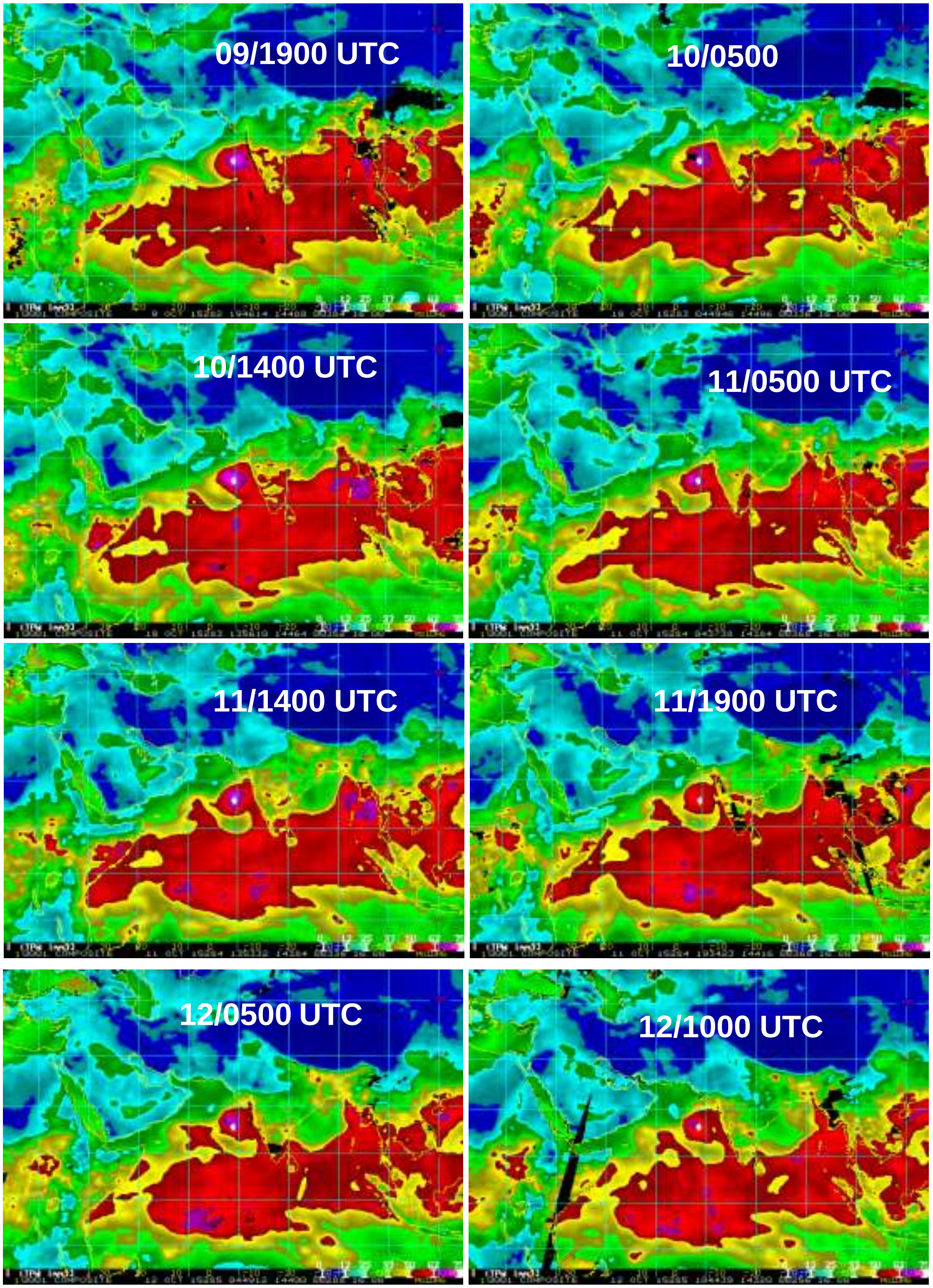


Fig. 2.9.1 (a) Total precipitable water imageries based on 1900 UTC of 9th, 0500 & 1400 UTC of 10th, 0500, 1400 & 1900 UTC of 11th and 0500 & 1000 Utc of 12th October in association with DD over AS (09-12 October). (source : CIRA)

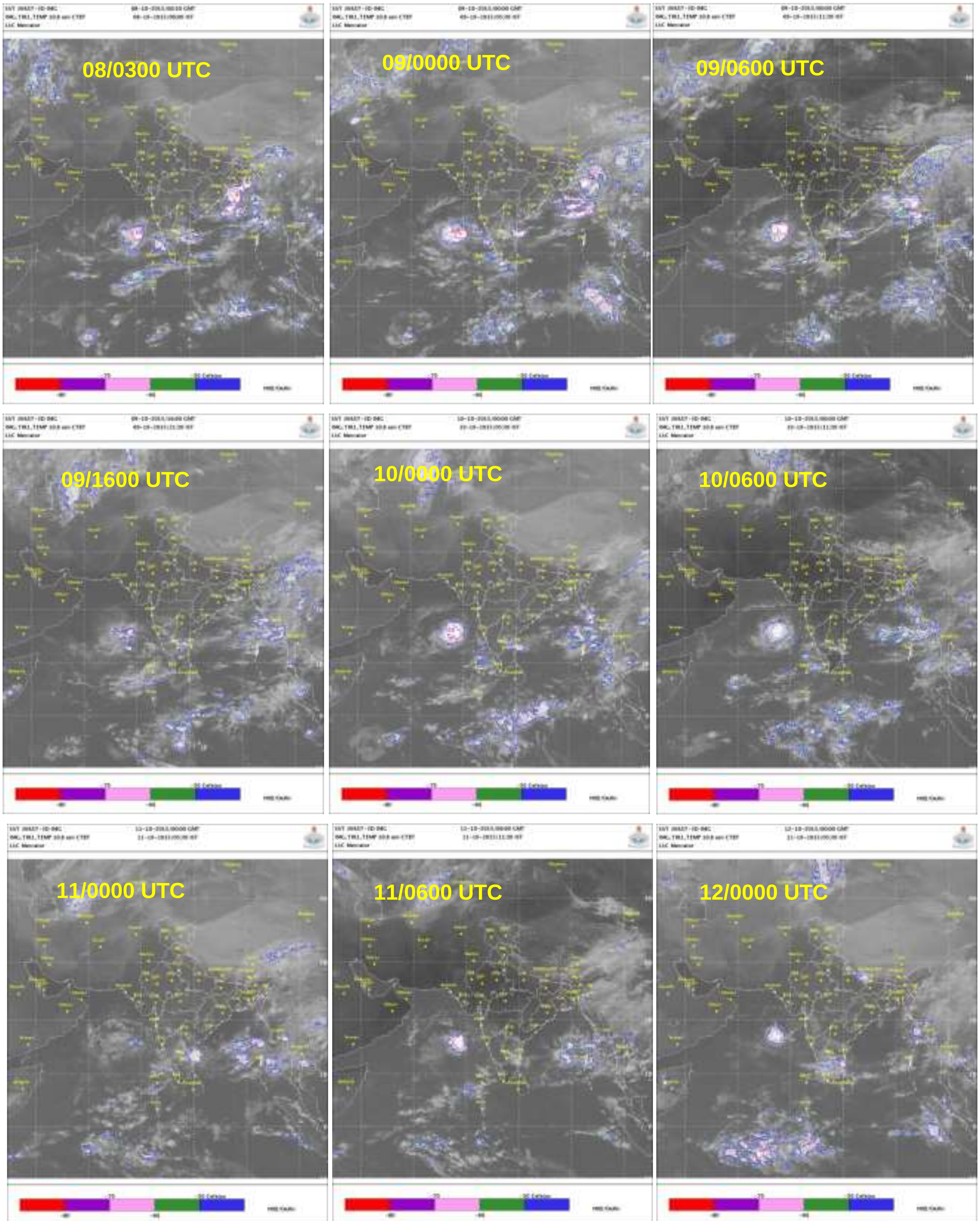


Fig. 2.9.1 (b) INSAT-3D cloud top brightness temperature imageries based on 0300 of 8th, 0000, 0600 & 1600 UTC of 9th, 0000 & 0600 UTC of 10th, 0000 & 0600 UTC of 11th and 0000 UTC of 12th October in association with DD over AS (09-12 October)

Table 2.9.1 Best track positions and other parameters of Deep Depression over the Arabian Sea during 09-12 October, 2015

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
09/10/2015	**0000**	14.0/70.3	1.5	1004	25	3	**D**
	0300	14.0/70.3	1.5	1004	25	4	D
	0600	14.1/70.3	1.5	1004	25	4	D
	1200	14.3/70.2	1.5	1002	25	4	D
	1800	14.7/69.9	2.0	1001	30	5	**DD**
10/10/2015	0000	15.0/69.6	2.0	1001	30	5	DD
	0300	15.1/69.5	2.0	1001	30	5	DD
	0600	15.1/69.4	2.0	1000	30	6	DD
	1200	15.2/69.3	2.0	1000	30	6	DD
	1800	15.3/69.2	2.0	1000	30	6	DD
11/10/2015	0000	15.5/69.2	2.0	1001	30	5	DD
	0300	15.6/69.2	1.5	1003	25	4	**D**
	0600	15.7/69.2	1.5	1003	25	4	D
	1200	15.9/69.2	1.5	1004	25	3	D
	1800	16.0/69.2	1.5	1004	25	3	D
12/10/2015	0000	16.1/69.0	1.5	1004	20	3	D
	0300	It weakened into a well marked low pressure area over east central Arabian Sea.					

2.9.3.3 Movement

The DD was basically steered north-northwestwards by the anticyclonic circulation lying to the east-northeast of the system centre in the middle and upper tropospheric levels. As the system lay close to the ridge and in the boundary of this anticyclonic circulation, the system moved north-northwestwards very slowly. The system underwent change in direction from 1800 UTC of 10th. The translational speed decreased about 12 hours prior to the change in direction of movement of the system. On an average the system moved with a translational speed of 3.8 kmph. On 11th night, the system started moving west-northwestwards under the influence of another anticyclonic circulation lying to the northwest of the system centre and the anticyclone to the east-northeast became less marked.

2.9.4 Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1, INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 and MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Microwave based total precipitable water imagery product of NOAA, NESDID-CIRA and typical satellite INSAT-3D imageries of DD during the life cycle of the system are shown in Fig. 2.9.2 (a-c). Intensity estimation using Dvorak's technique suggested that the system attained an intensity of T 1.5 on 0000 UTC 9th. Associated broken low and medium clouds with embedded intense to very intense convection lay over AS and adjoining Indian Ocean between latitude 11.0^0 N to 16.5^0 N and longitude 65.0^0 E to 71.0^0 E. The lowest CTT was about $-.86^0$C. The cloud pattern was shear type. At 0600 UTC of 10th, the system attained intensity of T2.0 corresponding to DD. Associated low and medium clouds with intense to very intense convective clouds at many places lay over area between latitude 13.0^0 N to 18.6^0 N and longitude 65.0^0 E to 70.0^0 E. The lowest cloud top temparature was - 80^0C. The cloud pattern was curved band type. At 1800 UTC of 10th, the system started weakening. Enhanced IR imageries depicting the growth of the system to T 1.5, T 2.0 and its weakening to T 1.5 are presented in Fig.4. The system further weakened with intensity becoming T1.0 on 13th June 2015 corresponding to a well marked low pressure area.

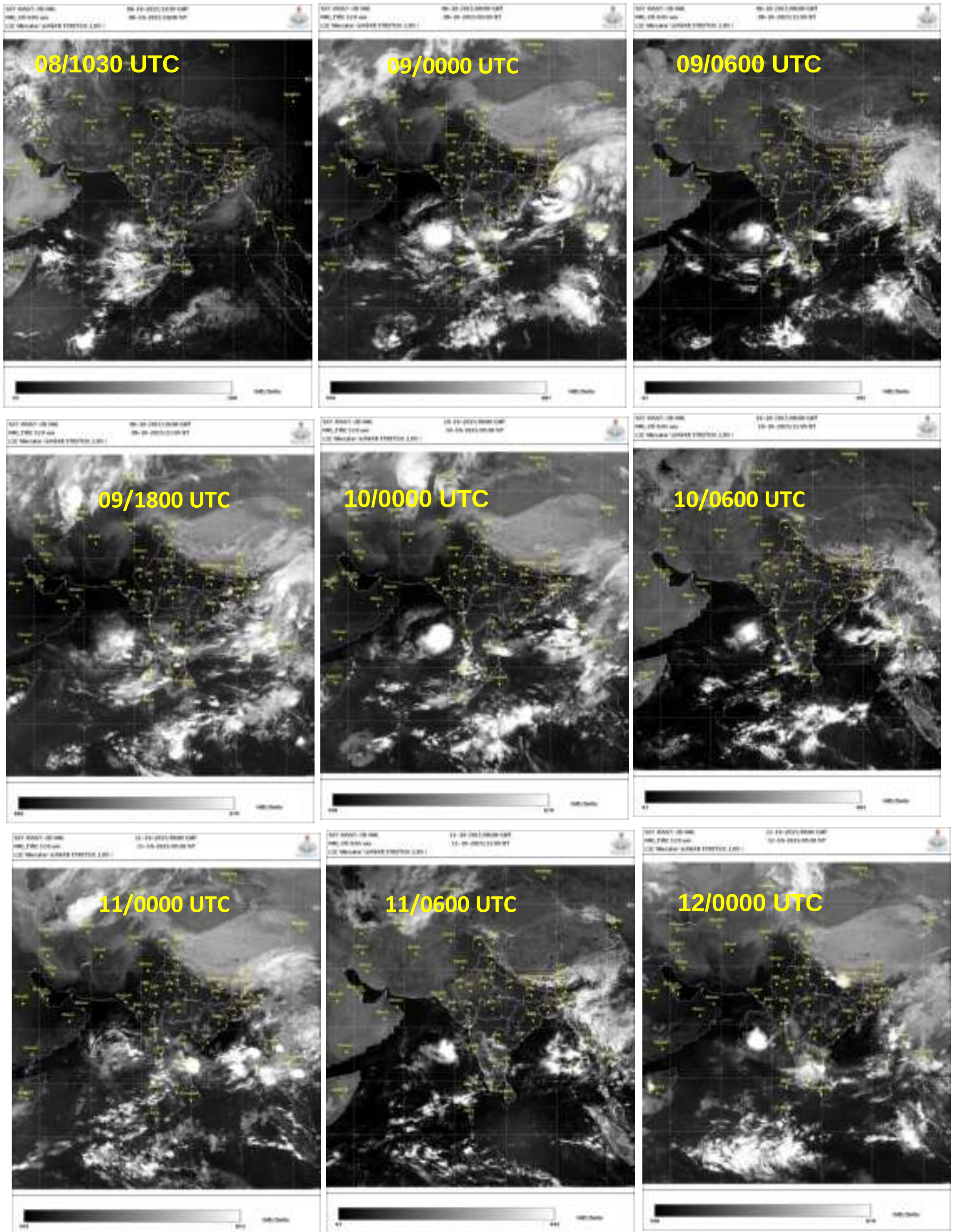


Fig. . 2.9.2 (a) INSAT-3D Visible imageries based on 1030 UTC of 8th , 00, 06, 18 UTC of 9th , 00,06 UTC of 10th , 00, 06 UTC of 11th and 12 UTC of 12th October in association with DD (09-12 October) over AS.

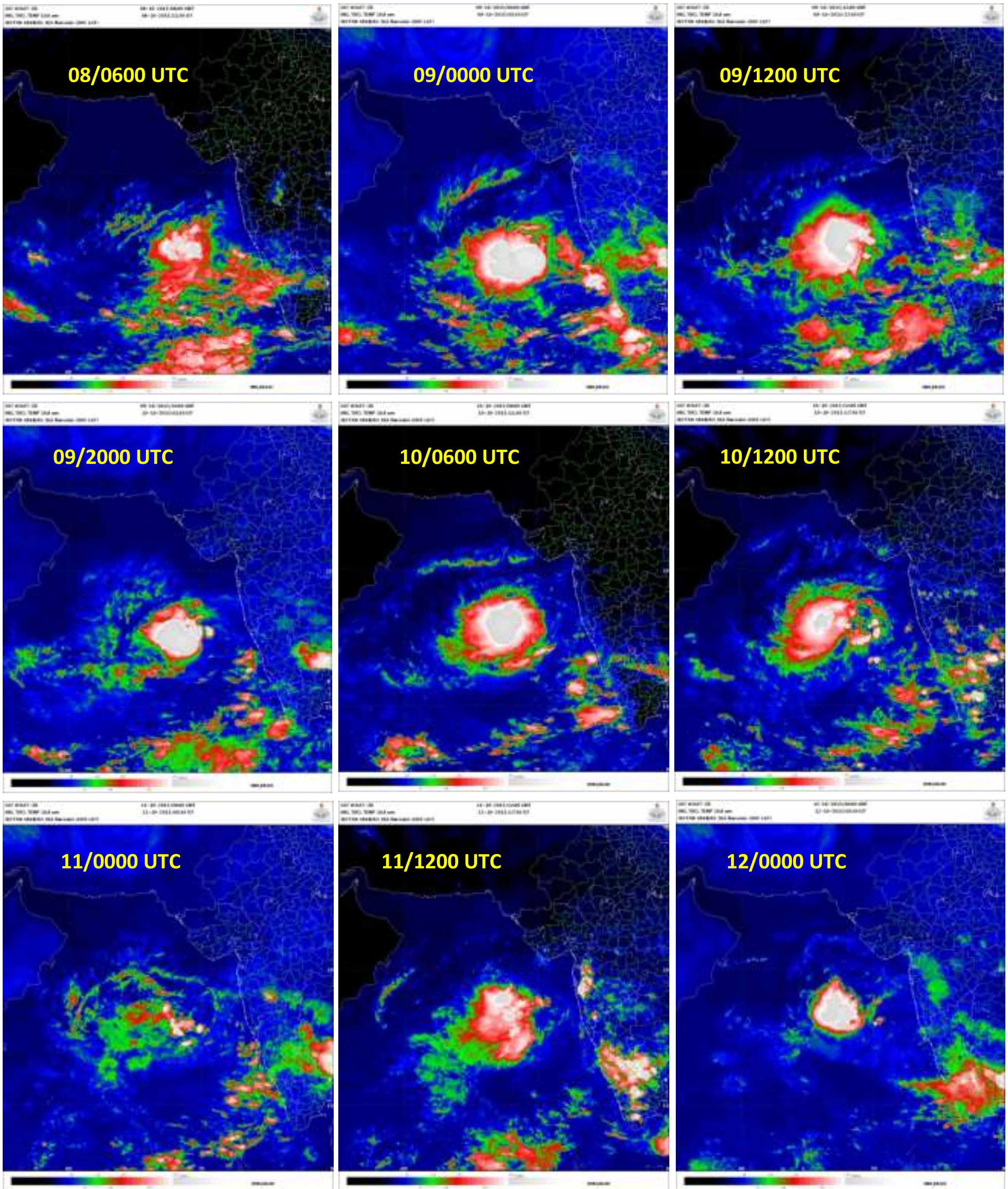


Fig. . 2.9.2 (b) INSAT-3D enhanced colored imageries based on 06 UTC of 9th , 00, 12, 20 UTC of 10th , 06,12 UTC of 10th , 00, 12 UTC of 11th and 00 UTC of 12th October in association with DD (09-12 October) over AS.

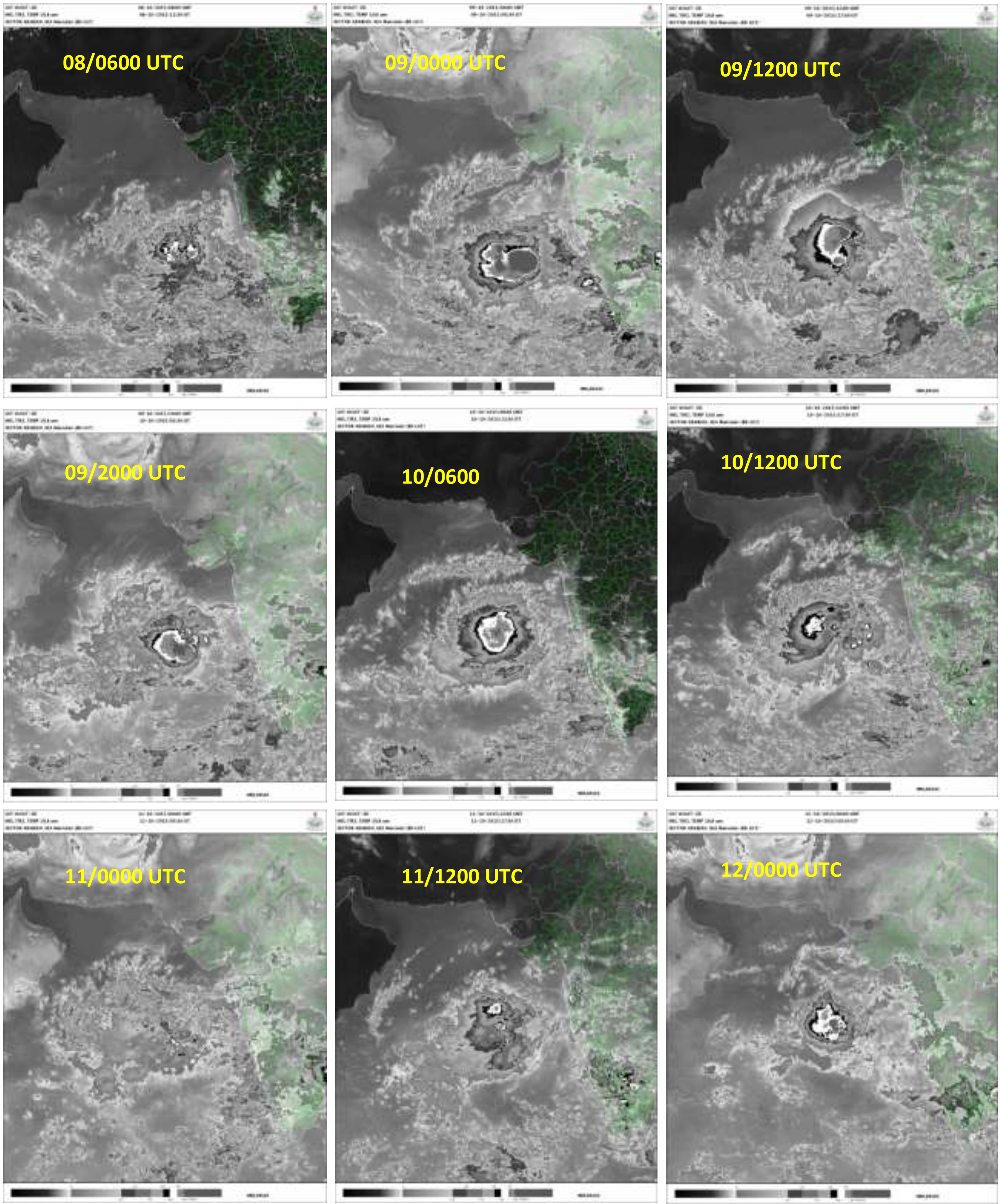


Fig. . 2.9.2 (c) INSAT-3D IR enhanced imageries based on 06 UTC of 9th , 00, 12, 20 UTC of 10th , 06,12 UTC of 10th, 00, 12 UTC of 11th and 00 UTC of 12th October in association with DD (09-12 October) over AS.

2.9.5 Dynamical Features

To analyse the dynamical features MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 00 UTC of 8th to 12th October 2015 are presented in Fig.2.9.3(a-e) based on IMD GFS analysis. The system extended upto 500 hPa level. As per IMD-GFS analysis, winds were higher in northeast and southeast sector on 8th, northeast and northwest sector on 9th, northeast and southern sector on 10th and around the system centre on 11th and 12th. Considering the MSLP, GFS analysis could pick up the initial conditions on 8th with two closed isobars and underestimated on 9th with 1 closed isobar. Further, it showed intensification on 10th with 2 closed isobars, weakening on 11th and again strengthening on 12th. Thus the model could not pick up the intensity of the system and exhibited oscillations in the intensification of the system. The upper tropospheric ridge of the anticyclonic circulation to the northeast of the system centre was captured by the model. However, the anticyclonic circulation to the northwest of the system centre on 12th leading to west-northwestward movement of the system could not be detected.

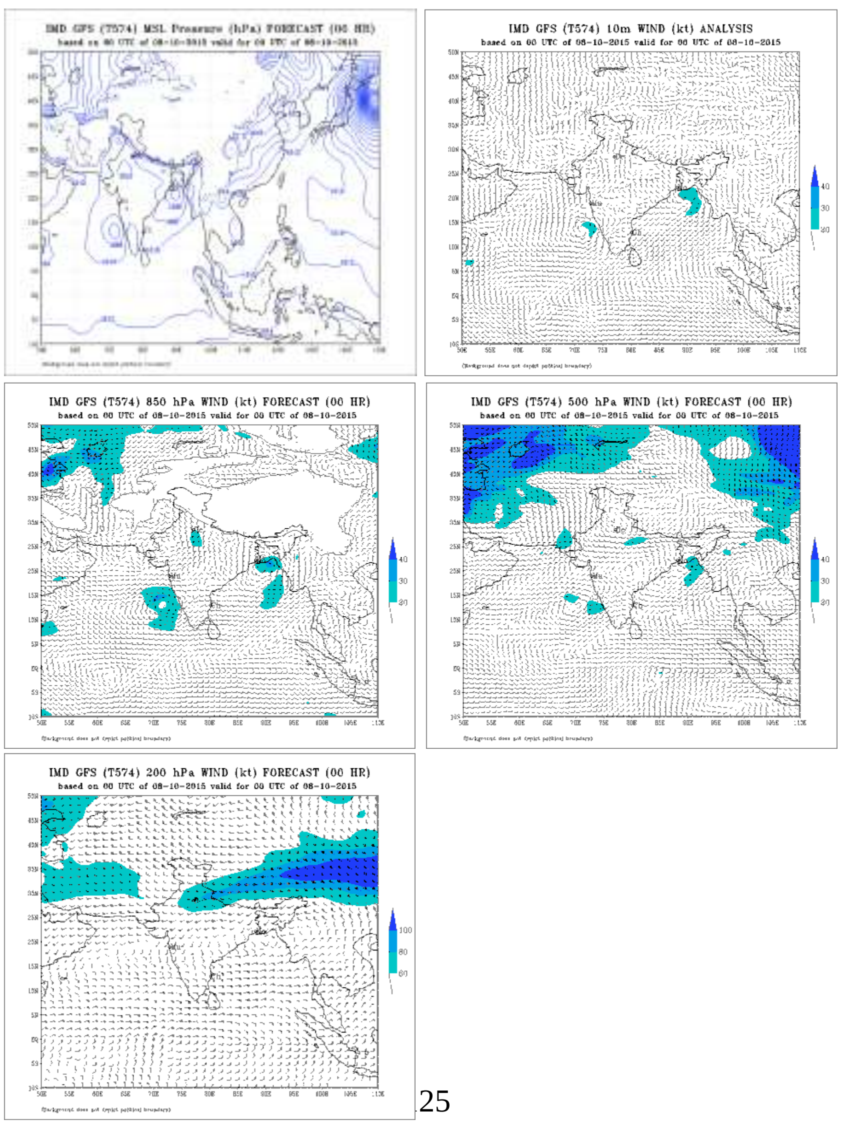


Fig. 2.9.3 (a) IMD-GFS MSLP, 10m wind, winds at 850, 500 and 200 hPa levels based on 00 UTC of 8th October 2015.

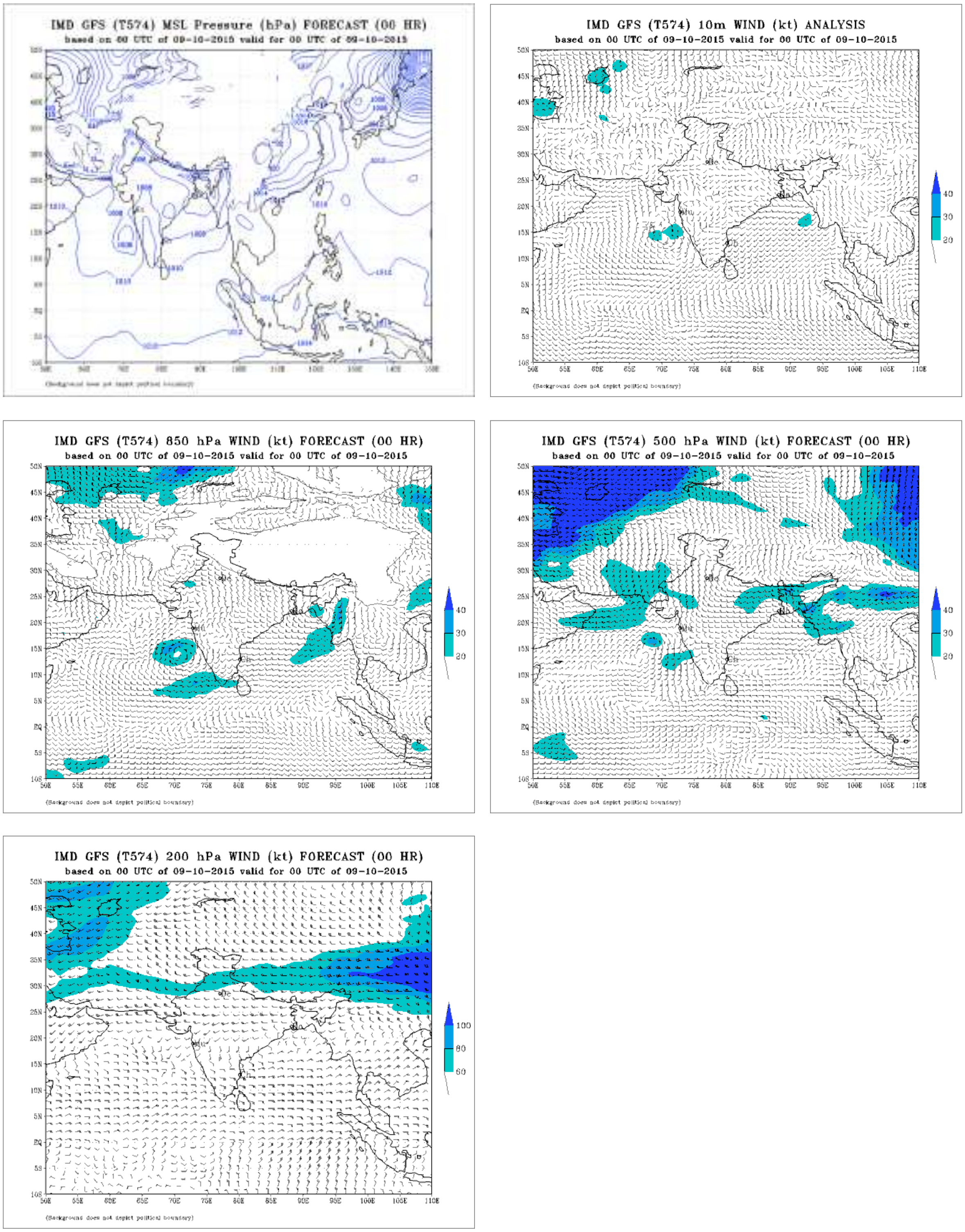


Fig. . 2.9.3 (b) IMD-GFS MSLP, 10m wind, winds at 850, 500 and 200 hPa levels based on 00 UTC of 9th October 2015.

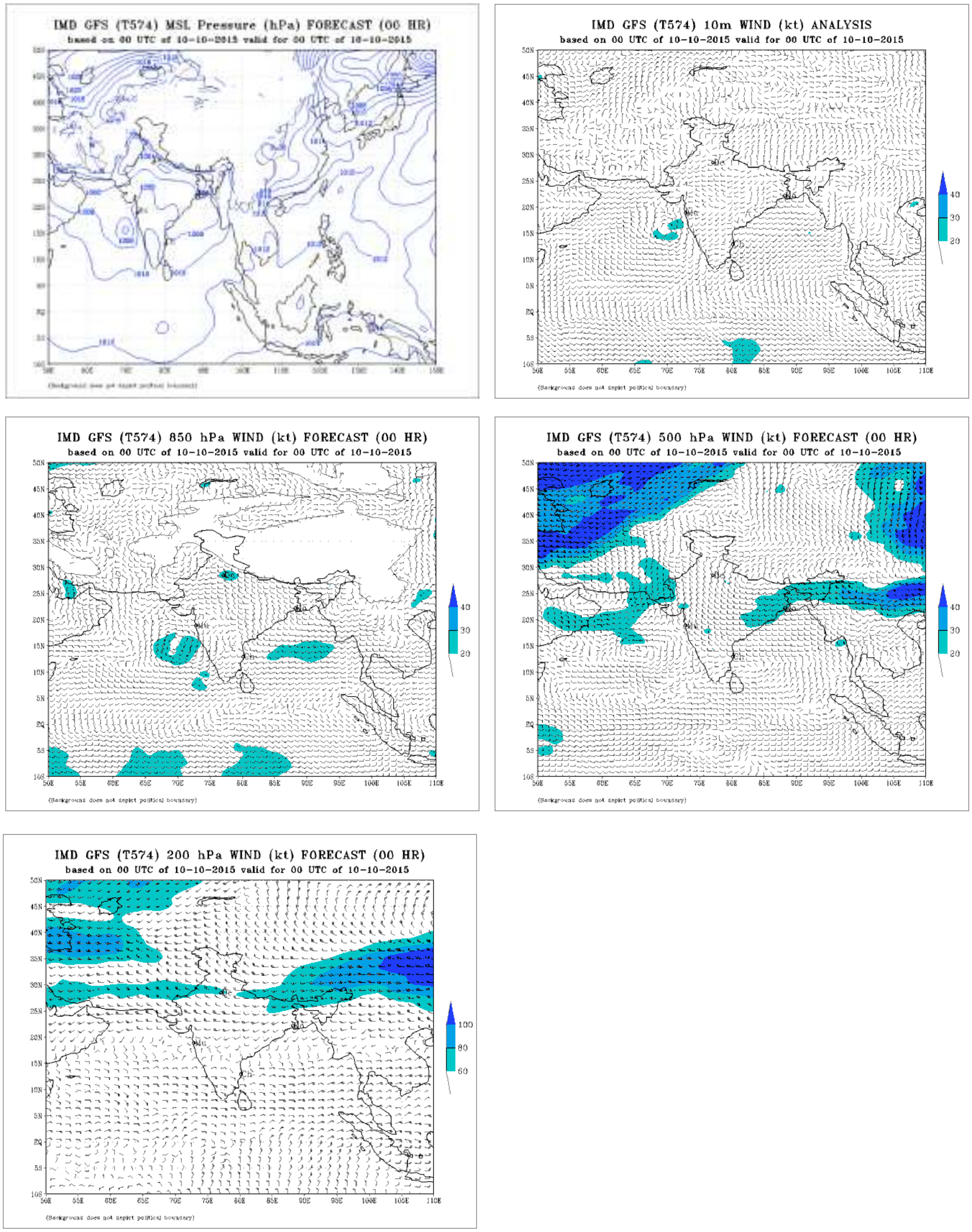


Fig. 2.9.3 (c) IMD-GFS MSLP, 10m wind, winds at 850, 500 and 200 hPa levels based on 00 UTC of 10th October 2015.

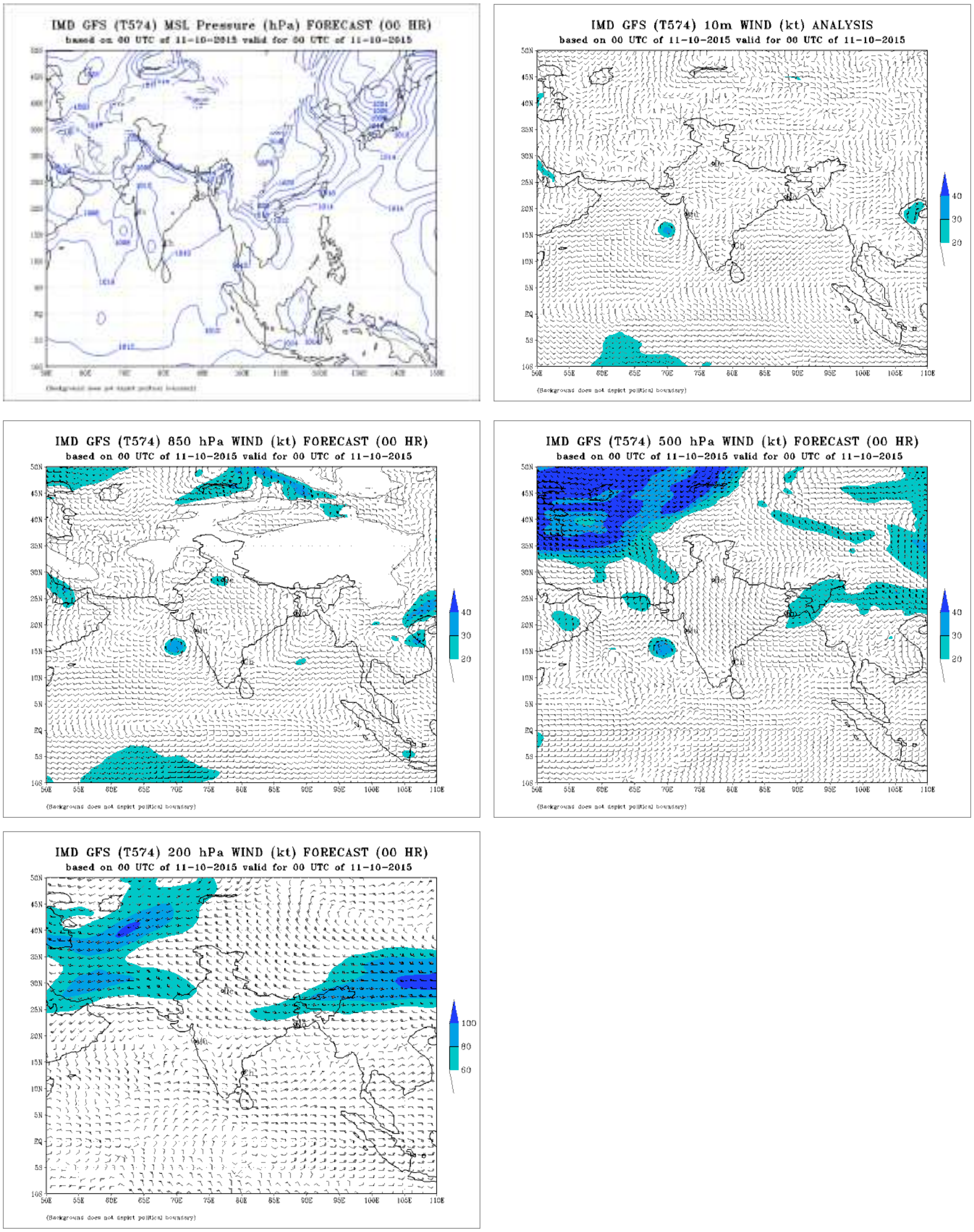


Fig. 2.9.3 (d) GFS MSLP, 10m wind, winds at 850, 500 and 200 hPa levels based on 00 UTC of 11th October 2015.

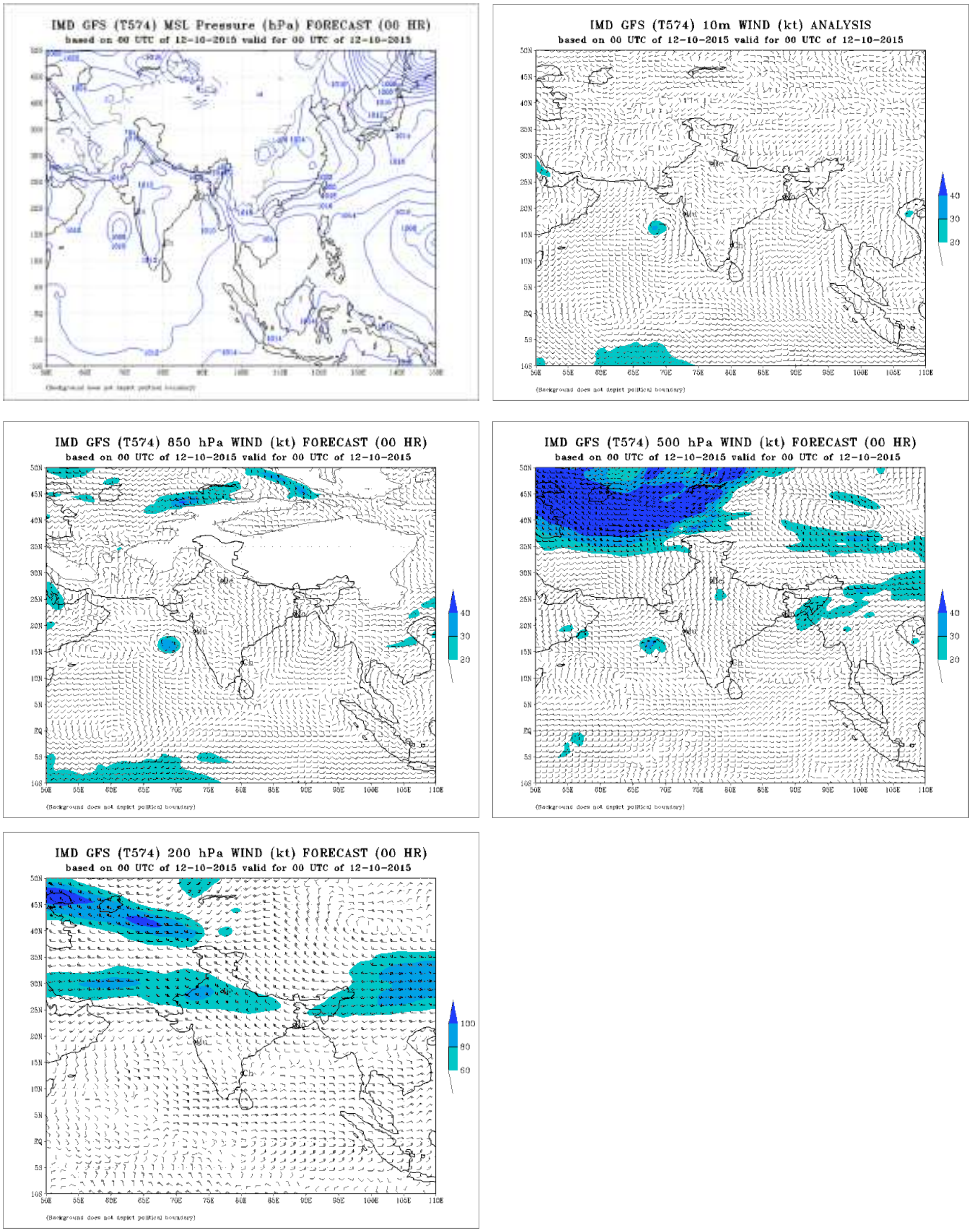


Fig. 2.9.3 (e) IMD-GFS MSLP, 10m wind, winds at 850, 500 and 200 hPa levels based on 00 UTC of 12th October 2015.

2.10 Extremely Severe Cyclonic Storm (ESCS) Chapala over the Arabian Sea (28 October - 04 November 2015)

2.10.1 Introduction

An Extremely Severe Cyclonic Storm 'Chapala' formed from a low pressure area over southeast Arabian Sea which concentrated into a depression in the morning of 28th October. It moved north-northwestwards and intensified into a deep depression in the same evening. It further intensified into a cyclonic storm in the early hours of 29th over eastcentral Arabian Sea. It then moved west-northwestwards, further intensified into a severe cyclonic storm in the evening and a very severe cyclonic storm in the midnight of 29th and into an extremely severe cyclonic storm in the morning of 30th. It then moved mainly westwards, maintained its intensity till 1st November and then started weakening gradually. Moving west-northwestwards, it crossed Yemen coast to the southwest of Riyan (14.1^{0}N/48.65^{0} E) during 0100-0200 UTC of 3rd November as very severe cyclonic storm. It further westwards and weakened into a severe cyclonic storm in the morning, into a cyclonic storm by noon and into deep depression around midnight of 3rd November. it then weakened into a depression in the early morning of 4th and lay as well marked low pressure area over Yemen at 0300 UTC of 4th November. The salient features of this cyclone are as follows.

i. ESCS Chapala is the first severe cyclone to cross Yemen coast after the severe cyclonic storm of May 1960.
ii. The ESCS Chapala had a life period of 7 days , which is above normal (average life period of VSCS/ESCS is 6 days in NIO and 4.7 days in Post monsoon season for VSCS/ESCS)
iii. It had the maximum intensity of 115 kts (215 kmph) and crossed Yemen coast with a speed of 65 knots (120 kmph).
iv. The system had the longest track length after VSCS Phet in 2010. It travelled a distance of about 2248 km during its life period.
v. The Accumulated Cyclone Energy (ACE) was about 18.29 X 10^{4} knot^{2} (the mean for the period (1990-2013) in the post monsoon season over Arabian Sea is 0.8 X 10^{4} knot^{2}), which is same as VSCS, Phet over Arabian Sea in 2010.
vi. The Power Dissipation Index was 17.92 X 10^{6} knot^{3} which is also same as that of VSCS Phet in 2010 (the mean for the period (1990-2013) in the post monsoon season is 0.4 X 10^{6} knot^{3}.
vii. The system rapidly intensified from 29th morning to 30th afternoon, when the speed increased from 35 kts at 0000 UTC of 29th Oct to 90 kts at 0900 UTC of 30th Oct.
viii. Though the system moved over to colder Gulf of Aden, experienced dry air intrusion and interacted with the land surface, it did not weaken rapidly due to low vertical wind shear around the centre and in the forward sector of the system.

ix. There was large divergence and hence higher than normal errors in NWP models for prediction of its track and intensity especially, the landfall over Yemen.

x. RSMC New Delhi predicted genesis on 25th October, 3 days in advance and its intensification to ESCS one day in advance on 29th October 2015. The forecast of landfall over Yemen and adjoining Oman coast was issued on the day of genesis i.e., 28th Oct., 6 days advance and landfall over Yemen was issued on 31 Oct. with a lead period of 5 days. Every 3 hourly Tropical Cyclone Advisories were issued to WMO/ESCAP panel countries including Oman and Yemen & Somalia.

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

2.10.2 Monitoring of ESCS, Chapala

The ESCS Chapala was monitored & predicted continuously since its inception by the India Meteorological Department (IMD). The forecast of its genesis (formation of Depression) on 28th October, its track, intensity, point & time of landfall was well predicted by IMD. The system was monitored mainly by observations from satellite throughout its life period. Various national and international NWP models and dynamical-statistical models including IMD and National Centre for Medium Range Weather Forecasting (NCMRWF) global and meso-scale models, dynamical statistical models for genesis and intensity were utilized to predict the genesis, track and intensity of the storm. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation.

2.10.3 Brief life history

2.10.3.1 Genesis

During the onset phase of northeast monsoon, a trough of low with embedded upper air cyclonic circulation in lower levels lay over southeast Bay of Bengal on 25th Oct. Under its influence, a low pressure area formed over southeast and adjoining southwest and eastcentral Arabian Sea at 0300 UTC of 26th Nov. with associated cyclonic circulation extending upto mid-tropospheric levels. It became well marked over the same region at 0300 UTC of 27th morning. It concentrated into a depression over southeast and adjoining southwest and central Arabian Sea at 0300 UTC of 28th October near Lat. 11.5°N and Long. 65.0°E.

The winds were stronger in northern sector (25-30 knots) under the influence of northeast monsoon current and were about 15-20 knots in other sectors as seen from multi-satellite surface winds. The Sea Surface Temperature (SST) was about 30°C around the region of depression. The vertical wind shear was moderate (10-20 knots) around the system centre and was low (5-10 knots) to the west-northwest of the system centre. The low level relative vorticity was about 100×10^{-5} $second^{-1}$ and low level convergence was 5-

10 x 10^{-5} $second^{-1}$. The upper level divergence was 30 x 10^{-5} $second^{-1}$. The ocean thermal energy was about 60-80kJ/cm^2. MJO lay in phase 2 (west equatorial region) with amplitude greater than 2.

2.10.3.2 Track and intensification

Best track parameters of ESCS, Chapala over AS (28th Oct.-4nd Nov., 2015) are given in Table 2.10.1. The observed track of the system is also shown in Fig. 2.1.

The environmental features and large scale features as mentioned in the previous section continuously favoured the intensification of the system during 28th -30 Oct. The system rapidly intensified from 29th to 30th, when the speed increased from 35 kts at 0000 UTC of 29th Oct to 90 kts at 0900 UTC of 30th Oct. There was land interaction and impact of dry air intrusion from northwest from 01 Nov. onwards. However, the impact of dry air intrusion from northwest and land interaction was slow because of low vertical wind shear to the west and west-southwest of the system as can be seen in Fig. 2.10.1 and hence the system could maintain its intensity of ESCS from 0000 UTC of 30th Oct. to 0900 UTC of 2 Nov. The Total Precipitable Water (TPW) imageries during 28 Oct. to 04 Nov. is shown in Fig. 2.10.3 which clearly exemplifies the low impact of dry air intrusion into the wall cloud region. From 0300 UTC of 2nd Nov. The system started interacting with land surface and also the convection in the wall cloud region showed signs of disorganisation indicating the weakening trend of the system. It crossed Yemen coast to the southwest of Riyan (14.1^{0}N/48.65^{0} E) during 0100-0200 UTC of 3rd November as Very Severe Cyclonic Storm (VSCS). It then weakened rapidly into SCS at 0300 UTC, into a CS at 0600 UTC and into a Deep Depression (DD) at 1800 UTC on the same day due to land interaction. It further weakened into a Depression at 0000 UTC and into a well marked low pressure area at 0300 UTC of 4th November 2015 over Yemen.

The system initially moved north-northwestwards in association with the anti-cyclonic circulation lying to the northeast of the system centre. It then came under the influence of another anti-cyclonic circulation to its northwest on 29th which increased westward component in the movement of the system. The system lay in the south eastern periphery of this anticyclone. Thus the system moved nearly westwards to west-southwestward upto 0300 UTC of 2 Nov. It then lay to the southwest of the anticyclone and the ridge (Lat. 16°N) at 200 hPa and thus moved west-northwestwards towards Yemen coast. It moved normally with a speed of 13 kmph initially, its speed gradually picked up and became about 20 kmph on the day before landfall. The direction and translational speed of movement of the system is illustrated in Fig. 2.10.2

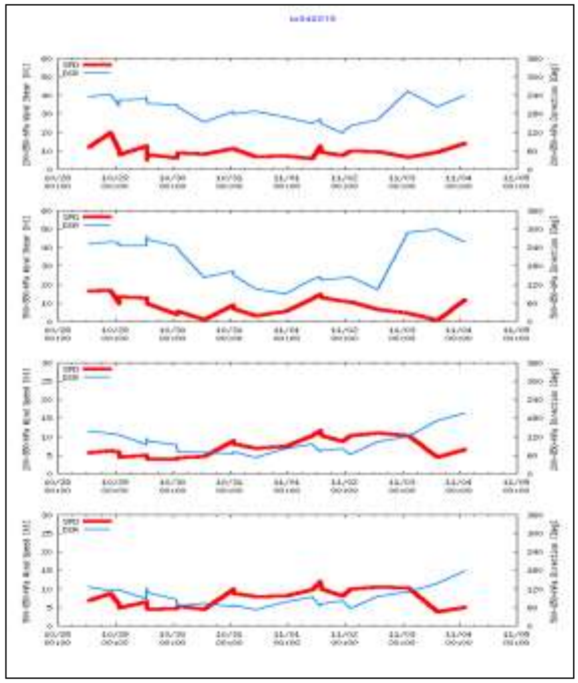


Fig.2.10.1 Wind shear and wind speed in the middle and deep layer around the system during 28th Oct. to 05th Nov 2015.

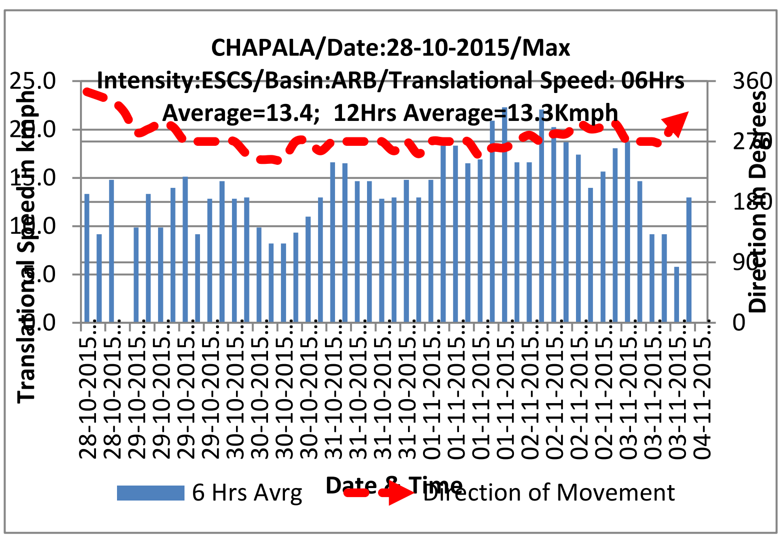


Fig. 2.10.2. Translational speed and direction of ESCS Chapala during 28th Oct. - 04th Nov 2015.

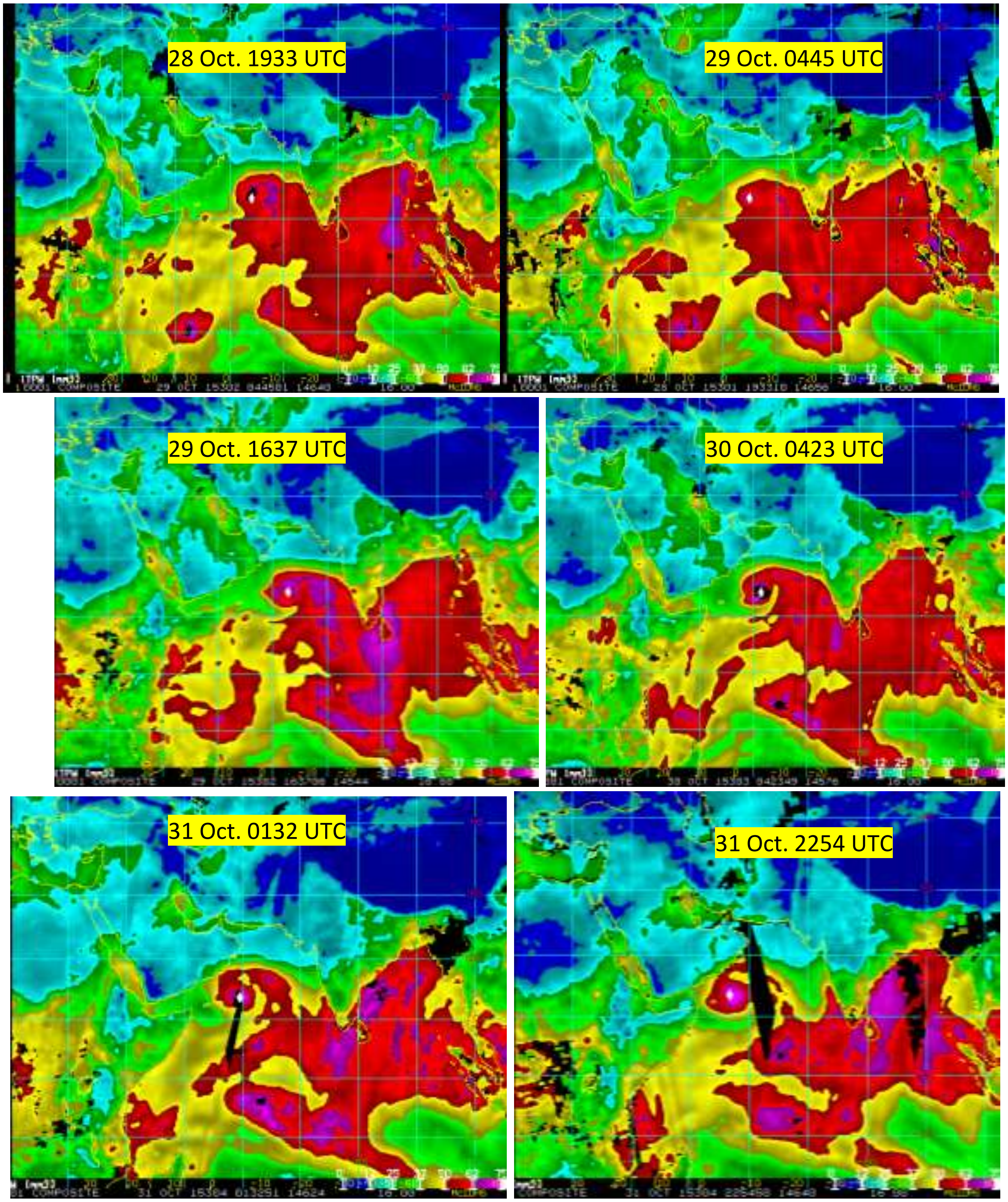


Fig. 2.10.3 TPW imageries of ESCS Chapala during 28th Oct. to 04th Nov 2015.

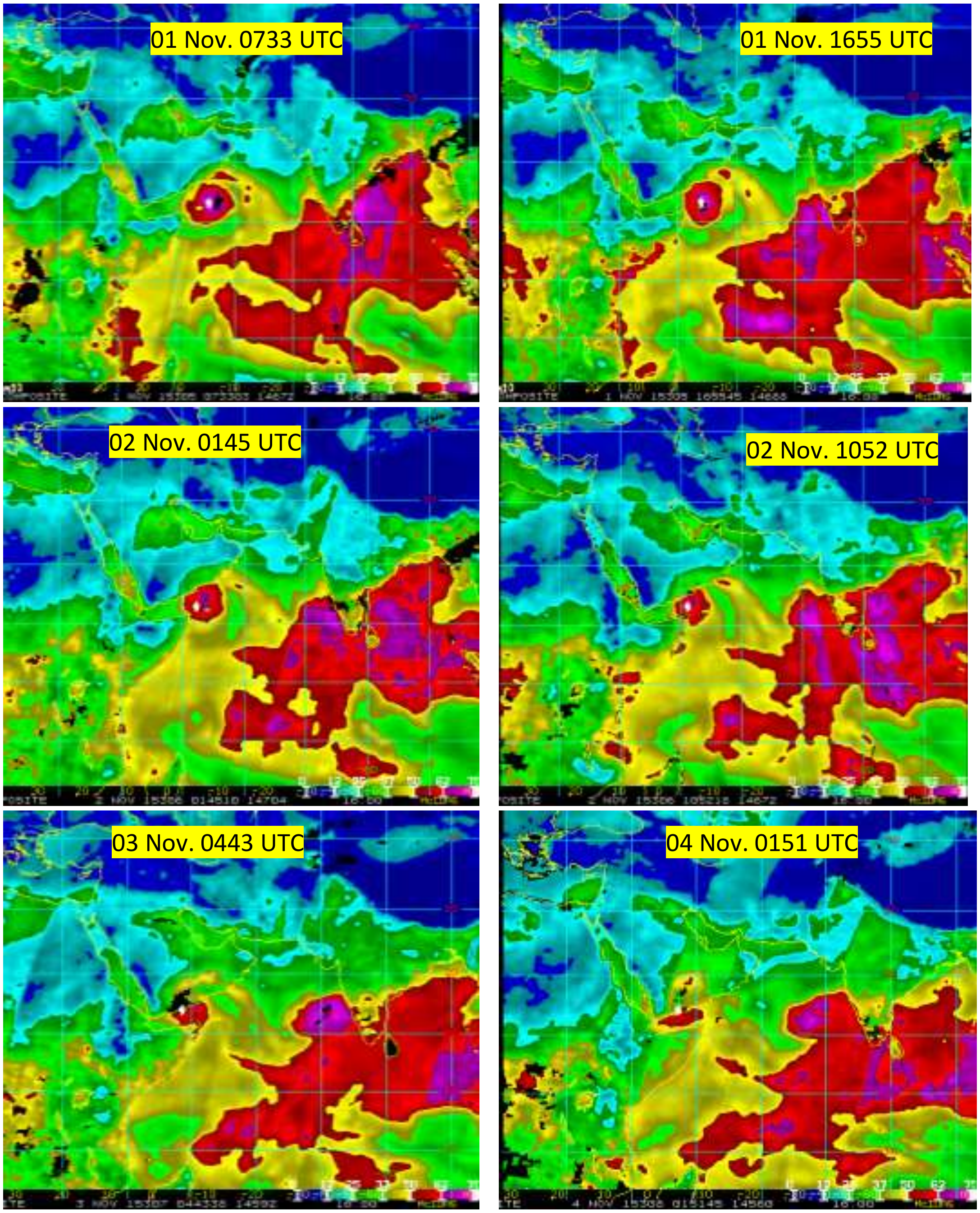


Fig. 2.10.3 contd. TPW imageries of ESCS Chapala during 28th Oct. to 04th Nov 2015.

Table 2.10.1 Best track positions and other parameters of ESCS CHAPALA over the Arabian Sea during 28 October-04 November, 2015

Date	Time (UTC)	Centre lat.° N/ long. ° E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
28/10/2015	0300	11.5/65.0	1.5	1005	25	3	**D**
	0600	11.8/64.9	2.0	1004	25	4	D
	1200	12.5/64.7	2.0	1001	30	5	**DD**
	1800	13.0/64.7	2.0	1001	30	5	DD
29/10/2015	0000	13.7/64.3	2.5	999	35	7	**CS**
	0300	13.8/64.2	2.5	997	40	9	CS
	0600	13.9/63.8	3.0	996	45	10	CS
	0900	14.0/63.5	3.0	994	50	12	**SCS**
	1200	14.1/63.3	3.5	990	55	16	SCS
	1500	14.3/62.8	3.5	988	60	18	SCS
	1800	14.3/62.5	4.0	984	65	22	**VSCS**
	2100	14.3/62.3	4.5	976	75	30	VSCS
30/10/2015	0000	14.3/61.8	5.0	966	90	40	**ESCS**
	0300	14.3/61.5	5.5	954	105	52	ESCS
	0600	14.3/61.1	5.5	948	110	58	ESCS
30/10/2015	0900	14.2/60.8	6.0	940	115	66	ESCS
	1200	14.1/60.6	6.0	940	115	66	ESCS
	1500	14.0/60.4	6.0	940	115	66	ESCS
	1800	13.9/60.2	6.0	940	115	66	ESCS
	2100	13.9/59.9	6.0	942	115	64	ESCS
31/10/2015	0000	13.9/59.6	5.5	944	110	62	ESCS
	0300	13.8/59.2	5.5	946	110	60	ESCS
	0600	13.8/58.7	5.5	950	105	56	ESCS
	0900	13.8/58.3	5.5	950	105	56	ESCS
	1200	13.8/57.9	5.5	950	105	56	ESCS
	1500	13.8/57.5	5.5	950	105	56	ESCS
	1800	13.8/57.2	5.5	950	105	56	ESCS
	2100	13.7/56.8	5.5	950	105	56	ESCS
01/11/2015	0000	13.7/56.4	5.5	950	105	56	ESCS
	0300	13.6/56.1	5.5	952	105	54	ESCS
	0600	13.6/55.6	5.5	954	100	52	ESCS

	0900	13.6/55.1	5.5	956	100	50	ESCS
	1200	13.6/54.6	5.5	956	100	50	ESCS
	1500	13.6/54.2	5.5	956	100	50	ESCS
	1800	13.4/53.7	5.5	956	100	50	ESCS
	2100	13.3/53.1	5.5	956	100	50	ESCS
02/11/2015	0000	13.2/52.5	5.5	958	100	48	ESCS
	0300	13.2/52.2	5.0	960	95	46	ESCS
	0600	13.3/51.6	5.0	964	90	42	ESCS
	0900	13.3/51.0	5.0	966	90	40	ESCS
	1200	13.4/50.5	4.5	968	85	38	**VSCS**
	1500	13.5/50.0	4.5	970	85	36	VSCS
	1800	13.7/49.6	4.5	974	80	32	VSCS
	2100	13.8/49.3	4.0	978	75	28	VSCS
3/11/2015	0000	14.0/48.8	4.0	984	65	22	VSCS
	Crossed Yemen coast to the southwest of Riyan (14.1/48.65) during 0100-0200 UTC.						
	0300	14.2/48.4	-	990	55	16	**SCS**
	0600	14.2/47.8	-	996	45	10	**CS**
	0900	14.2/47.6	-	998	40	8	CS
	1200	14.2/47.3	-	998	40	8	CS
	1500	14.2/47.1	-	998	40	8	CS
	1800	14.3/47.0	-	1001	30	5	**DD**
04/11/2015	0000	14.8/46.5	-	1003	25	3	**D**
	0300	Well marked low pressure area over Yemen.					

2.10.3.3 Maximum Sustained Surface Wind speed and estimated central pressure:

The lowest estimated central pressure has been 940 hPa. The estimated maximum sustained surface winds (MSW) was 115 knots during 0900 - 2100 UTC of 30th Oct. However, at the time of landfall, the ECP was 984 hPa and MSW was 65 knots (very severe cyclonic storm) due to weakening of the system over Gulf of Aden.

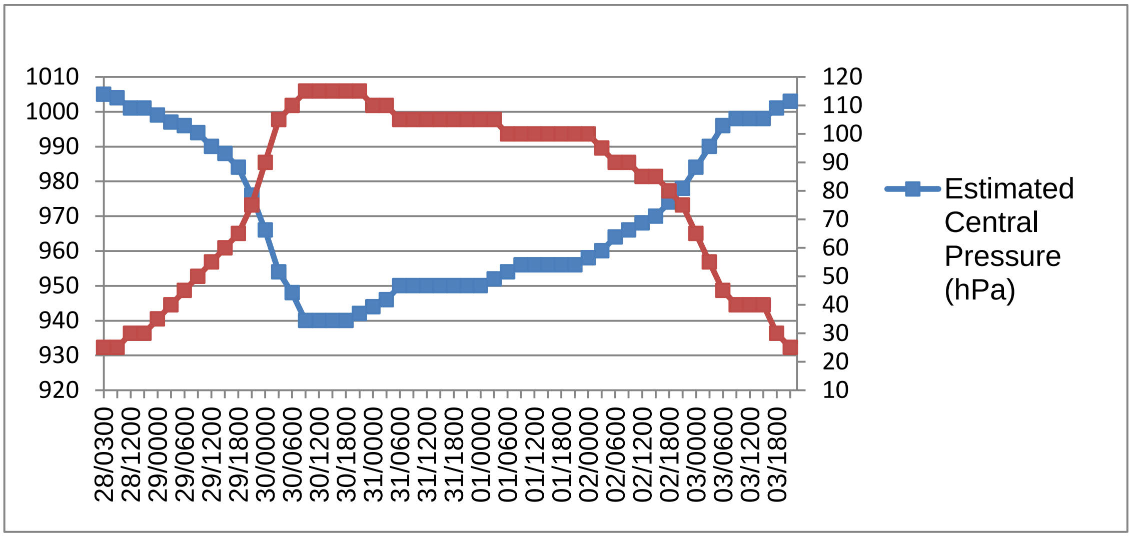


Fig. 2.10.4 Estimated Central Pressure (ECP) and estimated maximum sustained surface wind speed during 28th Oct./0300 UTC to 04th Nov/0000 UTC.

It can be seen from Fig. 2.10.4 that there was rapid intensification from 29/0000 UTC to 30/0900 UTC.

2.10.4 Climatological aspects

Climatologically, the severe cyclonic storms crossing Yemen coasts are very rare. Prior to Chapala, only one SCS in May 1960 crossed Yemen coast during the 1891-2014). The track of the SCS is shown in Fig. 2.10.5.

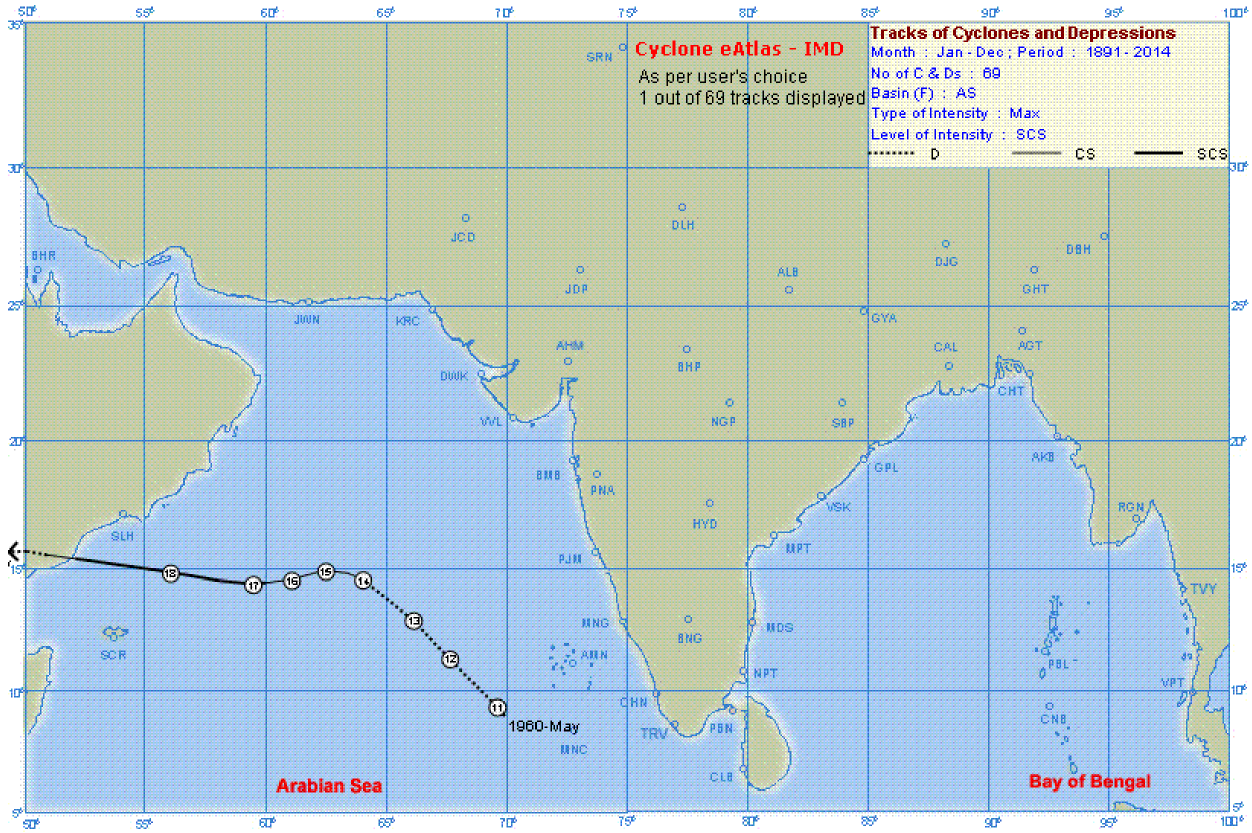


Fig. 2.10.5 Tracks of Severe cyclonic storm over Arabian Sea during the period 1891-2014 that crossed Yemen coast.

2.10.5 Features observed through satellite

(a) INSAT 3D and Kalpana imageries:

Half hourly Kalpana-1 and INSAT-3D imageries were utilised for monitoring of ESCS, Chapala. Satellite imageries of international geostationary satellites Meteosat-7 and MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical satellite INSAT-3D imageries (IR, visible, IRBD and enhanced colour imageries) of ESCS Chapala representing the life cycle of the cyclone are shown in Fig 2.10.6 to 2.10.9

As per the satellite imageries, on 26th October, broken low and medium clouds with embedded intense to very intense convection lay over south Arabian Sea between equator to latitude 10.0°N and longitude 61.0°E to 74.0°E in association with the low pressure area over the area.

On 27th/0300, vortex was observed over south Arabian Sea centered within half a degree of latitude 8.5˚N and longitude 66.0˚E with intensity T1.0 and poorly defined centre. Associated broken low and medium clouds with embedded moderate to intense convection lay over the area between latitude 6.0˚N to 14.5˚N and longitude 60.0˚E to 72.0˚E. The lowest cloud top temperature (CTT) associated with the vortex was -70°C. On 28th/0300

UTC, intensity of the system was T1.5 with convective clouds showing shear pattern and increase in organisation. On 28th/1200 UTC, the intensity of the system became T2.0 with increased convection and organisation into curved band pattern during the past 12 hours.

On 29th, the intensity of the system increased rapidly by three T numbers in 24 hrs. At 29/0000 UTC, the intensity of the system was T.2.5. At 29/0300 UTC, it became T3.0, at 1200 UTC,T3.5 and at 1800 UTC of the same day, it was T4.0 and eye started appearing. On 30th/0000 UTC, intensity further increased to T5.5 with convective cloud showing eye pattern with well-defined eye of diameter about 15 km in both visible and IR imageries. By 0900 UTC of 30th, intensity further increased to T6.0 with well-defined eye of diameter about 15 km. At 2100 UTC of the same day, the eye pattern became ragged. By 31st/0000 UTC, intensity became T5.5 / CI 6.0 and the eye was ragged. At 0600 UTC of the same day, intensity became T5.0 / CI 6.0. However, ragged eye was observed in both visible and IR imageries. Minimum wall cloud temperature was -80°C. By 0900 of the same day, weakening trend was observed in the associated convection. At 1200 UTC of 31st, eye was defined in visible and IR imageries. At 1800 UTC of the same day, minimum wall cloud temperature was -77°C. There was a good poleward outflow from 0000 UTC of 29th Oct. which changed to radial outflow from 0000 UTC of 31st Oct. The poleward outflow again was seen from 1200 UTC of 01st Nov. to 0000 UTC of 2nd Nov.

On 01st November/0300 UTC, ragged eye re-appeared and the minimum wall cloud temperature was -90°C. At 0300 UTC of the same day, intensity slightly decreased to T5.5/ CI 5.5 and convection showed ragged eye pattern. On 2nd/0000 UTC, the eye diameter increased to about 45 km. At 0300 UTC of the same day, intensity decreased to T5.0/ CI 5.5 and convection in the wall cloud region started showing disorganisation. At 1200 UTC of the same day, intensity further decreased to T4.5/ CI 5.5. However, well defined ragged eye was observed in both visible and IR imageries. At 2100 UTC, the intensity further decreased to T4.0 / CI 4.5 and on 03rd/0000 UTC, convection was sheared to the northwest due to increase in vertical wind shear and further disorganisation continued till day of landfall.

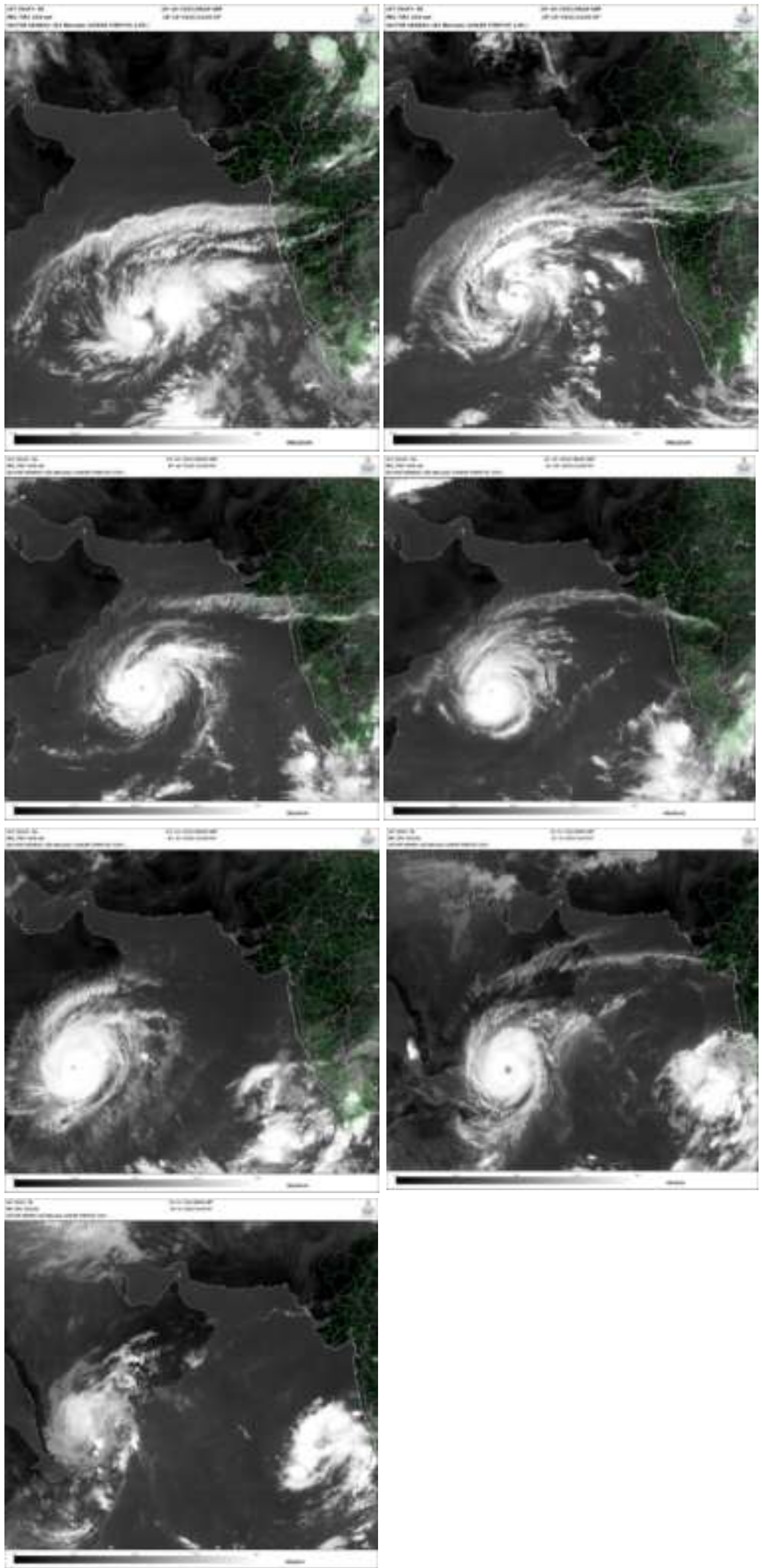


Fig. 2.10.6 INSAT 3D IR Imageries during 28 Oct.-3 Nov. 2015 based on 0600 UTC.

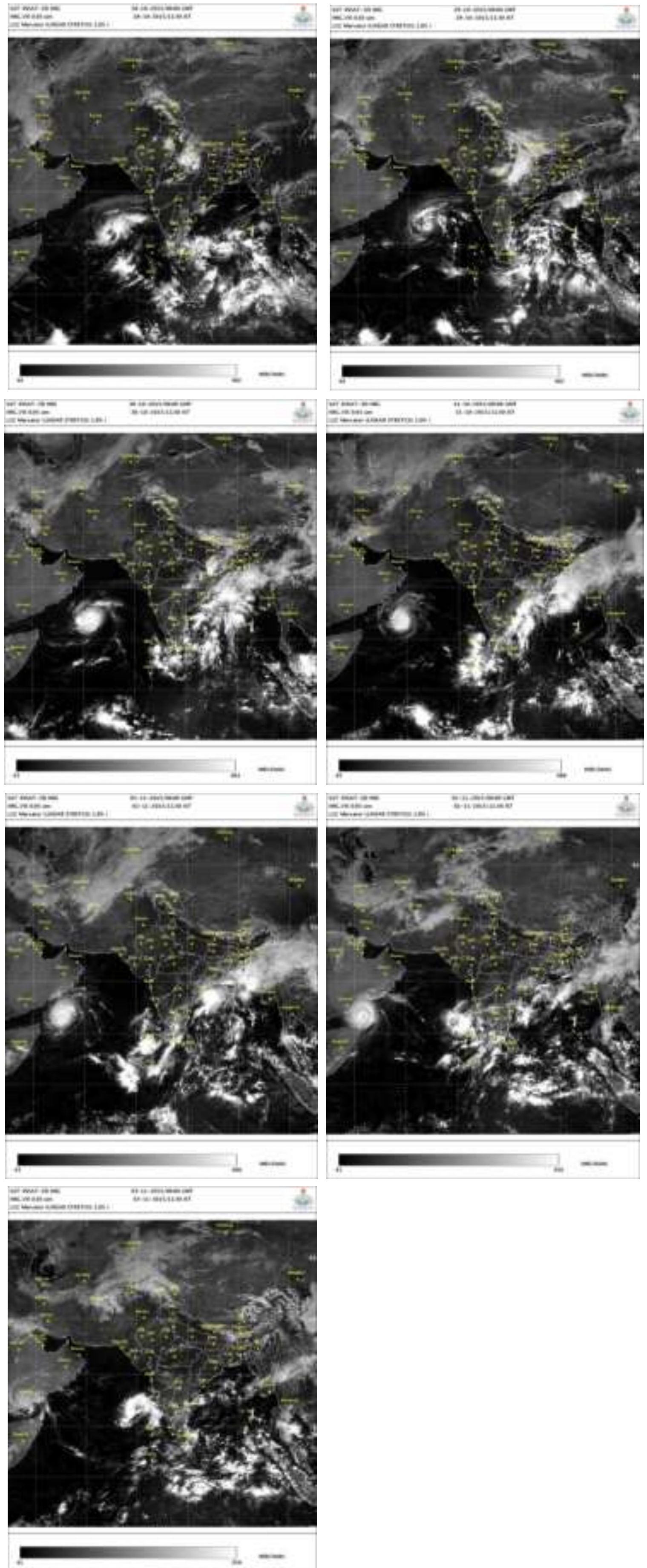


Fig. 2.10.7 INSAT 3D Visible Imageries during 28 Oct.-3 Nov. 2015 based on 0600 UTC.

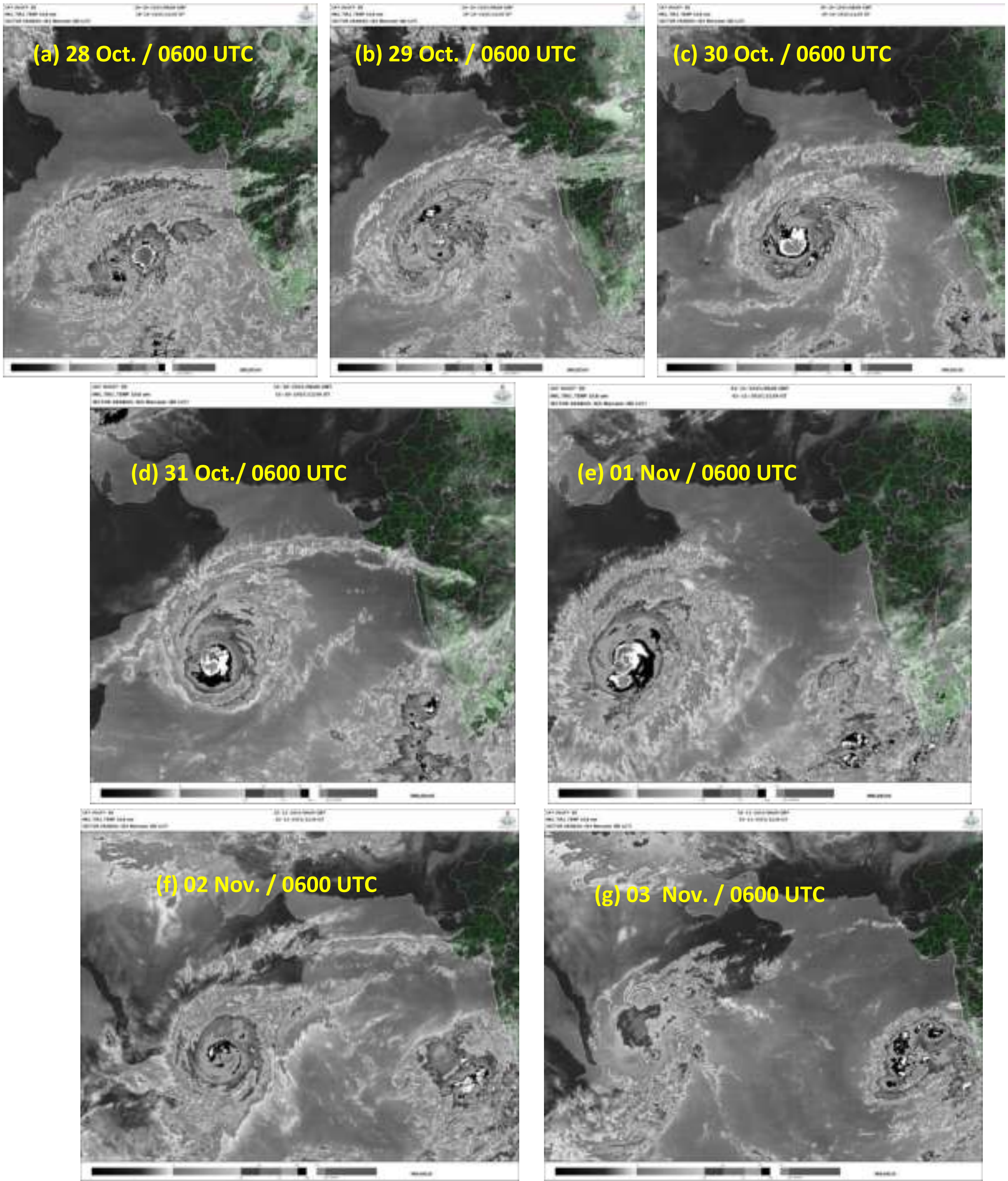


Fig. 2.10.8(a-e) INSAT 3D Imageries during 28 Oct. - 4 Nov. 2015 based on 0600 UTC.

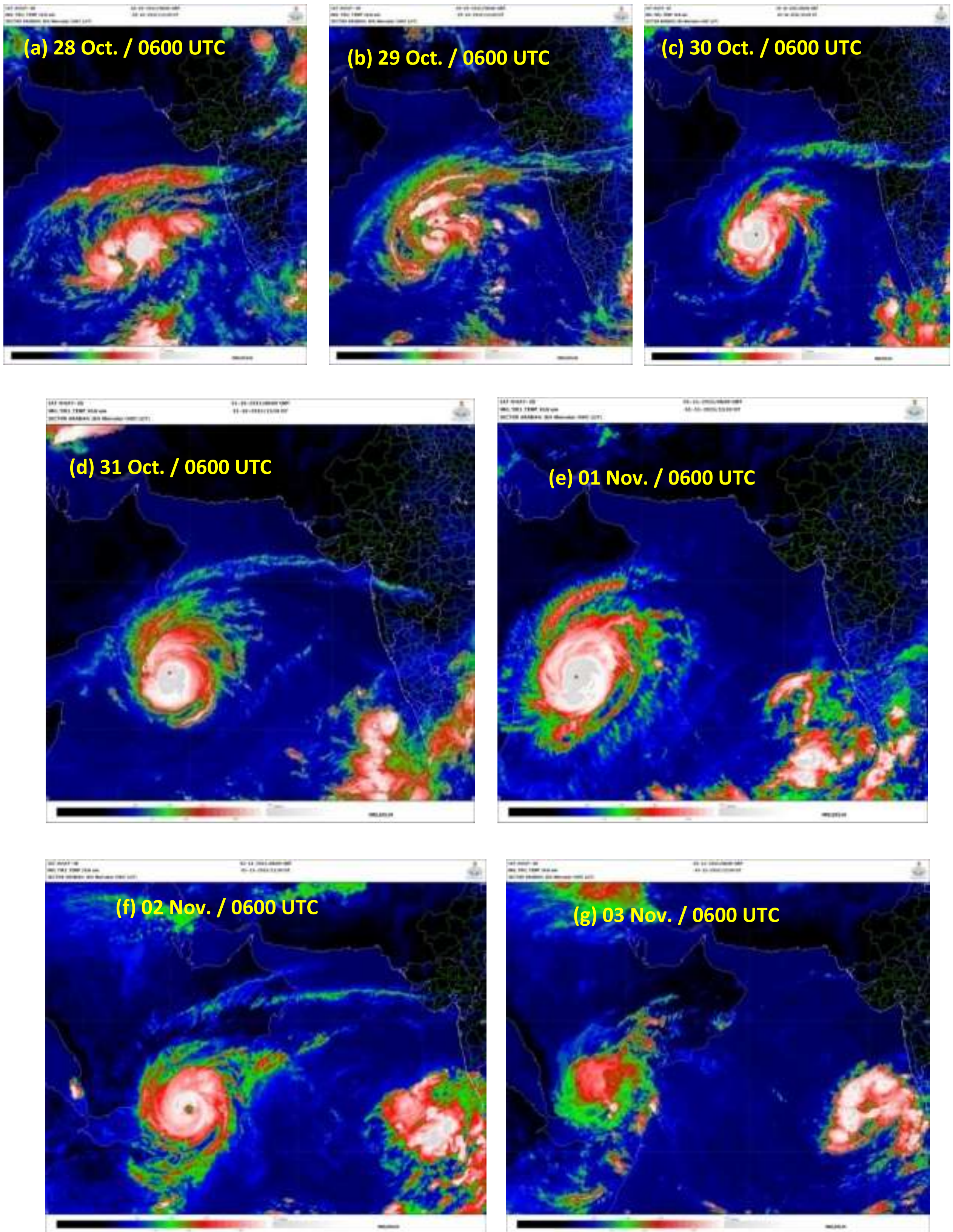
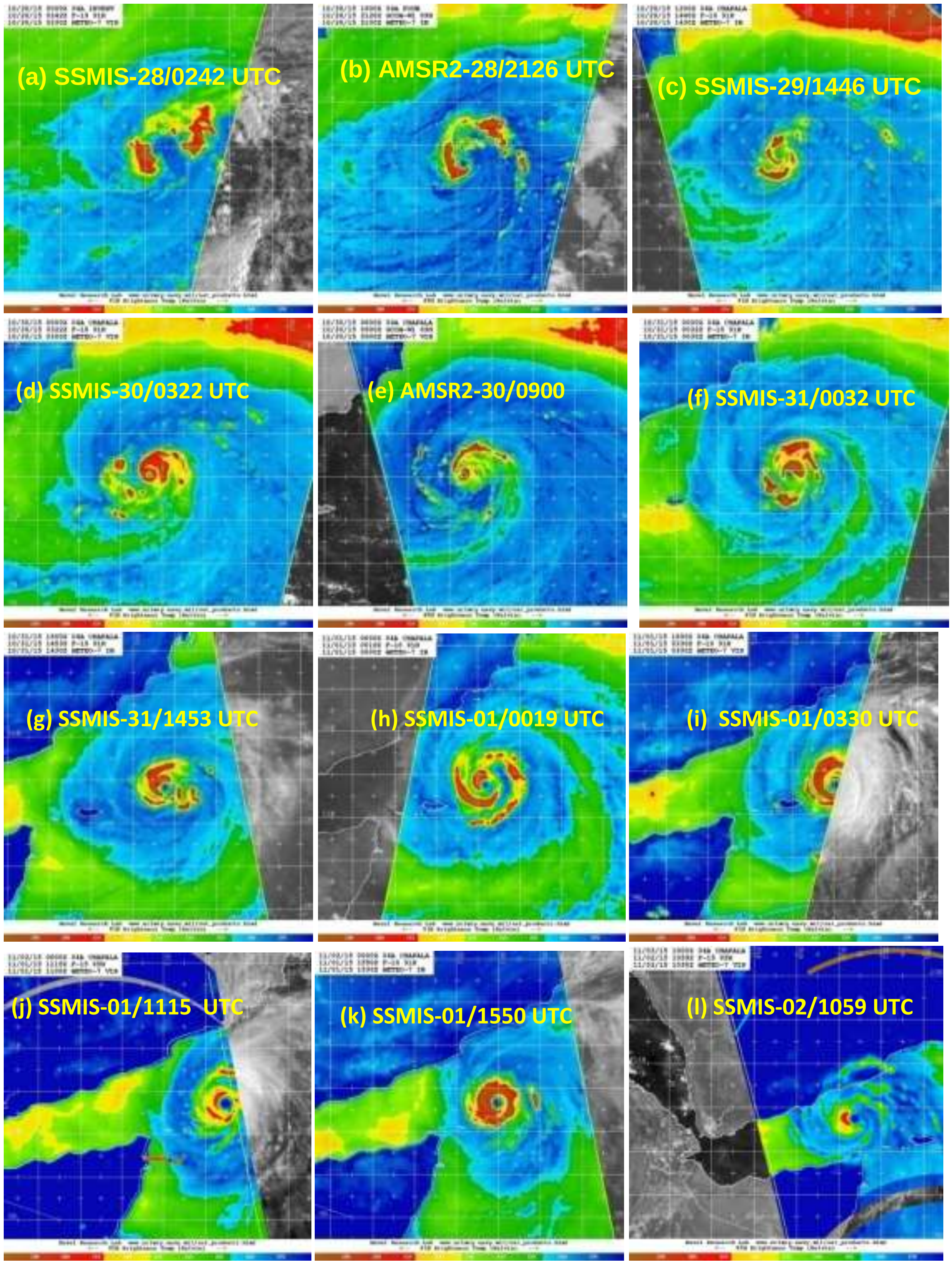


Fig. 2.10.9 (a-g) INSAT 3D enhanced imageries during 28 Oct. - 3 Nov. 2015 based on 0600 UTC.


(a) SSMIS-28/0242 UTC
(b) AMSR2-28/2126 UTC
(c) SSMIS-29/1446 UTC
(d) SSMIS-30/0322 UTC
(e) AMSR2-30/0900
(f) SSMIS-31/0032 UTC
(g) SSMIS-31/1453 UTC
(h) SSMIS-01/0019 UTC
(i) SSMIS-01/0330 UTC
(j) SSMIS-01/1115 UTC
(k) SSMIS-01/1550 UTC
(l) SSMIS-02/1059 UTC

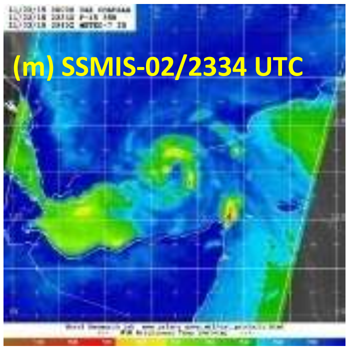


Fig. 2.10.10 (a-m). Evolution of TC Chapala during 28 Oct - 03 Nov 2015 based on microwave imageries (SSMIS / AMSR2).

(b) Microwave features and eye characteristics

Fig. 2.10.10 (a-m) presents the SSMIS / AMSR2 microwave imageries depicting the organisation of convective clouds associated with the system. As seen, on 28^{th} October, convective clouds organised from shear pattern to curved band pattern (a&b: 28/0242 & 28/2126). On 29^{th}, curved banding improved considerably and eye feature started appearing (c: 29/1446 UTC). Subsequently, as the system intensified, the eye feature became very well-defined and eye wall completely covered the eye (d: 30/0322 UTC). However, by 30/0900 UTC, the eye wall started opening (e), the eye became more and more exposed and an outer eye wall started forming on 31^{st} (f: 31/0032 UTC). Thereafter, on 31/1453 UTC, the outer eye wall is observed to have shifted inwards towards the partially dissolved inner eye wall (g). On 1^{st} November, by 01/0019 UTC, the inner eye wall has disappeared and the outer eye wall surrounds the eye (h). Associated with this eye wall replacement cycle, there has been a temporary weakening of the system on 30^{th}. With the formation and strengthening of the secondary eye wall (i: 01/0330 UTC), the intensity of the system increased further on 31^{st} October and 01^{st} November (j:01/1115 UTC). On 01/1530 UTC, the outer eye wall completely surrounds the eye and the system attained its mature stage (k). The eye diameter during this stage was about 37 km. Subsequently, by 02/0300 UTC, the intensity of the system started decreasing and at 02/1059 UTC, most of the wall cloud portion had dissolved and a partial eye wall with an exposed eye is seen (l). As the system approached close to the coast, further disorganisation occurred due to land interaction (m: 02/2334 UTC).

2.10.6. Surface wind structure

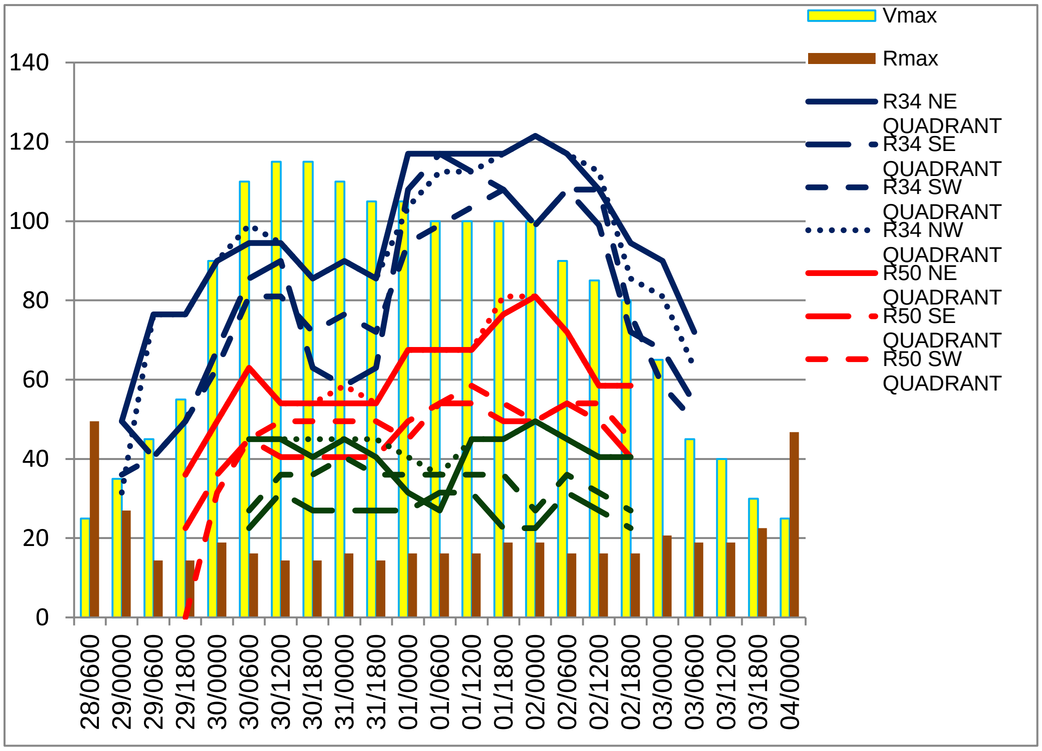


Fig. 2.10.11 : Radius 34 knot (R34), radius of 50 knot (R50) & radius of 64 knot (R64), estimated maximum sustained surface winds (Vmax in knots) and Radius of Maximum winds (Rmax in nautical mile) based on multi-satellite surface wind (http://rammb.cira.colostate.edu/)

The surface wind structure during the life period of ESCS, Chapala based on multi-satellite surface wind developed by CIRA, USA is shown in Fig. 2.10.11. It can be seen that the radius of 34 kt (outer core size) winds was higher in northeast (NE) sector. It was maximum of about 120 nm during its mature stage. Also in the radius of 50 kt/64 kt (inner core size), the winds were higher in the northeastern sector as compared to the other sector. Further it can be seen that the size of the outer core gradually increased till 0600 UTC of 30th Oct., then it slightly decreased upto 1800 UTC of 30 Oct. followed by a sharp increase upto 0000 UTC of 1st Nov. The size then almost remained same upto 0000 UTC of 2nd Nov. and then gradually decreased. The change in the inner core (R50) was similar to that of R34 and the temporal variation in R64 was less. Similarly the Radius of Maximum Winds (RMW) did not show significant variation throughout the TC stage and it varied from 15-20 nm.

2.10.7. Dynamical features

The genesis of the system took place on 28th under favourable environmental conditions of high SST (around 30°C), low to moderate wind shear (10-20 knots), conducive MJO conditions (phase 2 and amplitude greater than 1).

The system was initially located along the southwestern periphery of an anticyclone to the northeast which steered the system northward / north-northwestward on 28th. Subsequently, from 29th onwards, the system was steered by another anti-cyclone located to the northwest of its centre. On 29th October, the system was located along the southeastern periphery of the western anti-cyclone which steered the system westward to west-southwestward and subsequently, during 30th October to 01st November also the system was tracking west to west-southwestward under its influence. On 2nd, the system centre was located along the southwestern periphery of this anti-cyclone and was steered west-northwestward to northwestward on 2nd and 3rd November.

During the period 28th October to 01 November, outflow above the system centre strengthened significantly. On 29th, the poleward outflow increased and subsequently, during 30th October to 01st November, the outflow from the system centre was enhanced radially in all directions due to significant favourable interaction with upper tropospheric trough and divergence associated with sub tropical westerly jet located to the northeast of the system centre and the system continued to intensify despite intrusion of cold air from the northwest. The system underwent rapid intensification during 29/0000-30/00000 UTC in association with lowering of vertical wind shear to about 5-10 knots near the system centre, enhanced poleward outflow associated with an upper air westerly trough located to the northeast of the system centre and continued prevalence of favourable MJO conditions. However, as the system tracked more and more westwards towards Yemen coast on 2nd November, it started weakening due to intrusion of cold and dry air and interaction with land.

Dynamical features observed in the IMD-GFS analysis of MSLP, 10m, 850 hPa, 500 hPa and 200 hPa winds based on 0000 UTC of 28-October to 03 November 2015 (Fig. 2.10.2 (i) to (vii)) are discussed herewith.

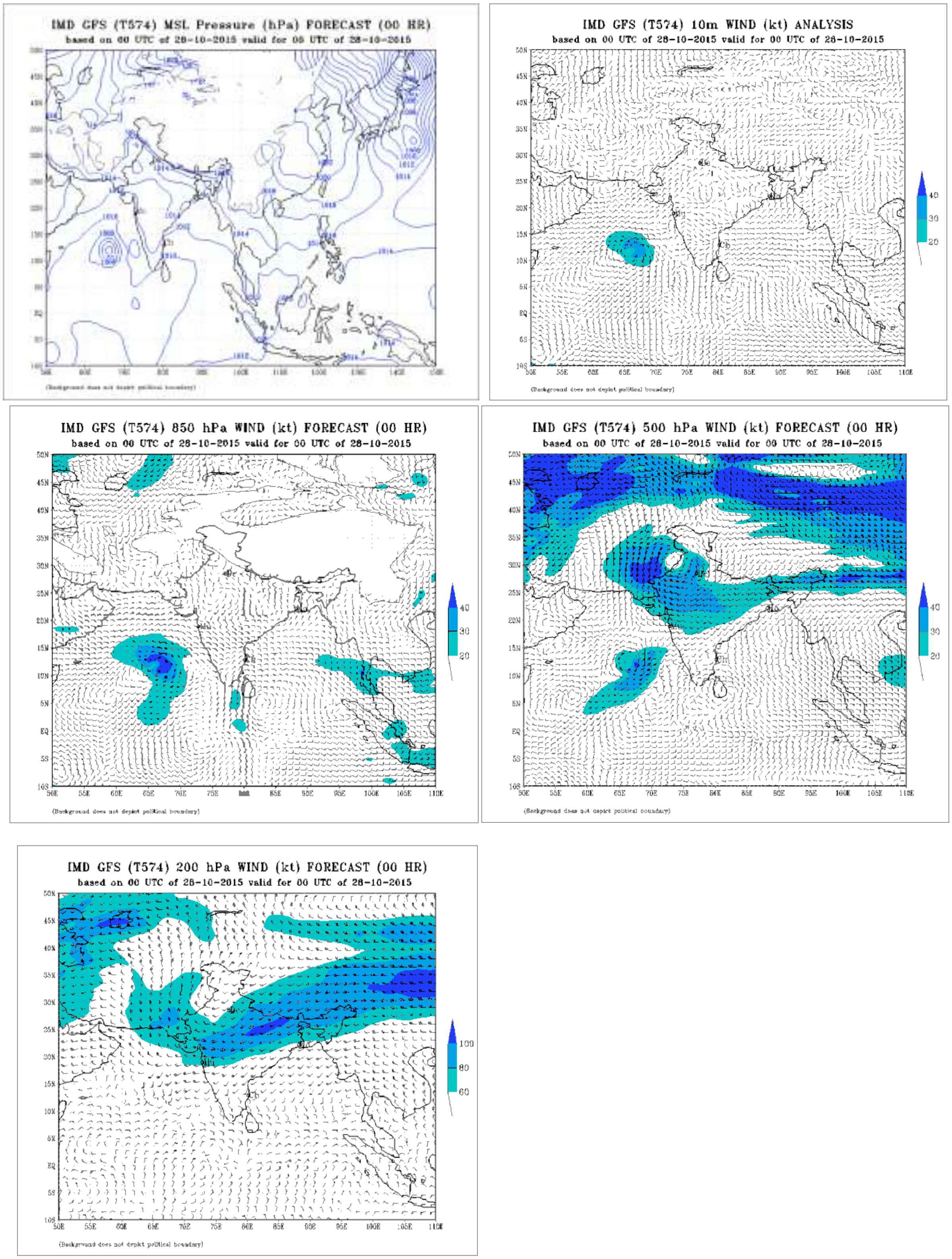


Fig 2.10.2 (i) IMD-GFS analyses of (a) MSLP and winds at (b) 10 m (c) 850 hPa (d) 500 hPa & (e) 200 hPa levels based on 0000 UTC of 28th October, 2015

As seen, cyclogenesis of the system and its subsequent intensification is indicated by the model. On 28th and 29th, surface winds of about 30-35 kts are predicted and winds are stronger over the northeastern sector. The extent of subsequent intensification is not indicated clearly by the model. However, major synoptic features associated with movement and intensification of the system are predicted well. A deep amplitude westerly trough at 500 hPa level is located north-northeast / northeast of the system centre on 28th and 29th. At 200 hPa level, northeast-southwest oriented westerly trough is located to the northeast of the system centre on 28th and 29th and poleward outflow from the system merges with the sub-tropical westerly jet located to the northeast of the system centre during 28th-31st. These features contributed significantly to enhanced deepening of the central pressure and hence intensification of the system. On 31st, associated with rapid intensification of the system, surface winds are symmetric about the centre.

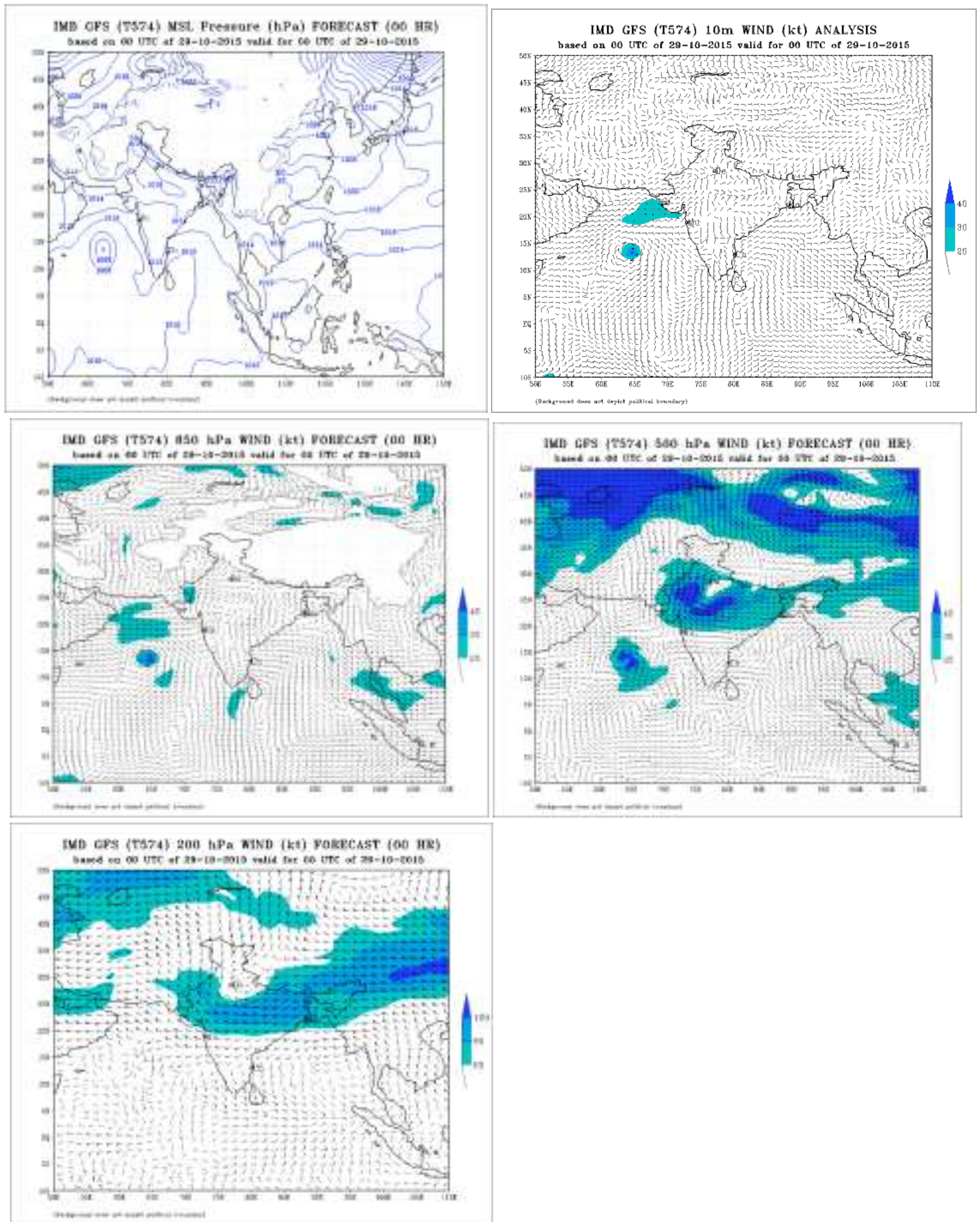


Fig 2.10.2 (ii) IMD-GFS analyses of (a) MSLP and winds at (b) 10 m (c) 850 hPa ,(d) 500 hPa & (e) 200 hPa levels based on 0000 UTC of 29th October, 2015

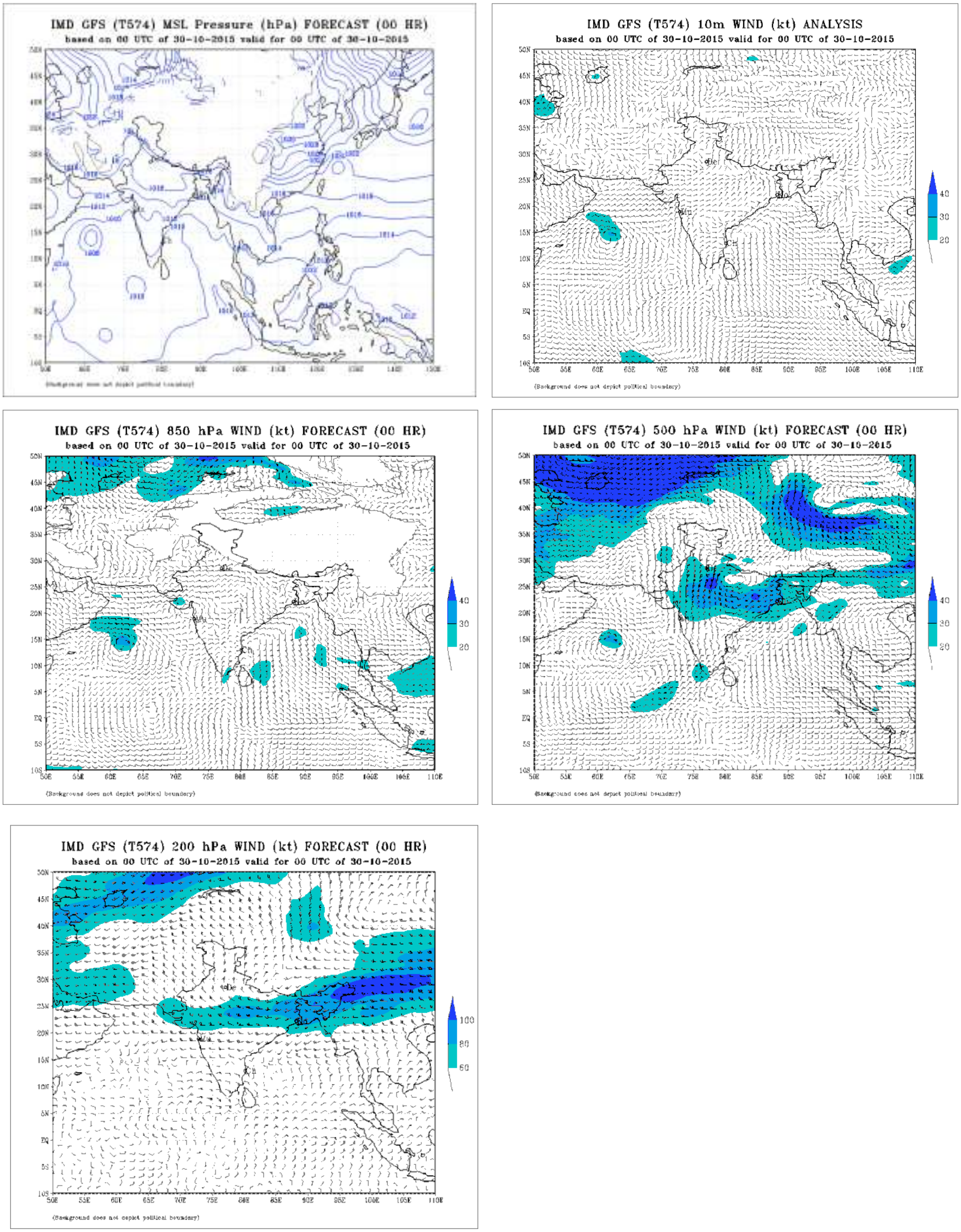


Fig 2.10.2 (iii) IMD-GFS analyses of (a) MSLP and winds at (b) 10 m (c) 850 hPa (d) 500 hPa & (e) 200 hPa levels based on 0000 UTC of 30th October, 2015

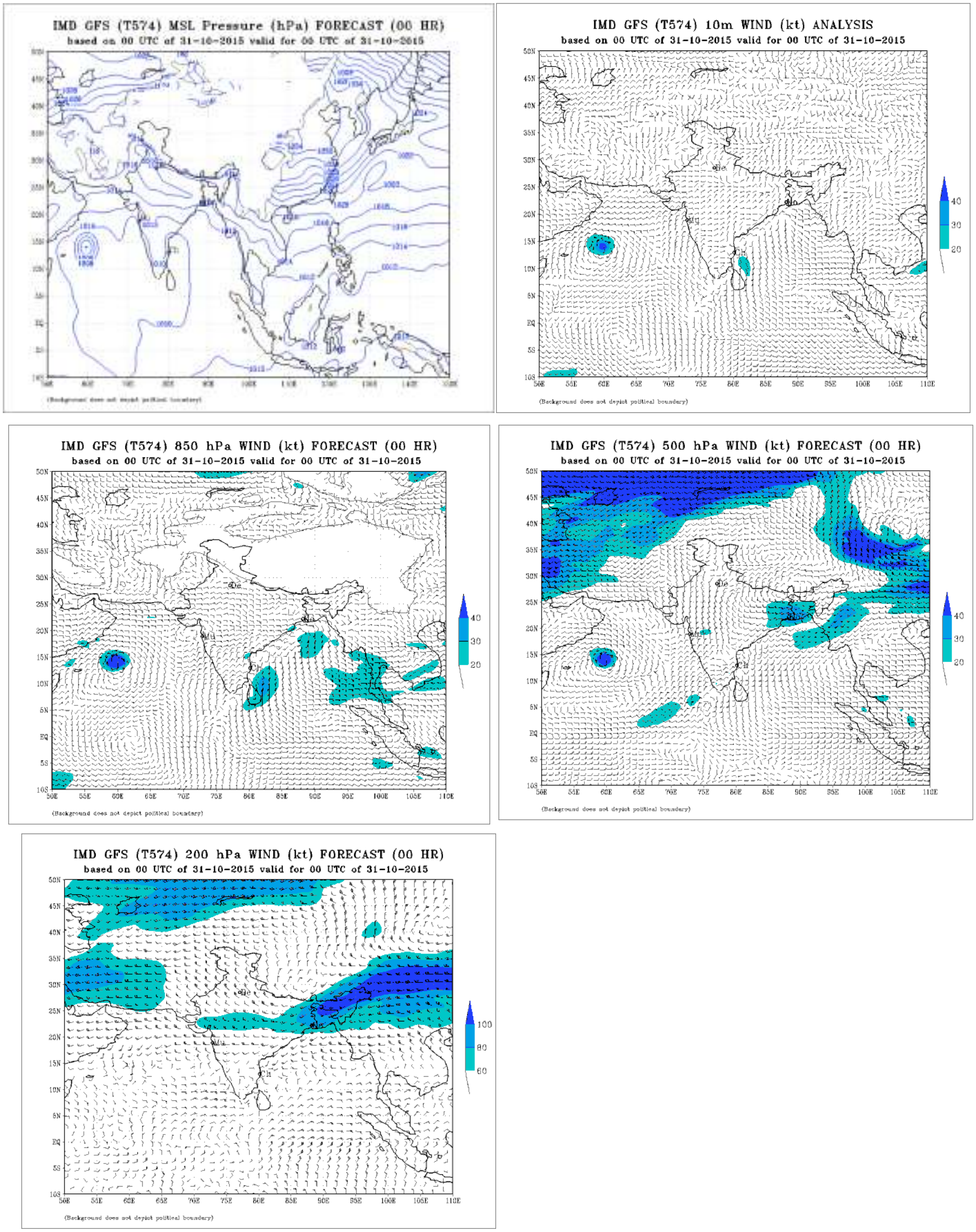


Fig 2.10.2 (iv) IMD-GFS analyses of (a) MSLP and winds at (b) 10 m (c) 850 hPa (d) 500 hPa & (e) 200 hPa levels based on 0000 UTC of 31st October, 2015

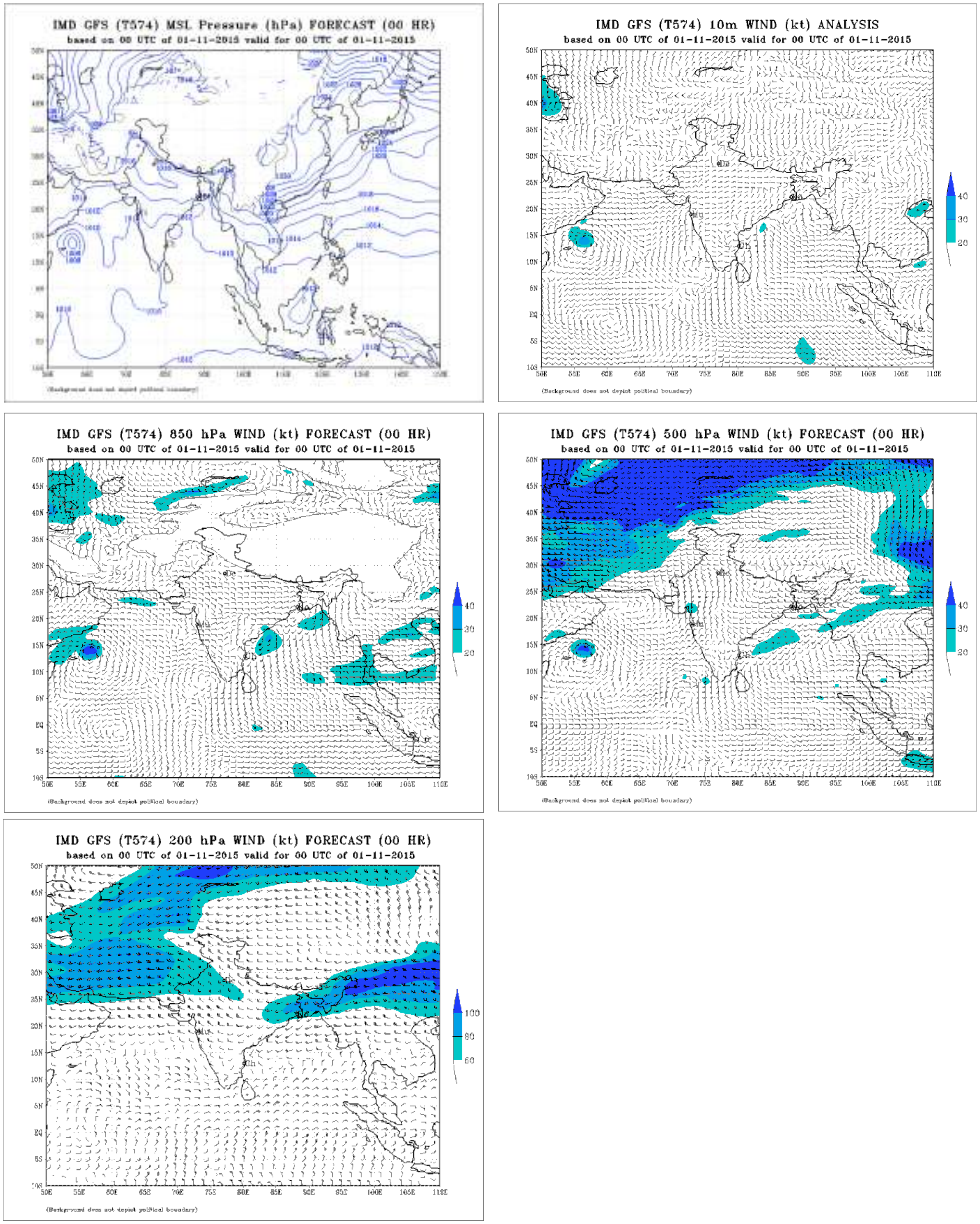


Fig 2.10.2 (v) IMD-GFS analyses of (a) MSLP and winds at (b) 10 m (c) 850 hPa (d) 500 hPa & (e) 200 hPa levels based on 0000 UTC of 1st November, 2015

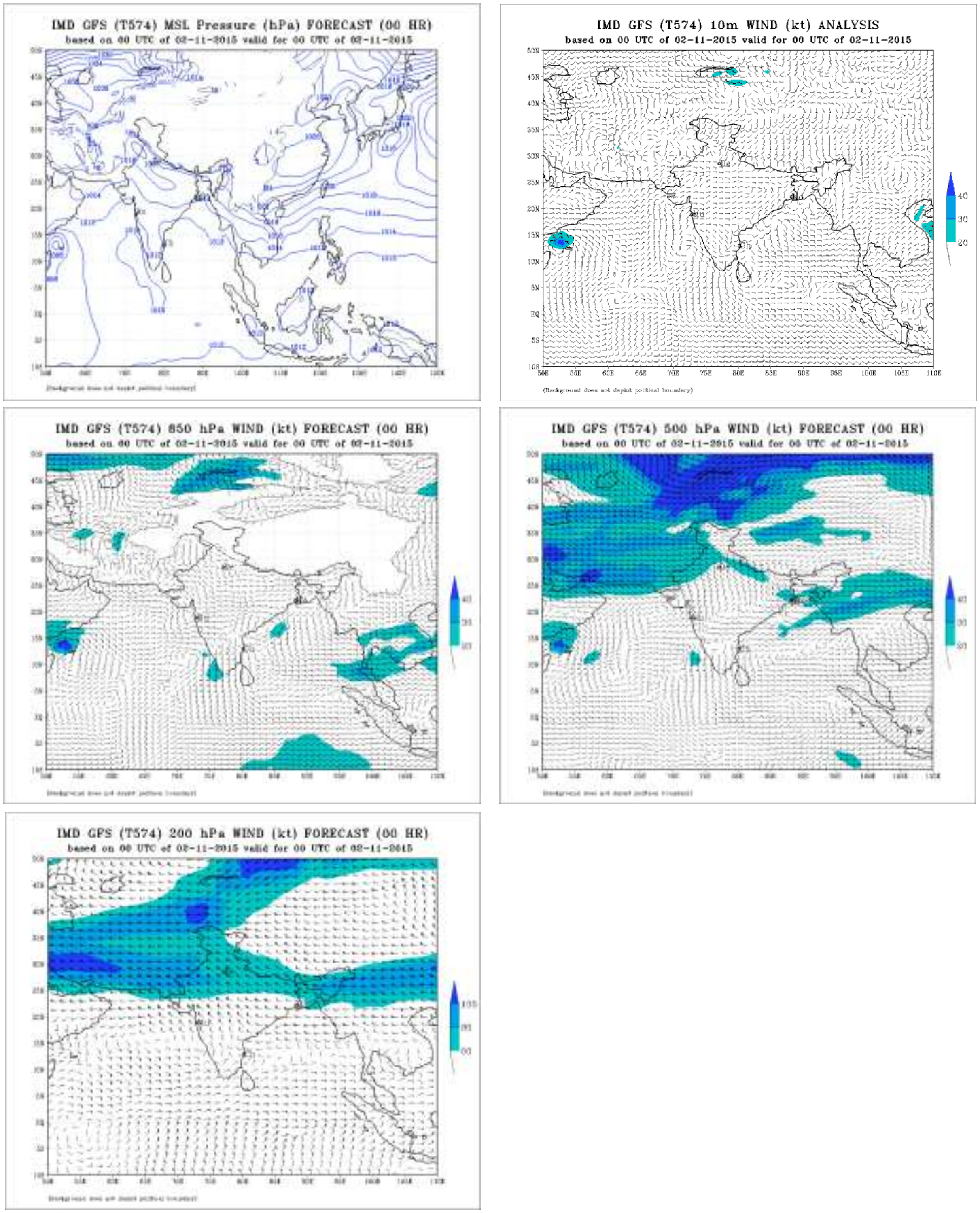


Fig 2.10.2 (vi) IMD-GFS analyses of (a) MSLP and winds at (b) 10 m (c) 850 hPa (d) 500 hPa & (e) 200 hPa levels based on 0000 UTC of 2nd November, 2015

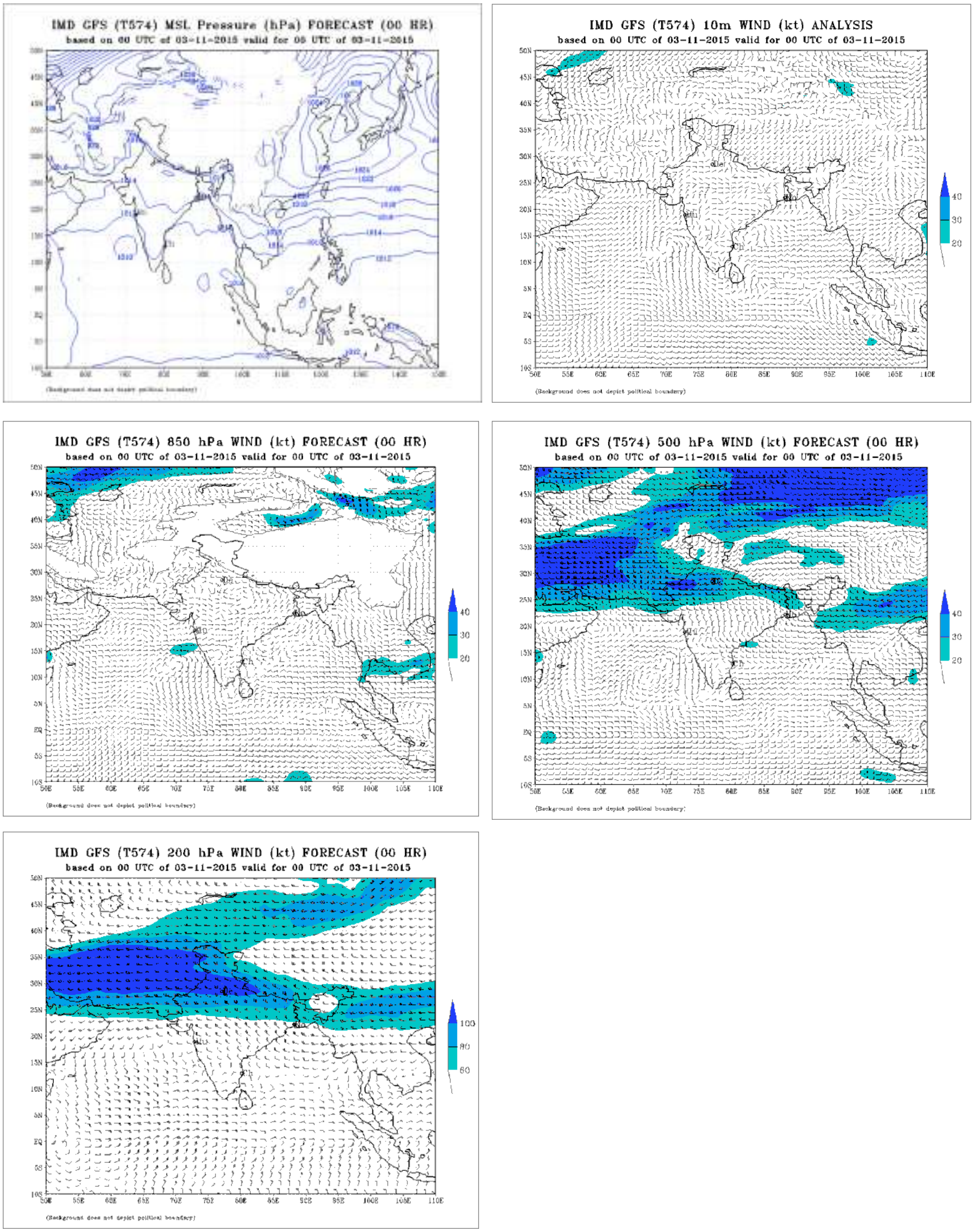


Fig 2.10.2 (vii) IMD-GFS analyses of (a) MSLP and winds at (b) 10 m (c) 850 hPa (d) 500 hPa & (e) 200 hPa levels based on 0000 UTC of 3rd November, 2015

2.10.8. Realized Weather:

Rainfall:

Rainfall associated with the system is depicted in Fig 2.10.3 (a-b) based on IMD-NCMRWF GPM merged gauge rainfall data.

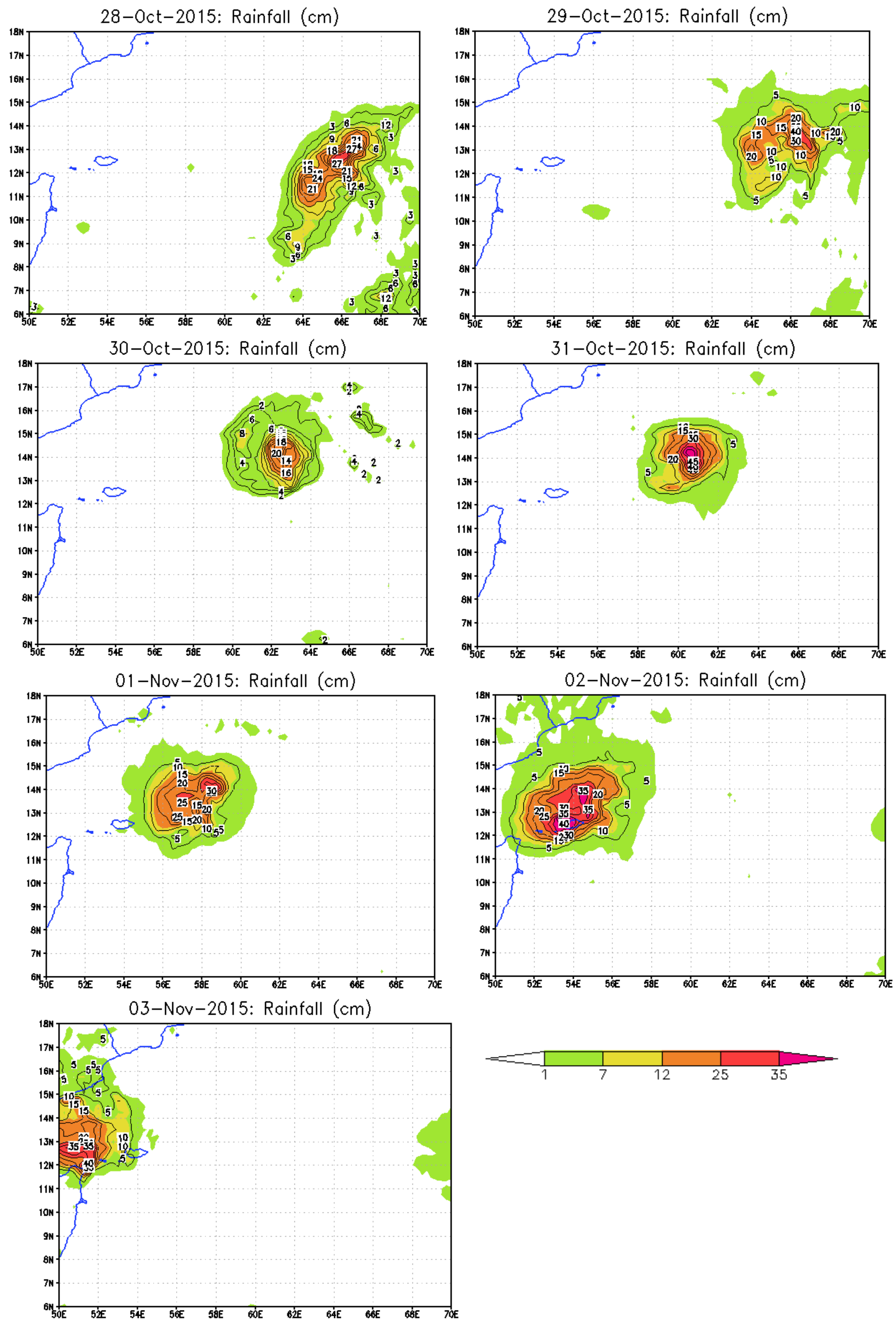


Fig. 2.10.3 (a) IMD-NCMRWF GPM merged gauge rainfall data during the period 28 ctober to 03 November 2015 (with the rainfall categories as per IMD as per IMD's criteria)

During the initial stage of formation of the system, on 28th, rainfall belt was oriented along NE-SW and the rainfall maximum was observed to the northeast of the system centre. Subsequently, with the organisation of the system, convection became more and more organised and rainfall was symmetric about the centre on 31st. Rainfall of the order of 25-30 cm was realised near the core of the system on 28th and about 30-45 cm was realised in the wall cloud region during 29th October to 03rd November.

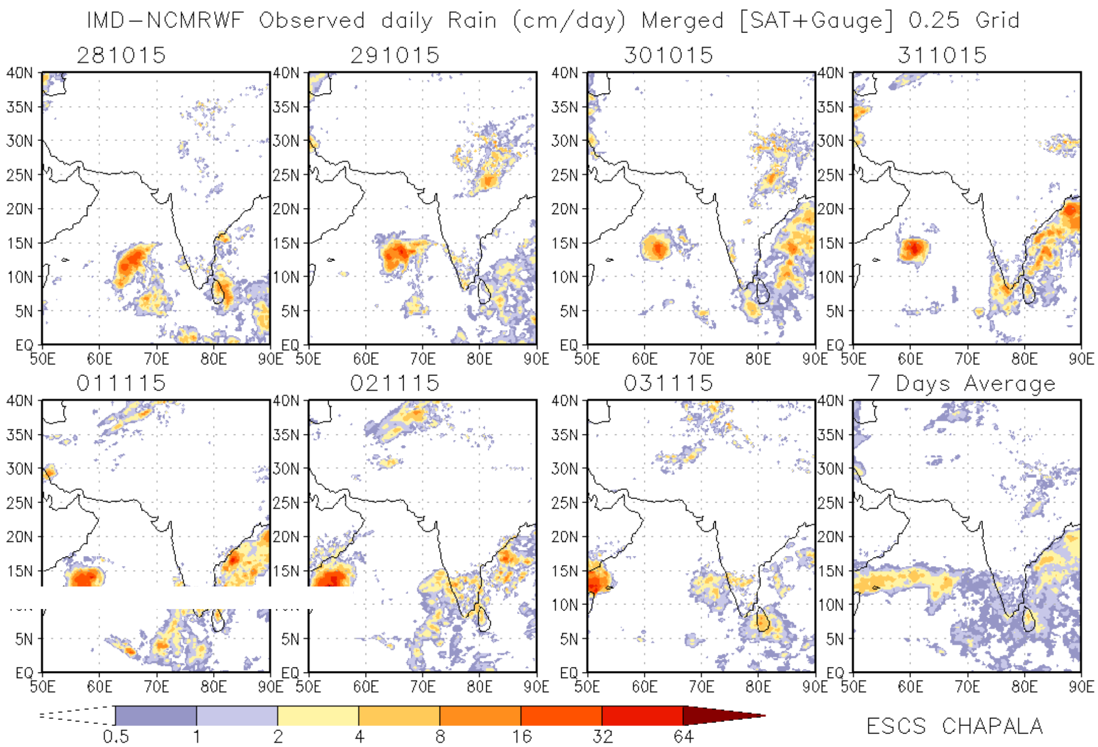


Fig. 2.10.3 (b) IMD-NCMRWF GPM merged gauge rainfall data during the period 28 October to 03 November 2015

2.10.9. Damage due to ESCS Chapala

As per media and press report, ESCS Chapala killed at least five people and caused widespread damage as it brushed past Socotra Island of Yemen. More than 50,000 people in Yemen, including about 18,000 on Socotra, were displaced because of Cyclone Chapala.

Some photographs of damages caused by ECSC Chapala in Yemen are given in Fig. 2.10.4

Shore of Hadramout, damaged vehicles due to heavy rains and winds

Vehicles swept away by water in Socotra

Mukkala, 2nd Nov

Southern Yemen hits by flooding and high winds

City flooded in Mukkala, 3rd Nov

City flooded in Mukkala, 2nd Nov

Fig. 2.10.4: Damages caused due to ESCS Chapala over Yemen

2.11 Extremely Severe Cyclonic Storm, 'Megh' over the Arabian Sea (05-10 November 2015)

2.11.1 Introduction

A depression formed over the eastcentral Arabian Sea at 0000 UTC of 5th November from a low level circulation over Lakshadweep and neighbourhood. It moved westwards/west-southwestwards and intensified into a cyclonic storm (CS) at 1200 UTC of 5th November. It continued its west-southwestward movement and intensified into a severe cyclonic storm (SCS) at 0600 UTC of 7th, into a very severe cyclonic storm (VSCS) at 1500 UTC of 7th and rapidly intensified into an extremely severe cyclonic storm (ESCS) at 0300 UTC of 8th. Maintaining its peak intensity for a short period of about 6 hrs, it weakened gradually into a VSCS at 0000 UTC of 9th. From 0600 UTC of 9th, it exhibited west-northwestward movement, weakened rapidly into an SCS at 2100 UTC of 9th, into a CS at 0300 UTC of 10th and deep depression (DD) at 0600 UTC of 10th. It recurved northeastwards from 0300 UTC of 10th and crossed Yemen coast near latitude 13.4°N and longitude 46.1°E around 0900 UTC 10th as a DD. Continuing its northeastwards movement, it weakened into a depression at 1500 UTC of 10th and into a well marked low pressure area over Yemen and neighborhood at 1800 UTC of 10th.

The salient features of the system are as follows.

i. ESCS Megh occurred just after a week of formation of ESCS, Chapala over Arabian Sea. Also, ESCS Megh has been the first back to back cyclone after Chapala that reached Gulf of Aden and crossed Yemen within a week.
ii. ESCS Megh was the second ESCS after Chapala crossing Yemen coast in the satellite era. Chapala crossed Yemen coast close to the southwest of Riyan near 14.1^0N/48.65^0E during 0100-0200 UTC as a VSCS (with maximum sustained wind speed (MSW) of 65 knots) and Megh crossed Yemen coast near 13.4°N/46.1°E around 0900 UTC as a DD (with MSW of 30 knots).
iii. Unlike Chapala, ESCS Megh was a small core system with a pin hole eye.
iv. Megh maintained the intensity of ESCS for 18 hours (0803-0821) unlike Chapala which maintained the intensity of ESCS for 78 hours (3003-0209). The peak intensity in Megh was 95 knots for a period of 3 hours (0806-0809) against 115 knots for a period of 15 hours (3009-3100) in case of Chapala.
v. Lowest estimated central pressure (ECP) was 964 hPa with a pressure drop of 44 hPa unlike Chapala where it was 940 hPa with a pressure drop of 66 hPa.
vi. Like Chapala, ESCS Megh also experienced rapid intensification on 0000 UTC of 7th when its MSW increased from 45 knots to 85 knots at 0000 UTC of 8th (rise in wind speed 40 knots in 24 hours). During same period the ECP fell from 994 hPa to 974 hPa (20 hPa fall in 24 hours).
vii. ESCS Megh experienced rapid weakening over Gulf of Aden from 1800 UTC of 9th (MSW 65 knots) to 0600 UTC of 10th (MSW 35 knots), i.e. Megh experienced a fall in MSW by 30 knots in 12 hours.
viii. The ESCS Megh moved west to west-southwestwards throughout its life period till landfall over Yemen. While, ESCS Chapala moved initially north-northwestwards and then west-southwestwards to Yemen.
ix. Both ESCS Chapala and Megh could intensify upto the stage of ESCS under favourable environmental conditions, mainly low vertical wind shear (5-10 knots) around the system centre and the forward sector of the storm.

x. The system had the longest track length after VSCS Phet in 2010, as it travelled a distance of about 2307 km during its life period.
xi. The Accumulated Cyclone Energy (ACE) was about 8.2 X 10^4 $knot^2$ which is also the maximum after VSCS Phet in 2010 and ESCS Chapala in 2015 over the Arabian Sea.
xii. The Power Dissipation Index was 6.07 X 10^6 $knot^3$ which is the maximum after VSCS Phet in 2010 and ESCS Chapala in 2015 over the Arabian Sea.
xiii. The ESCS Megh had a life period of 5.7 days against long period average of 4.7 days in post-monsoon season for VSCS/ESCS over Arabian Sea)
xiv. The westward movement of the cyclone away from the Indian coasts was predicted from the first bulletin itself i.e. on 5th November 2015 (0300 UTC). Every three hourly Tropical Cyclone Advisories were issued to WMO/ESCAP member countries, Yemen and Somalia.
xv. The numerical weather prediction (NWP) and dynamical statistical models provided reasonable guidance with respect to its genesis and track. However, most of the NWP and dynamical statistical models except HWRF could not predict the landfall and rapid intensification/ weakening of ESCS Megh.

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

2.11.2 Monitoring of ESCS,'Megh'

The cyclone was monitored & predicted continuously since its inception by IMD. The forecast of its genesis on 5th November, its track, intensity, landfall over Yemen were predicted with sufficient lead time. The observed track of the cyclone over AS during 5th - 10th November is presented in fig.2.1.

At the genesis stage, the system was monitored mainly with satellite observations. Various national and international NWP models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models, dynamical statistical models for genesis and intensity were utilized to predict the genesis, track and intensity of the cyclone. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation.

2.11.3 Brief life history

2.11.3.1 Genesis

An upper air cyclonic circulation in lower levels lay over southeast AS and adjoining Lakshadweep area on 1st November. It moved west-nothwestwards and lay over eastcentral AS on 2nd. It persisted over the same region on 3rd and extended upto mid-tropospheric levels. Under its influence, a low pressure area formed over eastcentral AS on 4th. On 0000 UTC of 5th, the winds were higher over the northeastern sector. The sea surface temperature (SST) was 29^0C and the ocean thermal energy (OTE) was about 60-80

KJ/cm^2 around system centre. The vertical wind shear was about 5-10 knots (low) around the system centre. The low level relative vorticity was 50 KJ/cm^2. Lower level convergence was 5X10^{-5}s^{-1} and upper level divergence was 10X10^{-5}s^{-1}. Vorticity at 850 hPa was 50 X10^{-5}s^{-1}. The low level relative vorticity and convergence had increased during previous 12 hrs. The upper tropospheric ridge at 200 hpa level ran along 16^{0}N. There was favourable poleward and westward outflow in association with the anti-cyclonic circulation lying to the northeast of the system centre alongwith this ridge. All these conditions led to intensification of the low pressure area into a depression at 0000 UTC of 5th. Considering the large scale features, the Madden Jullian Oscillation Index was in phase -2 over west-equatorial Indian Ocean with amplitude greater than 2. The Indian Ocean Dipole was positive, indicating higher warming over west equatorial Iindian Ocean, which helped in maintaining the warmer SST over AS even after passage of ESCS Chapala.

2.11.3.2 Intensification

Similar environmental conditions prevailed and the system intensified into a CS at 1200 UTC of 5th. Due to favourable large scale environmental features like MJO Index and weak vertical wind shear, the system experienced rapid intensification from 0300 UTC of 7th when its maximum sustained wind speed increased from 45 knots to 90 knots at 0300 UTC of 8th (rise in wind speed by 45 knots in 24 hours). During same period the ECP fell from 994 hPa to 968 (fall of 26 hPa in 24 hours). On 0300 UTC of 7th, the low level relative vorticity was 150 x 10^{-5} sec-1, convergence was 5-10 x 10^{-5} sec-1, and divergence was 30 x 10^{-5} sec-1. The SST around the system centre was 29°C. The OTE was about 35-50 KJ/cm^2 around system centre and 50-75 KJ/cm2 to west-southwest of the system centre The vertical wind shear was about 10 knots (low) around the system centre during the period of rapid intensification. The system reached its peak intensity (95 kt) at 0600 UTC of 8th.

The system started weakening from 1200 UTC of 8th. At 1200 UTC, the low level relative vorticity was 150 x 10^{-5} sec^{-1} and convergence was 20 x 10-5 sec-1. The upper level divergence decreased and was about 10 x 10^{-5} sec^{-1}. The SST around the system centre was 28°C. The OTE was 40-50 KJ/cm^2 around the system centre and then showed decreasing trends towards Gulf of Aden. The vertical wind shear was about 10 knots around the system centre. The low vertical wind shear was mitigating the adverse impact of cold and dry air intrusion from northwest. However, the system started weakening as it passed very close to Gulf of Aden around 0600 UTC of 8th and suffered land interaction. Also, it moved over an area with lower OTE over Gulf of Aden. Enhanced rapid weakening was observed from 1800 UTC of 9th due to land interaction with rugged terrain of Yemen, lower OTE over Gulf of Aden and dry air incursion. The system started weakening from 1200 UTC of 8th, the rate of weakening was slow till 1800 UTC of 9th. During this period the system passed close to the northern border of Socotra Island, moved into colder Gulf of Aden and the track was close to northern tip of Somalia, but the low vertical wind shear inhibited the adverse effect of cold and dry air from northwest in weakening the wall cloud region. It indicates that the internal dynamics played a significant role in maintaining intensity of the system apart from the external dynamics including environmental conditions. From 2100 UTC of 9th, the system exhibited rapid weakening as it lay over western part of Gulf of Aden and had interaction with rugged terrain of Yemen. It rapidly weakened from 65 kts at 1800 UTC of 9th to 30 kts at 0600 UTC of 10th just before landfall. The best track parameters of the systems are presented in Table 2.11.1**.** The total precipitable water imageries (TPW) during 5th to 10th November are presented in Fig.2.11.1 to show the role of TPW on intensification and weakening. The vertical wind shear during the life period of the system is shown in Fig. 2.11.2 to illustrate its impact on intensification and weakening.

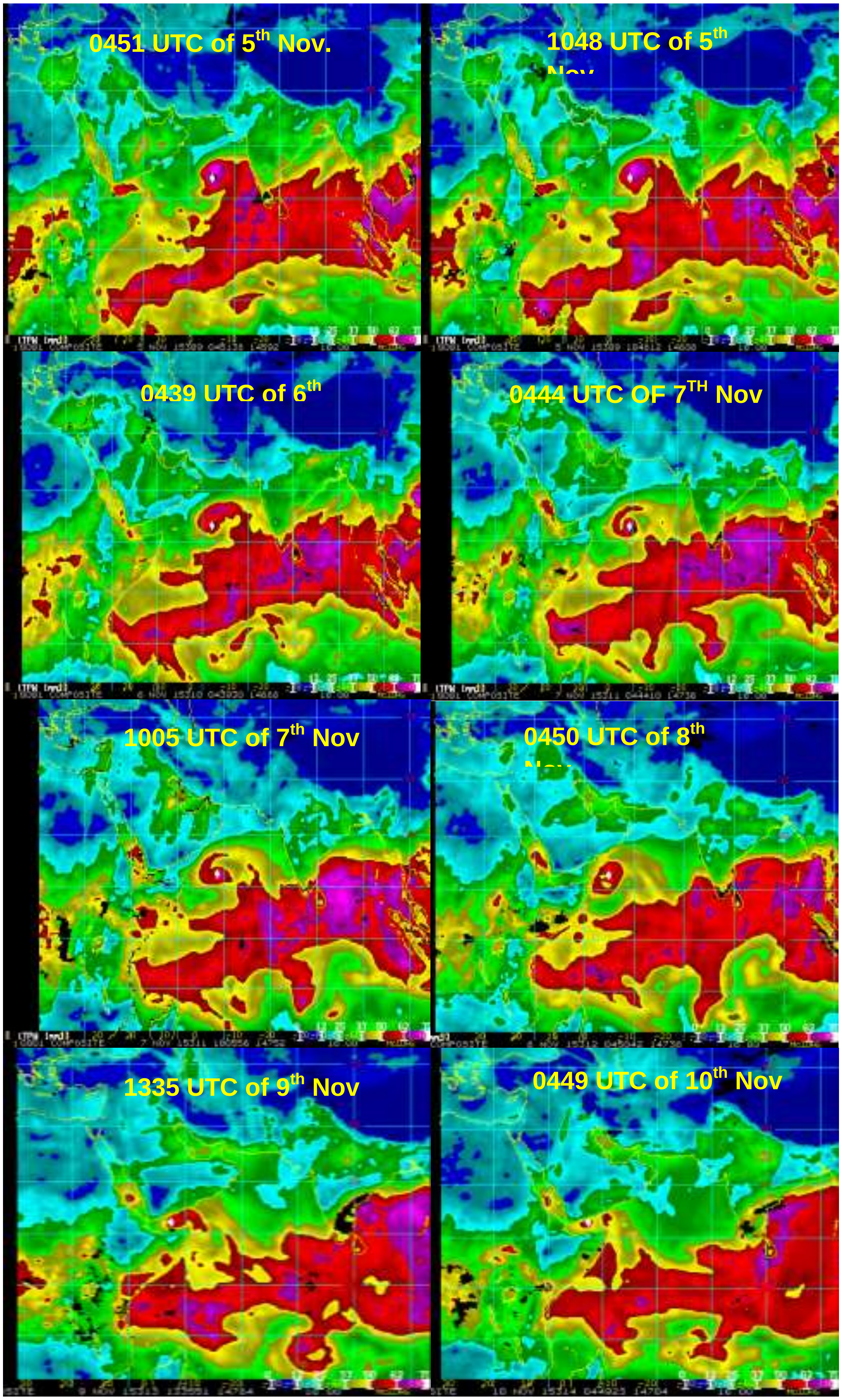


Fig.2.11.1 Total precipitable water imageries during 5th to 10th November 2015

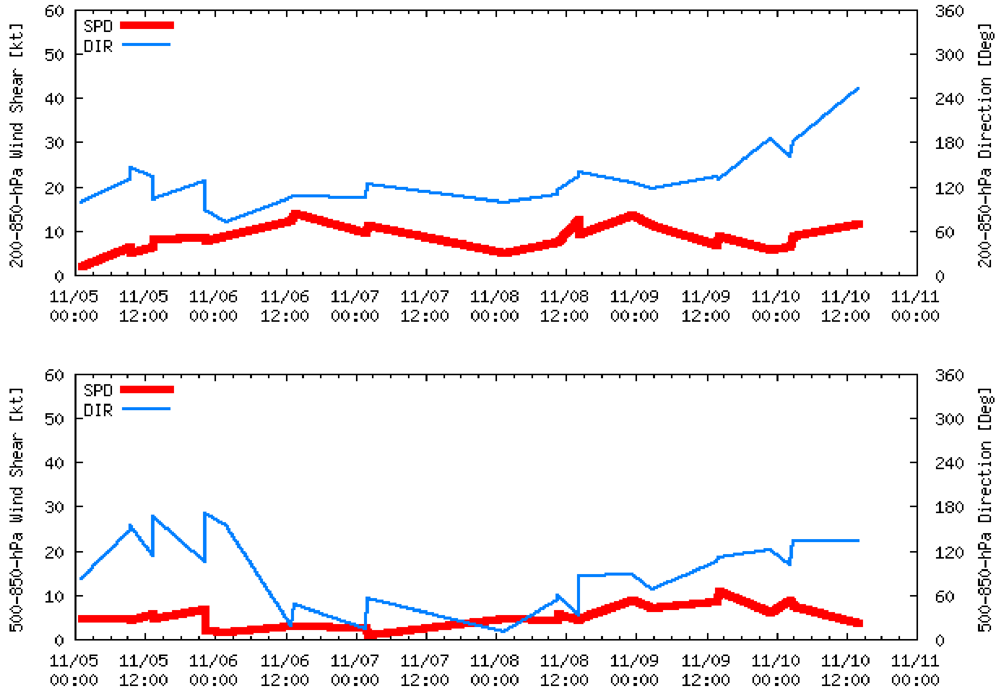


Fig. 2.11.2 Wind shear and wind speed in the middle and deep layer around the system during 05th to 10th Nov 2015.

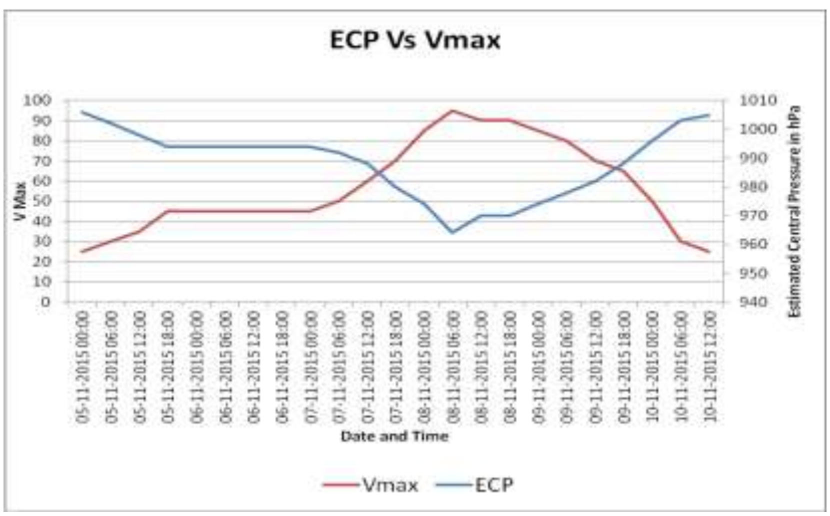


Fig. 2.11.3 Lowest estimated central pressure and the maximum sustained wind speed

2.11.3.3. MSW and estimated central pressure (ECP)

The lowest ECP and the MSW speed during the life cycle of ESCS Megh are presented in Fig. 2.11.3. The lowest ECP has been 964 hPa. The highest MSW speed was 95 knots during 0600 - 0900 UTC of 8th November. At the time of landfall, the ECP was

1003 hPa and MSW was 30 knots (deep depression) due to weakening of the system over Gulf of Aden. The figure also indicates that rapid intensification of the system commenced from 0300 UTC of 7th and continued upto 0600 UTC of 8th. It is mainly attributed to low vertical wind shear (05-10 kts) around the system centre and the forward sector of the system accompanied with favourable upper level divergence due to radial outflow. Also the large scale features like IOD and MJO were favouring amplification of the convection.

2.11.3.4 Translational Speed and direction of movement

The six hourly translational speed and direction of movement of ESCS is presented in Fig. 2.11.4 (a).

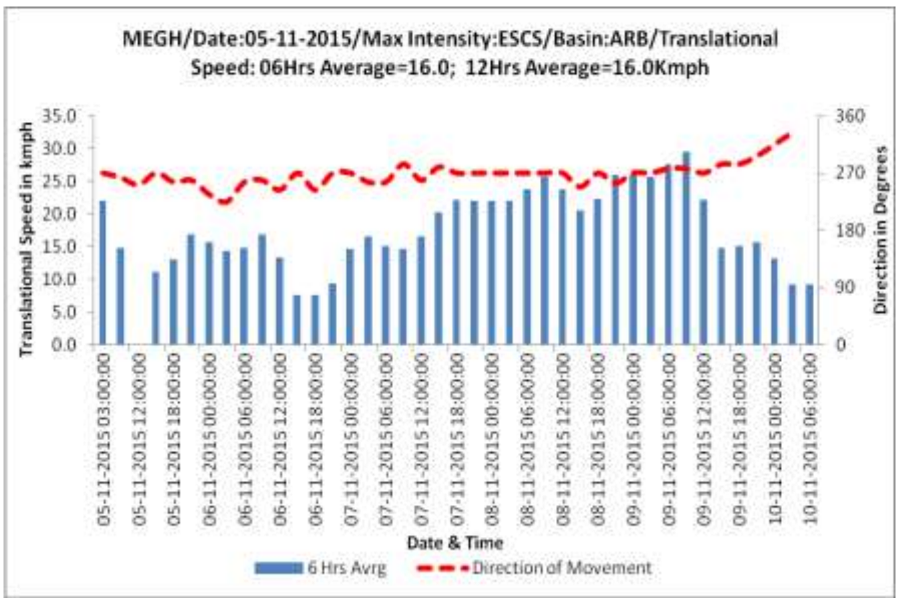


Fig. 2.11.4 (a).Six hours average translational speed and direction of movement in association with ESCS Megh

The average translational speed of the system during entire life cycle was 16 kmph. However, on 8th and 9th November it moved with an average translational speed of 22.0 kmph and reached maximum of 29.6 kmph at 1200 UTC of 9th. It the decreased sharply till 1500 UTC of 9th (14.8 kmph). It moved slowly till 0000 UTC of 10th and then decreased sharply.

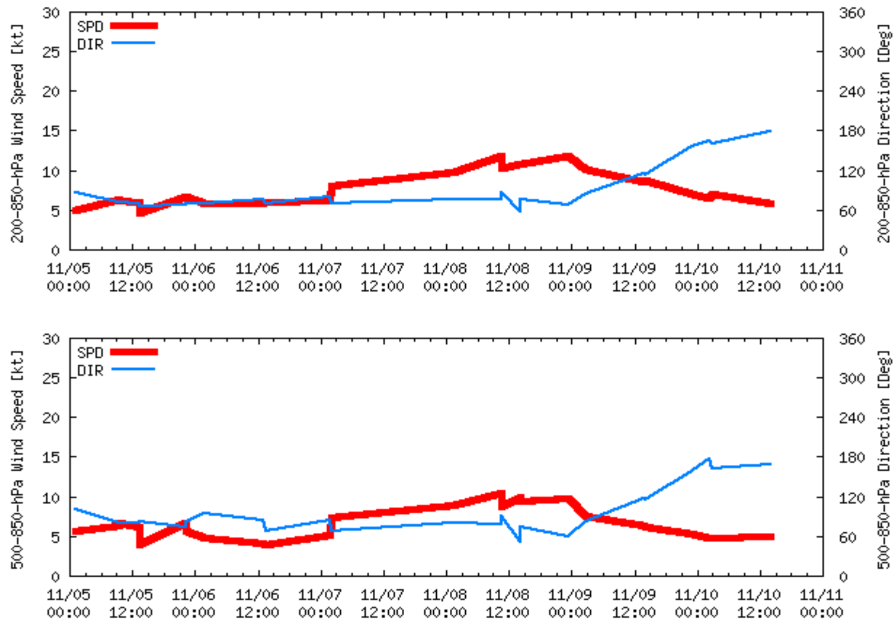


Fig. 2.11.4 (b).Wind speed and direction in the middle and deep layer around the system during 05-10 Nov 2015.

ESCS Megh moved west to west-southwestwards till 10th November, then recurved northeastwards and crossed Yemen coast. The upper tropospheric ridge was running along 16.0^{0}N in association with anti-cyclonic circulation lying to the northeast of the system centre. Under its influence, the system moved west/west-southwestwards till 0900 UTC of 9th November. Thereafter, the system started recurving northwards as the anticyclonic circulation moved northeastwards gradually from 9th with the ridge extending southwestwards towards northern tip of Somalia adjacent to Gulf of Aden on 0600 UTC of 10th leading to northeastwards recurvature. Continuing its northeastwards movement, the system crossed Yemen coast near lat. 13.4^{0}N/long.46.1^{0}E. To examine the steering flow, the mean wind speed and direction in middle and deep layer around the cyclone field is shown in Fig. 2.11.4 (b). It indicates that the ESCS Megh was steered by middle to upper tropospheric winds.

The system had the longest track length after VSCS Phet in 2010 as it travelled a distance of about 2307 km during its life period (Chapala-2250 km).

To summarise, the genesis and intensification of the system just after the passage of ESCS Chapala, can be attributed to the favourable environmental conditions like vertical wind shear and large scale features like IOD and MJO.

Table 2.11.1 Best track positions and other parameters of Extremely Severe Cyclonic Storm (ESCS) 'MEGH' over the Arabian Sea during 05-10 November, 2015

Date	Time (UTC)	Centre lat.° N/ long. ° E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
05/11/2015	0000	14.1/66.0	1.5	1006	25	3	**D**
	0300	14.1/65.6	1.5	1004	25	4	D
	0600	14.1/64.8	2.0	1002	30	5	**DD**
	1200	14.0/64.0	2.5	998	35	7	**CS**
	1500	13.9/63.7	2.5	996	40	8	CS
	1800	13.9/63.4	3.0	994	45	10	CS
	2100	13.8/63.0	3.0	994	45	10	CS
06/11/2015	0000	13.7/62.5	3.0	994	45	10	CS
	0300	13.5/62.2	3.0	994	45	10	CS
	0600	13.2/61.9	3.0	994	45	10	CS
	0900	13.1/61.5	3.0	994	45	10	CS
	1200	13.0/61.0	3.0	994	45	10	CS
	1500	12.9/60.8	3.0	994	45	10	CS
	1800	12.9/60.6	3.0	994	45	10	CS
	2100	12.8/60.4	3.0	994	45	10	CS
07/11/2015	0000	12.8/60.1	3.0	994	45	10	CS
	0300	12.8/59.6	3.0	994	45	10	CS
	0600	12.7/59.2	3.0	992	50	12	**SCS**
	0900	12.6/58.8	3.5	990	55	16	SCS
	1200	12.7/58.4	3.5	988	60	18	SCS
	1500	12.6/57.9	4.0	984	65	22	**VSCS**
	1800	12.7/57.3	4.0	980	70	26	VSCS
	2100	12.7/56.7	4.5	976	80	32	VSCS
08/11/2015	0000	12.7/56.1	4.5	974	85	36	VSCS
	0300	12.7/55.5	5.0	968	90	40	**ESCS**
	0600	12.7/54.9	5.0	964	95	44	ESCS
	0900	12.7/54.2	5.0	964	95	44	ESCS
	1200	12.7/53.5	5.0	970	90	40	ESCS
	1500	12.7/52.9	5.0	970	90	40	ESCS
	1800	12.5/52.4	5.0	970	90	40	ESCS

	2100	12.5/51.7	5.0	970	90	40	ESCS
09/11/2015	0000	12.3/51.0	4.5	974	85	36	**VSCS**
	0300	12.3/50.3	4.5	976	80	32	VSCS
	0600	12.3/49.6	4.5	978	80	30	VSCS
	0900	12.4/48.8	4.0	980	75	28	VSCS
	1200	12.5/48.0	4.0	982	70	26	VSCS
	1500	12.5/47.6	4.0	986	65	22	VSCS
	1800	12.6/47.2	4.0	988	65	20	VSCS
	2100	12.7/46.8	3.5	990	60	18	**SCS**
10/11/2015	0000	12.9/46.4	3.0	996	50	14	SCS
	0300	13.1/46.2	3.0	998	40	12	**CS**
	0600	13.3/46.1	2.0	1003	30	5	**DD**
	0900	System crossed Yemen coast near Lat. 13.4°N/Long. 46.1°E around 0900 UTC					
	1200	13.6/46.5	-	1005	25	3	**D**
	1800	Weakened into a well marked low pressure area over Yemen and neighbourhood					

D: Depression, DD: Deep Depression, CS: Cyclonic Storm, SCS: Severe Cyclonic Storm, VSCS: Very Severe Cyclonic Storm, ESCS: Extremely Severe Cyclonic Storm

2.11.4. Climatological aspects

Climatologically, the severe cyclonic storms crossing Yemen coasts are very rare. Prior to Megh and Chapala, one SCS (May 1960) crossed Yemen coast during 1891-2014. The track of the SCS crossing Yemen coast is shown in Fig. 2.11.5.

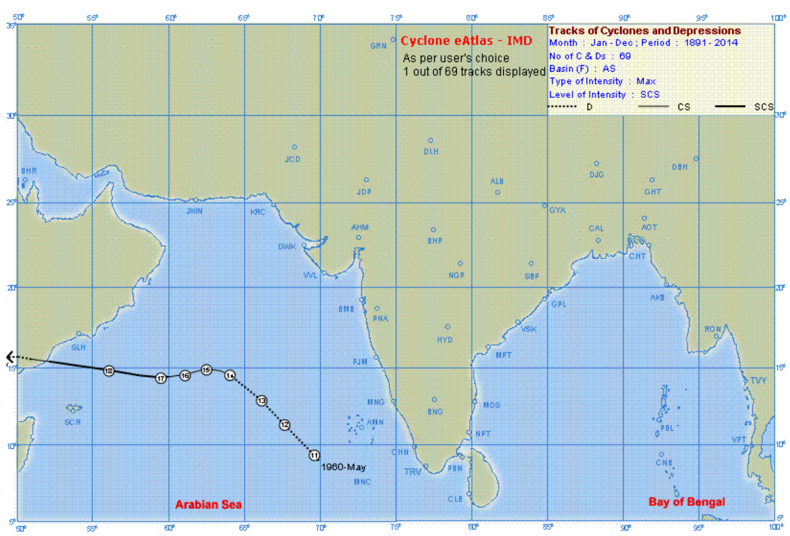


Fig. 2.11.5 Track of Severe cyclonic storm over Arabian Sea during the period 1891-2014 that crossed Yemen coast.

2.11.5 Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness tempearture imageries are presented in fig. 2.11.6- 2.11.8.

2.11.5.1 INSAT-3D features

Intensity estimation using Dvorak's technique suggested that the system attained the intensity of T 1.5 on 0000 UTC of 5$^{th.}$ Associated broken low and medium clouds with embedded moderate to intense convection lay over AS between latitude 12.0^{0}N to 17.5^{0}N and longitude 63.0^{0}E to 69.5^{0}E. Lowest cloud top temperature (CTT) was -81^{0}C. The cloud pattern was curved band type. Convection wrapped 0.5 on log 10 spiral. At 0600 UTC of 5^{th,} the system intensified to T2.0. At 1200 UTC of 5th, the depth of convection increased, the lowest CTT was -83^{0}C and system intensified to T2.5. At 1800 UTC of 5th convection further organised and the system intensified to T3.0. Convection wrapped 0.6 on log10 spiral. The system maintained its intensity till 0300 UTC of 7th. At 0600 UTC of 7th, convection further organised and intensity was T3.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over the area between latitude 10.5^{0}N to 15.0^{0}N and longitude 57.0^{0}E to 61.0^{0}E. Lowest CTT was -80°C. Ragged eye was seen. The system further intensified to T3.5 at 0900 UTC of 7th. The convection showed eye pattern. Ragged eye was seen in visible imagery. Lowest CTT in wall cloud region was -81°C. Area of convection extended between latitude 10.5^{0N} to 15.0^{0}N and longitude 56.5^{0}E to 60.5^{0}E. The system further intensified to T5.0 at 0300 UTC of 8th. Area of convection extended between latitude 11.0^{0}N to 14.5^{0}N and longitude 54.0^{0}E to 57.0^{0}E. Eye was seen in both visible and IR imageries. Lowest CTT in wall cloud region was -85°C. From 1200 UTC of 8th, the system started weakening. Lowest CTT in wall cloud region was -84°C. The clouds started disorganising. At 1430 UTC, the system lost its distinct eye feature in IR imagery. Thereafter the system underwent rapid weakening from 1800 UTC of 9th.

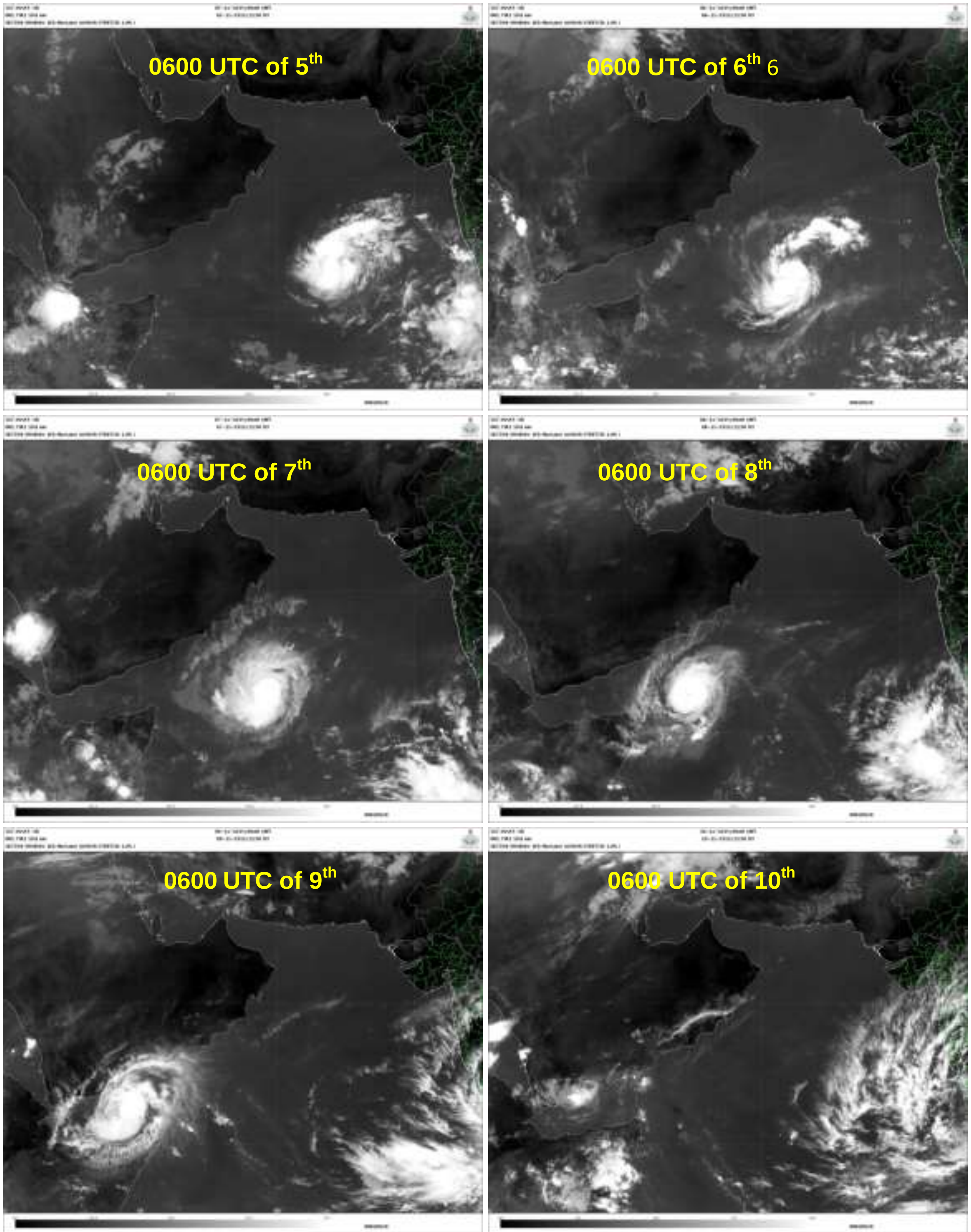


Fig2.11.6 INSAT-3D IR imageries based on 0600 UTC of 5^{th} to 10^{th} November 2015

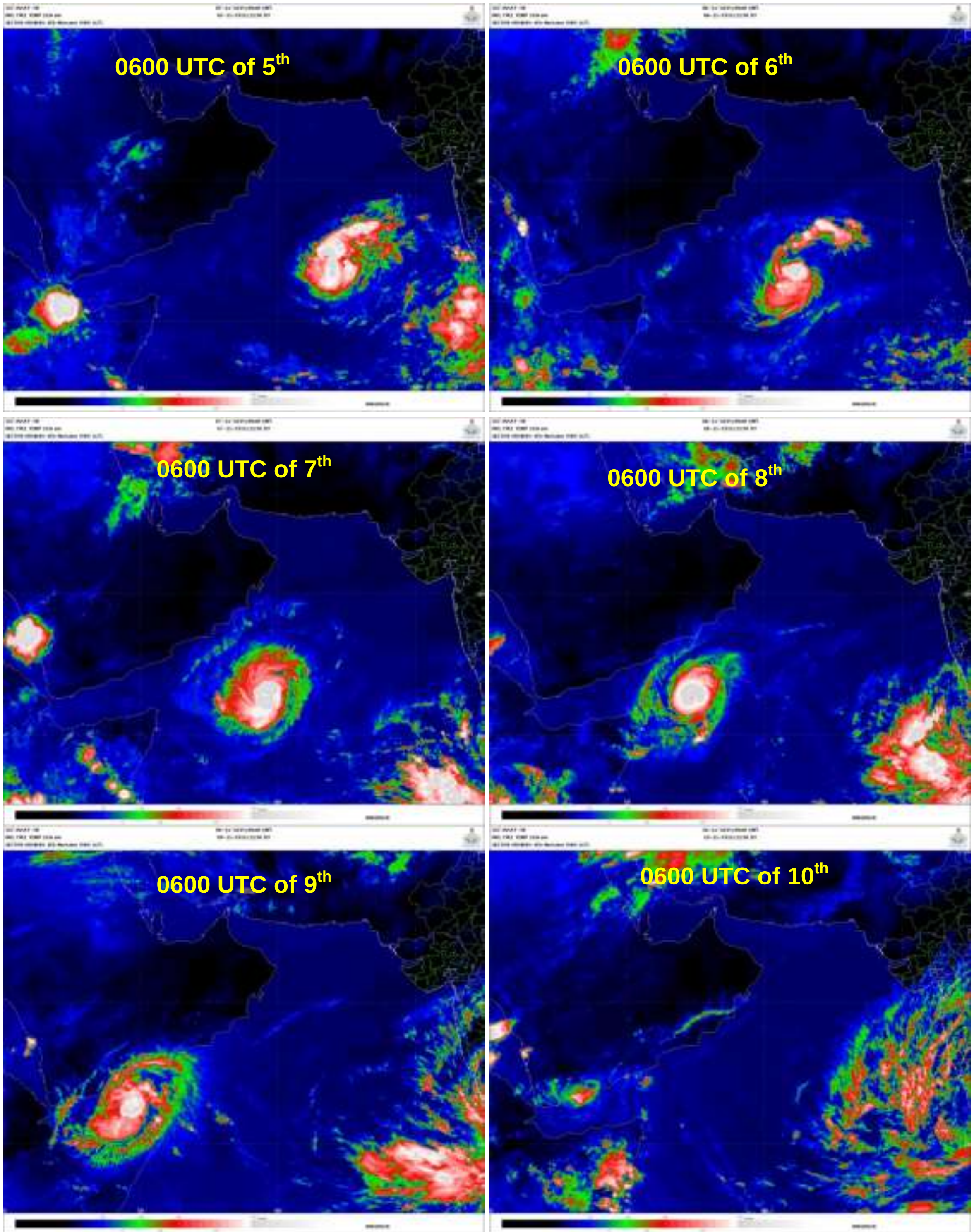


Fig. 2.11.7 INSAT-3D enhanced colored imageries based on 0600 UTC of 5th to 10th November 2015

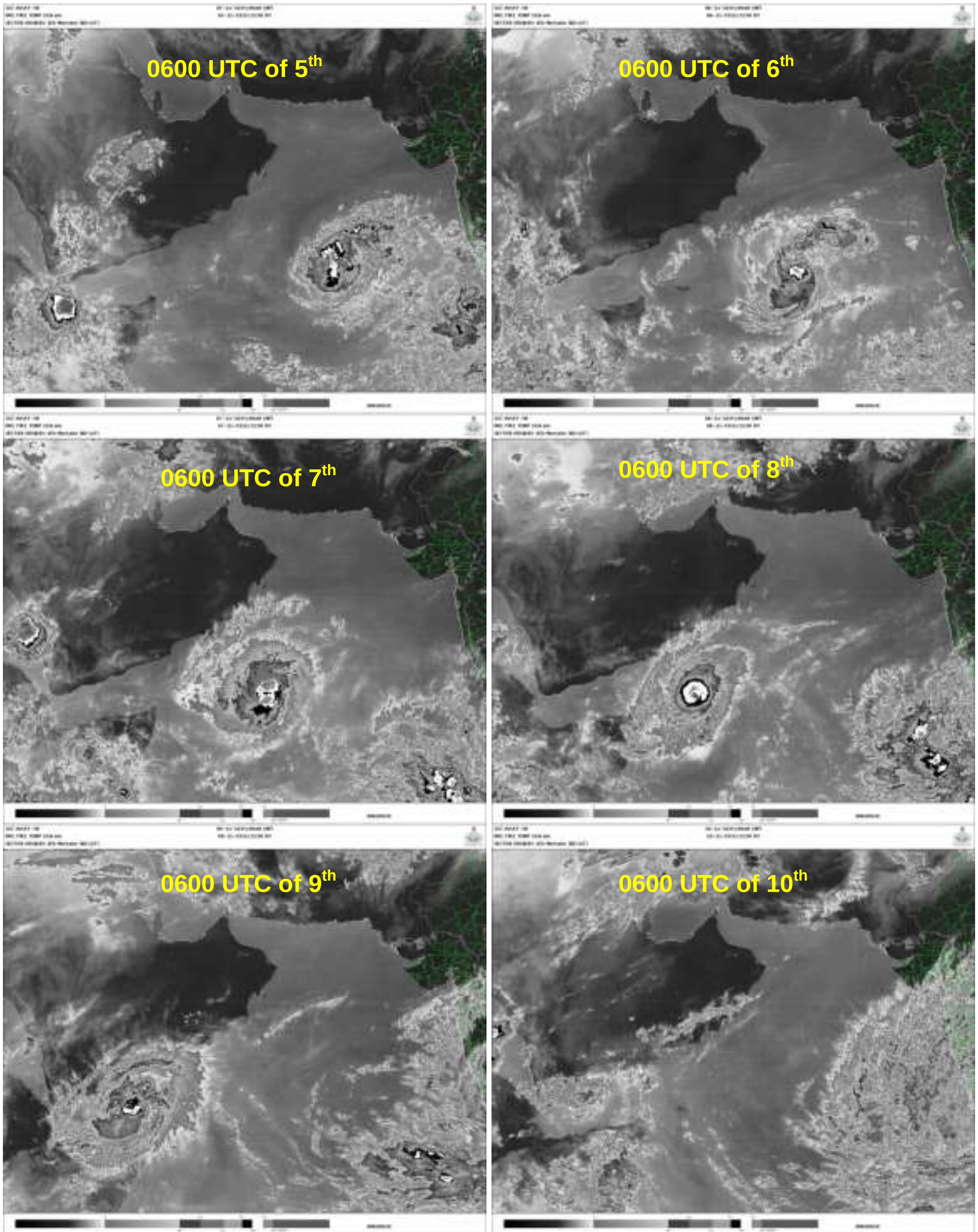


Fig. 2.11.8 INSAT-3D cloud top brightness temperature imageries based on 0600 UTC of 5th to 10th November 2015

2.11.5.2 Microwave features

SSMIS, AMSR2 and WINDSAT(37) microwave imageries of the ESCS Megh covering its life period from 05th to 10th November 2015 are presented in Fig. 2.11.9 .

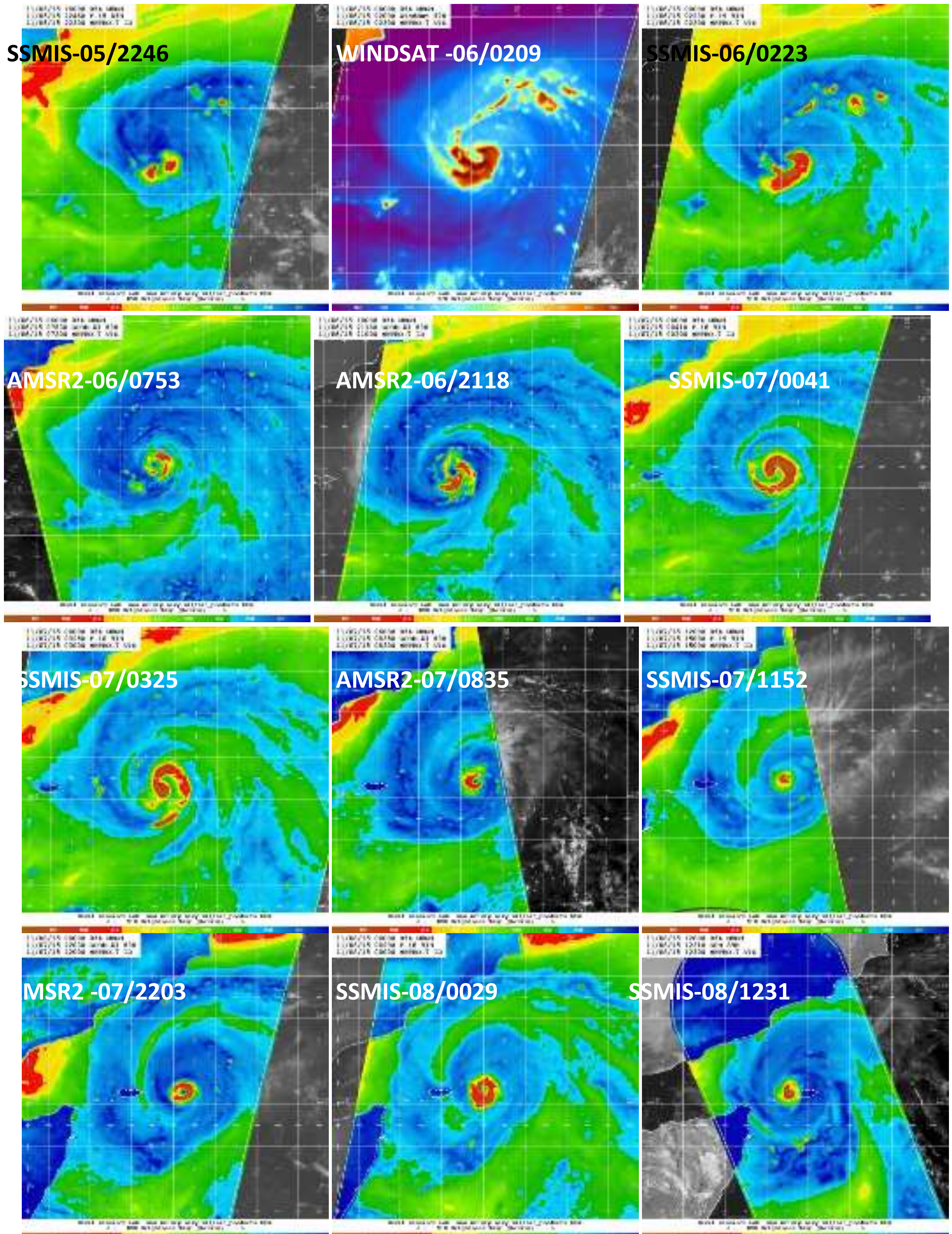


Fig. 2.11.9 Typical microwave imageries during 5th to 8th November 2015 in association with ESCS Megh.

On 05th and 06th, organisation of convective clouds along curved band is seen. On 06th/0753 UTC, formation of eye and development of wall cloud are observed. On 07th, the wall cloud region developed further and expanded. It is observed to spiral inwards cyclonically and completely covering the eye by 08th/0029 UTC. However, by 08th/1231 UTC, the eye-wall opened and the eye became exposed. Subsequently, disorganisation of convective clouds took place, eye became ill-defined and the system underwent rapid weakening on 09th (from T.5.0 at 09/0000 UTC to T 2.5 at 10/0000 UTC).

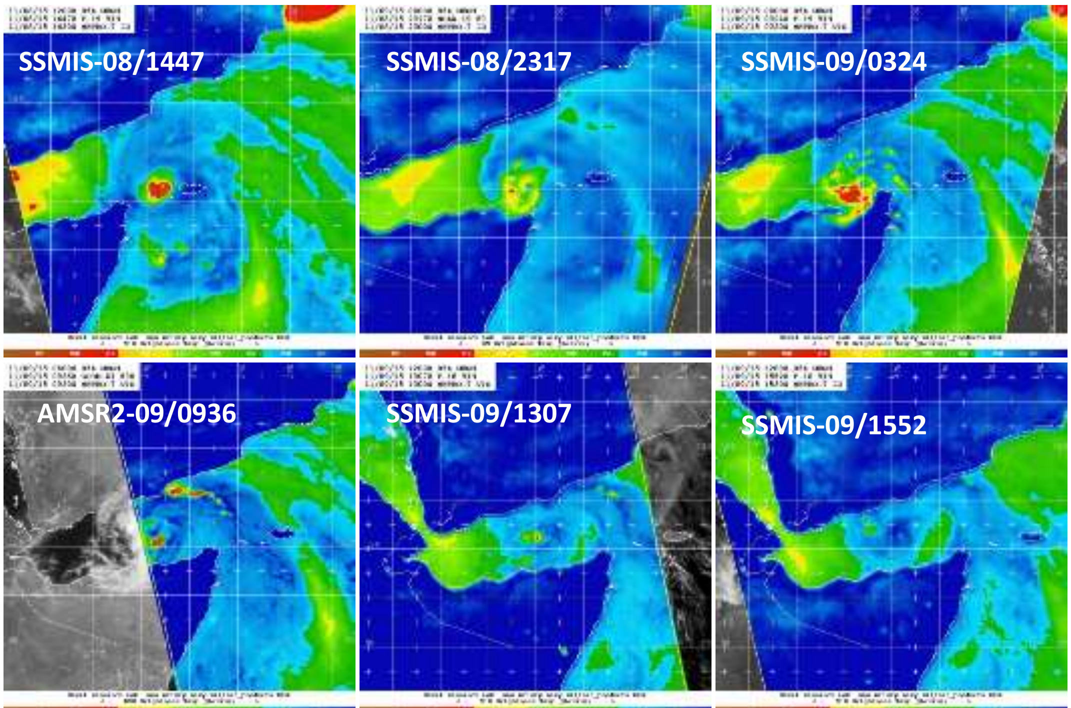


Fig. 2.11.9 (contd.) Typical microwave imageries during 8th to 9th November 2015 in association with ESCS Megh.

2.11.6. Surface wind structure

The surface wind structure during the life period of ESCS, Megh based on multi-satellite surface wind developed by CIRA, USA is shown in Fig. 2.11.10. It can be seen that the radius of 34 kt (outer core size) winds was higher in northeast (NE) sector. It was maximum of about 125 nm during its mature stage. Also in the radius of 50 kt/64 kt (inner core size), the winds were higher in the northeastern sector as compared to the other sector. The size of the system was maximum, especially in northeast quadrant at 0600 UTC of 9th November, while the intensity was decreasing gradually. Then it decreased sharply to 63 nm at 1200 UTC of 9th. The size then remained same upto 1800 UTC of 9th Nov. and then gradually decreased. The change in the inner core (R50) was similar to that of R34 and the temporal variation in R64 was less. The radius of maximum winds (RMW) remained almost same till 1800 UTC of 6th November. It then decreased gradually reaching minimum of 8nm at 1800 UTC of 8th, as the cyclone experienced rapid intensification from

0300 UTC of 7th to 0300 UTC of 8th. It then increased with weakening of the system from 1200 UTC of 8th. It was one of the lowest RMW, as the cyclone was associated with one of the smallest eye or a pin hole eye.

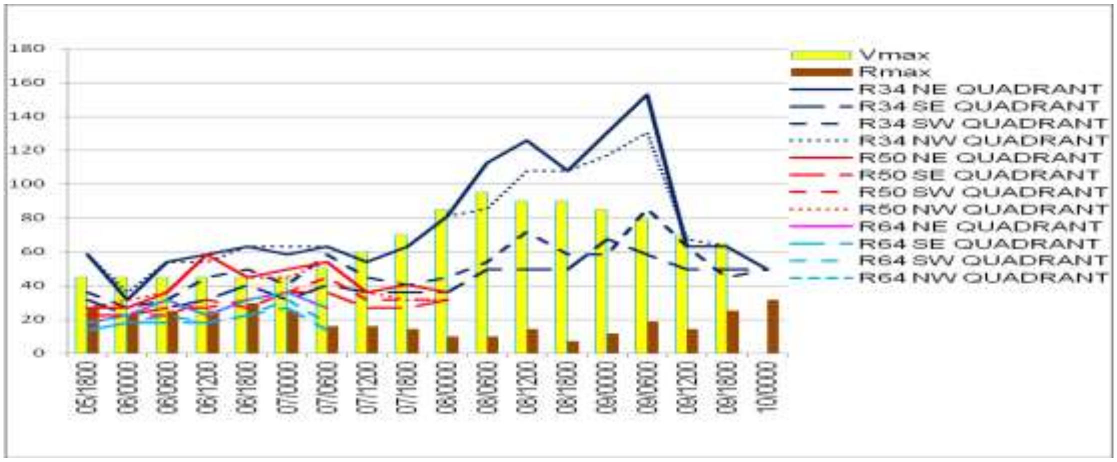


Fig. 2.11.10 Radius 34 knot (R34), radius of 50 knot (R50) & radius of 64 knot (R64), estimated maximum sustained surface winds (Vmax in knots) and Radius of Maximum winds (Rmax in nautical mile) based on multi-satellite surface wind (http://rammb.cira.colostate.edu/)

2.11.7 Dynamical features

To analyse the dynamical features, the mean sea level pressure (MSLP), 10 metre wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 5th to 10th November are presented in fig. 2.11.11 (a-f). From the analysis of MSLP and 10m wind, it is observed that the GFS model underestimated the intensification of the system. However, it could detect the genesis at 0000 UTC of 5th November with the formation of 2 closed isobars at the interval of 2 hPa and ECP of 1008 hPa against the best track ECP of 1006 hPa. It could detect the movement towards Yemen coast across the Gulf of Aden, but could not predict the landfall. Though the centre based on GFS analysis lay to the south of the best track. The rapid intensification on 7th and rapid weakening on 10th could not be detected. The associated cyclonic circulation extended upto mid-tropospheric levels. Considering the upper tropospheric wind analysis, ridge over AS ran along 15.0^{0}N throughout the life period at 200 hPa level. At 500 hPa level, it ran along 18.0^{0}N during 5th to 7th and along 20.0^{0}N during 8th to 10th November. Under the influence of this ridge, northerly to northeasterly winds prevailed over the cyclone field leading to west-southwestwards movement of the system. From the GFS analysis, it can be concluded that the system was steered west-southwestwards by the lower mid-tropospheric winds. However, on 10th November the system recurved northeastwards which can be associated with the upper tropospheric flow at 200 hPa level.

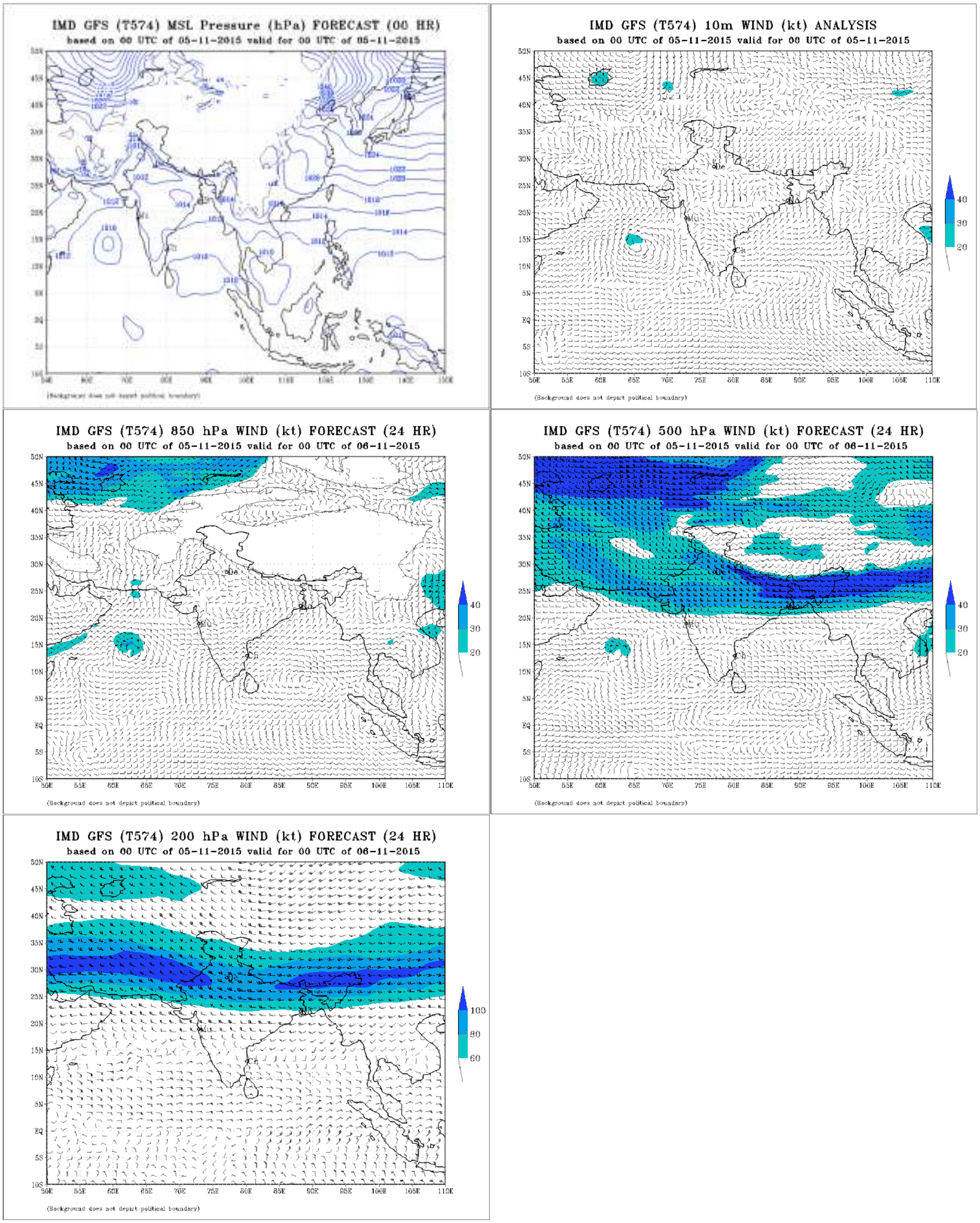


Fig. 2.11.11 (a) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 5th November.

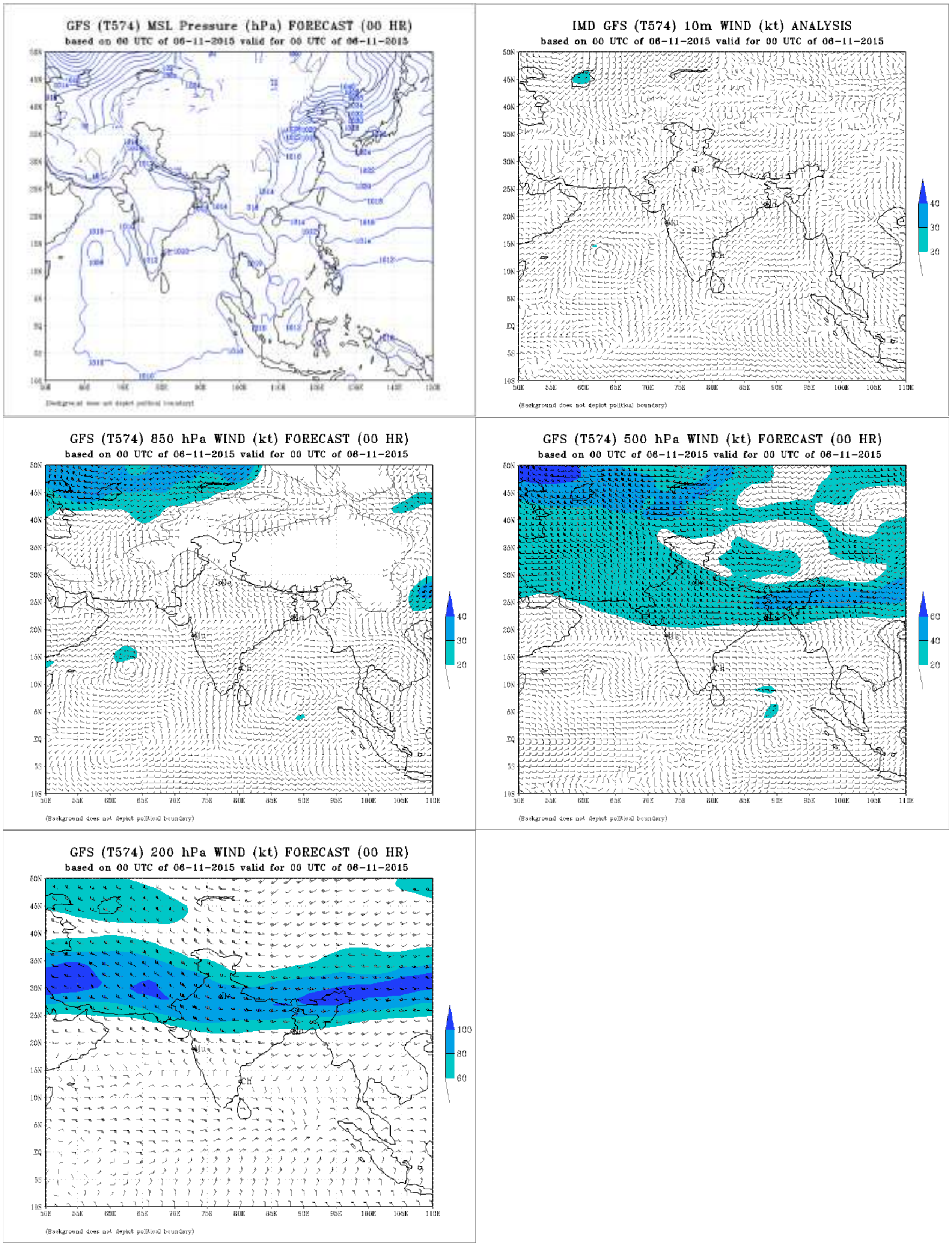


Fig. 2.11.11 (b) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 6th November.

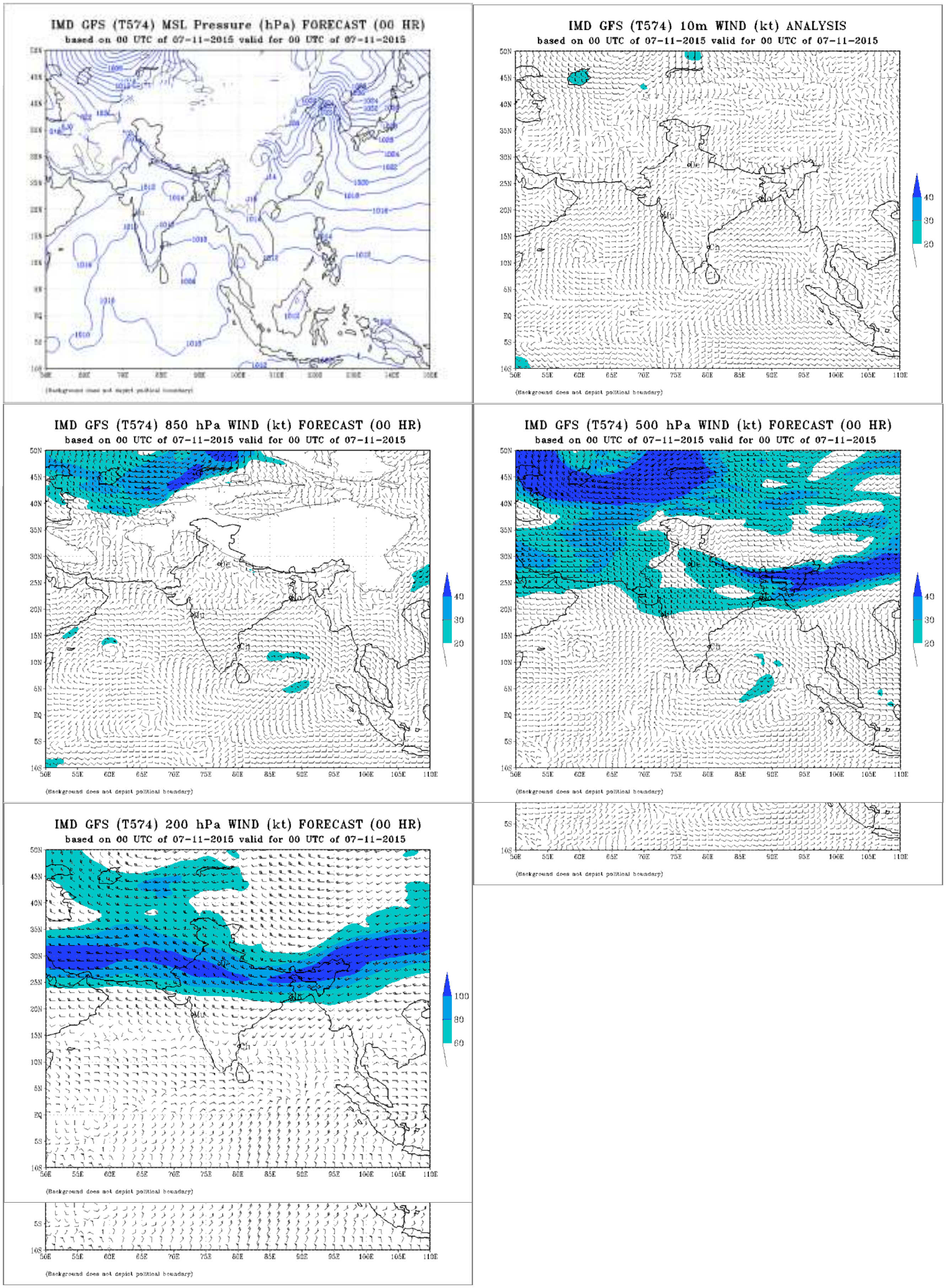


Fig. 2.11.11 (c) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 7th November.

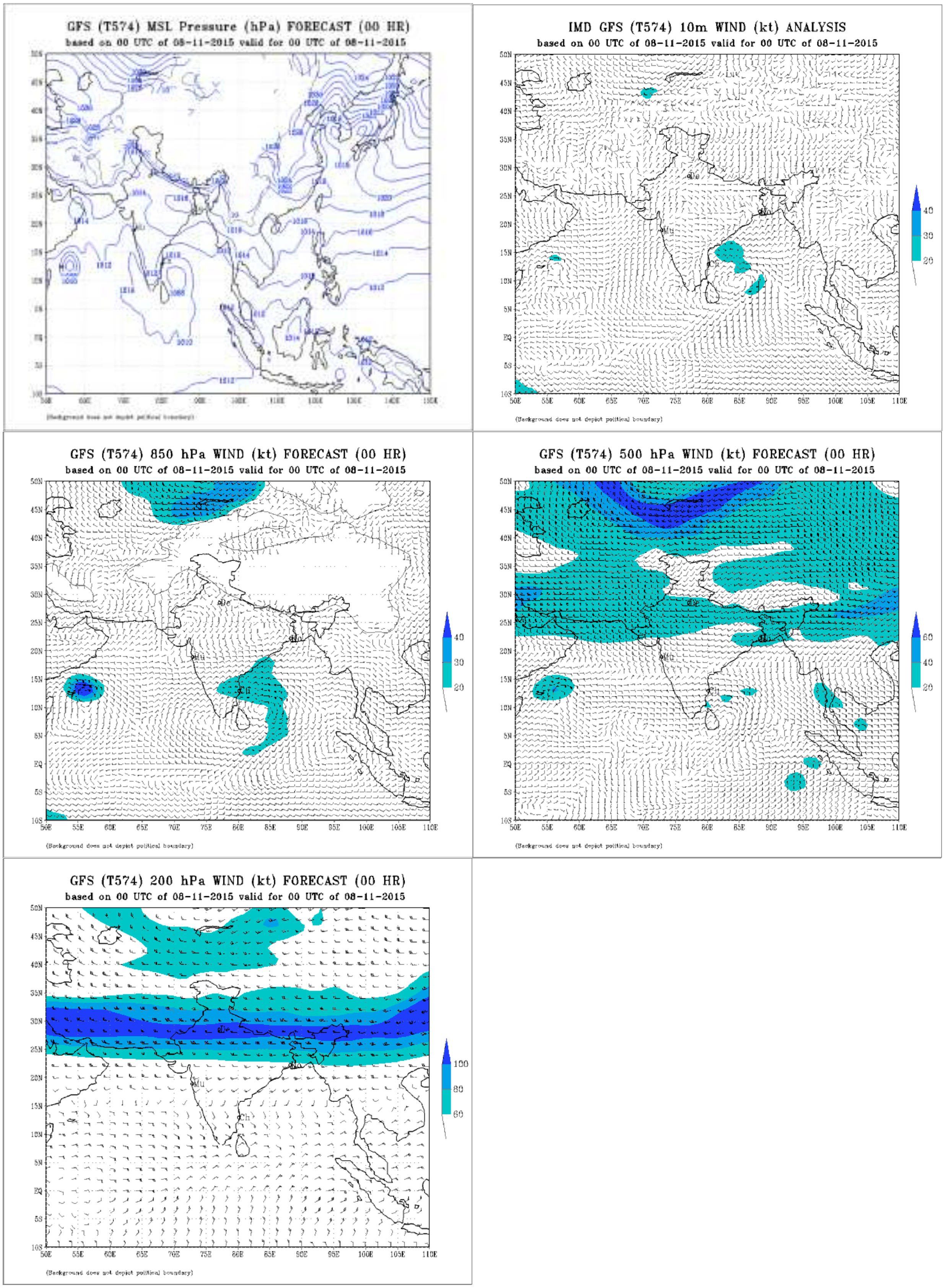


Fig. 2.11.11 (d) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 8th November.

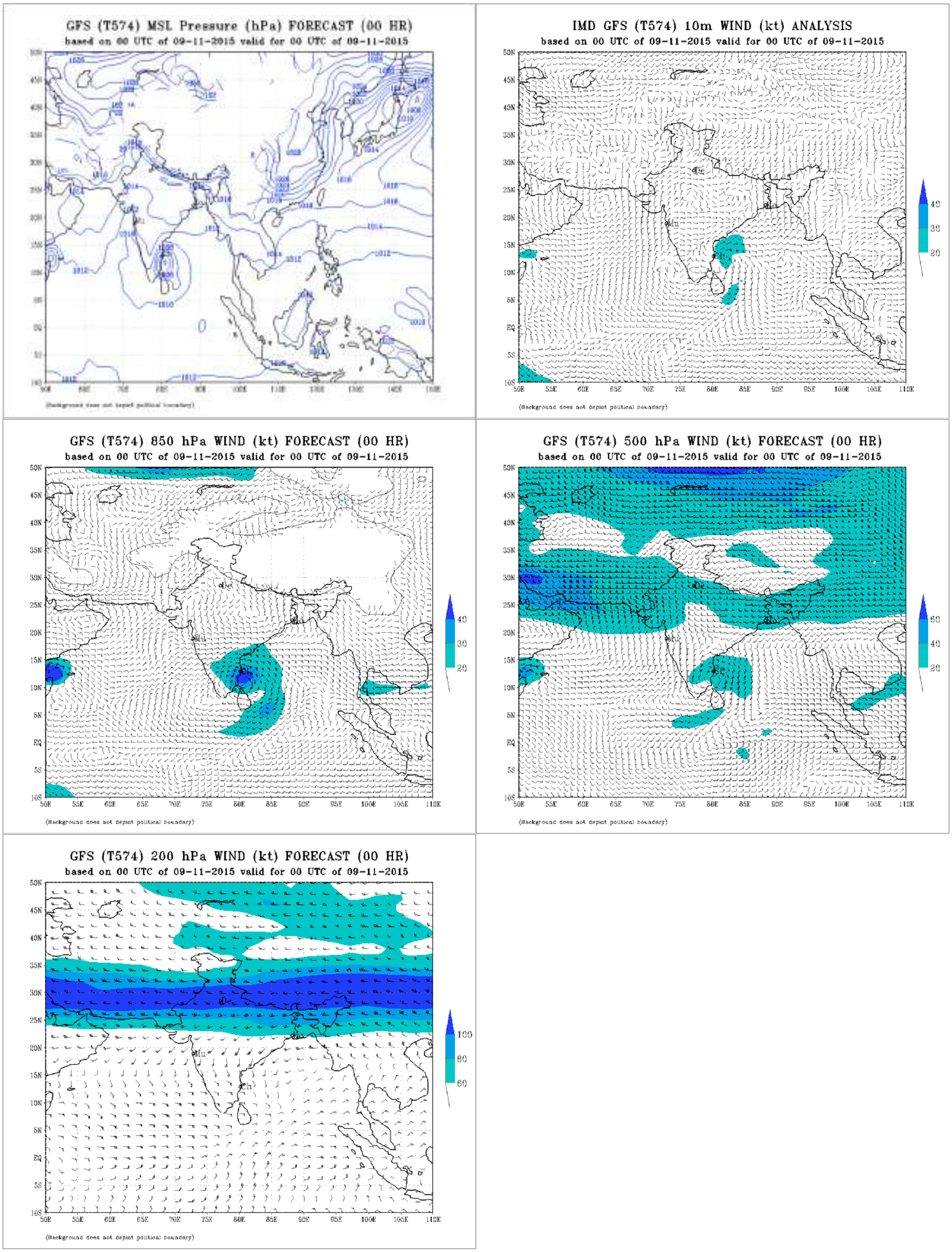


Fig. 2.11.11 (e) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 9th November.

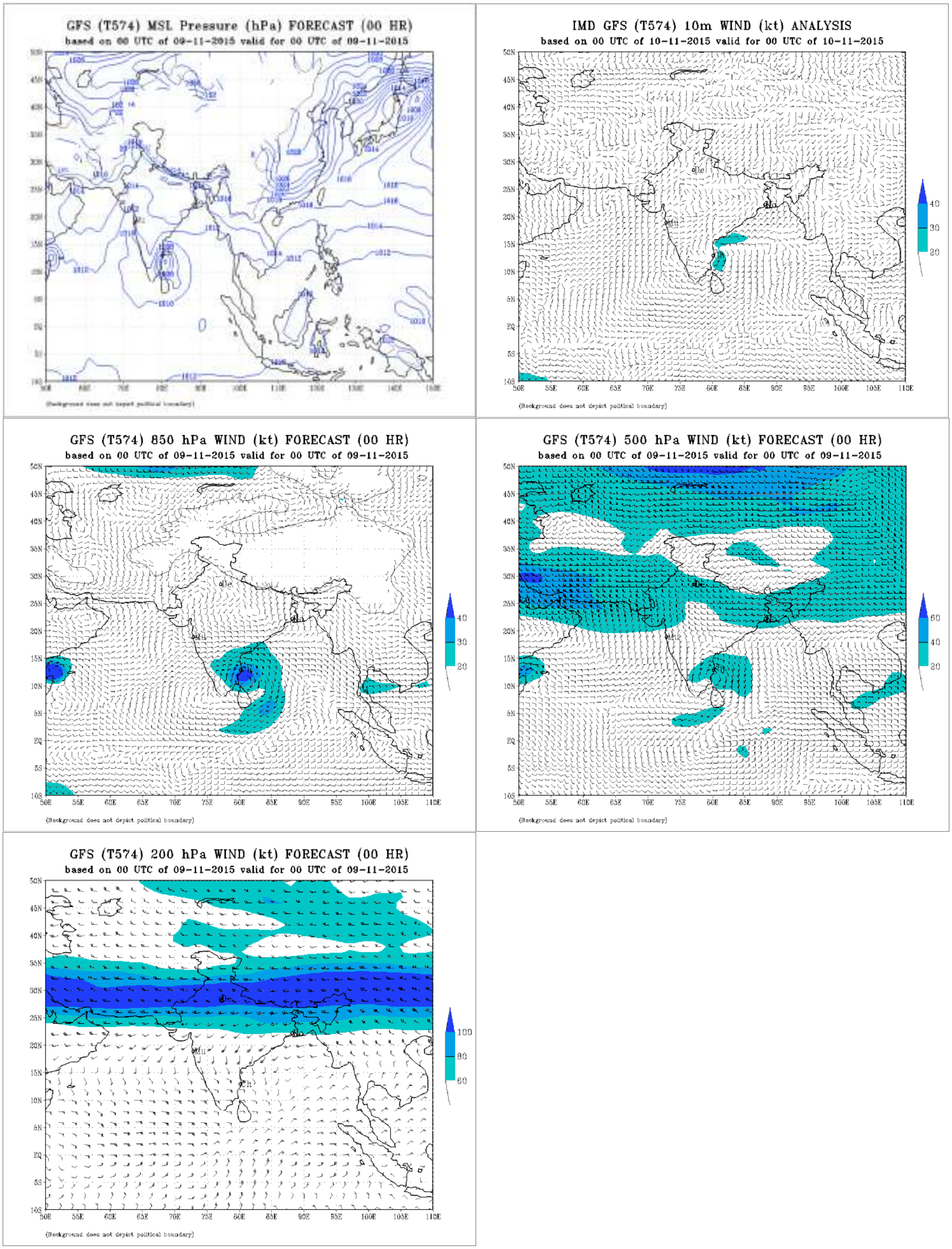


Fig. 2.11.11 (f) IMD GFS analysis of MSLP, 10m wind and winds at 850, 500 & 200 hPa levels based on 0000 UTC of 10th November.

2.11.8. Realized Weather:

2.11.8.1 Rainfall:

Rainfall associated with the system is depicted in Fig. 2.11.12 based on IMD-NCMRWF GPM merged gauge rainfall data

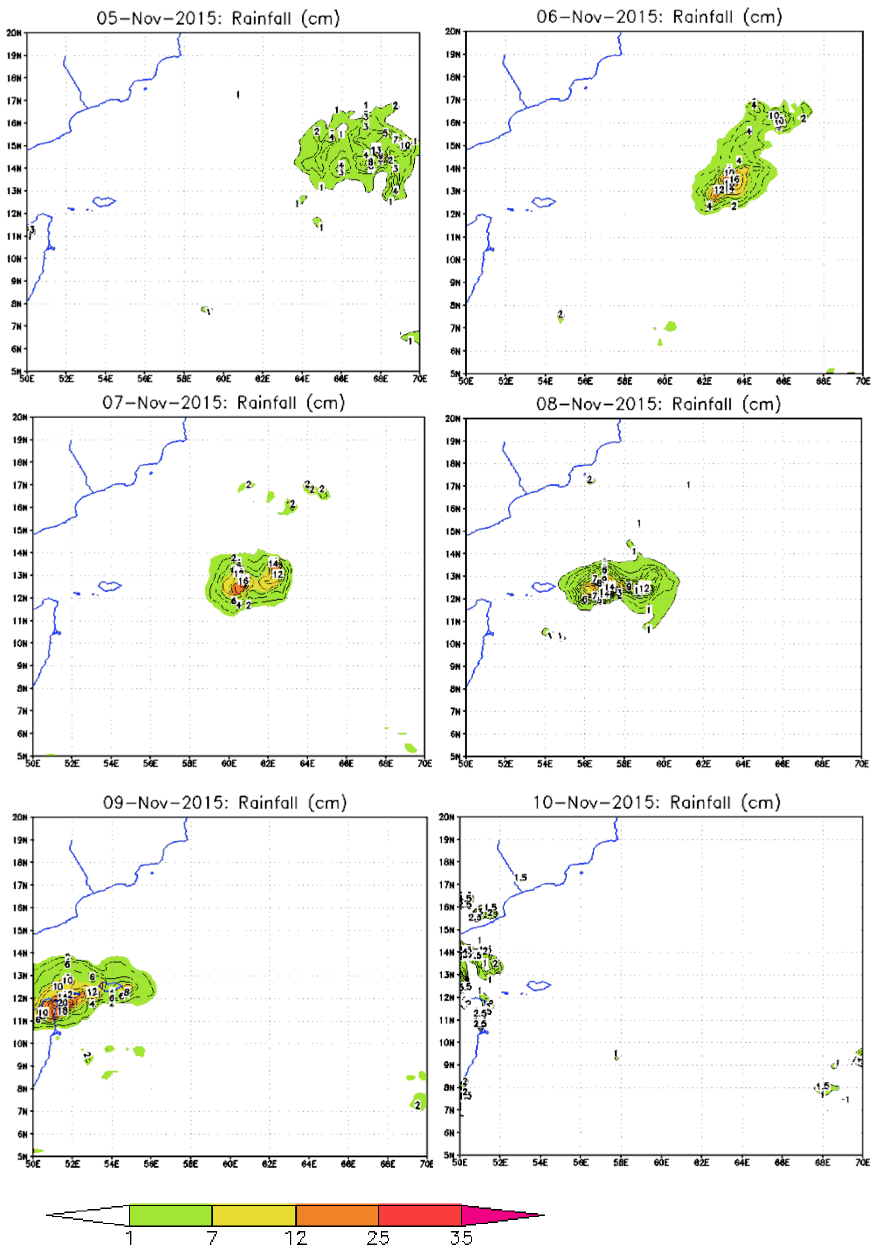


Fig.2.11.12 IMD-NCMRWF GPM-gauge merged 24-hr rainfall as on 0300 UTC of the date indicated in each plot for the period 05-10 November 2015

During the initial stage of formation of the system, on 5th November, rainfall belt was east-west oriented and the rainfall maximum was observed to the northeast of the system centre. Similar pattern was observed on 6th November with extension of rainfall belt from southwest to northeast. Subsequently, with the organisation of the system, convection became more and more organised and rainfall was symmetric about the centre on 7th and 8th November. However, gradually the rainfall maximum shifted to the southwest with gradual weakening of the system from 8th and west-southwestwards movement, the rainfall belt was elongated towards west-southwest from east-northeast. As a result the northern tip of Somalia experienced haevy rainfall on 9th. The rainfall almost decreased on 9th and 10th due to rapid weakening of the system.

2.11.9. Damage due to ESCS Megh

As per media and press report, ESCS Megh caused extensive devastation, killing at least eighteen people and injuring dozens of others. More than 500 houses were completely destroyed and another 3,000 were damaged. In addition, hundreds of fishing boats were damaged and more than 3,000 families were displaced. The typical damage photographs over Socotra Island are presented in fig 2.11.13.

Yemini Island, Socotra lashed by high winds and torrential rains

Dragon's blood tree is seen on the ground after Megh hits Socotra Island

Fig. 2.11.13 Typical damage photographs over in asssociation with ESCS Megh over Socotra Island

2.12 Deep Depression over the Bay of Bengal (08-10 November 2015)

2.12.1 Introduction

The Deep Depression over the Bay of Bengal (BOB) during 08-10 November 2015, formed from a low pressure area (LOPAR) that lay over southwest BOB on 06th. It concentrated into a depression (D; maximum sustained surface wind speed (MSW):17-27 kts) over southwest BOB close to north Tamil Nadu and Sri Lanka coasts at 0300 UTC (0830 IST) of 08th. Moving initially west-northwestward with a speed of 17 kmph, it intensified into a DD (MSW: 28-33 kts) around 08th/midnight. It subsequently moved slowly northwestwards at a speed of about 10 kmph towards north Tamil Nadu and Puducherry coasts on 09th morning. By 09th noon, when the system was close to the coast, it moved very slowly (with a speed of about 5 kmph) nearly northward off north Tamil Nadu and Puducherry coasts and made landfall over north Tamil Nadu coast close to north of Puducherry near latitude 12.2°N and longitude 80.0°E around 1930 hrs IST of 09th. Due to its proximity to the coast throughout the day, it caused exceptionally heavy rainfall over north Tamil Nadu on 9th. The salient features of this system are as follows:

(i) It was a short lived system, forming over southwest BOB close to Tamil Nadu and Sri Lanka coasts, intensifying into a DD and crossing coast within 36 hrs of formation.

(ii) On the day of landfall, the 9th November, maintaining the intensity of DD and moving very slowly northward along the coast, it caused heavy to extremely heavy rainfall over north Tamil Nadu. Even after landfall, the system moved slowly and dissipated over north Tamil Nadu, within about 100 km from the coast, by 1130 hrs IST of 10th November.

(iii) It weakened rapidly after landfall into a well marked low pressure area within 15 hrs of landfall.

(iv) It was the first cyclonic disturbance over the BOB during the post-monsoon season (October-December) of 2015. The activity over BOB in terms of frequency and intensity of cyclonic disturbances has been below normal during this season, mainly due to the fact that 2015 is a strong El Nino year and El Nino has adverse impact on cyclonic activity over BOB.

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.

2.12.2 Monitoring of DD (08-10 November,2015)

The DD (08-10 November, 2015) was monitored & predicted by IMD continuously since its formation. Despite the system forming and intensifying close to the coast and making landfall within 36 hrs of formation, forecast of its genesis, movement, intensity, point & time of landfall, as well as associated adverse weather like heavy rain and strong wind were predicted well by IMD with sufficient lead time to enable civil administrators and disaster managers to take necessary mitigatory actions. The genesis of the system on 08th

November was forecast by IMD on 02nd November itself. Its movement towards north Tamil Nadu coast, maximum intensity it would attain (DD / Cyclonic Storm (MSW: 34-47 kts) , landfall near to Puducherry coast and expected adverse weather such as extremely heavy rainfall along north coastal Tamil Nadu on 09th November were predicted by IMD even before its genesis, i.e., from 07th morning itself.

Since the pre-genesis stage itself, the system was monitored continuously by satellite based observations available at every half-an-hour interval. Enhanced INSAT-3D imageries formed the basic satellite input for cyclone monitoring. As the system formed close to the coast, the system was monitored with meteorological buoys, coastal and ship observations from the genesis stage onwards in addition to satellite based observations. Special hourly synoptic observations were taken along Tamil Nadu and Puducherry coasts from 08th morning onwards. As the system moved within the range of coastal radars, continuous radar observations were also taken at Doppler Weather Radar (DWR) facilities at Karaikal and Chennai. Observations from Automatic Weather Stations (AWS) and High Wind Speed Recorders (HWSR) installed along coastal Tamil Nadu also provided crucial data for successful monitoring of the system. Satellite data products and scatterometry products available from other leading meteorological services of the globe were also used for location, intensity and structure estimations.

Various national and international NWP models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models, dynamical statistical models for genesis and intensity prediction were utilized to predict the genesis, track and intensity of the system. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various model guidances, decision making process and warning products generation.

2.12.3 Brief life history

2.12.3.1 Genesis

Under active northeast monsoon conditions, an upper air cyclonic circulation lay over southwest BOB and adjoining equatorial Indian Ocean on 04th November 2015 which was observed over southwest BOB and neighbourhood extending upto mid-tropospheric levels on 05th. Under its influence, a LOPAR formed over southwest BOB off Sri Lanka and Tamil Nadu coasts on 06th morning which became well-marked over the same region on 07th. It concentrated into a Depression and lay centred at 0830 hrs IST of 08th November over southwest BOB off Tamil Nadu coast near latitude 10.7°N and longitude 83.7°E about 440 km east-southeast of Puducherry. According to satellite imagery, intensity at 08th/0300 IST was T 1.5 as convection became more organised during the previous 6 hours. Based on synoptic analysis using buoy, ship and coastal observations and satellite wind analysis products available from leading satellite based analysis centre, MSW was determined to be 25 knots gusting to 35 knots. Winds were higher over the northeast sector due to basic northeast monsoon circulation. The estimated central pressure was about 1004 hPa. State of sea around system centre was rough to very rough. Minimum cloud top temperature associated with the system was -88°C.

The environmental features associated with the genesis of the system were high sea surface temperature (SST) near the system centre (around 29-30°C), increased upper level divergence and low level relative vorticity & convergence, moderate vertical wind shear (VWS; 10-20 kts) and favourable Madden-Jullian Oscillation (MJO) conditions [MJO index was in phase-3 (east equatorial Indian ocean) with amplitude greater than 1 which is favourable for genesis and intensification of cyclonic disturbances over the BOB].

2.12.3.2 Intensification and movement

On 08th/0300 UTC, the upper tropospheric ridge at 200 hPa level was observed along 16°N latitude. In association with an upper air anticyclonic circulation that lay to the northeast of the system centre, the middle and upper tropospheric winds near the system centre were east-southeasterly and the system was initially steered west-northwestward by the steering current. The system moved at a speed of about 20 kmph on this day under the influence of the anticyclonic circulation.

By 08th/1200 UTC, VWS near the system centre decreased considerably and was about 5-10 kts. This, along with other favourable environmental conditions of high SST near the system centre (around 29-30°C), increased poleward outflow above the system centre and favourable MJO conditions (as mentioned in previous section), caused intensification of the system and the system attained the intensity of DD on 08th/2330 IST near latitude 11.5°N and longitude 82.0°E. According to satellite imagery, the intensity was T 2.0.

On 09th 0300 UTC, as the system was located close to the coast, it started interacting with the land which restricted further intensification of the system. By 09th noon, the system started showing signs of slight weakening due to land interaction and slight increase in vertical wind shear. Subsequently, the system started moving northward off Tamil Nadu / Puducherry coasts into regions of higher VWS (20-30 kts) by 09th/1200 UTC. At 1200 UTC of 09th, the system was located near latitude 12.1°N and 80.1°E before crossing coast close to north of Puducherry near latitude 12.2° N and longitude 80.0°E around 1930 hrs IST of 09th with a wind speed of 55-65 kmph. By 09th/1800 UTC, the system was located over north coastal Tamil Nadu near latitude 12.4°N and 79.9°E. As the system was over land, moisture supply decreased considerably and under the influence of higher vertical wind shear, the system weakened gradually into a D on 10th by 0830 IST and subsequently into a well marked LOPAR by 1130 IST of 10th.

The observed track of DD (08-10 November, 2015) and the best track parameters of the system are given in Fig.2.1 and Table.2.12.1 respectively.

Table 2.12.1 Best track positions and other parameters of Deep Depression over the Bay of Bengal during 08-10 November, 2015

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
08/11/2015	0300	10.7/83.7	1.5	1003	25	3	D
	0600	10.8/83.2	1.5	1003	25	3	D
	1200	11.0/82.5	1.5	1002	25	4	D
	1800	11.2/81.4	2.0	1000	30	5	DD
09/11/2015	0000	11.4/80.7	2.0	999	30	6	DD
	0300	11.6/80.3	2.0	998	30	6	DD
	0600	11.7/80.1	2.0	996	30	6	DD
	1200	12.1/80.0	2.0	996	30	6	DD
	Crossed north Tamil Nadu coast close to Marakanam, north of Puducherry near latitude 12.2°N/80.0°E around 1400 UTC						
	1800	12.4/79.9	-	998	30	6	DD
10/11/2015	0000	12.4/79.6	-	1000	30	5	DD
	0300	12.4/79.3	-	1002	20	4	D
	0600	Well marked low pressure area over north Tamil Nadu and neighbourhood.					

D: Depression; DD: Deep Depression

Speed and direction of movement of the system based on the best track parameters are furnished in Fig. 2.12.1 On 08th/0600 UTC, the six hourly average speed of movement of the system was high at about 20 kmph. Subsequently, its speed decreased gradually to about 12 kmph at 1800 UTC. The direction of movement was west-northwestward during this period. However, on 09th/0000 UTC, the direction of movement changed to northward and at 0600 UTC of 09th, speed decreased considerably to about 5-6 kmph when the system centre was located about 50-60 km from the coast.

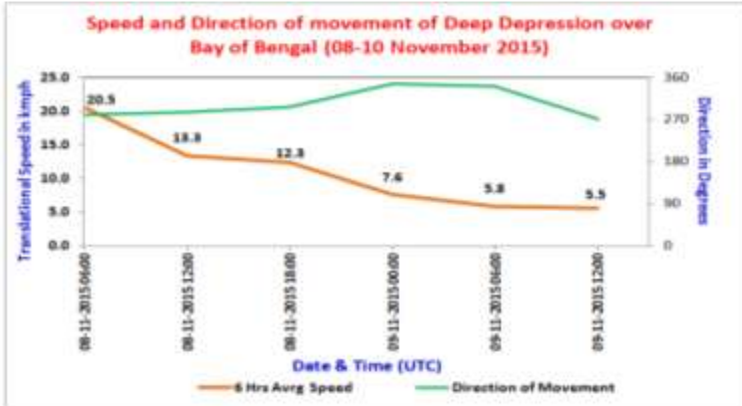


Fig.2.12.1 Speed and direction of movement of Deep Depression over Bay of Bengal (08-10 November 2015)

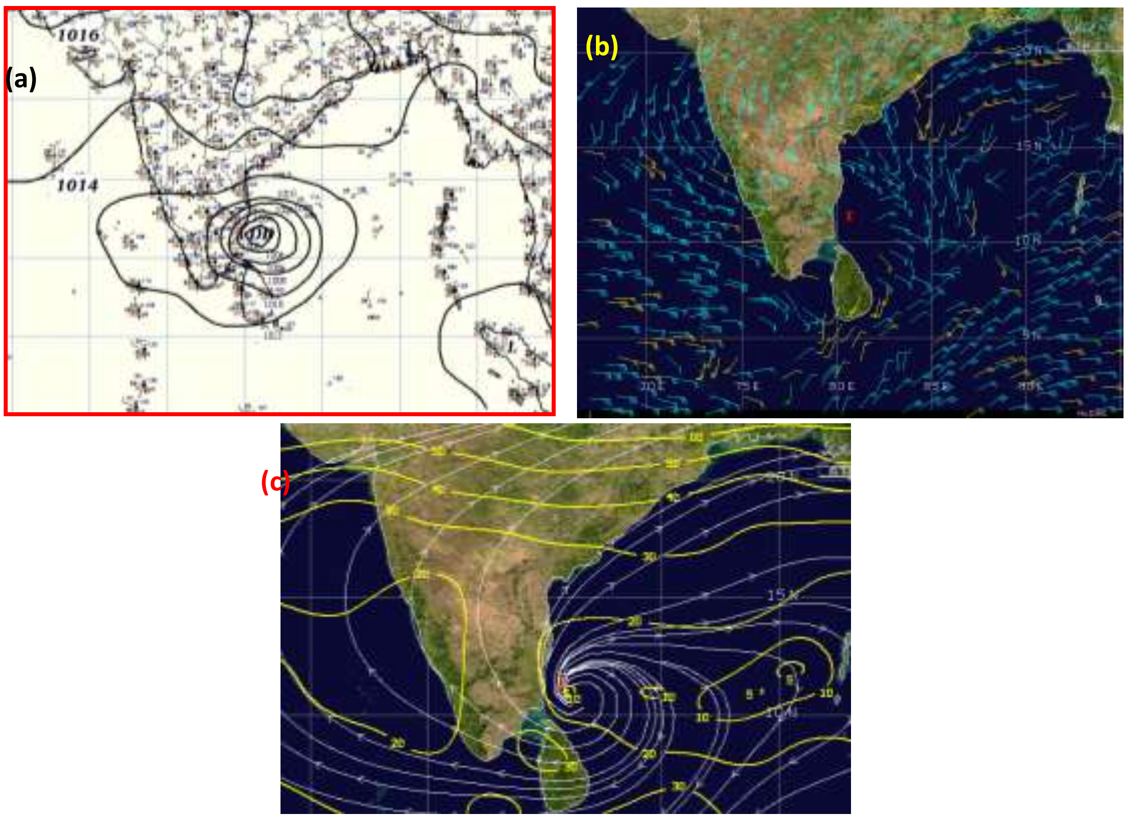


Fig.2.12.2 (a) Analysed surface chart (09/0300 UTC), (b) satellite based upper tropospheric winds (09/0000 UTC) and (c) vertical wind shear between upper and lower tropospheric levels (09/0000 UTC) (Source for b & c: CIMSS Tropical Cyclones)

Synoptic features associated with the location, movement and intensification of the system on 09th when the system was close to the coast are depicted in Fig.2.12.2 (a) surface analysed chart based on 09th/0300 UTC, 2.12.2 (b) upper level winds based on 09th/0000 UTC satellite winds (CIMSS - METEOSAT-7 product) and 2.12.2 (c) VWS based on 09th/0000 UTC (CIMSS - METEOSAT-7 product). The anti-cyclone located to the northeast of the system centre initially steered it west-northwestwards. However, subsequently, when the system moved to the southwestern periphery of the anti-cyclone, it was steered slowly northwards just prior to landfall.

2.12.4 Landfall

The place and time of landfall was determined through monitoring of hourly observations from the coastal stations as shown in Fig.2.12.3. The veering of wind over Chennai and backing of wind over Puducherry along with the lowest pressure and maximum sustained surface wind over Puducherry clearly suggested landfall close to north of Puducherry by 1930 IST.

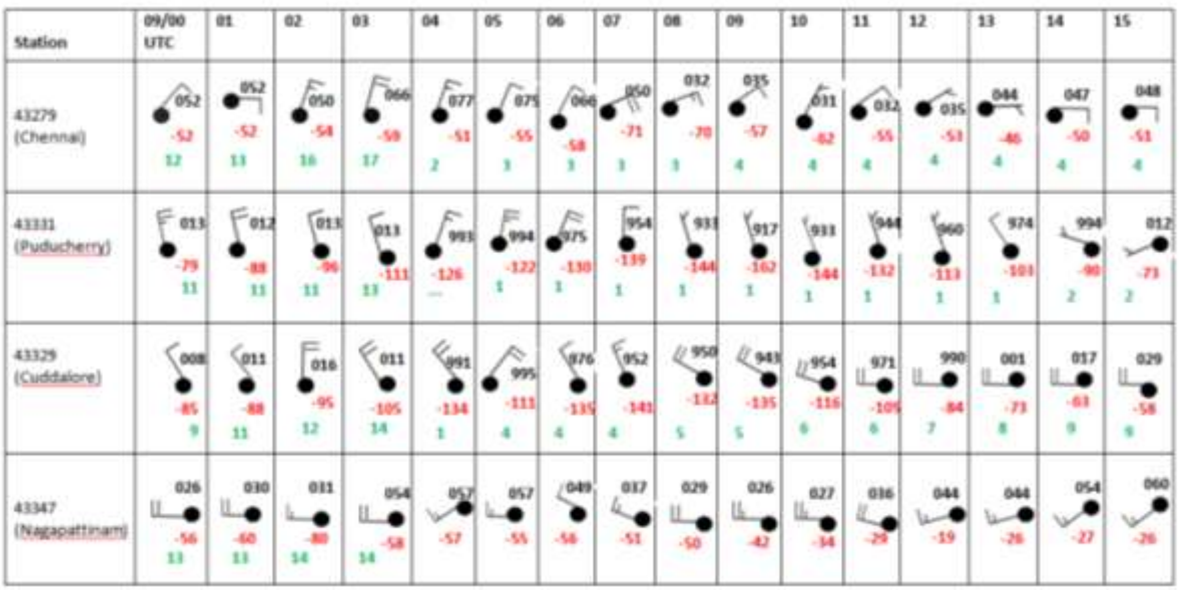


Fig.2.12.3 Hourly observations from coastal stations on 09th November 2015

At 0600 UTC of 09th, the system centre was located about 40-50 km south-southeast of Puducherry. The lowest MSLP of 997.5 hPa was recorded at Puducherry and the ECP was 996 hPa. At 1200 UTC of 09th, the system was located about 30 km east-northeast of Puducherry with 996 hPa MSLP over Puducherry and ECP also about 996 hPa. However, Puducherry recorded the lowest MSLP of 991.7 hPa at 0900 UTC (1430 IST) of 09th thus indicating slight intensification of the system during this time. However, this intensity did not sustain as seen from increase in MSLP over Puducherry from 1000 UTC onwards indicating signs of weakening of the system just prior to landfall.

2.12.5 Maximum Sustained Surface Wind speed and estimated central pressure at the time of landfall:

The MSW in association with a cyclonic disturbance affecting Indian coasts is defined as the average surface wind speed over a period of 3 minutes measured at a height of 10 meters. The MSW is either estimated by the remotely sensed observations or recorded by the surface based instruments. As the system crossed north Tamil Nadu coast north of Puducherry, the MSW associated with it at the time of landfall is determined from coastal observations as well as wind speed recorded by the HWSR at Chennai and Karaikal. The DWRs at Karaikal and Chennai also continuously monitored the MSW in terms of radial velocity. Based on satellite imagery, intensity is estimated in terms of T number using Dvorak technique and using the empirical relation between the T.No and MSW, the corresponding MSW is estimated. Further, surface observatories along North Tamil Nadu and Puducherry coasts has continuously monitored the Mean Sea Level Pressure (MSLP) on the day of landfall, the 09th November. Based on the observation of the pressure drop at the centre, MSW is estimated using the empirical pressure-wind relationship (MSW= 14.2* √ pressure drop at the centre).

2.12.5.1 Estimated central pressure

The lowest MSLP of 991.7 hPa was recorded at Puducherry, located close to the point of landfall at 09th/0900 UTC. Hourly MSLP recorded at Puducherry on the day of landfall is shown in Fig.2.12.4. At 0600 UTC, MSLP over Puducherry was 997.5 hPa and the ECP was 996 hPa and at 1200 UTC, the corresponding values were 996 hPa each. During the period from 0600 UTC to 0900 UTC, MSLP over Puducherry fell from 997.5 hPa to 991.7 hPa after which it started rising gradually as the system started moving slightly northwards along the coastline for some time before the landfall over north of Puducherry around 1400 UTC of 09th November.

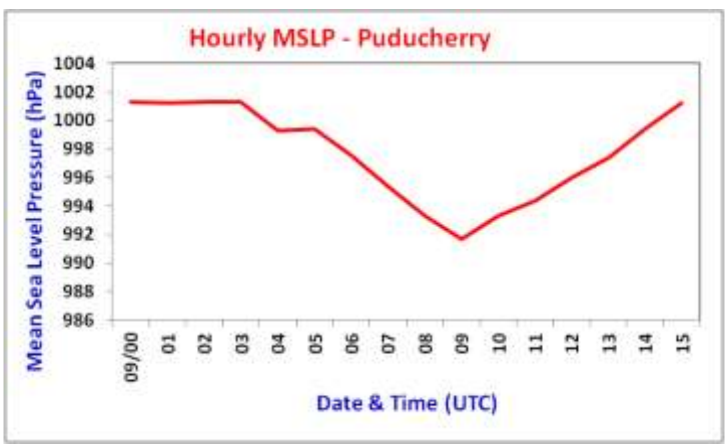


Fig.2.12.4 Hourly MSLP recorded at Puducherry during 0000-1500 UTC of 09th November 2015

2.12.5.2 Maximum Sustained Surface Wind speed

2.12.5.2.1 MSW based on coastal observations:

As the system was located very close to the coast when the system maintained the intensity of a deep depression, wind speeds recorded by hourly coastal observations provided the crucial input for determination of MSW during the time of landfall. Fig.2.12.5 depicts the wind speed recorded at Cuddalore, Puducherry and Chennai (Meenambakkam) during 0000 UTC to 1500 UTC on 09th November 2015, the day of landfall. As seen, highest wind speed of 25 knots has been recorded by Puducherry observatory at 0000 and 0500 UTC of 09th. Wind speed over Puducherry decreased to less than 05 kts at 0800 UTC and continued to remain around 5 knots until landfall as the system centre was located close to Puducherry during the period 0800 to 1400 UTC prior to landfall.

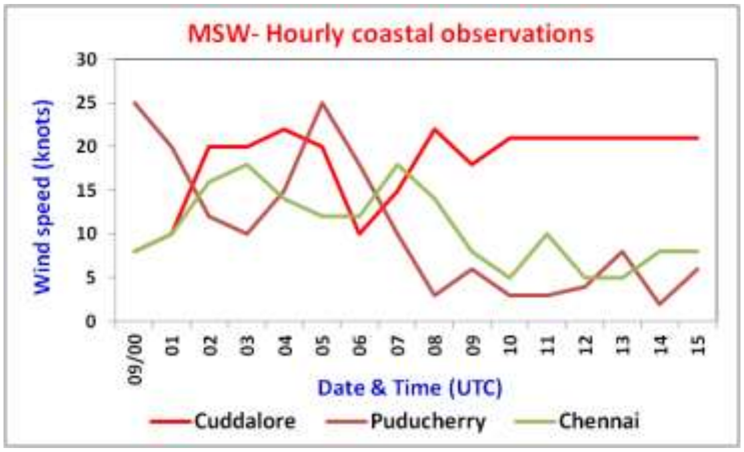


Fig.2.12.5 Hourly wind speeds recorded by coastal observatories during 0000-1500 UTC of 09th November 2015

2.12.5.2.2 MSW based on HWSR:

HWSR Karaikal has recorded one -minute average MSW of 22 kts wind at around 0200 UTC (0730 IST) of 09th and HWSR Chennai, 20 kts at about 0530 UTC (1100 IST). The 3-minute average MSW (standard practice of IMD) was about 18 knots at Chennai around 1103 hours IST of 09th November 2015 (Fig.2.12.6).

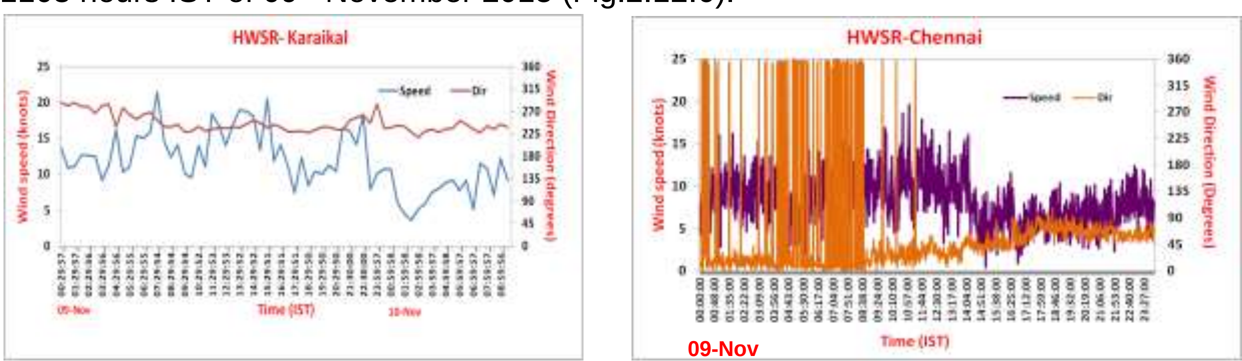


Fig.2.12.6 Wind speed and direction recorded by Karaikal and Chennai High Wind Speed Recorders on 09th November 2015.

2.12.5.2.3 Satellite based MSW

As per IMD's intensity estimation based on Dvorak technique, maximum intensity of the system at the time of landfall was T2.0 which corresponds to an MSW of about 30 knots (55-60 kmph).

2.12.5.2.3.1 MSW based on satellite derived winds

NOAA satellite ASCAT winds indicate highest wind speeds of about 40 knots at around 0430 UTC of 09th (Fig.2.12.7). This, when reduced to 3-min average wind, indicates MSW of about 30 knots.

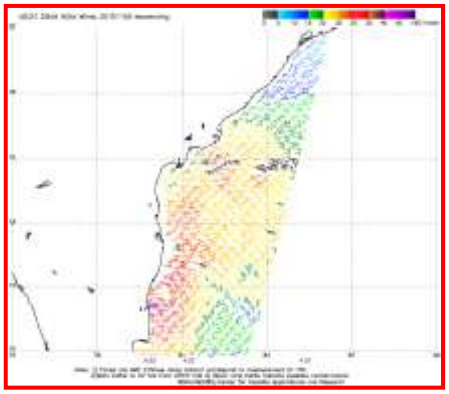


Fig.2.12.7: NOAA-ASCAT winds at 0430 UTC of 09th November 2015

NOAA, NESDIS, Cooperative Institute for Research in Atmosphere (CIRA) multi-platform satellite wind analysis product indicated highest winds of 35 knots (one-minute average) on 08th/1800 UTC with stronger winds on the northeast and northwest sectors (Fig.2.12.8).

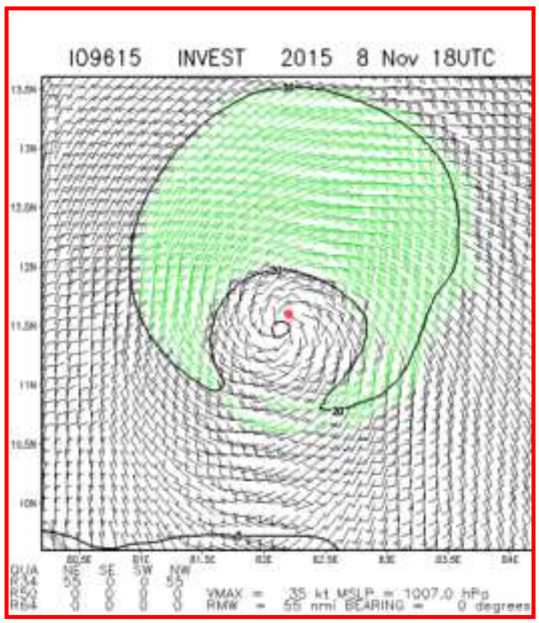


Fig.2.12.8 CIRA-multiplatform satellite wind analysis product based on 08th/1800 UTC.

2.12.5.2.4 MSW based on radar

DWRs Karaikal and Chennai reported highest maximum radial winds on 09th at 0030 UTC and 0500 UTC respectively (Fig.2.12.9). Highest maximum radial wind reported by DWR Karaikal (at about 0030 UTC of 09th) works out to 42 knots radial wind (surface level, 3-min average) at a distance of about 40 km along 90° azimuth from the radar (Fig.2.12.9). Highest maximum radial wind reported by DWR Chennai (at 0500 UTC of 09th) when reduced to surface level and corrected for 3-minute average works out to about 40 knots at a distance of about 150 km along 220° azimuth from the radar, near 12.0°N and 79.4°E (over land) (Fig.2.12.9), against the surface wind of 25 knots reported by the nearest observatory, Puducherry at that time. The radar based winds also decreased gradually thereafter.

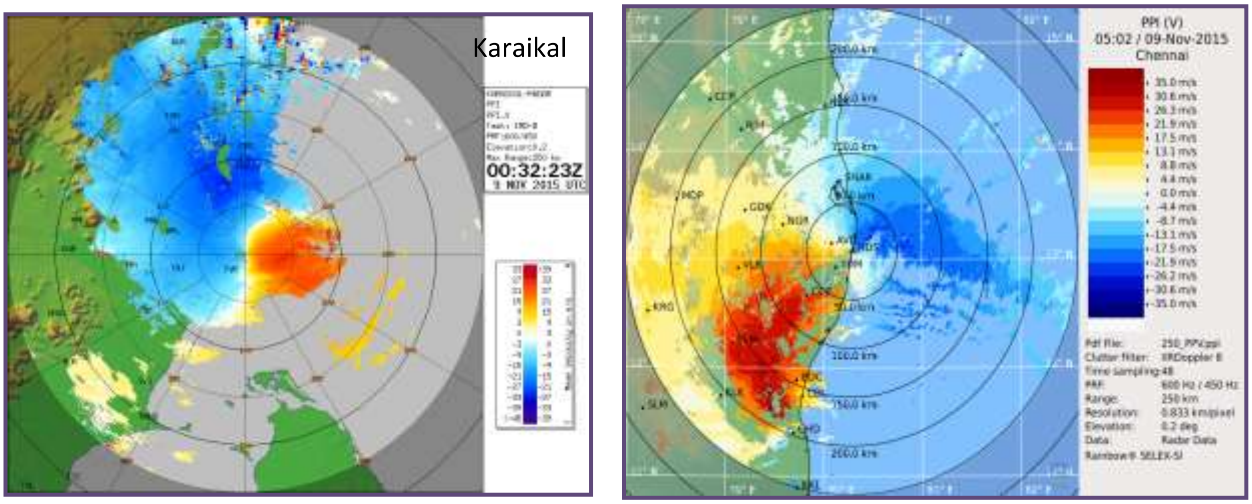


Fig.2.12.9 DWR Karakal and DWR Chennai based radial wind observation at 0030 and 0500 UTC of 09th Nov 2015 respectively.

2.12.5.2.5 MSW based on pressure drop

According to the hourly coastal observations, the lowest MSLP of 991.7 hPa was recorded at Puducherry at 0900 UTC of 09th. Hence, the lowest central pressure could be considered as 991 hPa. Thus, the pressure drop at the centre could have been of the order of 11 hPa as the outermost pressure in the system was 1002 hPa. According to Mishra and Gupta formula, the MSW=14.2*SQRT (pressure drop) = 47 knots. Though this estimation ties in with radar estimation, recorded coastal wind observations do not indicate wind speeds greater than 25 knots.

2.12.5.2.5 6 Final estimate of MSW

Considering all these observations and estimates, it can be concluded that the system could have attained peak intensity of about 35-40 knots for a short while, around 0900 UTC of 09th. However, the MSW around the time of landfall was about 30 knots (55-60 kmph) based on coastal observations and satellite and radar based winds.

2.12.6 Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellite Meteosat-7 and and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical INSAT-3D imageries representing the life cycle of the system are shown in Fig. 2.12.10 (a-b).

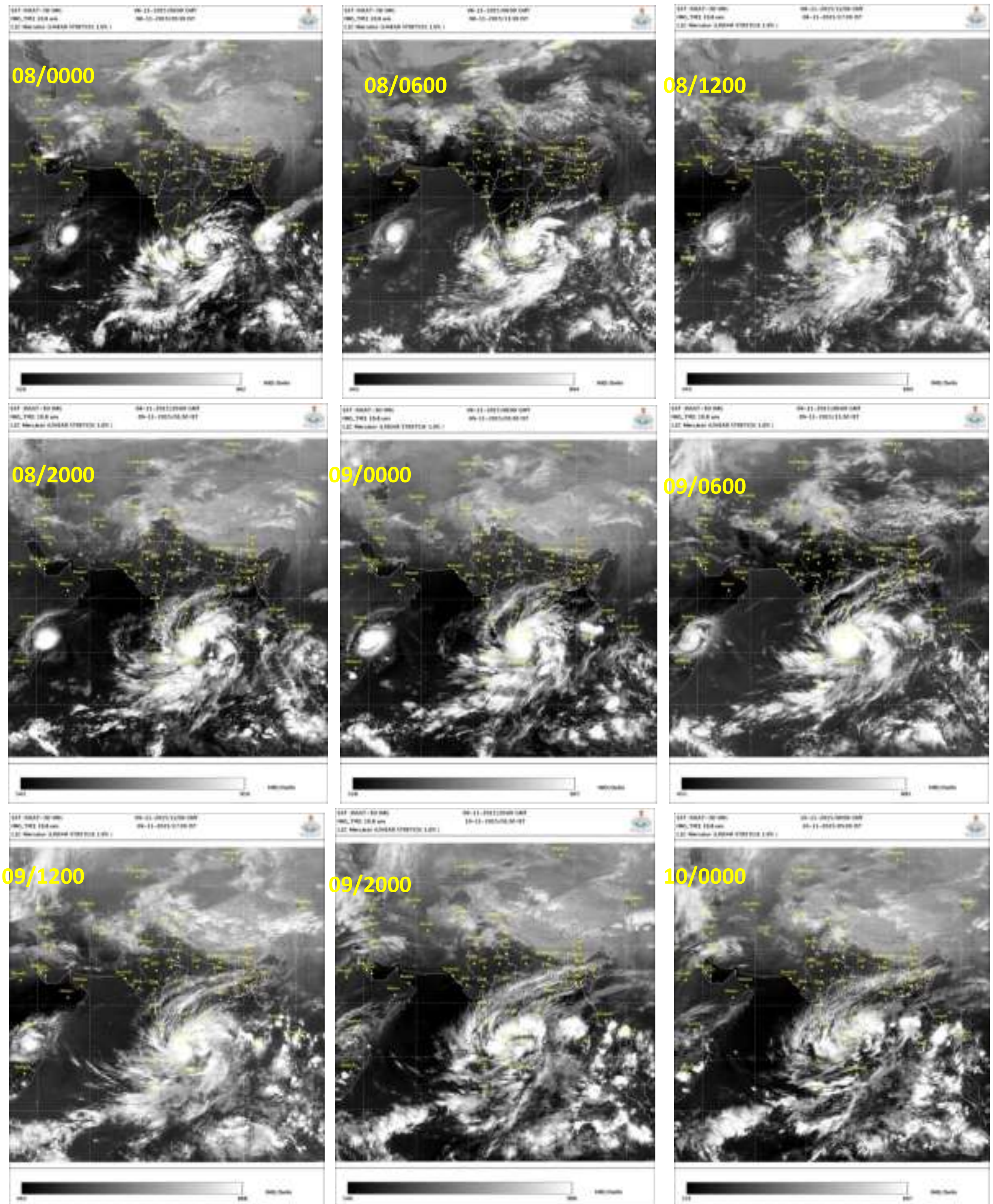


Fig.2.12.10(a) Typical INSAT-3D Infra-red (IR) imageries in association with Deep Depression (08-10 November 2015)

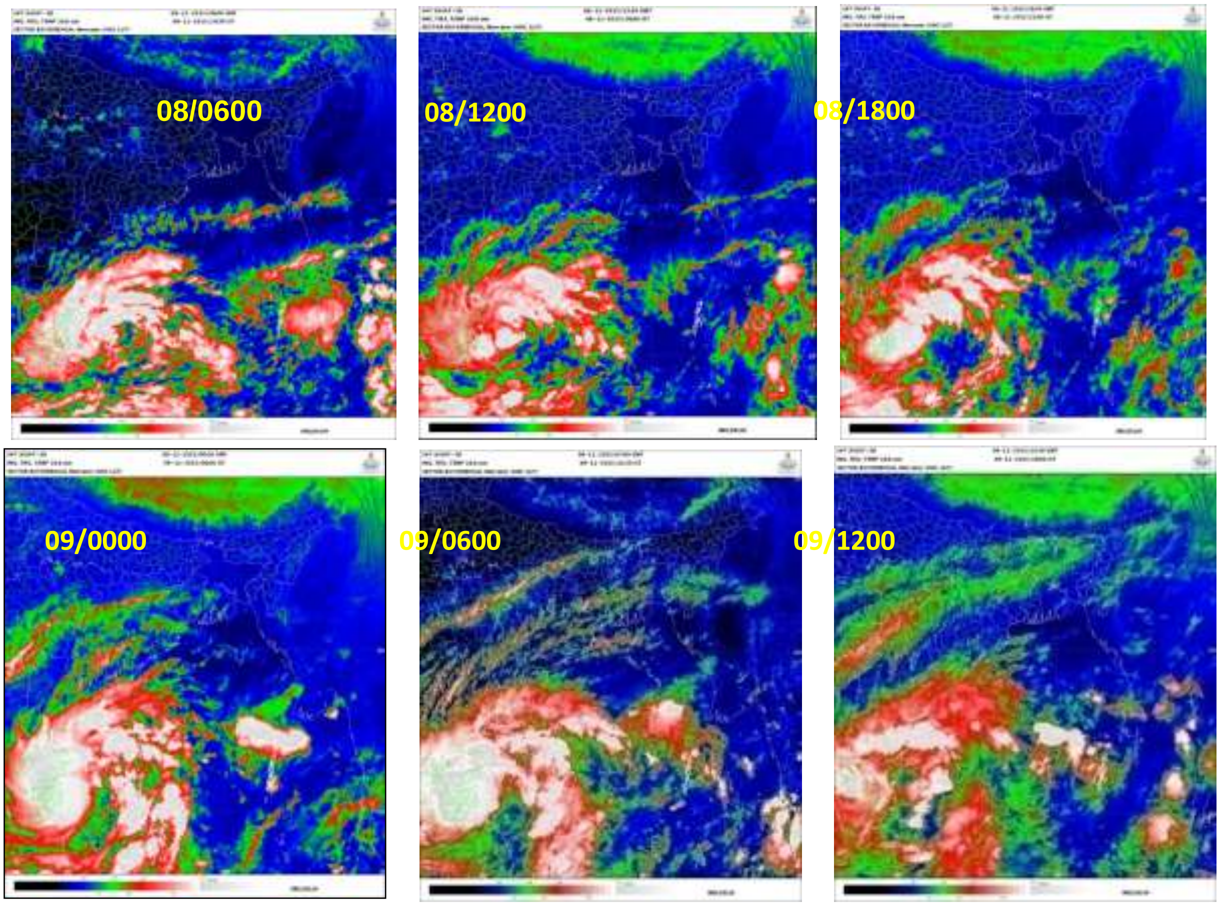


Fig.2.12.10 (b) Typical INSAT-3D enhanced Infra-red (IR) imageries in association with Deep Depression (08-10 November 2015)

According to INSAT-3D imageries and products, intensity of the system was T. 1.5 at 0300 UTC of 08th and convection showed shear pattern. Subsequently, the system intensified to T.2.0 at 1800 UTC of 08th and the convection showed curved band pattern. Lowest cloud top temperature associated with the system was -88.0°C. From 09th/0600 UTC onwards, intensity of the system could not be estimated as the system was located very close to land. Due to southwestward tilting of the system, the system centre, as observed through satellite, lay over land at about 0600 UTC of 9th.

2.12.7 Features observed through Radar

The Deep Depression (08-10 November 2015) was monitored by DWRs Karaikal and Chennai continuously when the system was within the range of these radars and hourly observations were taken. DWR Karaikal commenced hourly observations at 1800 UTC of 08th and DWR Chennai, at 09th/0000 UTC. Typical reflectivity products of both the radars, presented in Fig.2.12.11(a&b) indicate spiral band pattern. DWR Chennai reflectivity product based on 09th/1400 UTC also suggests landfall near north of Puducherry around 1400 UTC of 09th (Fig.2.12.11b).

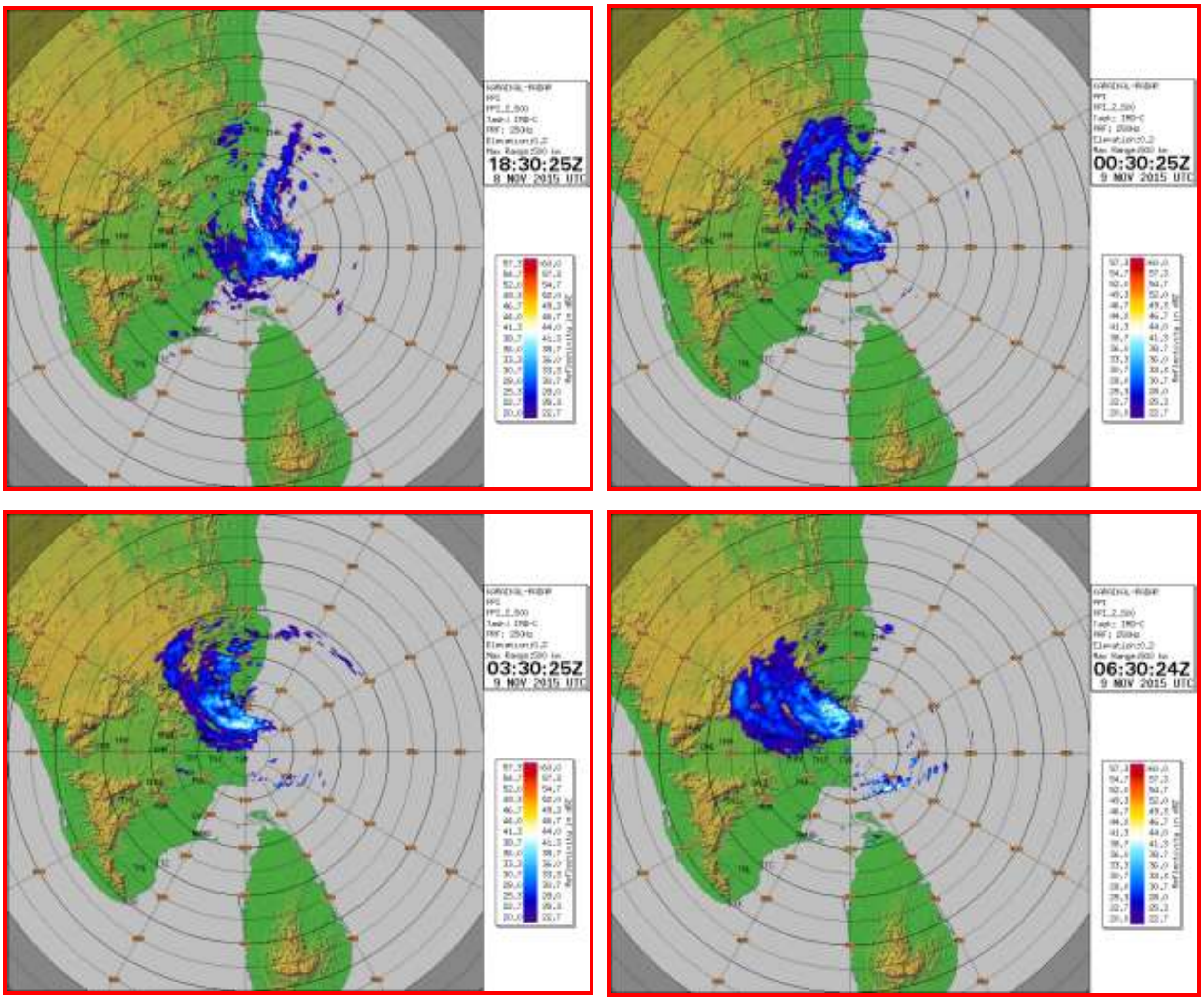


Fig.2.12.11 (a) DWR Karaikal imageries during 08th/1800 UTC to 09th/0600 UTC of November 2015

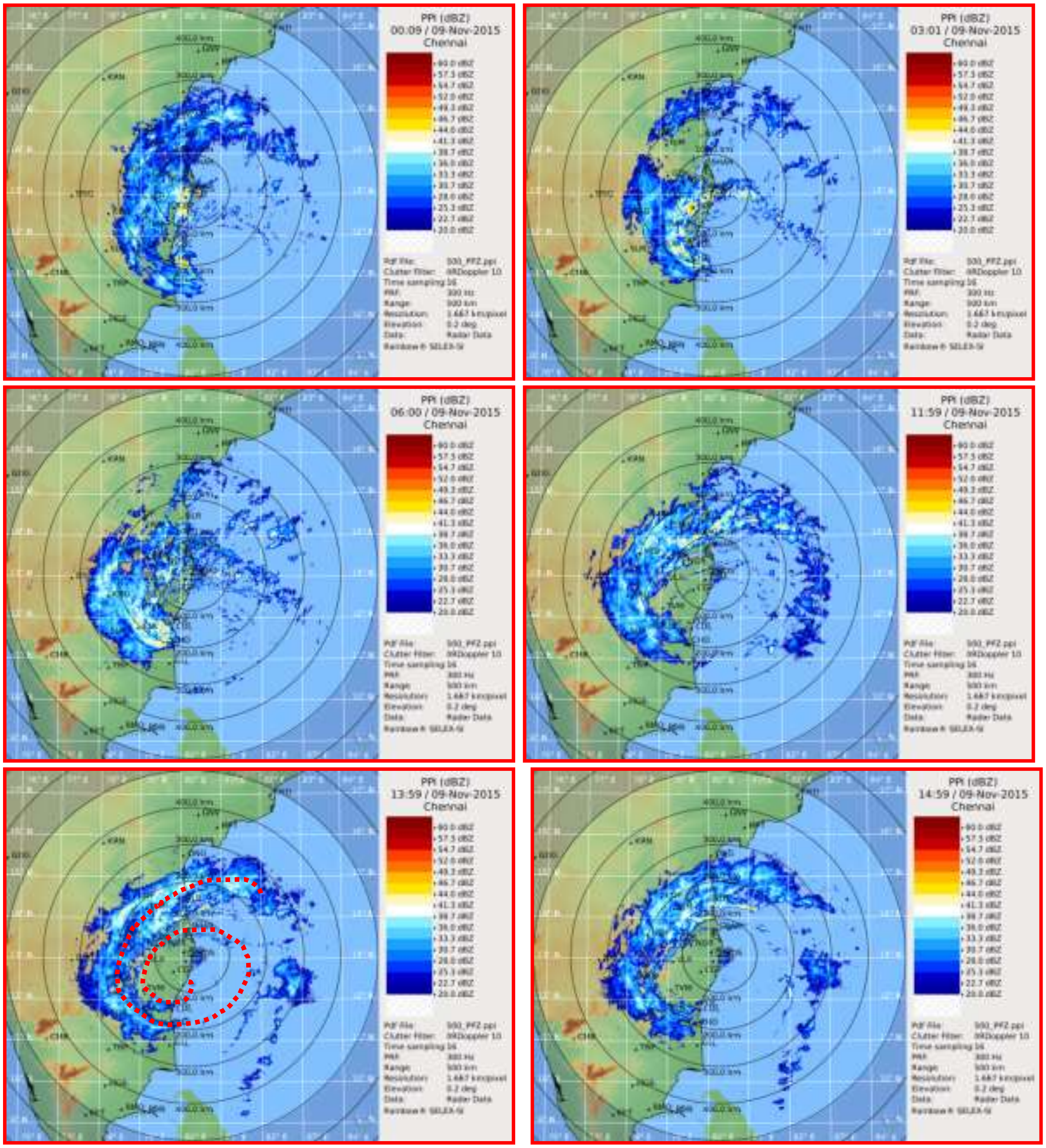


Fig.2.12.11 (b) DWR Chennai imageries during 0000-1500 UTC of 09th November 2015

2.12.8 Dynamical features

Dynamical models captured the genesis, track and intensity of the system fairly well. Dynamical features associated with the system are discussed based on IMD-GFS analysis fields of Mean Sea Level Pressure (MSLP), surface winds at 10 m height and winds at 850 hPa, 500 hPa and 200 hPa levels based on initial conditions of 0000 UTC of 8-10 November 2015 [Fig.2.12.12(a-c)]

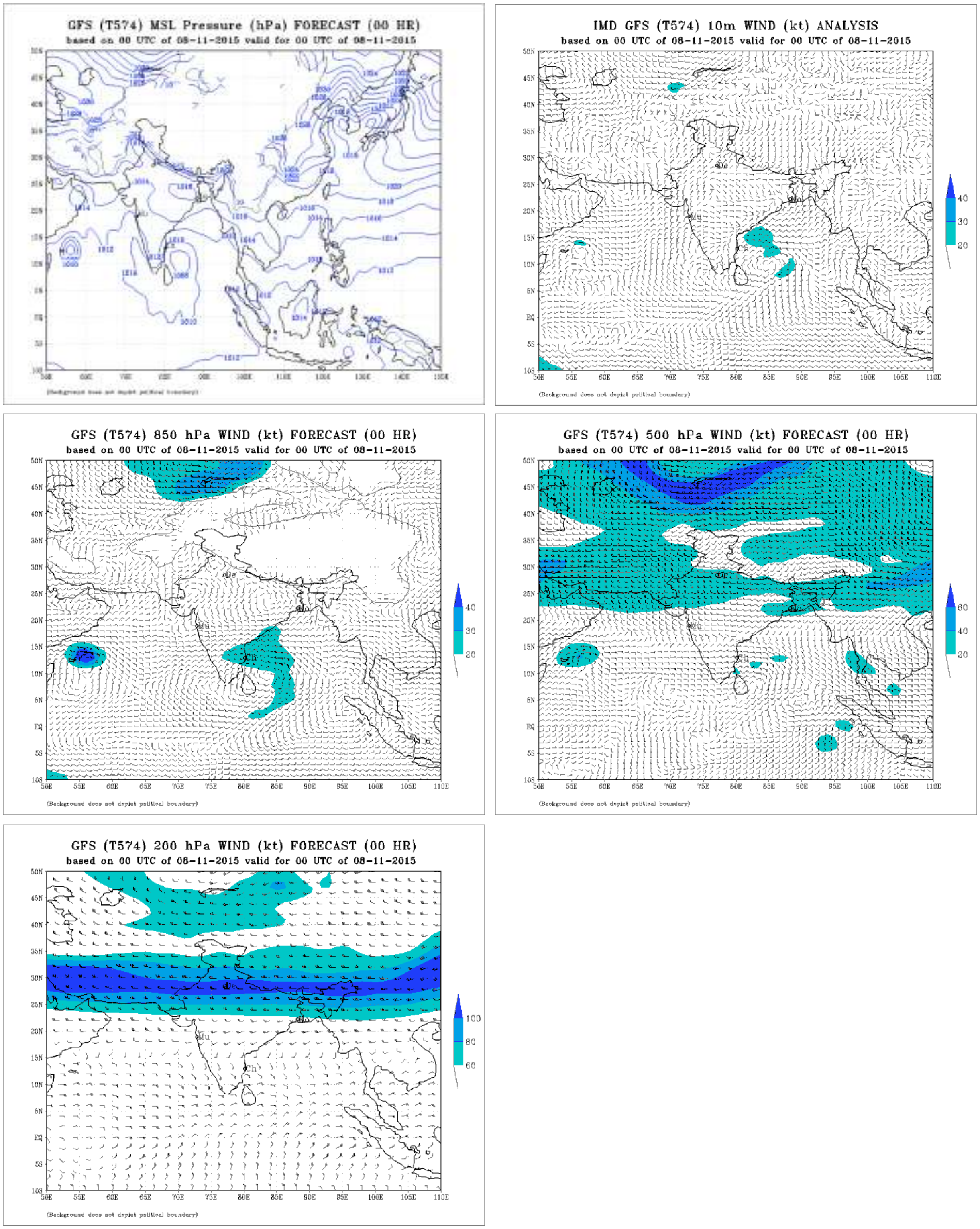


Fig.2.12.12 (a) IMD-GFS Analyses based on 0000 UTC of 8th November 2015 (a) MSLP (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds

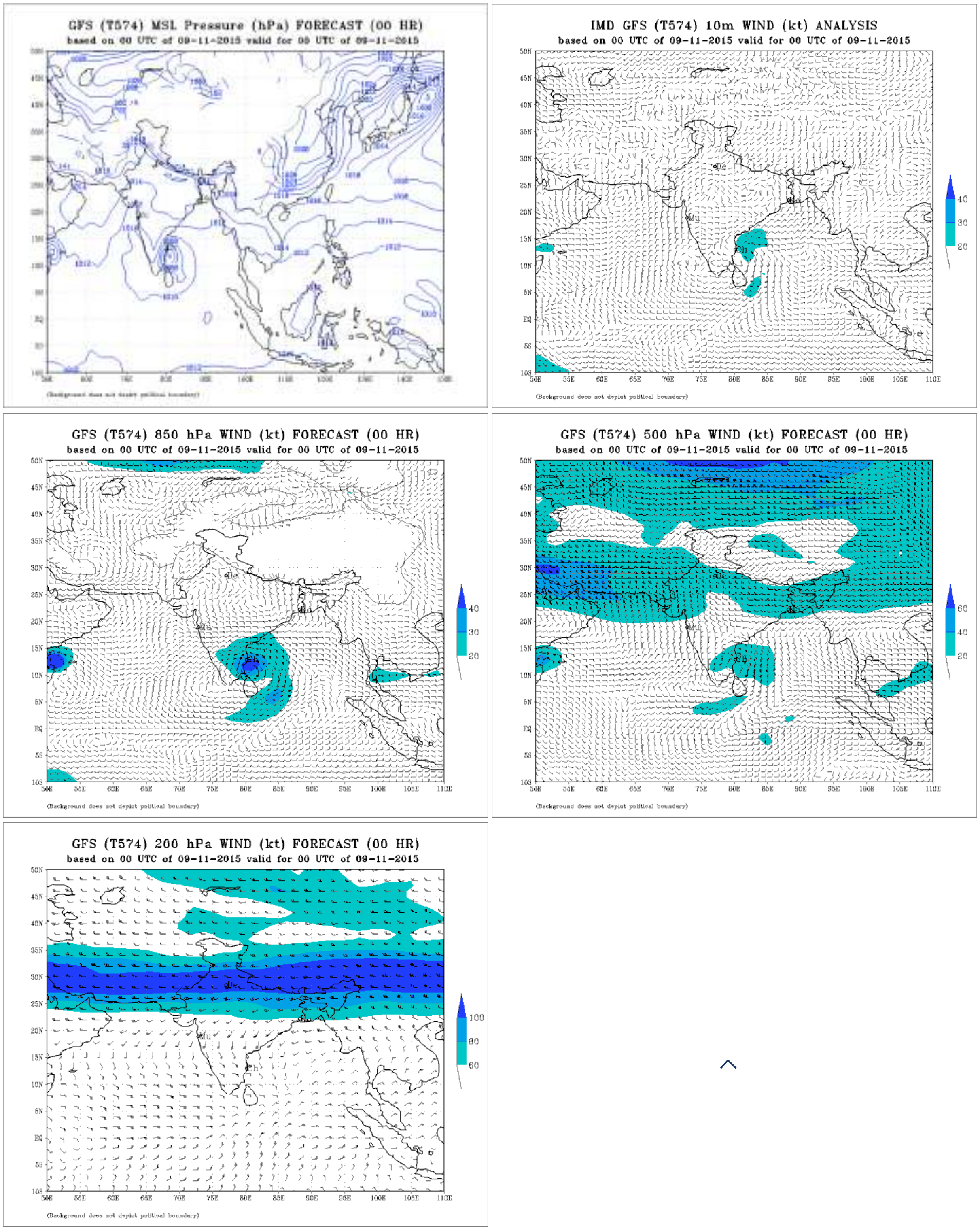


Fig.2.12.12 (b) IMD-GFS Analyses based on 0000 UTC of 9th November 2015 (a) MSLP (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds

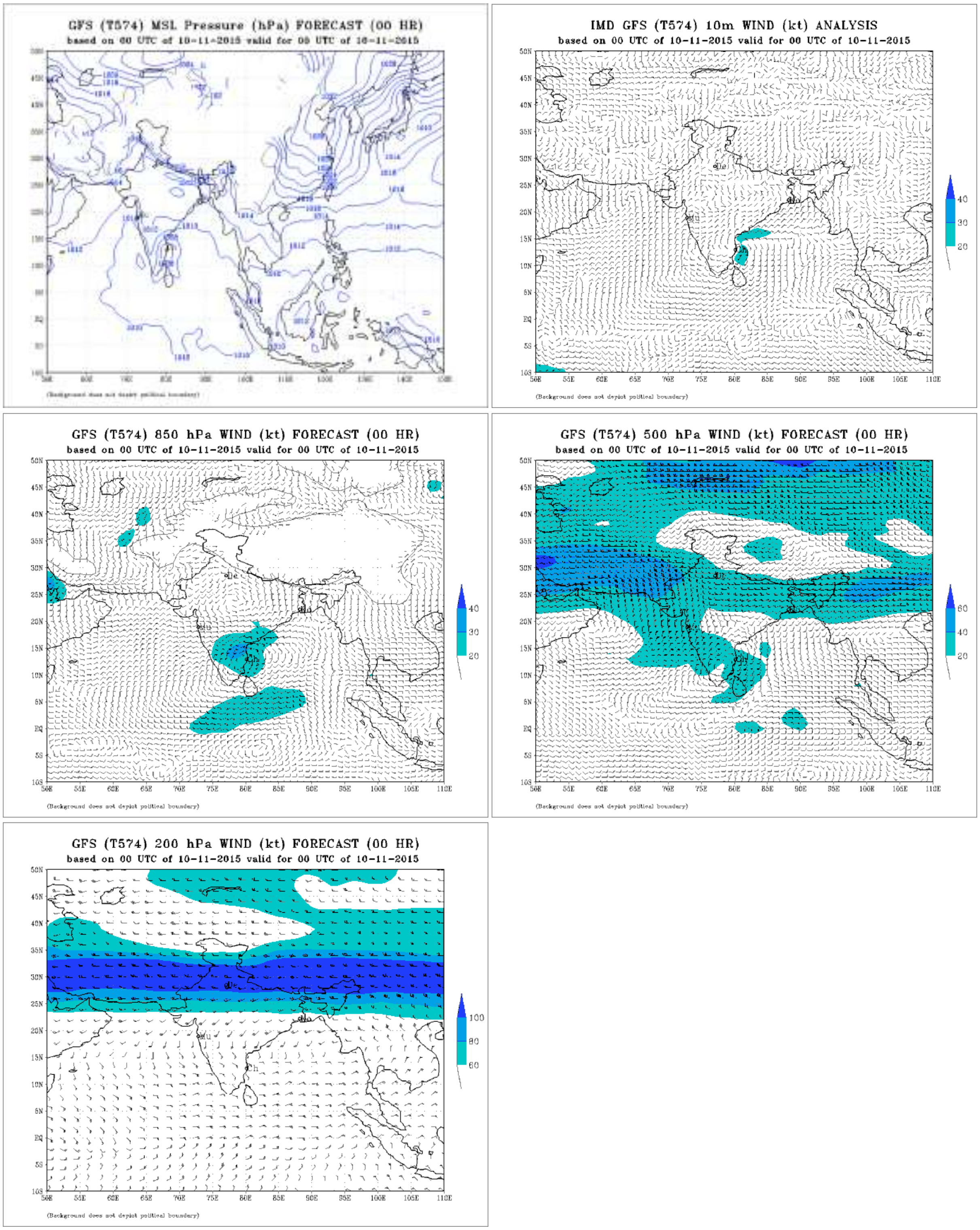


Fig.2.12.12 (c) IMD-GFS Analyses based on 0000 UTC of 10th November 2015 (a) MSLP (b) 10 m winds, (c) 850 hPa winds, (d) 500 hPa winds, (e) 200 hPa winds

It is observed that genesis of the system took place over the east-west shear zone of the inter-tropical convergence zone (ITCZ). Winds are stronger over the northeastern sector at the surface which extends to southeastern sector also at 850 hPa level on 08th and 09th. Wind speeds of the order of 40 knots are seen off the north Tamil Nadu coast on 09th. An upper air anti-cyclone at 200 hPa level is observed to the east of the system centre on 09th and the system being located close to the ridge, at the western periphery of the eastern anti-cyclone, was steered very slowly northwards prior to the landfall on 09th.

2.12.9. Realised Weather:

2.12.9.1 Heavy rainfall:

North Tamil Nadu and adjoining Rayalaseema received heavy to extremely heavy rainfall on 09th. (Description of rainfall terminologies: *Rainfall amount*: ***Heavy***: 64.5 to 124.4 mm, ***Very Heavy***: 124.5 to 244.4 mm and ***Extremely Heavy***: ≥244.5 mm; *Spatial distribution*: ***Isolated (ISOL)***: 1-25% of stations reporting rainfall, ***Scattered (SCT / A few places)*** : 26-50% of stations reporting rainfall, ***Fairly WideSpread (FWS/ Many places)***: 51-75% of stations reporting rainfall and ***Widespread (WS/ Most places)***: 76-100% of stations reporting rainfall during the last 24 hours ending at 0300 UTC of every day).

Neyveli of Cuddalore district in north coastal Tamil Nadu recorded highest 24 hr rainfall amount of 48 cm ending at 10th/0300 IST. Tirumala in Rayalaseema recorded extremely heavy rainfall of 30 cm during the same period. The chief amounts of rainfall ≥ 7 cm (associated with the system) realised in 24 hours ending 0300 UTC of 9-12 November 2015 are furnished below.

Rainfall ≥ 7 cm recorded at 0830 IST of 09-12th November 2015:

NORTH COASTAL TAMIL NADU:

District:Tiruvallur

09th: Red Hills, Chembarabakkam, Puzhal -19 each, Poonamallee - 17, Cholavaram - 16, Poonamalle ARG - 16, Ponneri - 15, Chembarambakkam ARG - 14, Madavaram - 14, Ennore - 12, Thamaraipakkam, Tiruvallur -11 each, Poondi – 7.

10th: Pallipattu - 13, Ponneri - 11, Red Hills, Chembarabakkam, Tiruvallur, R.K.pet, Tiruttani, Thiruvalangadu, Puzhal – 9 each, Cholavaram, Thamaraipakkam – 8 each, Madavaram, Poondi, Ennore, Poonamalle -7 each.

District:Chennai

09th: Anna University - 16, Anna Univ ARG -15, Chennai(NBK) - 14, DGP Office - 13,

10th: Chennai(NBK) – 7.

District: Kancheepuram

09th: Kattukuppam - 20, Chengalpattu, Tambaram - 18 each, Mahabalipuram, Chennai AP, Kelambakkam – 17 each, Taramani, Kancheepuram, Kolapakkam, Cheyyur – 15 each, Sriperumbudur -14, Maduranthagam, Uthiramerur – 10 each, Satyabama Univ – 8.

10th: Uthiramerur - 16, Kancheepuram - 13, Chengalpattu - 11, Sriperumbudur -8, Tambaram - 7.

District:Villupuram

09th: Mylam - 12, Marakkanam - 10, Vilupuram - 7, Gingee, Tindivanam – 7 each,

10th: Thirukoilur - 21, Vilupuram - 18, Sankarapuram - 15, Kallakurichi -15, Gingee - 12, Ulundurpet - 11, Tindivanam – 10.

District:Cuddalore

09th: Chidambaram AWS - 19, Chidambaram - 15, Neyveli, Cuddalore -14 each, Parangipettai - 11, Sethiathope -8, Panruti – 7.

10th: Neyveli - 48, Panruti - 35, Sethiathope , Chidambaram – 34 each, Parangipettai -33, Chidambaram AWS - 24, Virudachalam - 19, Cuddalore - 11, Tozhudur – 7.

Puducherry

09th: Karaikal -17, Puducherry – 13.

District:Nagapattinam

09th: Sirkali, Anaikaranchatram - 20, Nagapattinam -14, Mayiladuthurai -12, Vedaranyam - 10, Tarangambadi- 7.

10th: Anaikaranchatram- 15, Tarangambadi- 10, Sirkali – 7.

District:Tiruvarur

09th: Tiruvarur, Nannilam – 10 each, Thiruthuraipoondi - 9, Valangaiman – 7.

District:Thanjavur

09th: Thiruvidaimaruthur, Kumbakonam, Aduthurai – 7 each.

<u>NORTH INTERIOR TAMIL NADU:</u>

District:Tiruvannamalai: **09th:** Cheyyar – 13.

10th: Sathanur Dam – 19.

District:Vellore

09th: Arakonam -7.

10th: Ambur - 19, Vaniaymbadi, Alangayam - 18 each, Tirupattur - 17, Vellore - 11, Kaveripakkam, Melalathur, Gudiyatham – 10 each, Kalavai - 9, Arakonam – 7.

District:Dharmapuri

10th: Dharamapuri - 21, Pappireddipatti - 17, Pennagaram, Harur – 15 each, Palacode - 14, Hogenekal, Marandahalli – 11 each.

District:Krishnagiri

10th: Uthangarai - 19, Barur - 15, Shoolagiri, Penucondapuram – 14 each, Pochampalli, Krishnagiri – 13 each, Hosur - 11, Anjatti - 10, Thali, Rayakottah, Denkanikottai -9 each.

District:Salem

10th: Yercaud - 25, Omalur - 13, Salem - 12, Vazhapadi - 10, Attur, Mettur - 8 each, Thammampatty – 7.

District:Namakkal- **10th:** Rasipuram - 10, Mangalapuram – 8.

District:Perambalur: **10th:** Perambalur – 7.

COASTAL ANDHRA PRADESH:

Nellore district:

10th: Venkatagiri-24, Gudur-20, Rapur-19, Atmakur-17, Podalakur-13, Vinjamur, Nellore-10 each, Tada-8, Sullurpeta, Udayagiri, Shar, Kavali-7 each.

11th: Atmakur-23, Rapur-20, Gudur-14, Nellore-8.

12th: Atmakur-9.

RAYALASEEMA:

Chittoor district:

09th: Tirumalla- 12, Satyavedu - 8, Puttur -7.

10th: Tirumala-30, Kalakada-15, Chittoor-14, Mandapalle, Pakala, Palamaner-13 each, Tirupati, Arogyavaram -12 each, Palasamudram, Tirupati Aero, Santhipuram, Thottambedu, Gurramkonda -11 each, Venkatagiri Kota -9

11th: Kalakada-9.

12th: Chittoor-7.

Cuddapah district:

09th: Kodur, Srikalahasti – 7 each.

10th: Kodur-23, Ananthrajpeta-20, Pullampeta-15, Rajampet-12, Penagaluru -11, Nagari, Kuppam, Punganur, Satyavedu, Srikalahasti -10 each, Chinnamandem, Royachoti -9 each.

11th: Rajampet-18, Sambepalle-17, Pullampeta-16, Penagaluru-13, Royachoti-8, Chinnamandem, Kodur, Lakkireddipalle -7 each.

Anantapur district:

11th: Nambulipulikunta-7

SOUTH INTERIOR KARNATAKA:

10th: M M Hills-18, Anekal-9, Kolar, Kanakapura, Yelandur, Chamarajanagar -7 each.

IMD-NCMRWF GPM gauge merged rainfall during the life period of the system are depicted in Fig.2.12.13 (a&b). Fig.2.12.13 (a) depicts the spatial distribution of rainfall occurrence over the Indian region during the above period and Fig.2.12.13 (b) depicts the spatial distribution of heavy rainfall amounts (at 24-hr ending 0300 UTC of the date indicated in the plots) associated with the system.

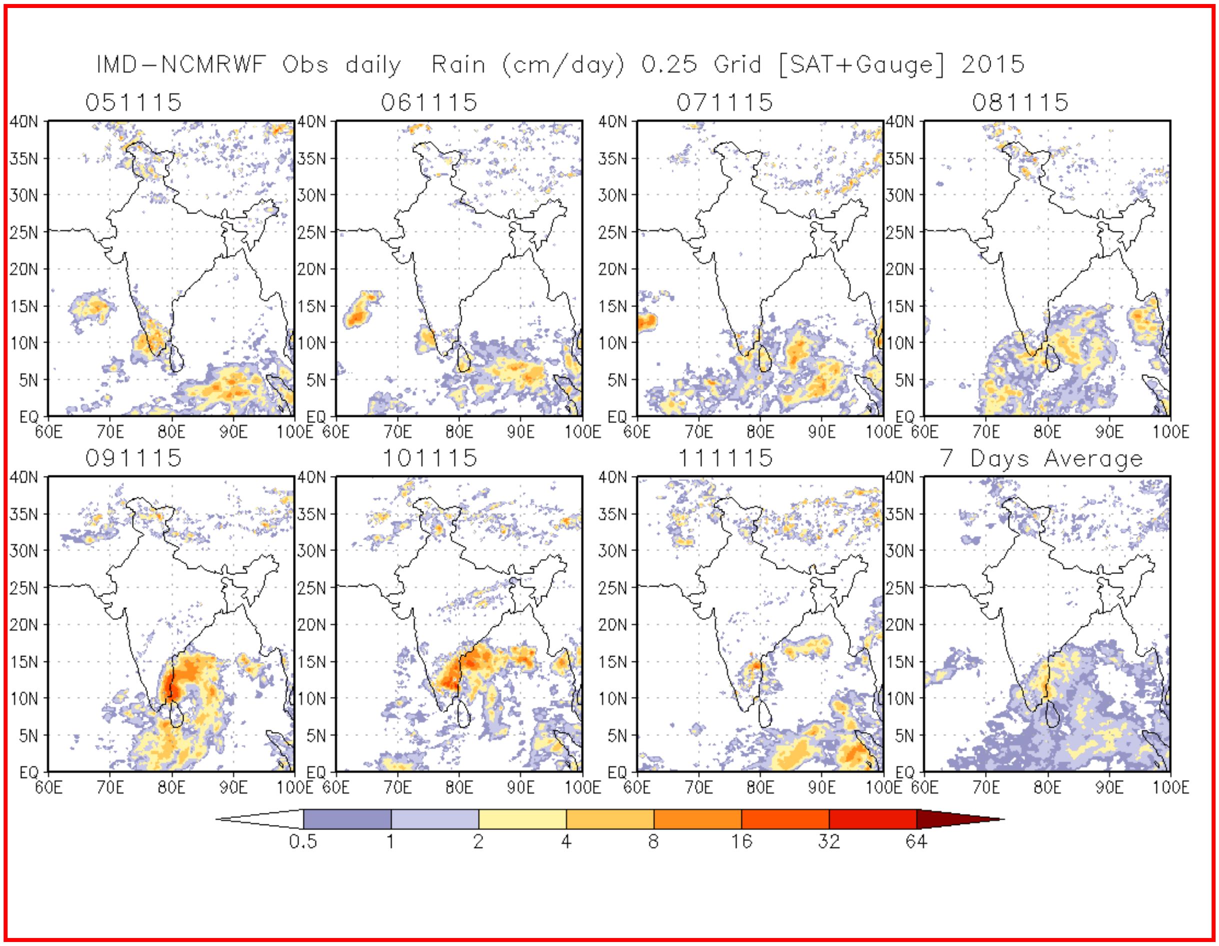


Fig.2.12.13 (a) IMD-NCMRWF GPM gauge merged rainfall during the life period of the Deep Depression (08-10 November 2015)

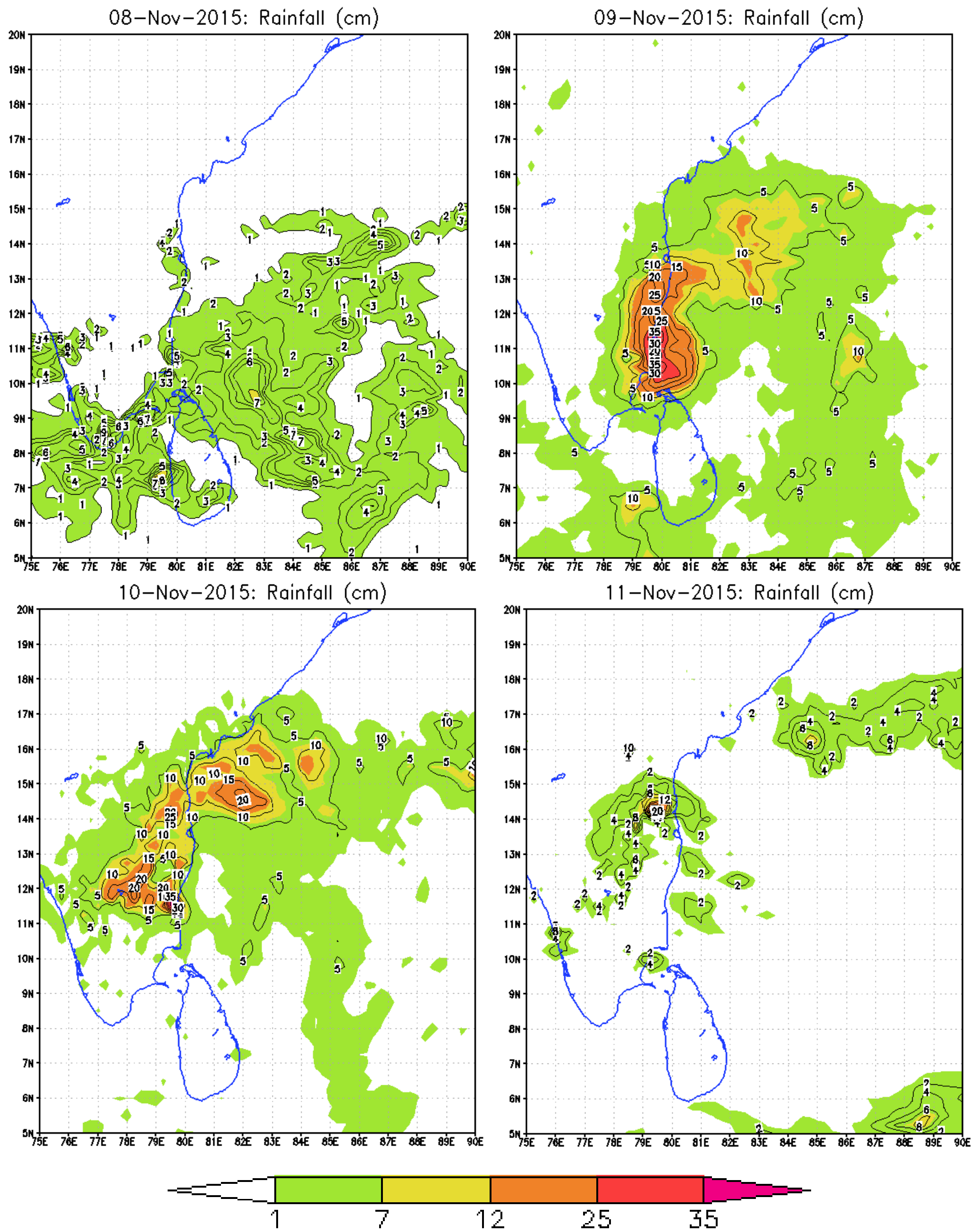


Fig.2.12.13 (b) IMD-NCMRWF GPM gauge merged rainfall depicting heavy rainfall occurences in association with the Deep Depression (08-10 November 2015) (24-hr ending 0300 UTC as on the date indicated in each plot).

The above rainfall figures indicate that extremely heavy rainfall (≥ 25 cm) is observed along coastal districts of north Tamil Nadu between 10°N to 11.5°N as on 09^{th}/0300 UTC. Rainfall > 35 cm is observed near 10.4°N and 79.7°E. Rainfall amount decreases sharply over the interior parts thus suggesting role of frictional convergence along the coast in enhancing the rainfall along the coastal districts.

2.12.9.2 Strong Wind

Strong winds of the order of 25-30 knots prevailed along and off north Tamil Nadu coast on 08th and 09th November 2015. Winds were stronger over the northeastern sector due to the northeast monsoon seasonal flow. NOAA-NESDIS- CIRA, Multi-platform satellite wind analysis based on 0000 UTC of 08th and 09th depicting prevalence of strong winds of the order of 30 knots (55-60 kmph) along and off the north Tamil Nadu coast on 09th are presented in Fig.2.12.14.

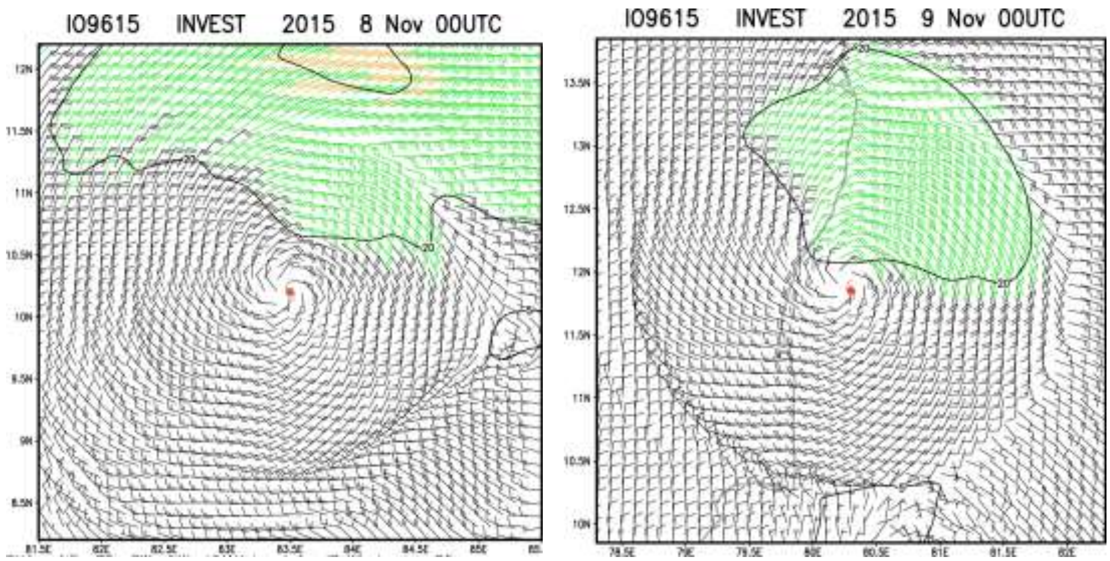


Fig.2.12.14 Multi-platform satellite wind analysis based on 0000 UTC of 08th and 09th November.

(Source: NOAA-NESDIS-Coperative Institute for Research in Atmosphere (CIRA))

2.12.9.3 Storm Surge

No storm surge has been reported in association with the system as it was a deep depression.

2.12.10 Damages due to Deep Depression (08-10 November 2015)

As the system caused extremely heavy rainfall, it caused extensive inland flooding over coastal districts of north coastal Tamil Nadu. IMD's issued warnings on 09th morning (based on 09/0830 IST) regarding expected damages - Minor damage to banana trees and near coastal agriculture due to salt spray. Damage to ripe paddy crops. Some breaches in Kutcha road due to flooding. Minor damage to Kutcha embankments. Minor damage to loose / unsecured structures.

About 31 deaths were reported in Tamil Nadu and Puducherry in association with the damages caused by the system (flood related casualities and due to wall collapses in kutcha houses). A few photographs depicting the flood situation in north Tamil Nadu are shown in Fig **.**2.12.15.

Fig.2.12.15 A few damage photographs due to the Deep Depression (08-10 November 2015)

Performance of operational NWP models for forecasting tropical cyclones over the North Indian Ocean during the year 2015

3.1 Introduction:

India Meteorological Department (IMD) operationally runs two regional models, WRF and HWRF for short-range prediction and one Global model T574L64 for medium range prediction (7 days). The WRF-Var model is run at the horizontal resolution of 9 km and 3 km with 45 Eta levels in the vertical and the integration is carried up to 72 hours over three domains covering the area between lat. 23^o S to 46^o N long 40^o E to 120^o E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 23 km. The boundary conditions are updated at every six hours interval. The HWRF model (resolution 27 km, 9 km and 3 km) is used for cyclone track & intensity prediction over the north Indian Ocean. 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), UKMO (UKMet), JMA (Japan Meteorological Agency) & MetoeFrance. The single model Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

In addition to the above NWP models, IMD also runs operationally “Dynamical Statistical Models” namely (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction by statistical cyclone intensity predication (SCIP)model, (d) Rapid intensification technique and (e) model for prediction of decay in 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, GFS (NCEP), ECMWF, UKMO and JMA. The SCIP model is used for 12 hourly intensity predictions up to 120-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 2015 are presented and discussed.

3.2. Cyclonic storm ‘ASHOBAA’ over the Arabian Sea during (07-12) June, 2015

3.2.1 **Grid point analysis and forecast of GPP**

Fig.3.1(a-f) below shows the predicted zone of formation of cyclogenesis.

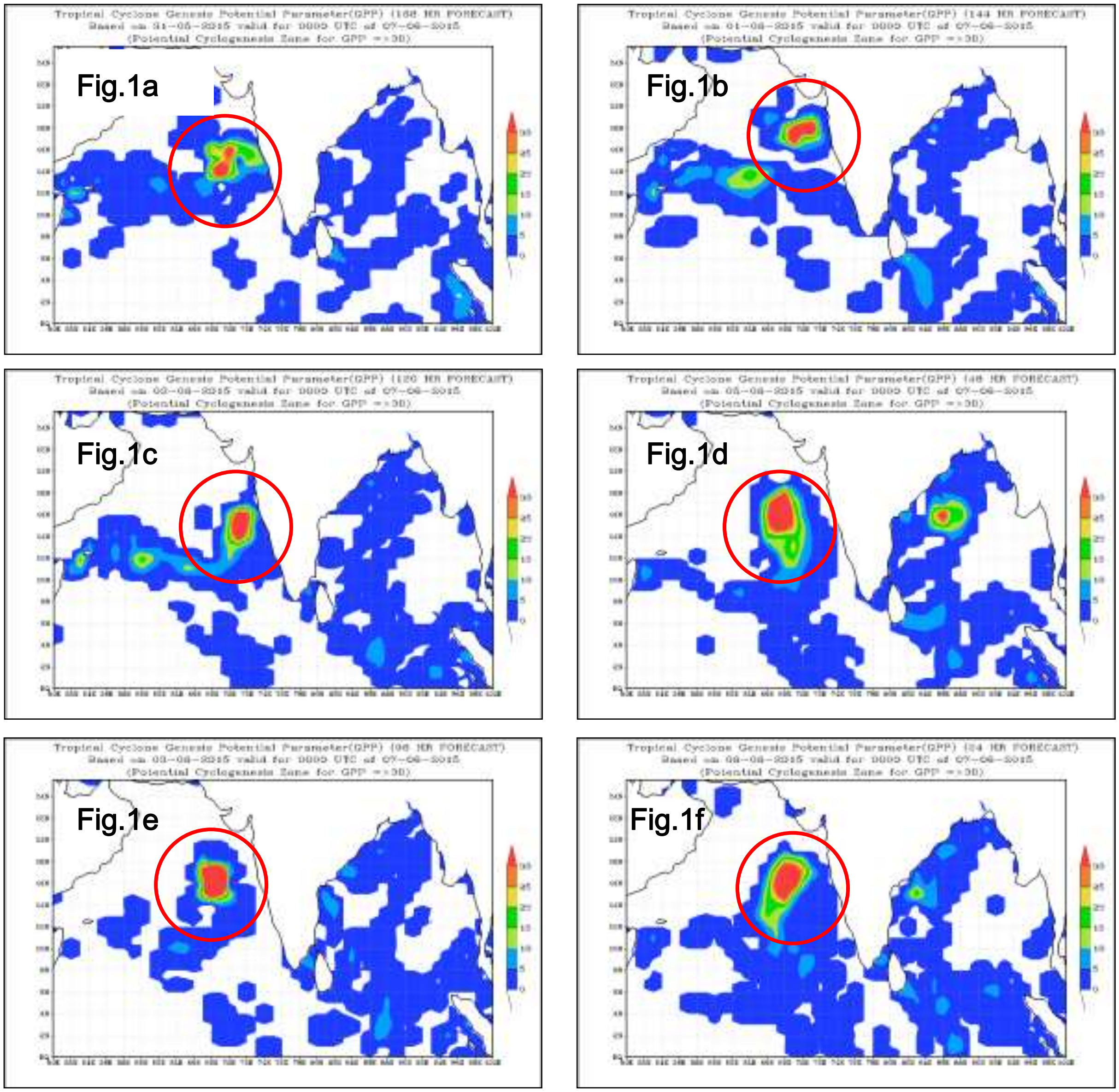


Fig. 3.1(a-f): Predicted zone of cyclogenesis based on 0000 UTC of 31.05.2015 to 06.06.2015 for genesis on 7th June, 2015.

Grid point analysis and forecasts of GPP (Fig.1(a-f)) shows that it could 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/Analysis1.htm)

3.2.2 Area average analysis of GPP

Conditions for genesis:
(i) Developed system (T3.0 or more): Threshold value of GPP ≥ 8.0

(ii) Non-developed system (T2.5 or less): Threshold value of GPP < 8.0

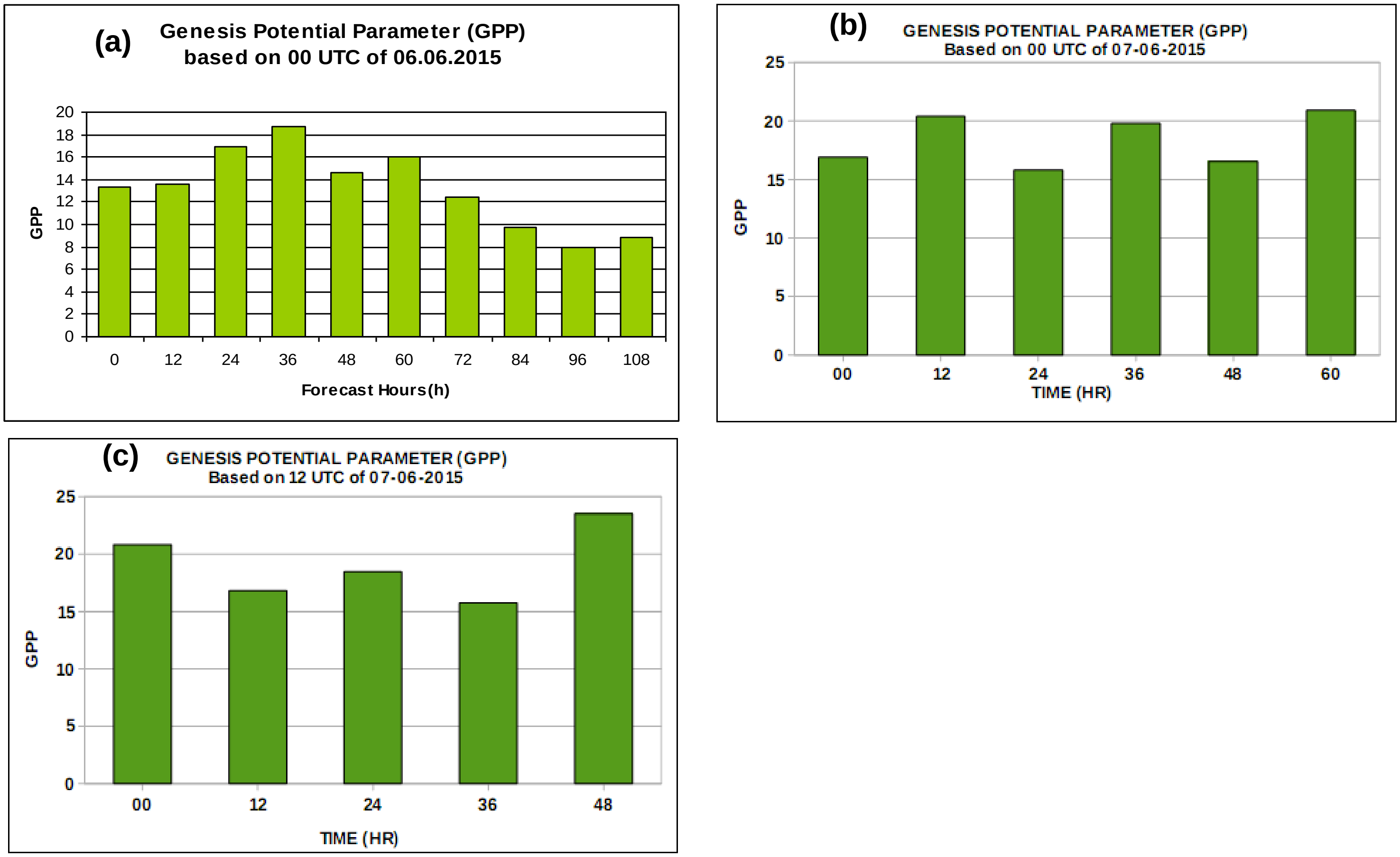


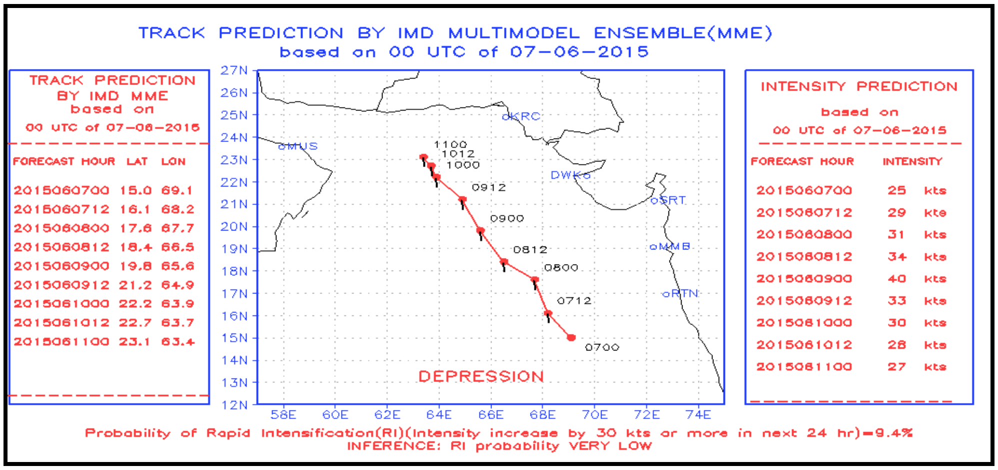
Fig. 3.2(a-c) Area average analysis of GPP based on 0000 UTC of 6th & 1200 UTC of 07.06.2015 with T1.0 & 1.5 respectively

Inference: Analysis and forecasts of GPP [Fig. 3.2(a-c)] shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated potential for intensification into a cyclone at early stages of development (T.No. 1.0 to 1.5).

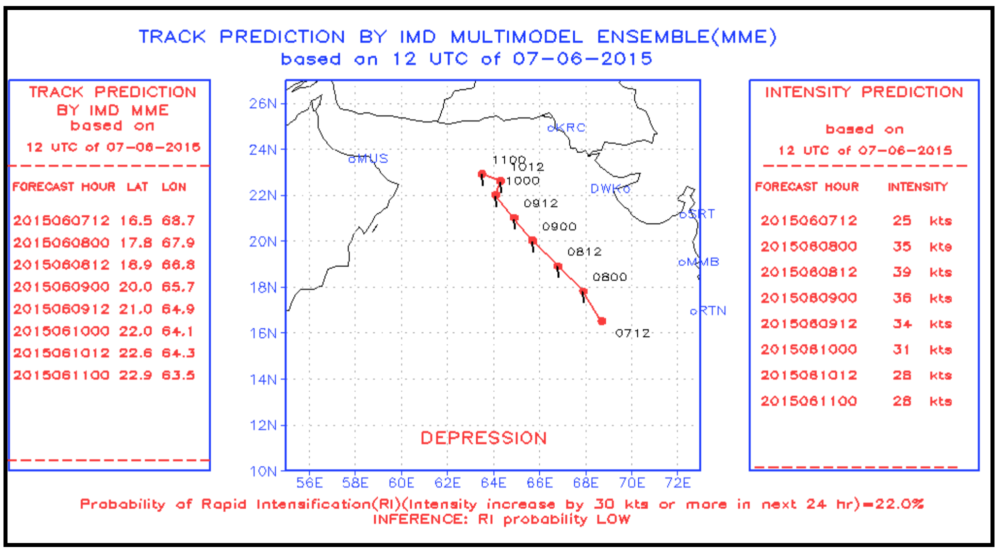
3.2.3 Track and intensity prediction

Consensus track prediction by MME and Intensity forecast by SCIP model

(1) MME TRACK: MME track forecast based on 0000 UTC of 07.06.2015



(2) MME TRACK: MME track forecast based on 1200 UTC of 07.06.2015.



(3) MME TRACK: MME track forecast based on 0000 UTC of 08.06.2015

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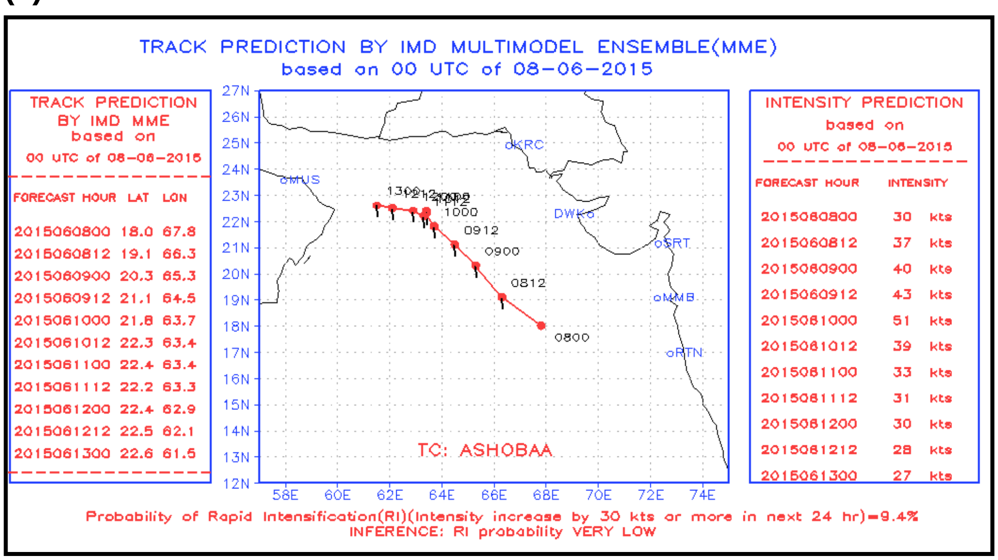
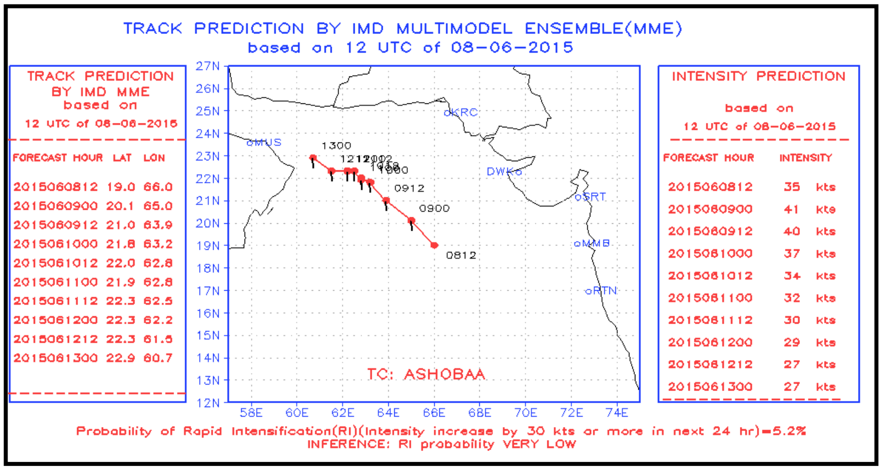
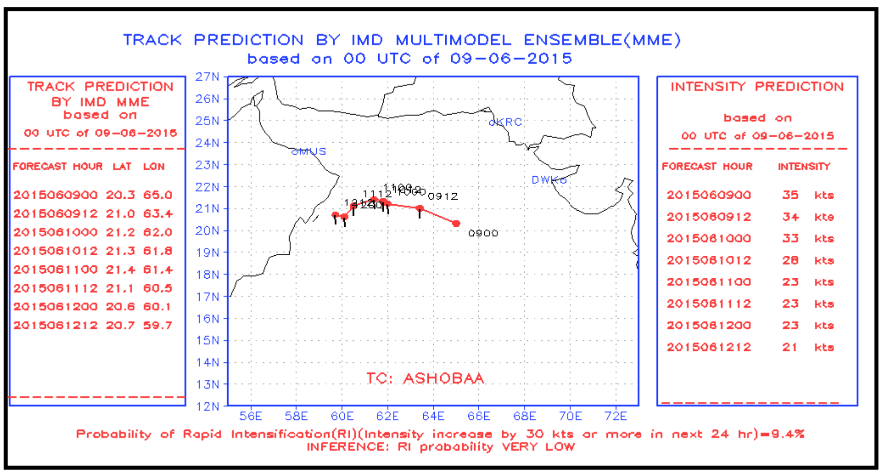


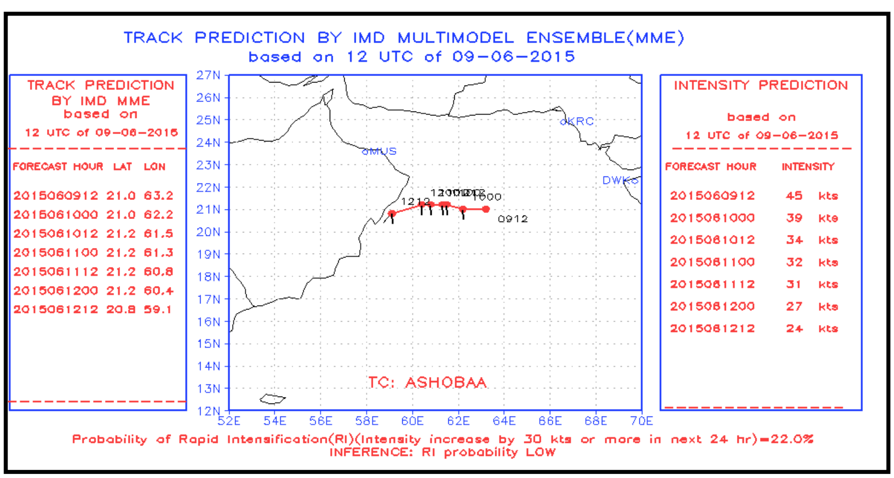
(4) MME TRACK: MME track forecast based on 1200 UTC of 08.06.2015.



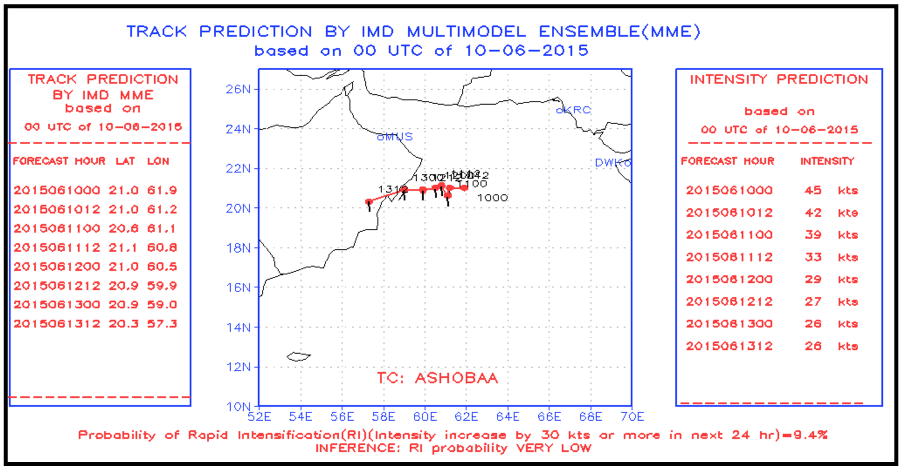
(5) MME TRACK: MME track forecast based on 0000 UTC of 09.06.2015.



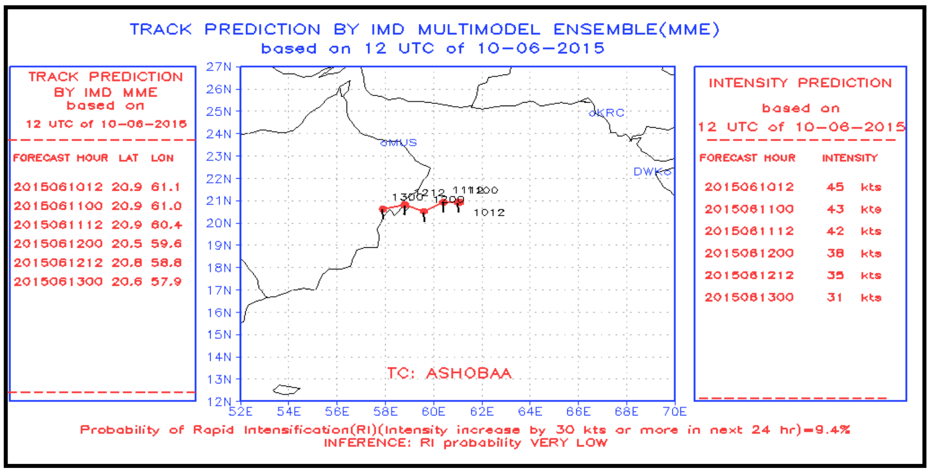
(6) MME TRACK: MME track forecast based on 1200 UTC of 09.06.2015.



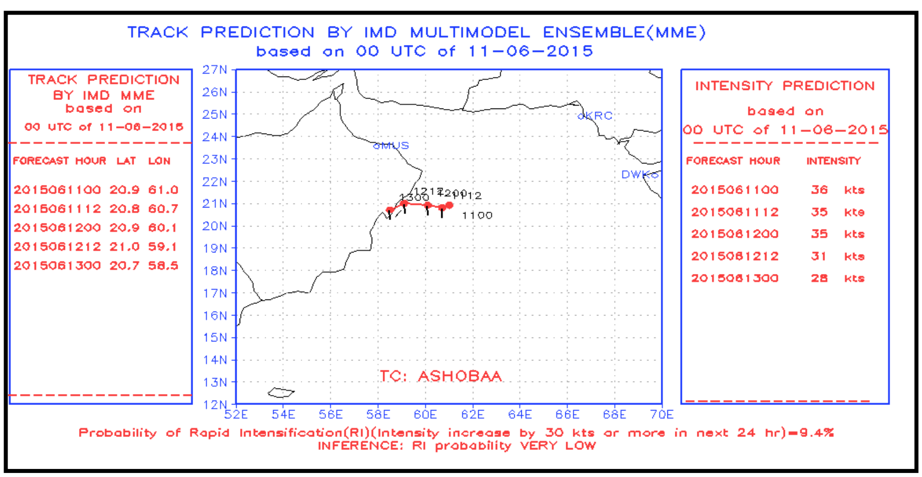
(7) MME TRACK: MME track forecast based on 0000 UTC of 10.06.2015.



(8) MME TRACK: MME track forecast based on 1200 UTC of 10.06.2015.



(9) MME TRACK: MME track forecast based on 0000 UTC of 11.06.2015.



(10) MME TRACK: MME track forecast based on 1200 UTC of 11.06.2015.

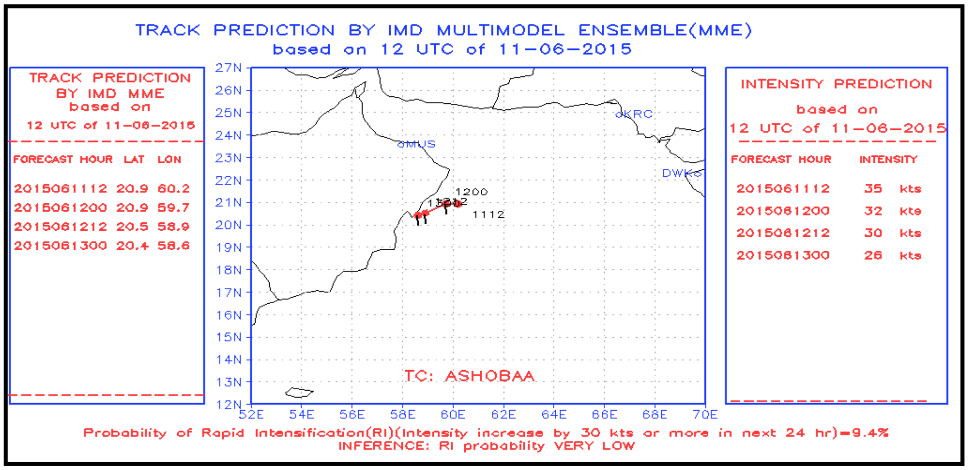
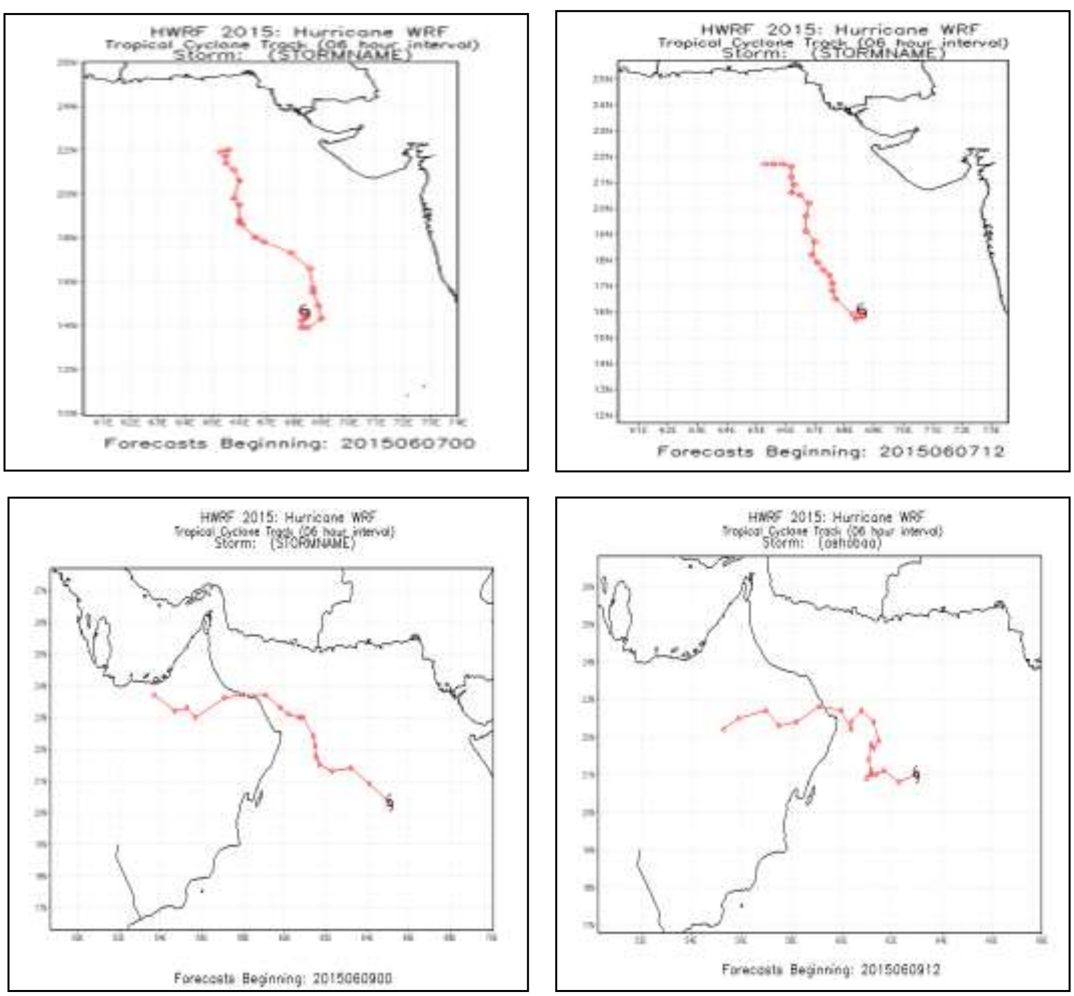


Fig. 3.3: Consensus track prediction by MME and Intensity forecast by SCIP model

Track prediction by HWRF model



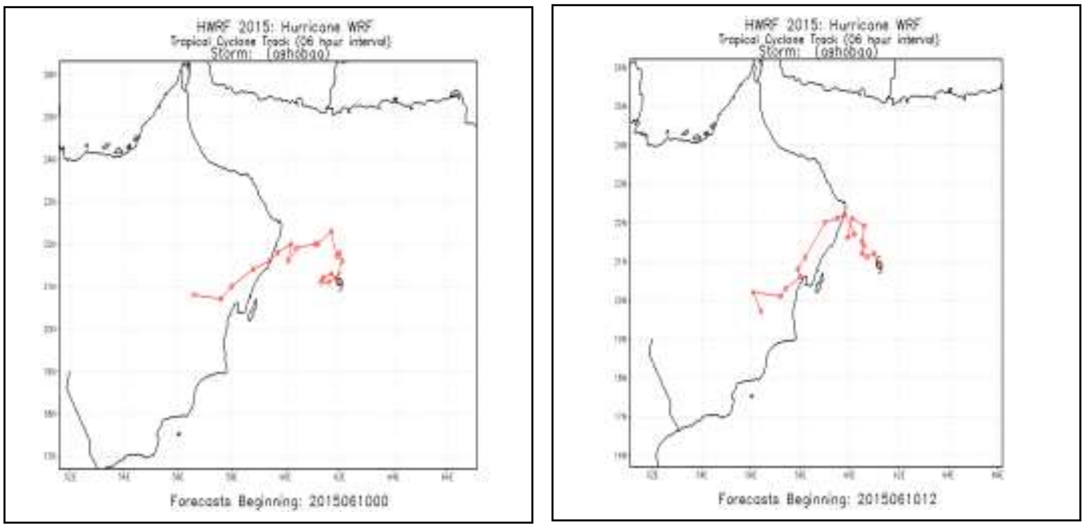


Fig. 3.4: Track prediction by HWRF model

The track prediction by HWRF model is presented in Fig. 3.4

The track forecast error by individual models & MME are presented in Table 3.1. The track error was minimum in case of MME than the individual models for 12 & 24 hrs forecasts. It was minimum in case NCEP(GFS) for 36 & 48 hrs forecasts. JMA followed by NCEP-GFS for 60-84 hrs forecasts.

Table-3.1 Average track forecast errors (Direct Position Error) in km (Number of forecasts verified is given in parentheses)

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr
D-WRF	25(10)	207(9)	268(8)	291(7)	290(6)	305(5)	-	-
IA	55(10)	67(9)	92(8)	116(7)	132(6)	155(5)	171(4)	-
CEP-GFS	40(10)	63(9)	72(8)	89(7)	150(6)	226(5)	231(4)	316(2)
KMO	45(10)	61(9)	76(8)	127(7)	208(6)	308(5)	412(4)	408(2)
CMWF	50(10)	80(9)	138(8)	215(7)	306(6)	393(5)	464(4)	530(2)
D-HWRF	100(7)	135(7)	217(6)	339(5)	408(4)	462(3)	569(2)	598(2)
D-MME	39(10)	52(9)	80(8)	132(7)	182(6)	254(5)	345(4)	382(2)

The intensity prediction by SCIP and HWRF Model are presented in Table 3.2 & 3.3 respectively. The error was higher in HWRF than SCIP model for all time scales upto 84 hrs.

Table-3.2 Average absolute errors (AAE) and RMSE (kt) of SCIP model (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
EE	.2(10)	6.6(9)	5.9(8)	7.6(7)	8.2(6)	8.2(6)	8.0(4)	6.5(2)
MSE	.0(10)	7.4(9)	8.2(8)	8.3(7)	9.4(6)	0.5(6)	9.6(4)	6.6(2)

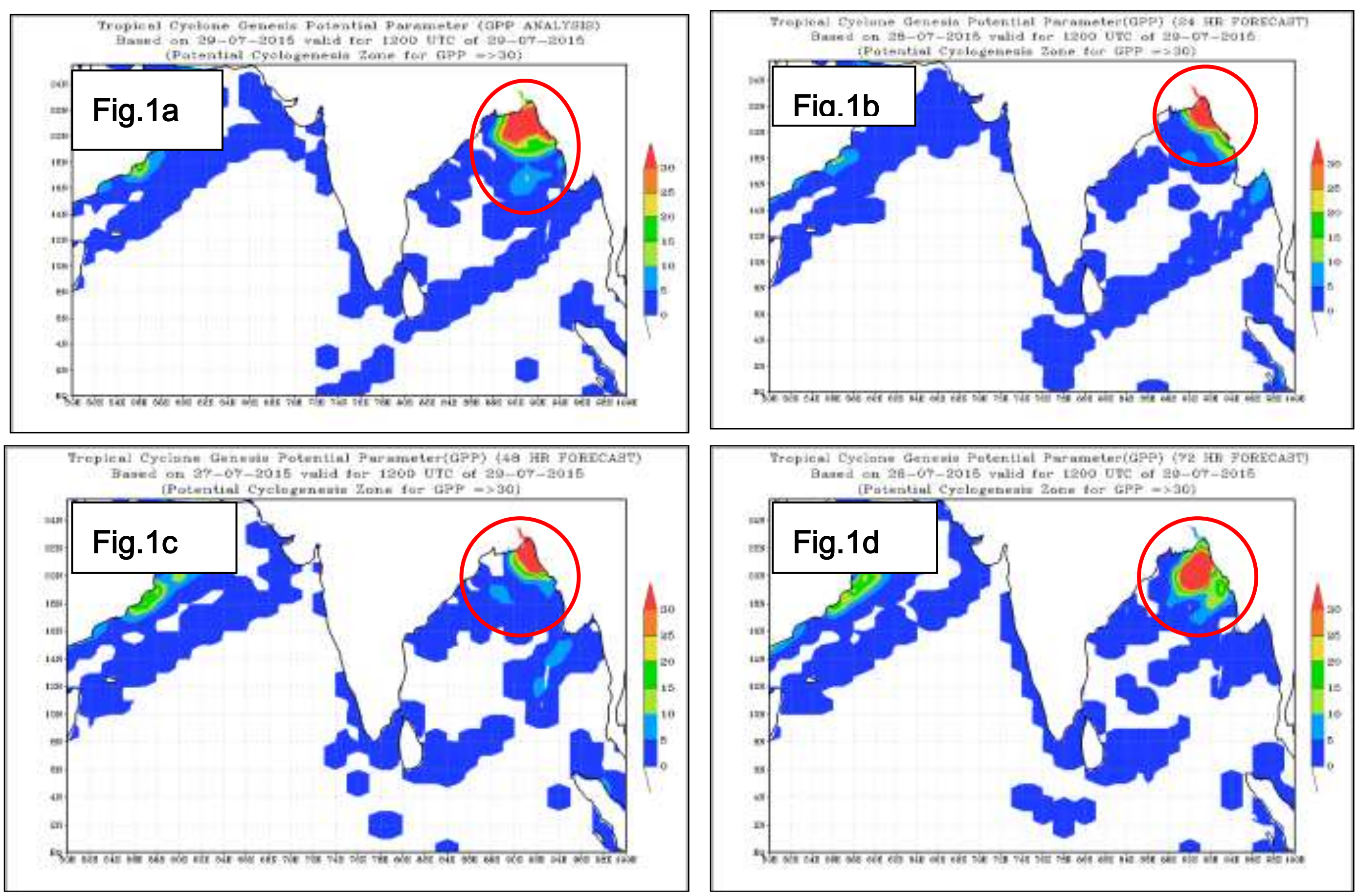
Table-3.3 Average absolute errors (AAE) and RMSE (kt) of HWRF model (Number of forecasts verified is given in the parentheses)

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr
AEE	14.0(7)	1.9(7)	2.7(6)	2.4(5)	5.3(4)	5.0(3)	1.0(2)	1.5(2)
RMSE	15.0(7)	3.1(7)	4.2(6)	4.4(5)	7.8(4)	3.2(3)	3.6(2)	1.6(2)

3.3 Cyclonic storm KOMEN over the Bay of Bengal (26th July-2nd August, 2015)

3.3.1 **Grid point analysis and forecast of GPP**

Fig. 3.5(a-f) shows the predicted zone of formation of cyclogenesis.



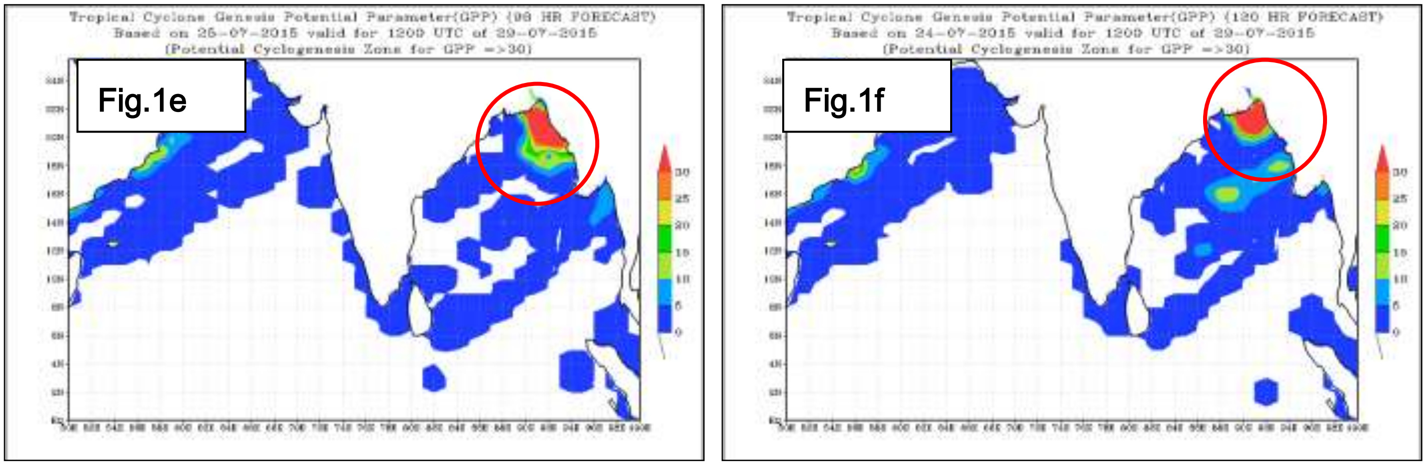


Fig. 3.5(a-f): Predicted zone of cyclogenesis based on 1200 UTC of 24-29 July 2015 valid for 1200 UTC of 29 July, 2015.

3.3.2 Track and intensity prediction

Consensus track prediction by MME and Intensity forecast by SCIP model are presented in Fig. 3.6

The track prediction by individual models are presented in Fig. 3.7

The track prediction by ensemble prediction system is presented in Fig. 3.8

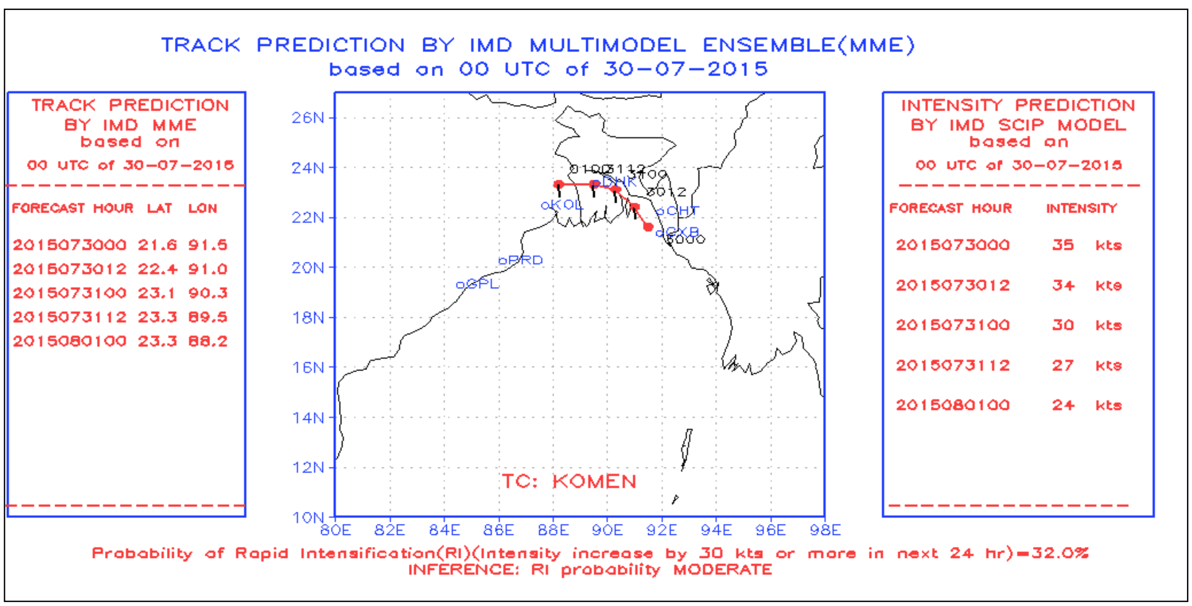


Fig. 3.6 Consensus track prediction by MME and Intensity forecast by SCIP model

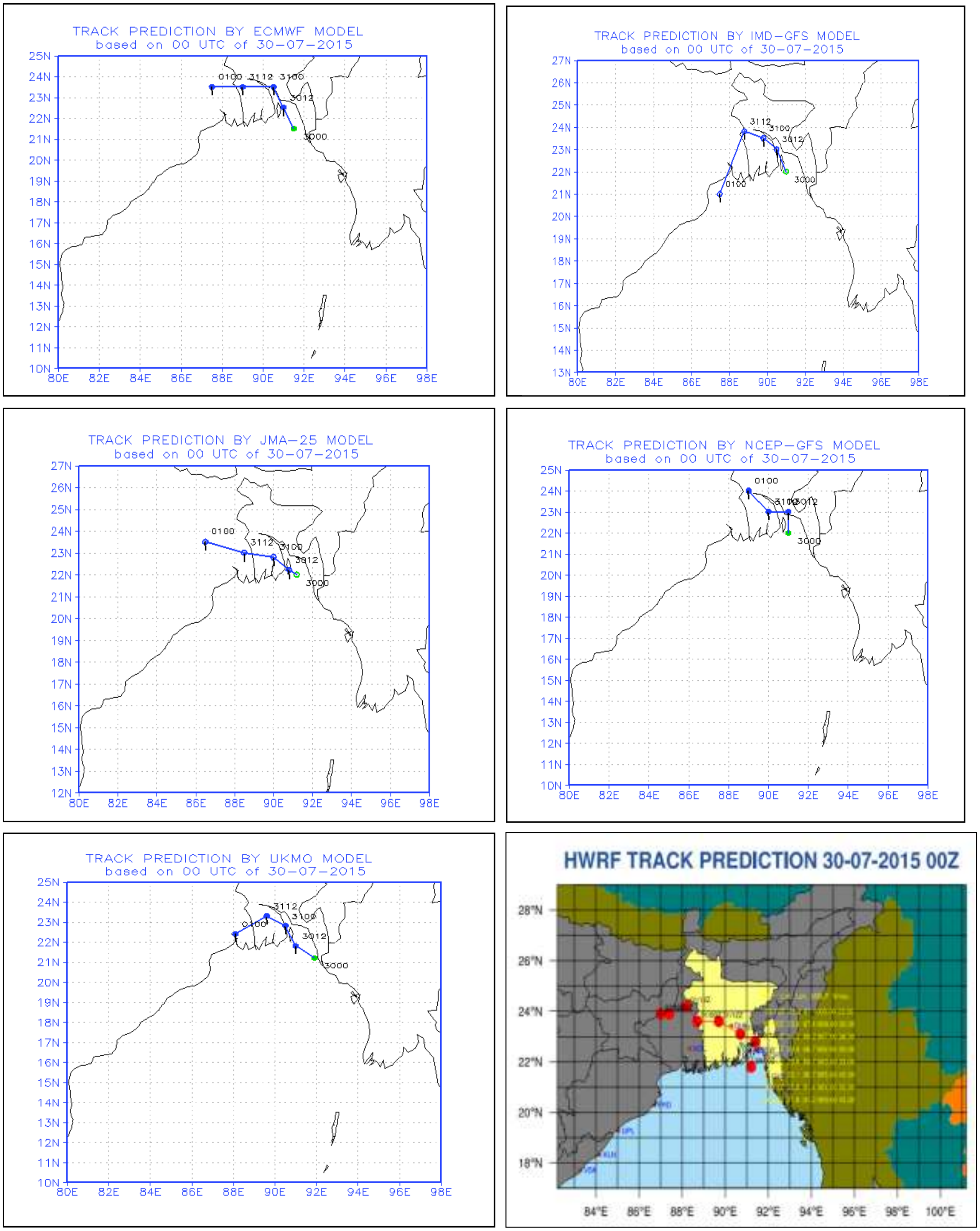
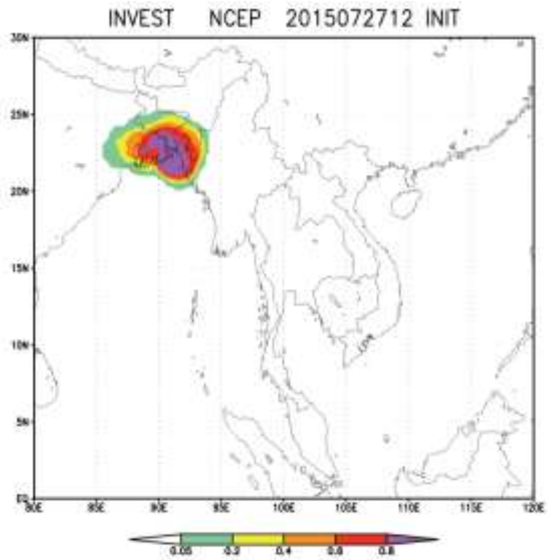
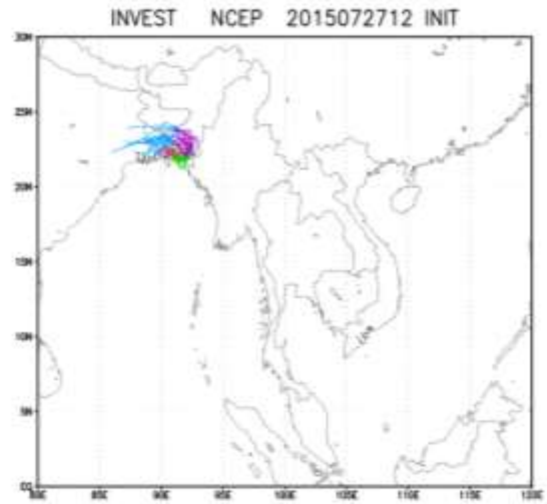


Fig. 3.7 Track prediction of cyclonic storm 'Komen' by individual models based on 0000 UTC of 30th July, 2015


INVEST NCEP 2015072712 INIT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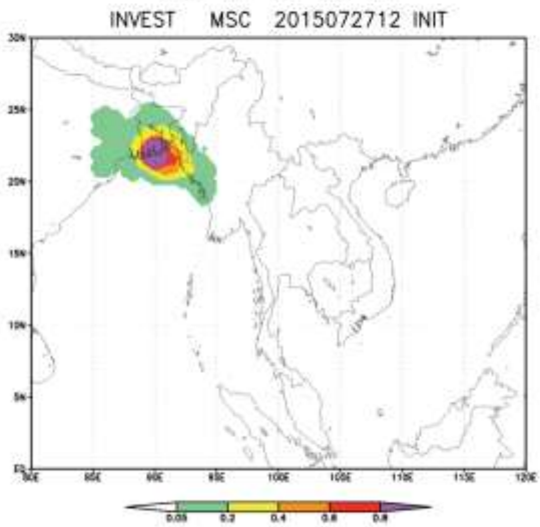
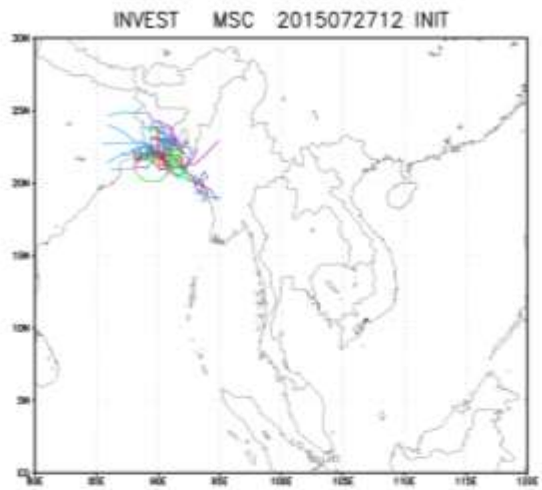

INVEST MSC 2015072712 INIT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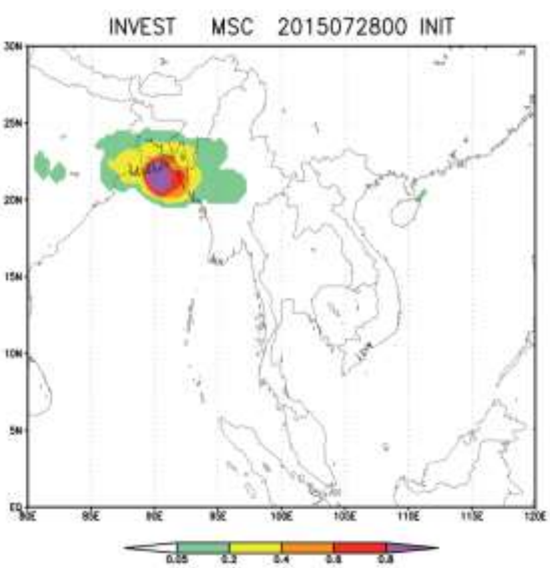
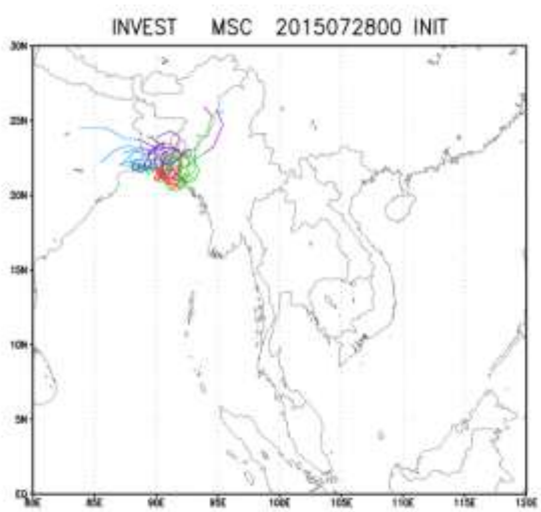
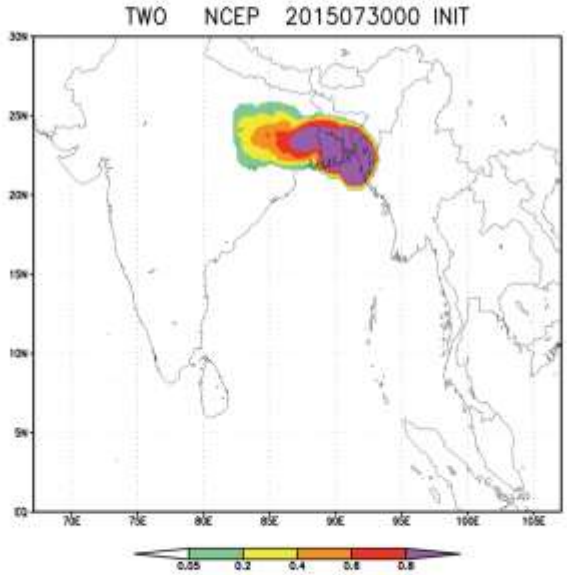
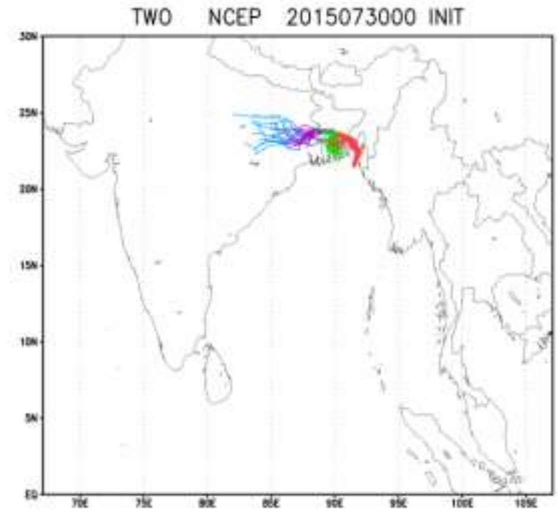
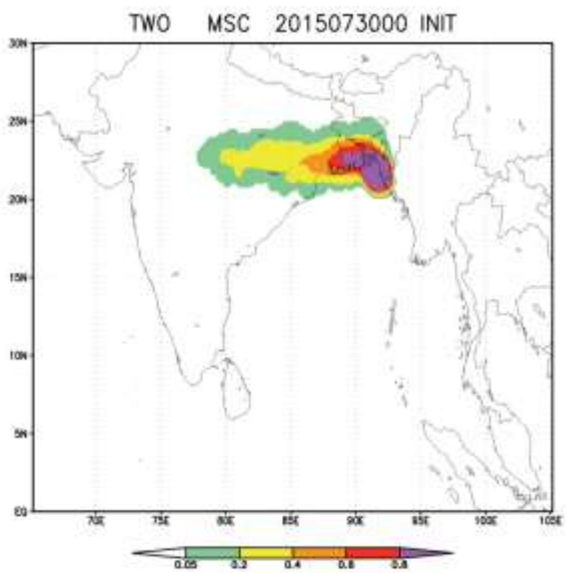
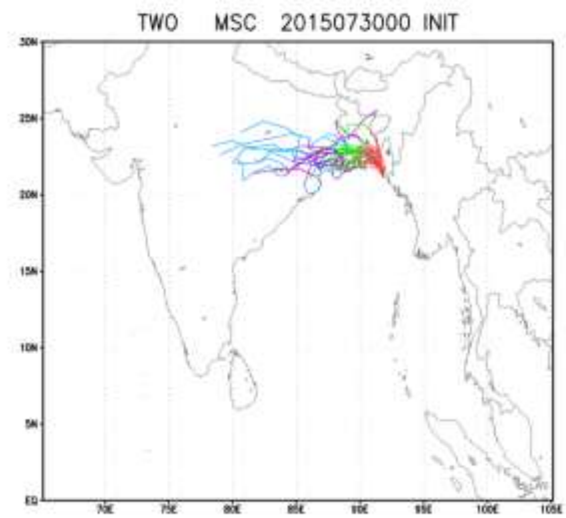

INVEST MSC 2015072800 INIT

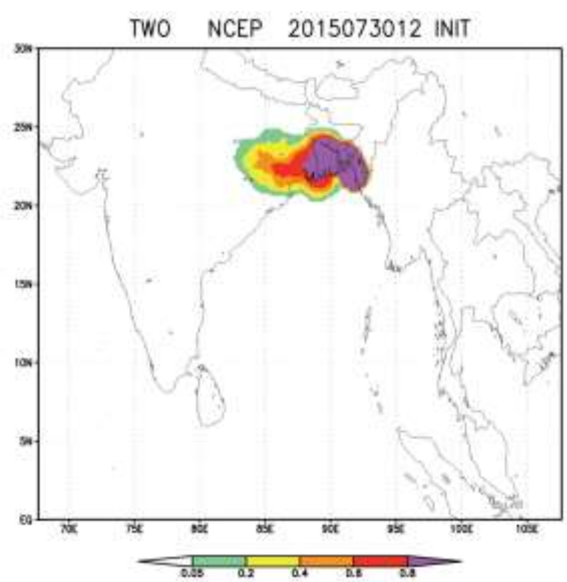

INVEST MSC 2015072800 INIT

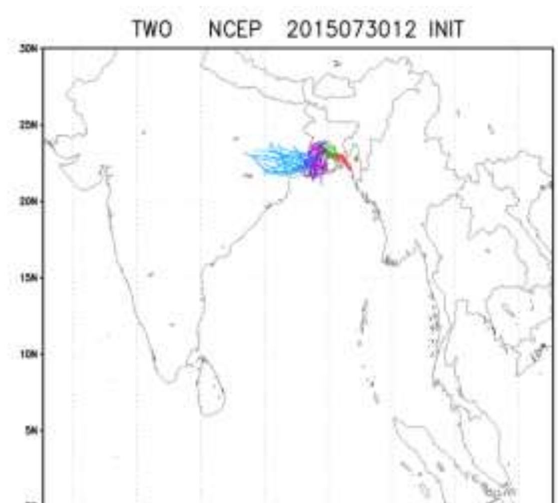

TWO NCEP 2015073000 INIT
0.05 0.2 0.4 0.6 0.8


TWO NCEP 2015073000 INIT


TWO MSC 2015073000 INIT
0.05 0.2 0.4 0.6 0.8


TWO MSC 2015073000 INIT


TWO NCEP 2015073012 INIT
0.05 0.2 0.4 0.6 0.8


TWO NCEP 2015073012 INIT

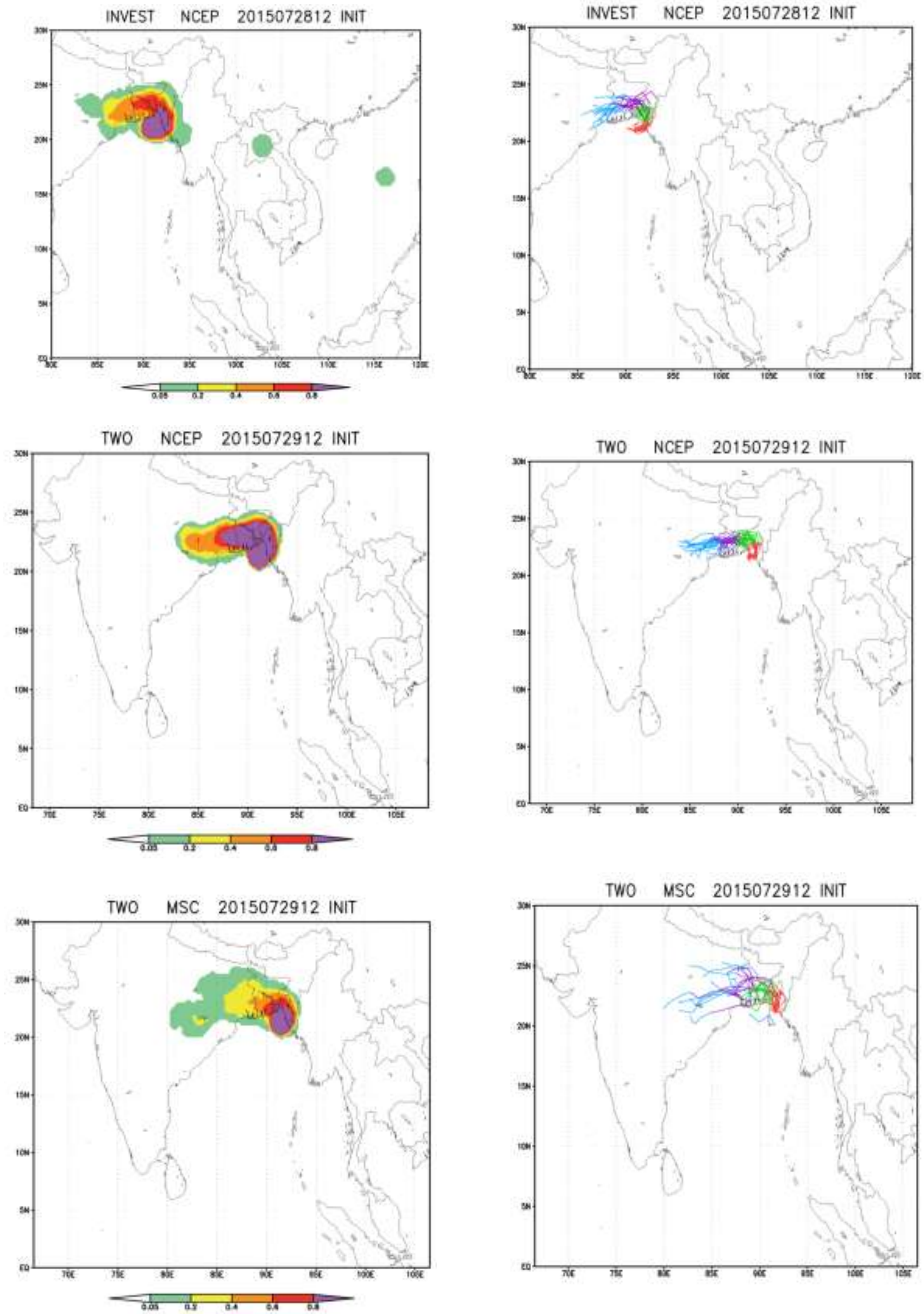


Fig. 3.8 Track prediction of cyclone 'Komen' by ensemble prediction system based on 1200 UTC of 27th July and 0000 & 1200 UTC of 28th , 1200 UTC of 29th and 0000 & 1200 UTC of 30th July, 2015

Table-3.4 Average track forecast errors (Direct Position Error) in km

Lead time	12 hr	24 hr	36 hr	48 hr
IA	66	33	103	277
CEP-GFS	78	11	52	91
KMO	78	61	24	144
CMWF	43	68	68	177
D-GFS	114	49	106	301
D-HWRF	92(4)	123(4)	84(4)	101(4)
D-MME	41	31	22	103

Table 3.5 Average absolute errors of SCIP model

Lead time	12 hr	24 hr	36 hr	48 hr
bserved (kt)	35	30	25	20
edicted (kt)	34	30	27	24
ror (kt)	-1	0	2	4

Table 3.6 Average absolute error(AAE) and RMSE (kt) of HWRF model

.ead time →	12 hr	24 hr	36 hr	48 hr
AAE	10.8(4)	7.7(4)	6.3(4)	7.8(4)
RMSE	12.0	8.8	7.2	8.1

The average track forecast error of individual models are presented in Table 3.4. The error is minimum in case of MME for 12 hrs forecast, NCEP-GFS for 24 and 48 hrs. forecast

The average intensity forecast error of SCIP and HWRF models are presented in Table 3.5 and 3.6 respectively. The performance of SCIP was better than HWRF for all forecasts times.

3.4 Deep Depression over the Arabian Sea during 09-12 October, 2015

3.4.1. Grid point analysis and forecast of GPP

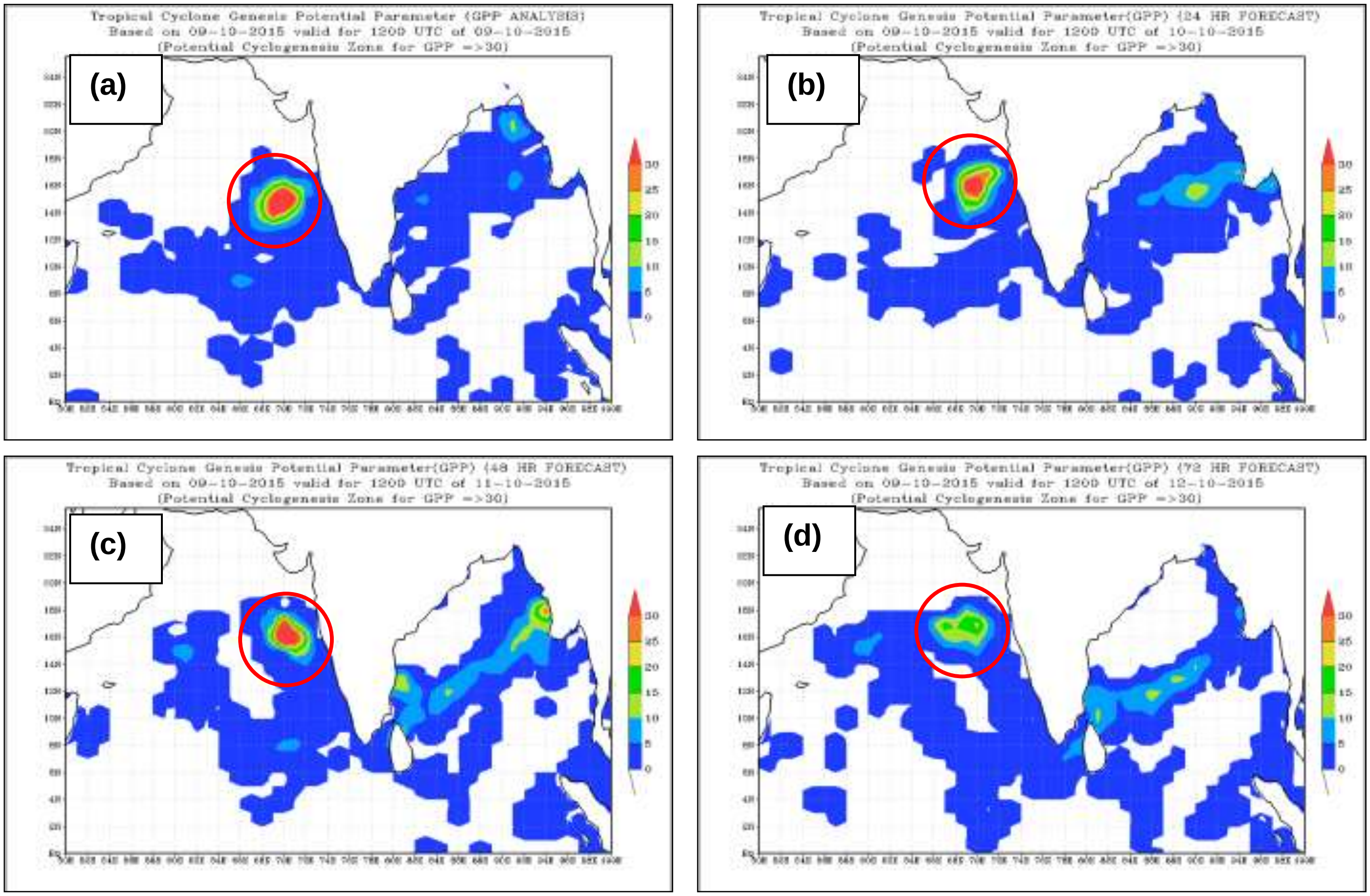


Fig. 3.9(a-d): Predicted zone of cyclogenesis

Inference: Grid point analysis and forecasts of GPP (Fig. 3.9(a-d)) shows that it was able to predict the formation and subsequently weakening of the system over the Sea.

3.4.2 Area average analysis of GPP

Conditions for genesis:

(i) Developed system (T3.0 or more): Threshold value of GPP ≥ 8.0 (ii) Non-developed system (T2.5 or less): Threshold value of GPP < 8.0

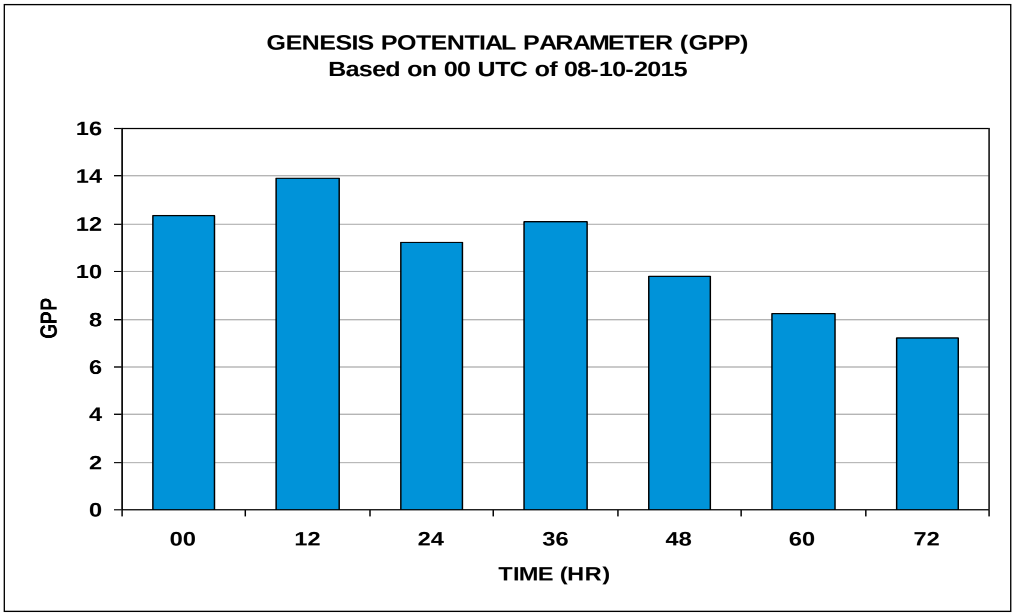


Fig. 3.10 Area average analysis and forecasts of GPP based on 0000 UTC of 8.10.2015 (T1.0)

Analysis and forecasts of GPP (Fig.3.10) indicated genesis of cyclone

3.4.2 Track and intensity prediction

Consensus track prediction by MME and Intensity forecast by SCIP model are presented in Fig. 3.11. The track prediction by individual models is presented in Fig. 3.12. The track forecast by HWRF model is presented in Fig. 3.12

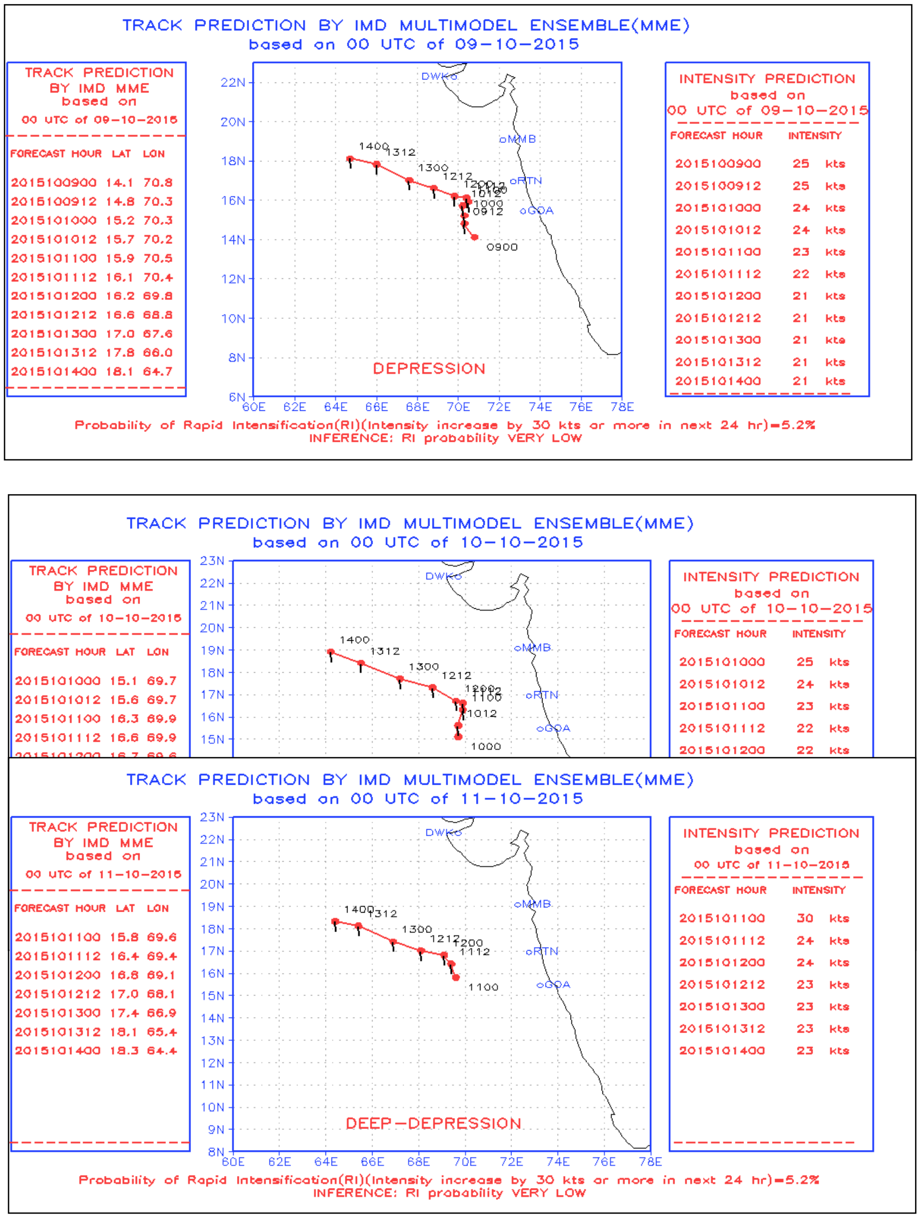
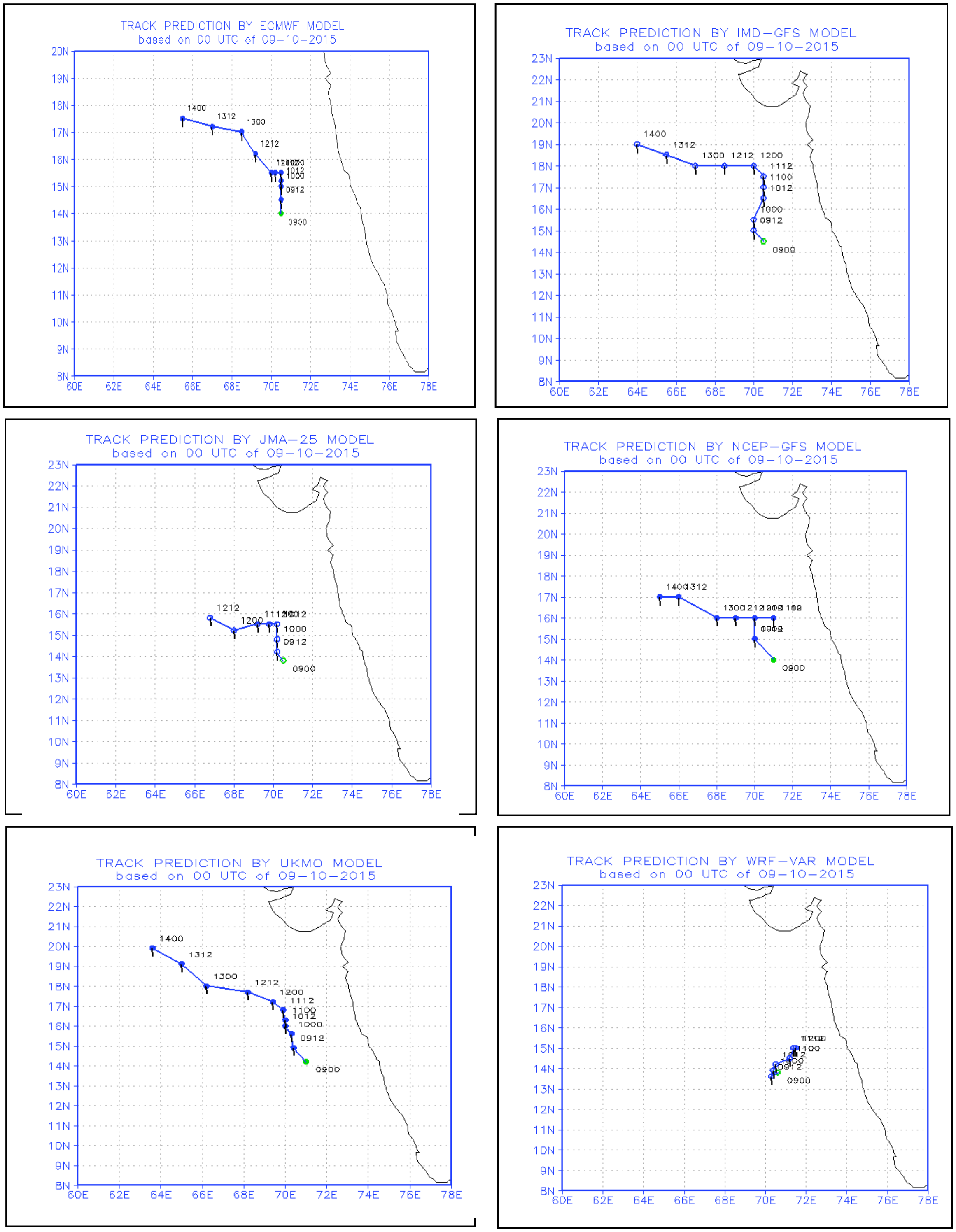
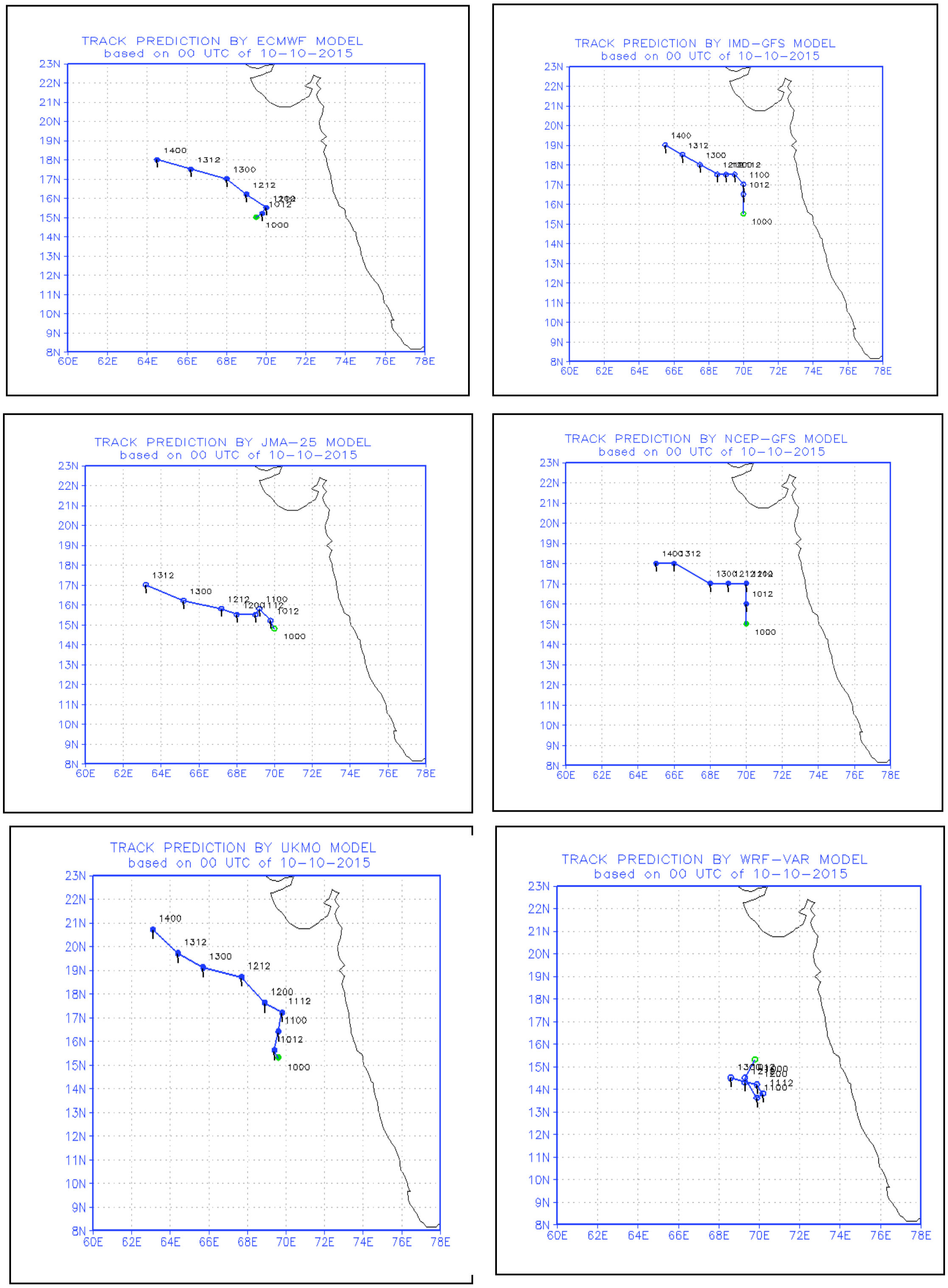


Fig. 3.11 Consensus track prediction by MME and Intensity forecast by SCIP model

***a.* Track prediction by NWP models based on 0000 UTC of 09.10.2015**



b. Track prediction by NWP models based on 0000 UTC of 10.10.2015



c. Track prediction by NWP models based on 0000 UTC of 11.10.2015

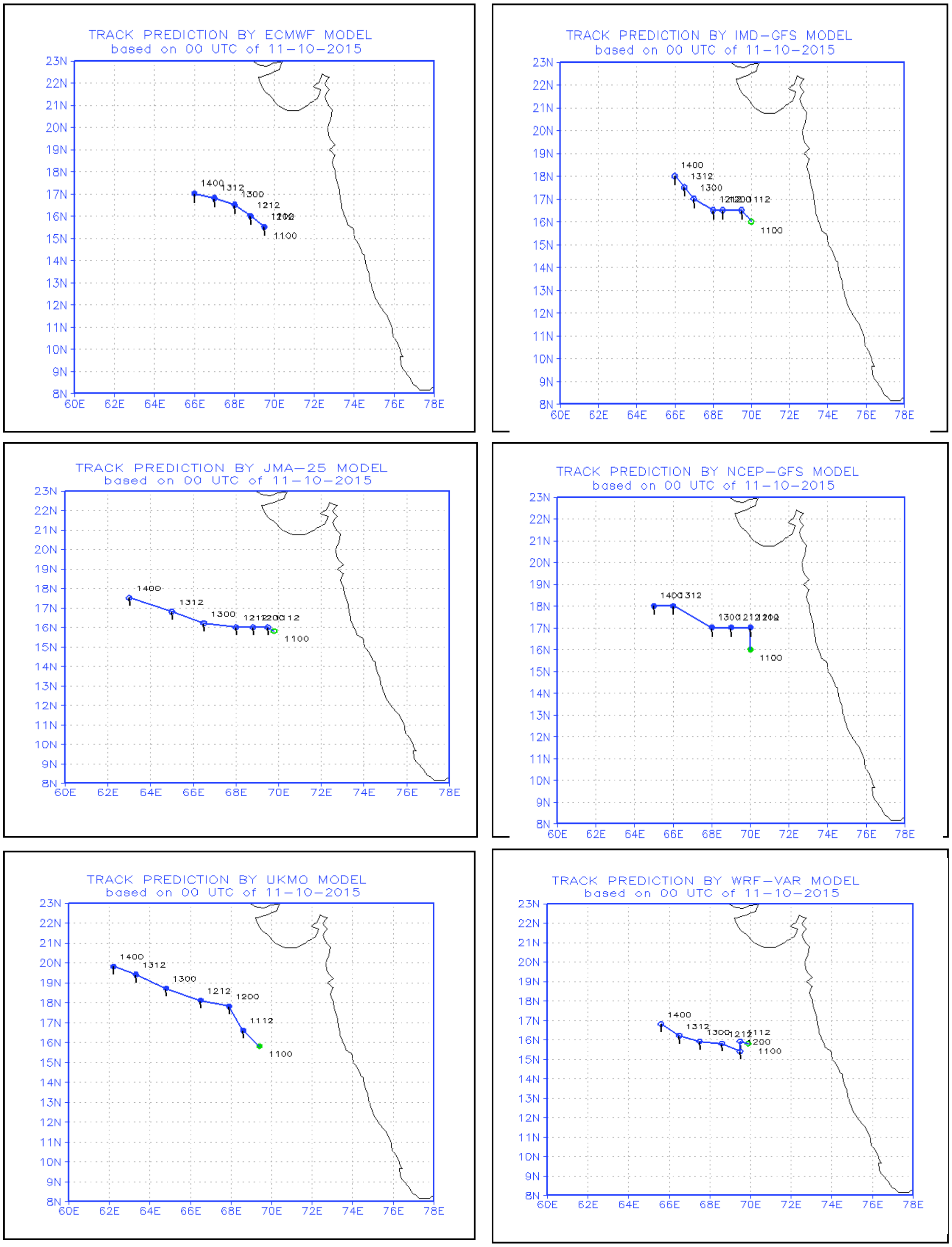


Fig. 3.11(a-c): Track prediction by NWP models

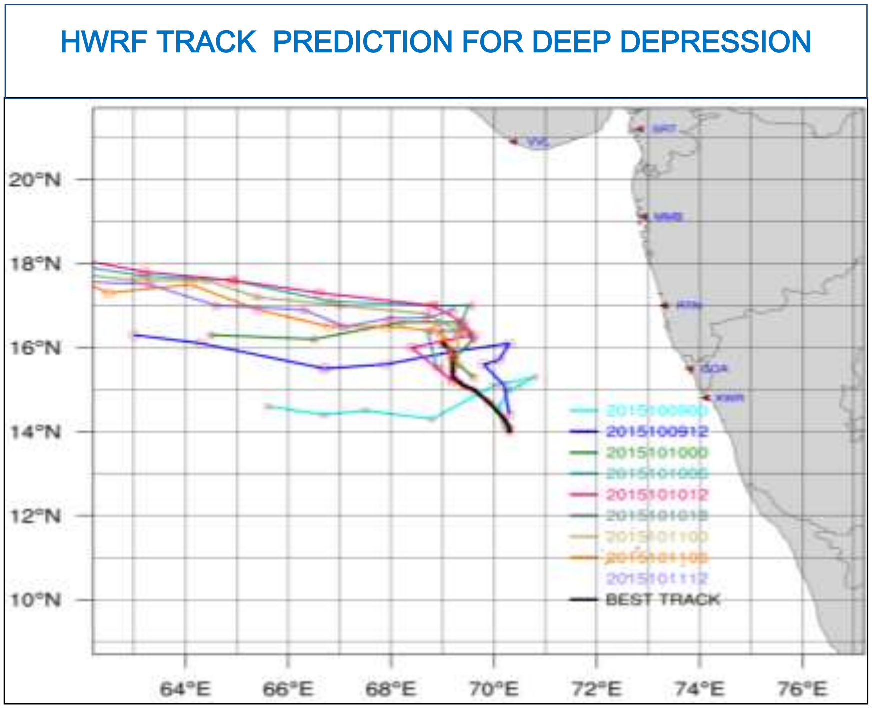


Fig 3.12 Cluster Composite of HWRF tracks along with Best Track

Table 3.7 Average track forecast errors (Direct Position Error) in km (Number of forecasts verified)

ead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
D-GFS	106(3)	109(3)	187(2)	186(2)	225(1)	236(1)
D-WRF	63(3)	156(3)	214(2)	237(2)	256(1)	294(1)
MA	33(3)	42(3)	76(2)	95(2)	44(1)	146(1)
CEP	115(3)	125(3)	133(2)	173(2)	193(1)	107(1)
KMO	72(3)	144(3)	137(2)	145(2)	125(1)	129(1)
CMWF	49(3)	89(3)	113(2)	133(2)	116(1)	126(1)
D-HWRF	73(8)	77(6)	99(5)	123(2)	124(1)	-
D-MME	59(3)	91(3)	110(2)	119(2)	130(1)	86(1)

The track forecast error of individual model and MME are presented in Table 3.7. The error was minimum in case of JMA for all forecast times upto 60 hrs and MME for 72 hrs forecast.

The intensity prediction error of SCIP and HWRF models are presented in Table 3.8 and 3.9 respectively. The errors were similar in both the models and less than 10 knots.

Table 3.8 Average absolute errors (AAE) and Root Mean Square (RMSE) errors of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
D-SCIP (AAE)	2.3(3)	5.1(3)	4.5(2)	4.5(2)	3.0(1)	1.0(1)
IMD-SCIP (RMSE)	3.5(3)	5.6(3)	4.7(2)	5.1(2)	3.0(1)	1.0(1)

Table 3.9 Average Absolute Error (INTENSITY) of IMD-HWRF Model

(Number of forecasts verified is given in the parentheses)

Lead time →	00 hr	06 hr	12 hr	18 hr	24 hr	36 hr	48 hr	60 hr
AAE	2(9)	9(9)	5(8)	2(7)	2(6)	2(5)	8(2)	9(1)
RMSE	2	10	5	3	5	3	9	9

3.5 Extremely severe cyclonic storm CHAPALA over the Arabian Sea during 28 October-04 November, 2015

3.5.1. Grid point analysis and forecast of GPP

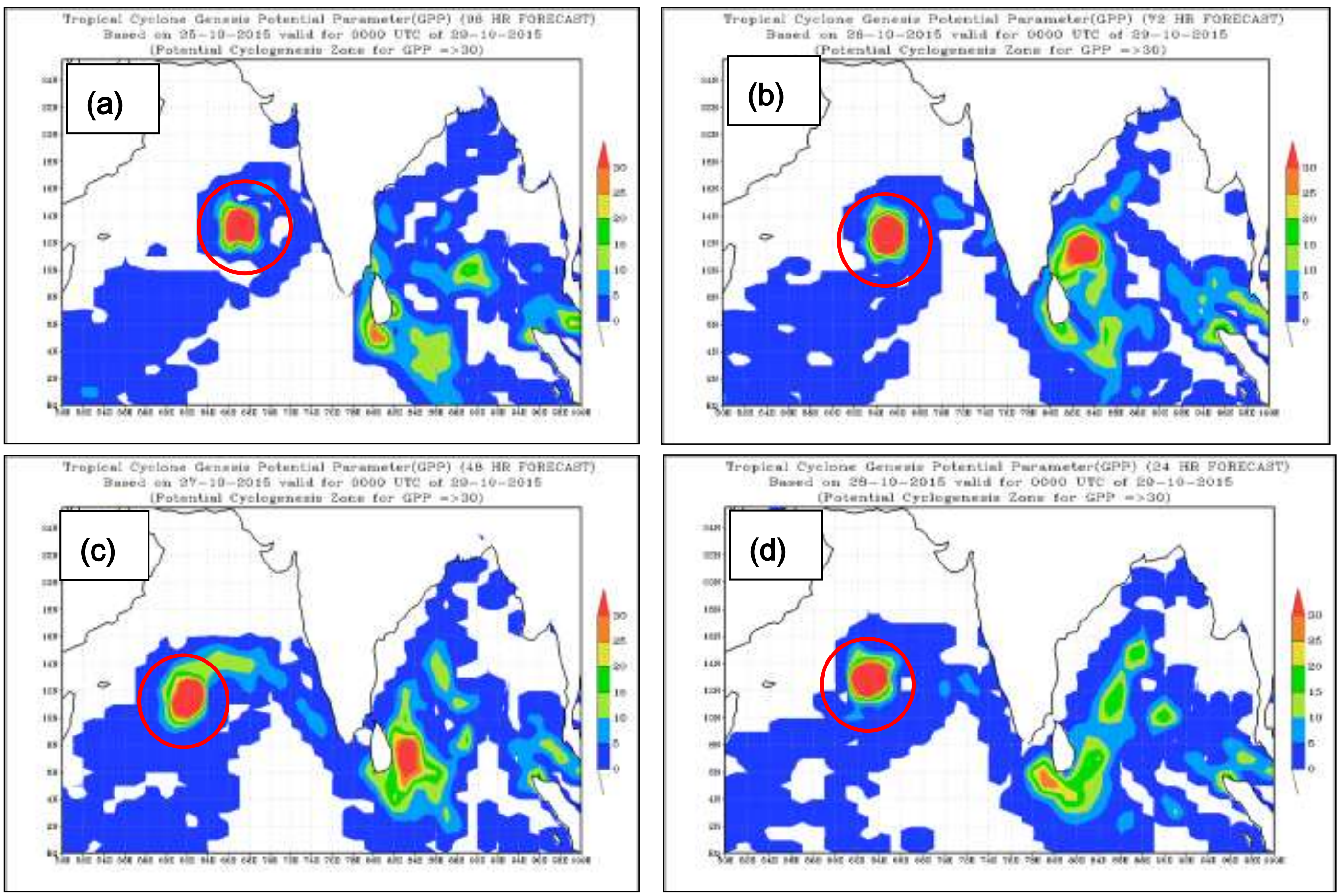


Fig. 3.13(a-d) Predicted zone of cyclogenesis

Grid point analysis and forecasts of GPP (Fig. 3.13(a-d)) shows that it was able to predict the formation and location of the system 96 hrs before its formation.

Fig. 3.14(a-f) below shows the course of movement of cyclogenesis zone based on 0000 UTC of 29.10.2015.

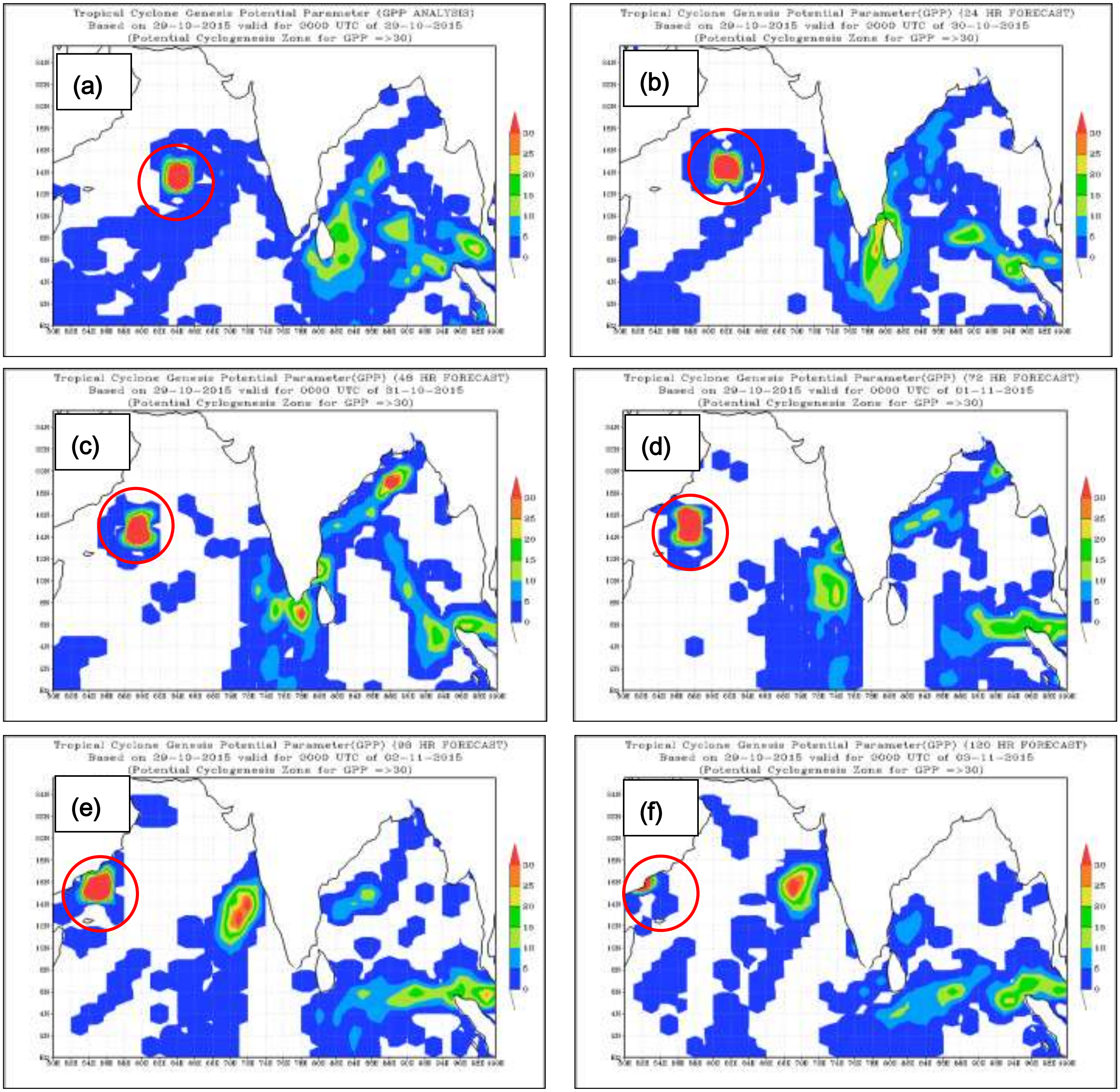
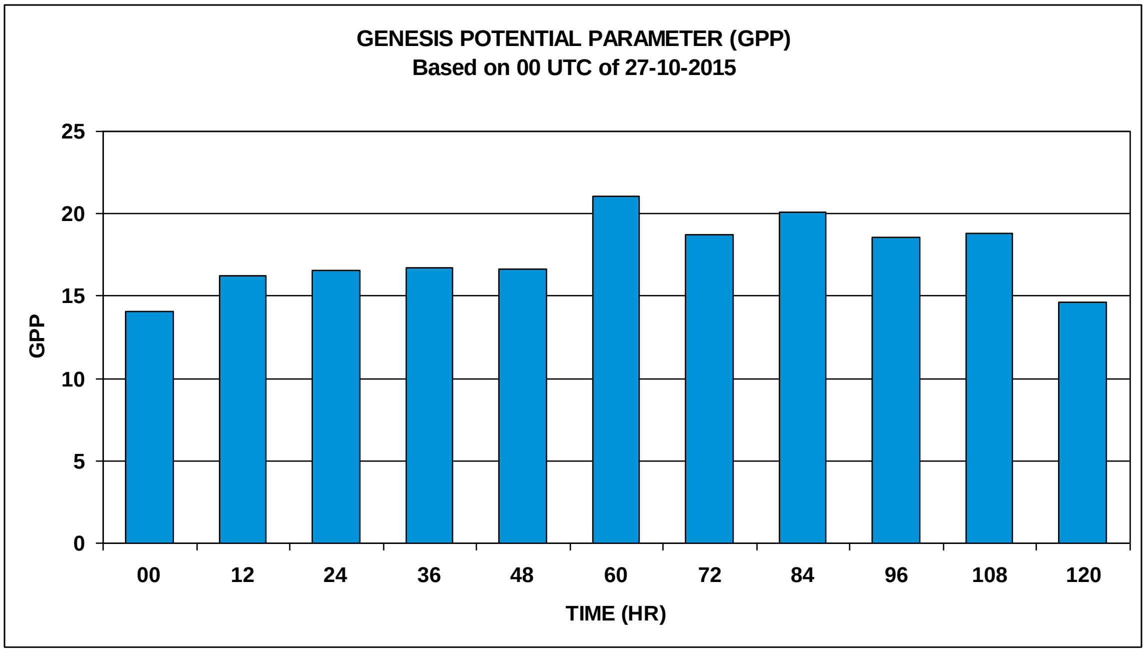


Fig. 3.1.4(a-f) course of movement of cyclogenesis zone

3.5.2 Area average analysis of GPP

Conditions for genesis:

(i) Developed system (T3.0 or more): Threshold value of GPP ≥ 8.0 (ii) Non-developed system (T2.5 or less): Threshold value of GPP < 8.0



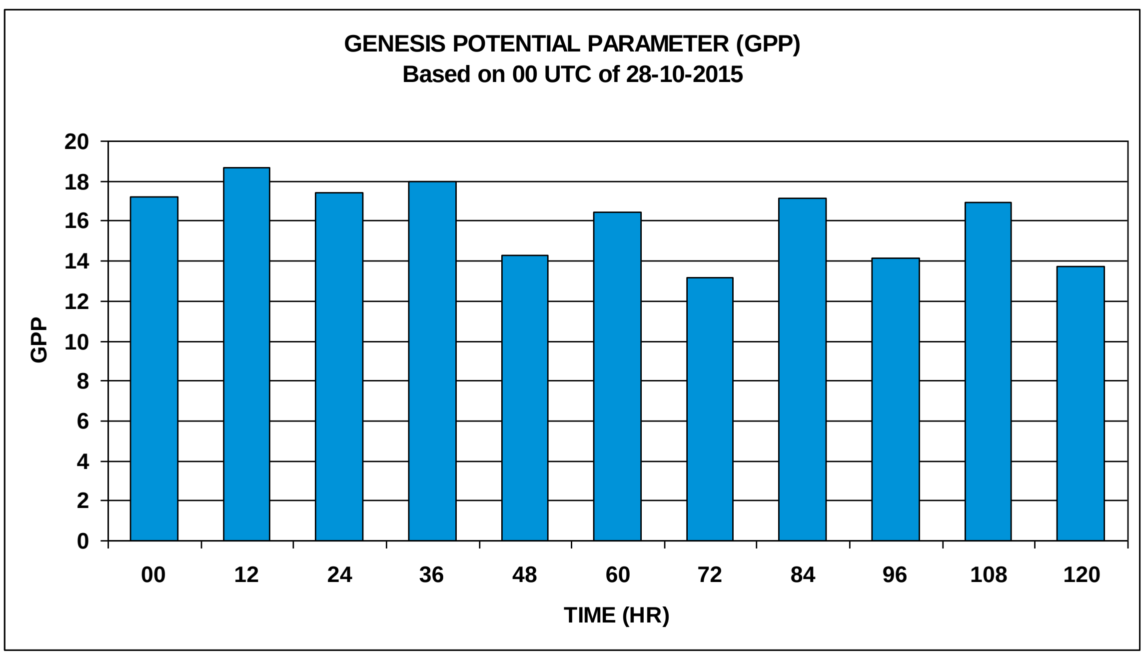
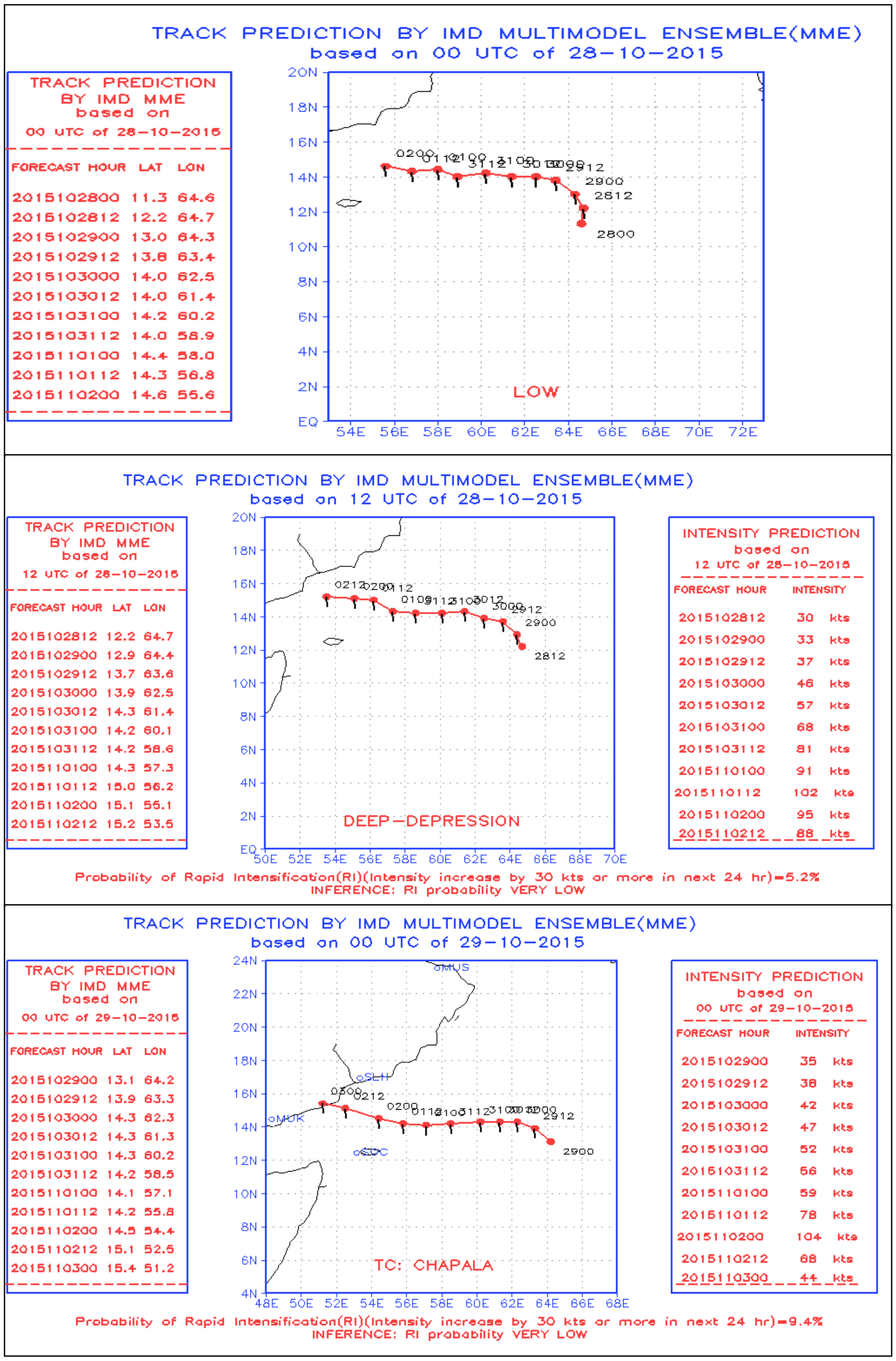


Fig. 3.15 Area average analysis and forecasts of GPP based on 0000 UTC of 27.10.2015 and 28.10.2015 (T1.0 &T1.5)

Analysis and forecasts of GPP (Fig.3.15) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated potential for intensification into a cyclone at early stages of development (T.No. 1.0 to 1.5).

3.5.3 Track and Intensity prediction

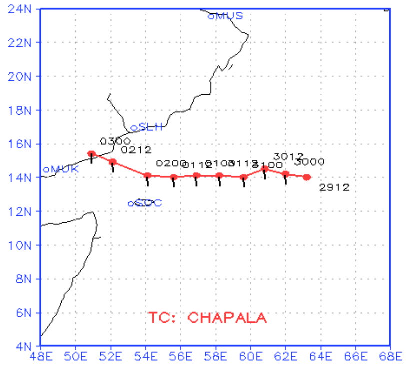
Consensus track prediction by MME and Intensity forecast by SCIP model are presented in Fig. 3.15. The track prediction by individual models are presented in Fig. 3.16. The track forecast by EPS are shown in Fig. 3.17



TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 12 UTC of 29-10-2015

TRACK PREDICTION BY IMD MME based on 12 UTC of 29-10-2015

FORECAST HOUR	LAT	LON
2015102912	14.0	63.2
2015103000	14.2	62.0
2015103012	14.5	60.8
2015103100	14.0	59.6
2015103112	14.1	58.2
2015110100	14.1	56.9
2015110112	14.0	55.6
2015110200	14.1	54.1
2015110212	14.9	52.1
2015110300	15.4	50.9



INTENSITY PREDICTION based on 12 UTC of 29-10-2015

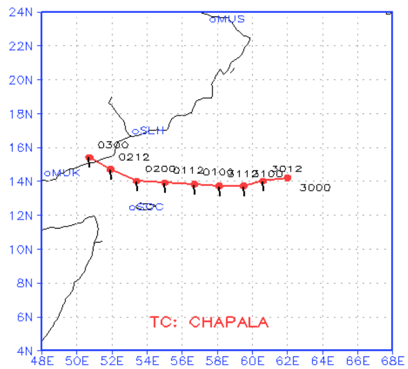
FORECAST HOUR	INTENSITY
2015102912	55 kts
2015103000	60 kts
2015103012	64 kts
2015103100	69 kts
2015103112	74 kts
2015110100	83 kts
2015110112	91 kts
2015110200	97 kts
2015110212	103 kts
2015110300	82 kts

Probability of Rapid Intensification(RI)(Intensity increase by 30 kts or more in next 24 hr)=32.0%
INFERENCE: RI probability MODERATE

TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 00 UTC of 30-10-2015

TRACK PREDICTION BY IMD MME based on 00 UTC of 30-10-2015

FORECAST HOUR	LAT	LON
2015103000	14.2	62.0
2015103012	14.0	60.6
2015103100	13.7	59.5
2015103112	13.7	58.1
2015110100	13.8	56.7
2015110112	13.9	55.0
2015110200	14.0	53.4
2015110212	14.7	51.9
2015110300	15.4	50.7



INTENSITY PREDICTION based on 00 UTC of 30-10-2015

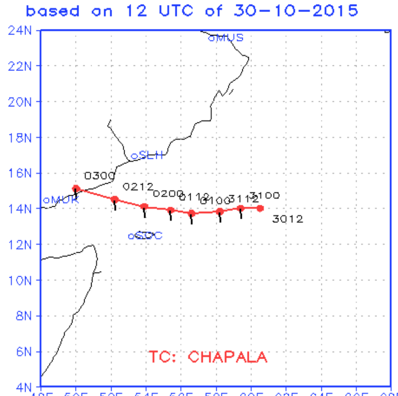
FORECAST HOUR	INTENSITY
2015103000	80 kts
2015103012	93 kts
2015103100	104 kts
2015103112	109 kts
2015110100	113 kts
2015110112	117 kts
2015110200	121 kts
2015110212	108 kts
2015110300	93 kts

Probability of Rapid Intensification(RI)(Intensity increase by 30 kts or more in next 24 hr)=72.7%
INFERENCE: RI probability HIGH

TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 12 UTC of 30-10-2015

TRACK PREDICTION BY IMD MME based on 12 UTC of 30-10-2015

FORECAST HOUR	LAT	LON
2015103012	14.0	60.5
2015103100	14.0	59.4
2015103112	13.8	58.2
2015110100	13.7	56.6
2015110112	13.9	55.4
2015110200	14.1	53.9
2015110212	14.5	52.2
2015110300	15.1	50.0



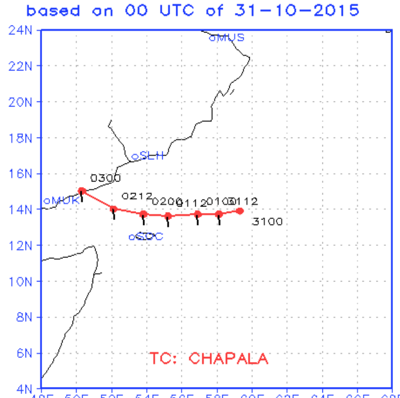
INTENSITY PREDICTION based on 12 UTC of 30-10-2015

FORECAST HOUR	INTENSITY
2015103012	115 kts
2015103100	122 kts
2015103112	128 kts
2015110100	125 kts
2015110112	121 kts
2015110200	122 kts
2015110212	109 kts
2015110300	85 kts

TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 00 UTC of 31-10-2015

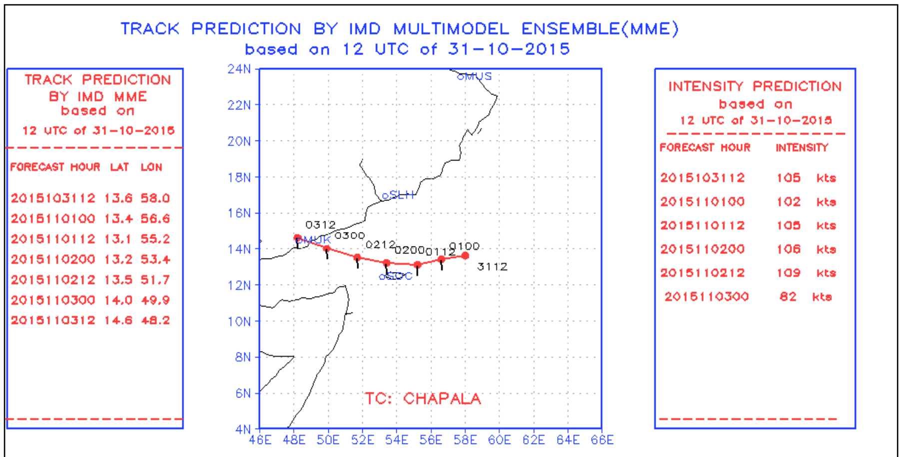
TRACK PREDICTION BY IMD MME based on 00 UTC of 31-10-2015

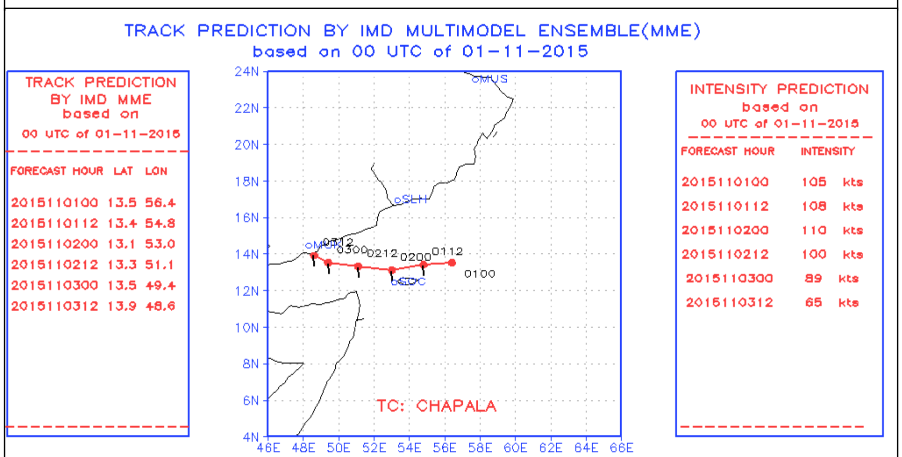
FORECAST HOUR	LAT	LON
2015103100	13.9	59.3
2015103112	13.7	58.1
2015110100	13.7	56.9
2015110112	13.6	55.2
2015110200	13.7	53.8
2015110212	14.0	52.1
2015110300	15.0	50.3

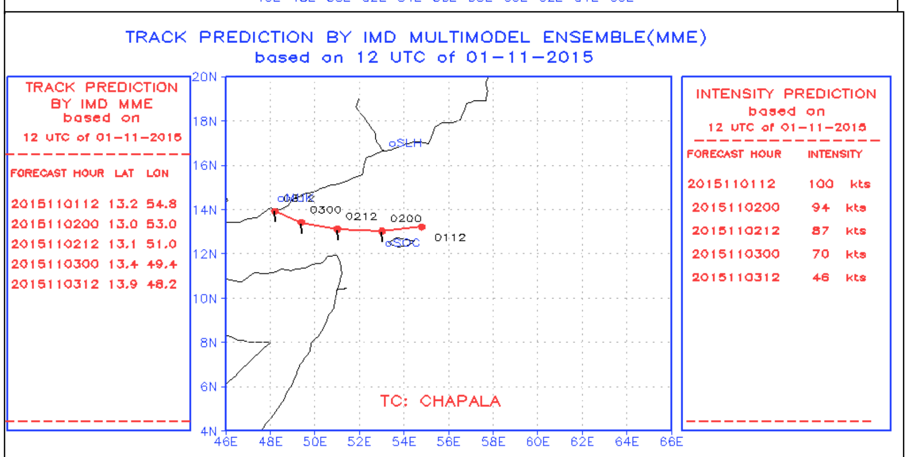


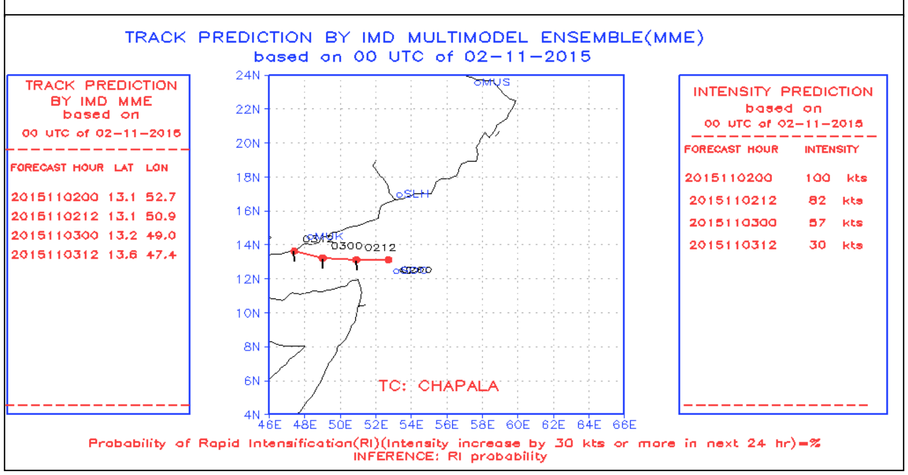
INTENSITY PREDICTION based on 00 UTC of 31-10-2015

FORECAST HOUR	INTENSITY
2015103100	115 kts
2015103112	111 kts
2015110100	107 kts
2015110112	103 kts
2015110200	108 kts
2015110212	94 kts
2015110300	88 kts


TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 12 UTC of 31-10-2015
TRACK PREDICTION BY IMD MME based on 12 UTC of 31-10-2015
FORECAST HOUR LAT LON
2015103112 13.6 58.0
2015110100 13.4 56.6
2015110112 13.1 55.2
2015110200 13.2 53.4
2015110212 13.5 51.7
2015110300 14.0 49.9
2015110312 14.6 48.2
INTENSITY PREDICTION based on 12 UTC of 31-10-2015
FORECAST HOUR INTENSITY
2015103112 105 kts
2015110100 102 kts
2015110112 105 kts
2015110200 106 kts
2015110212 109 kts
2015110300 82 kts
TC: CHAPALA


TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 00 UTC of 01-11-2015
TRACK PREDICTION BY IMD MME based on 00 UTC of 01-11-2015
FORECAST HOUR LAT LON
2015110100 13.5 56.4
2015110112 13.4 54.8
2015110200 13.1 53.0
2015110212 13.3 51.1
2015110300 13.5 49.4
2015110312 13.9 48.6
INTENSITY PREDICTION based on 00 UTC of 01-11-2015
FORECAST HOUR INTENSITY
2015110100 105 kts
2015110112 108 kts
2015110200 110 kts
2015110212 100 kts
2015110300 89 kts
2015110312 65 kts
TC: CHAPALA


TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 12 UTC of 01-11-2015
TRACK PREDICTION BY IMD MME based on 12 UTC of 01-11-2015
FORECAST HOUR LAT LON
2015110112 13.2 54.8
2015110200 13.0 53.0
2015110212 13.1 51.0
2015110300 13.4 49.4
2015110312 13.9 48.2
INTENSITY PREDICTION based on 12 UTC of 01-11-2015
FORECAST HOUR INTENSITY
2015110112 100 kts
2015110200 94 kts
2015110212 87 kts
2015110300 70 kts
2015110312 46 kts
TC: CHAPALA


TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 00 UTC of 02-11-2015
TRACK PREDICTION BY IMD MME based on 00 UTC of 02-11-2015
FORECAST HOUR LAT LON
2015110200 13.1 52.7
2015110212 13.1 50.9
2015110300 13.2 49.0
2015110312 13.6 47.4
INTENSITY PREDICTION based on 00 UTC of 02-11-2015
FORECAST HOUR INTENSITY
2015110200 100 kts
2015110212 82 kts
2015110300 57 kts
2015110312 30 kts
TC: CHAPALA
Probability of Rapid Intensification(RI)(Intensity increase by 30 kts or more in next 24 hr)=%
INFERENCE: RI probability

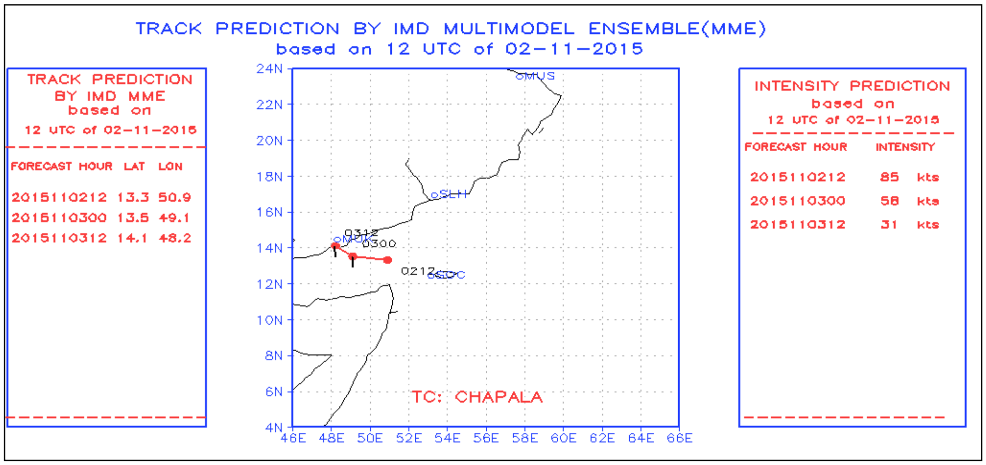


Fig. 3.15 Consensus track prediction by MME and Intensity forecast by SCIP model ESCS Chapala

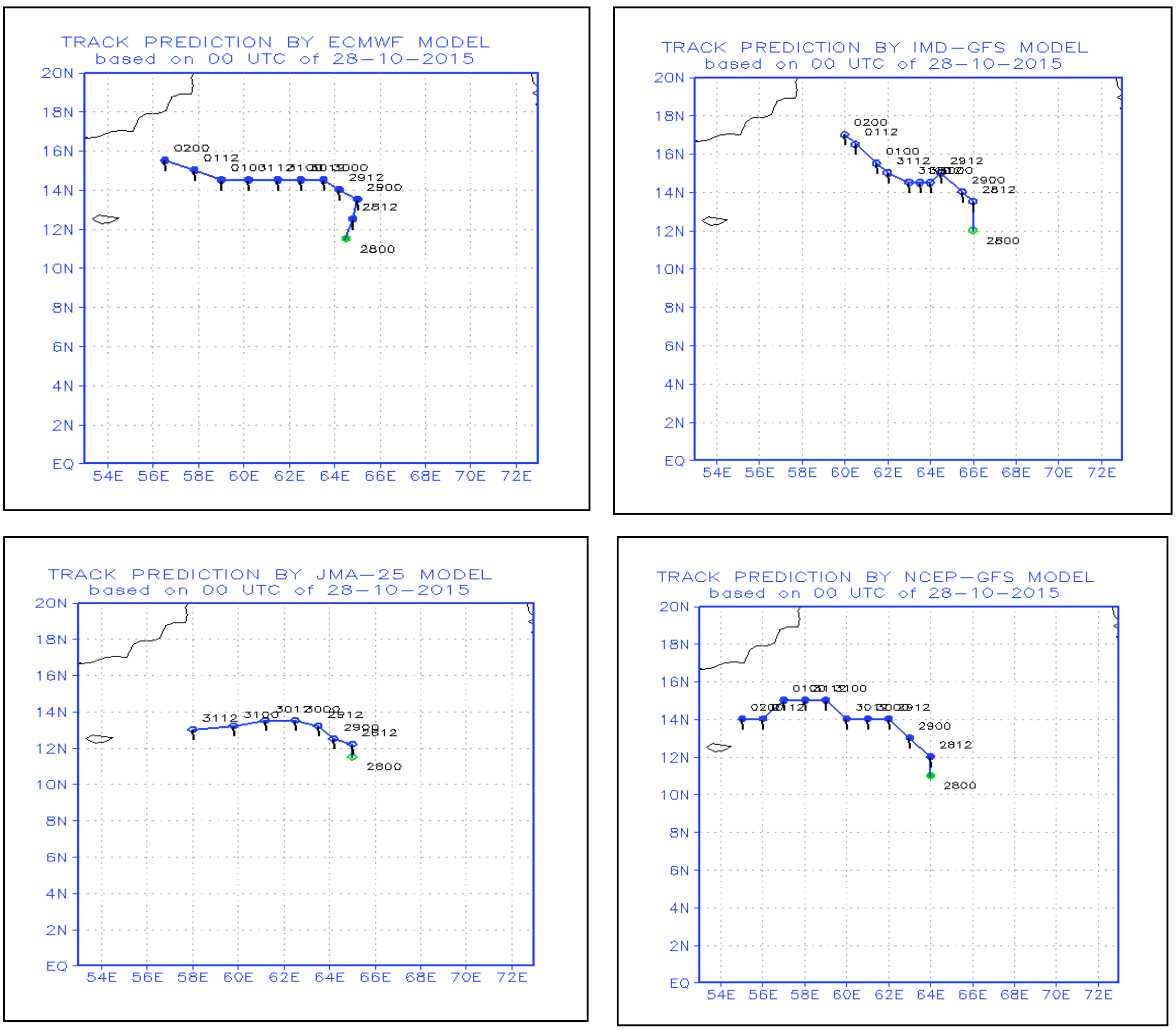
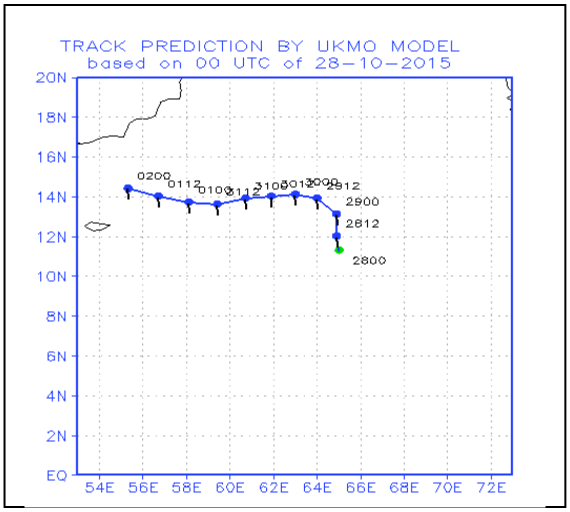
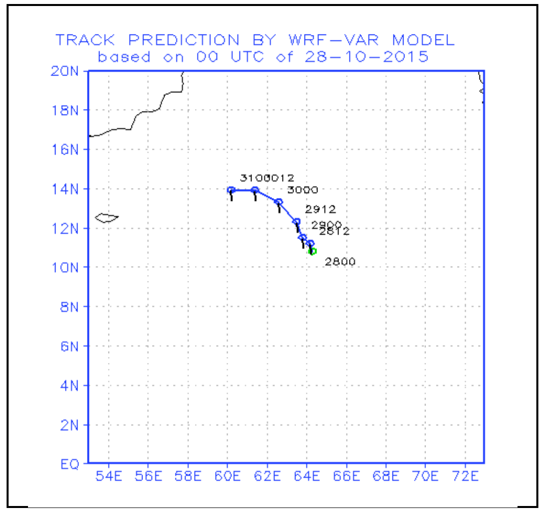
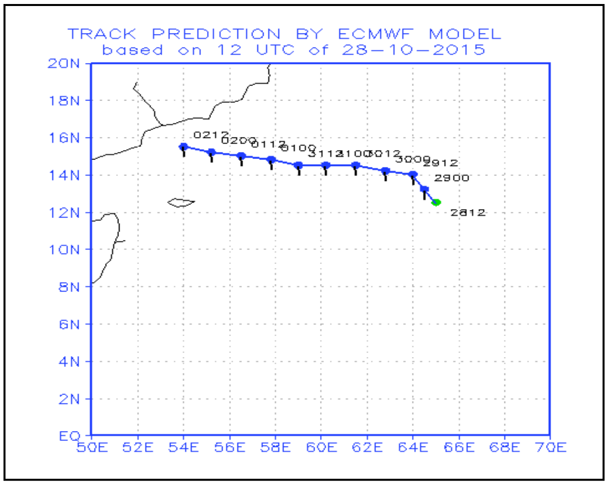
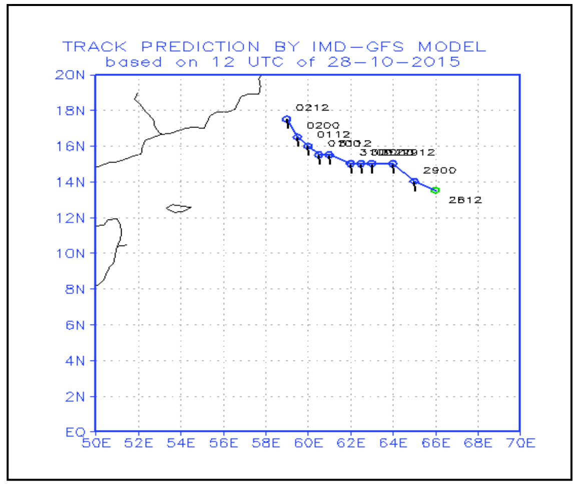


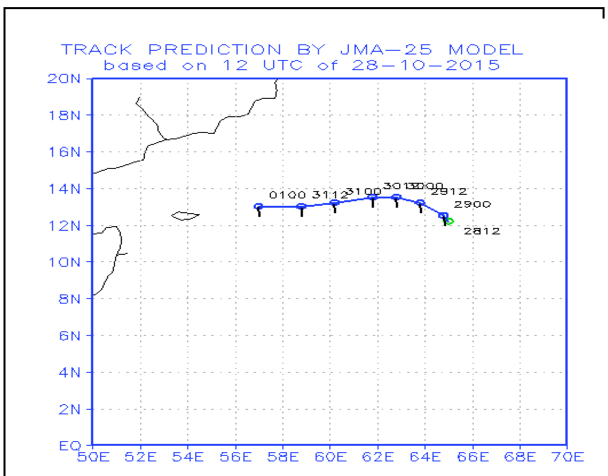
Fig. 3.16 a. Track prediction by NWP models based on 0000 UTC of 28.10.2015

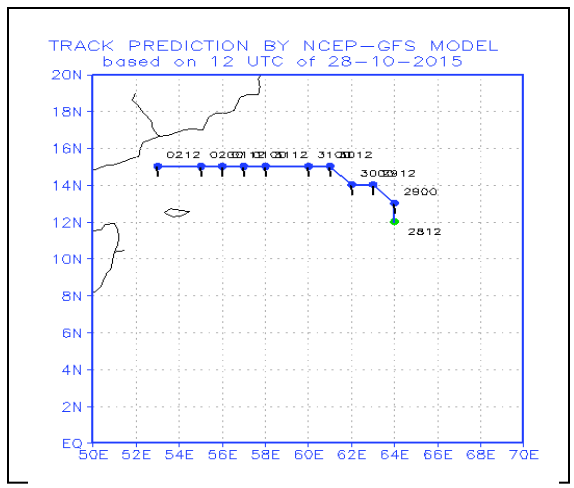












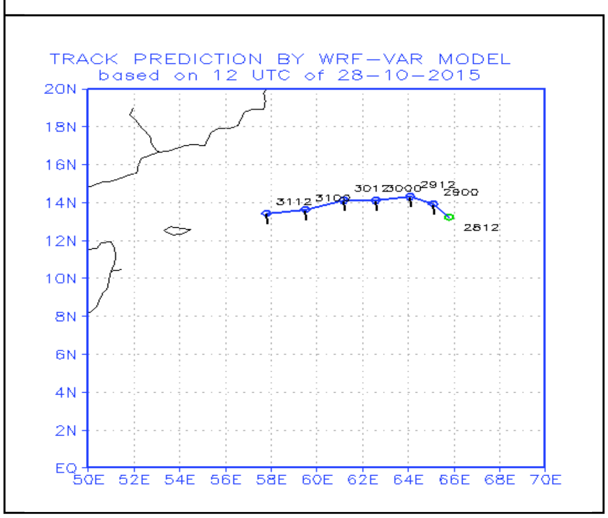


Fig. 316 b. Track prediction by NWP models based on 1200 UTC of 28.10.2015

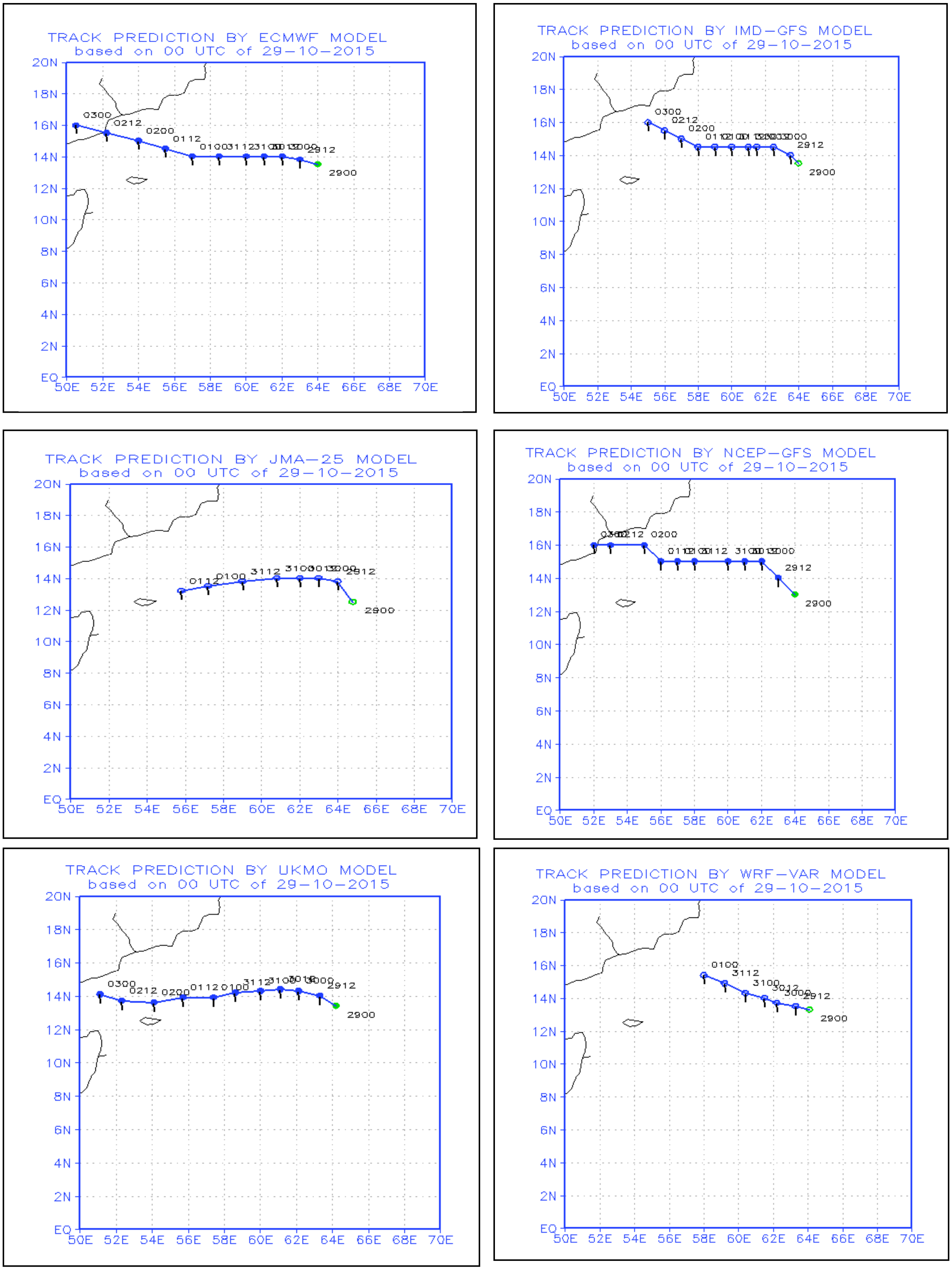


Fig. 3.16 c Track prediction by NWP models based on 0000 UTC of 29.10.2015

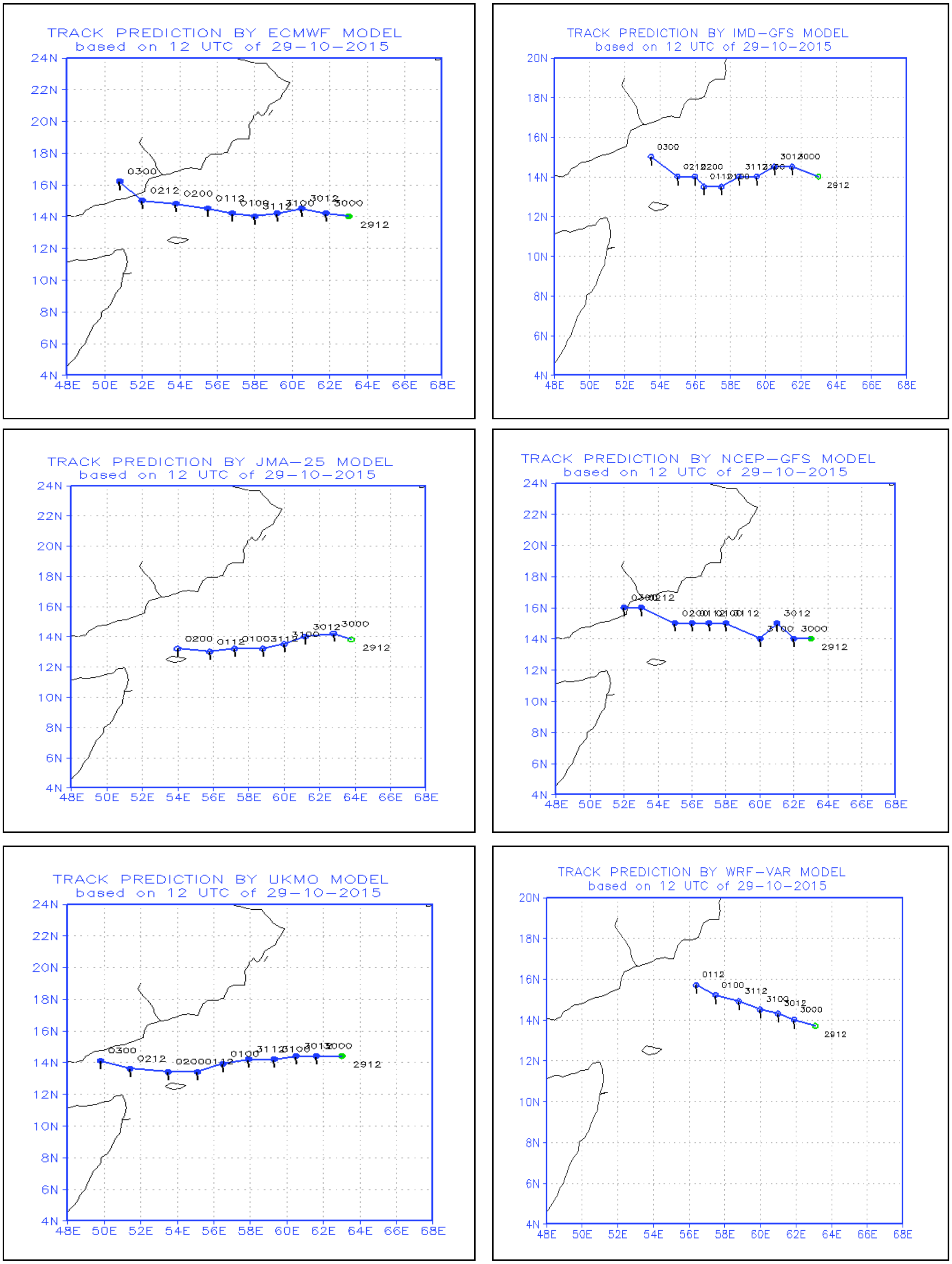


Fig. 3.16d Track prediction by NWP models based on 1200 UTC of 29.10.2015

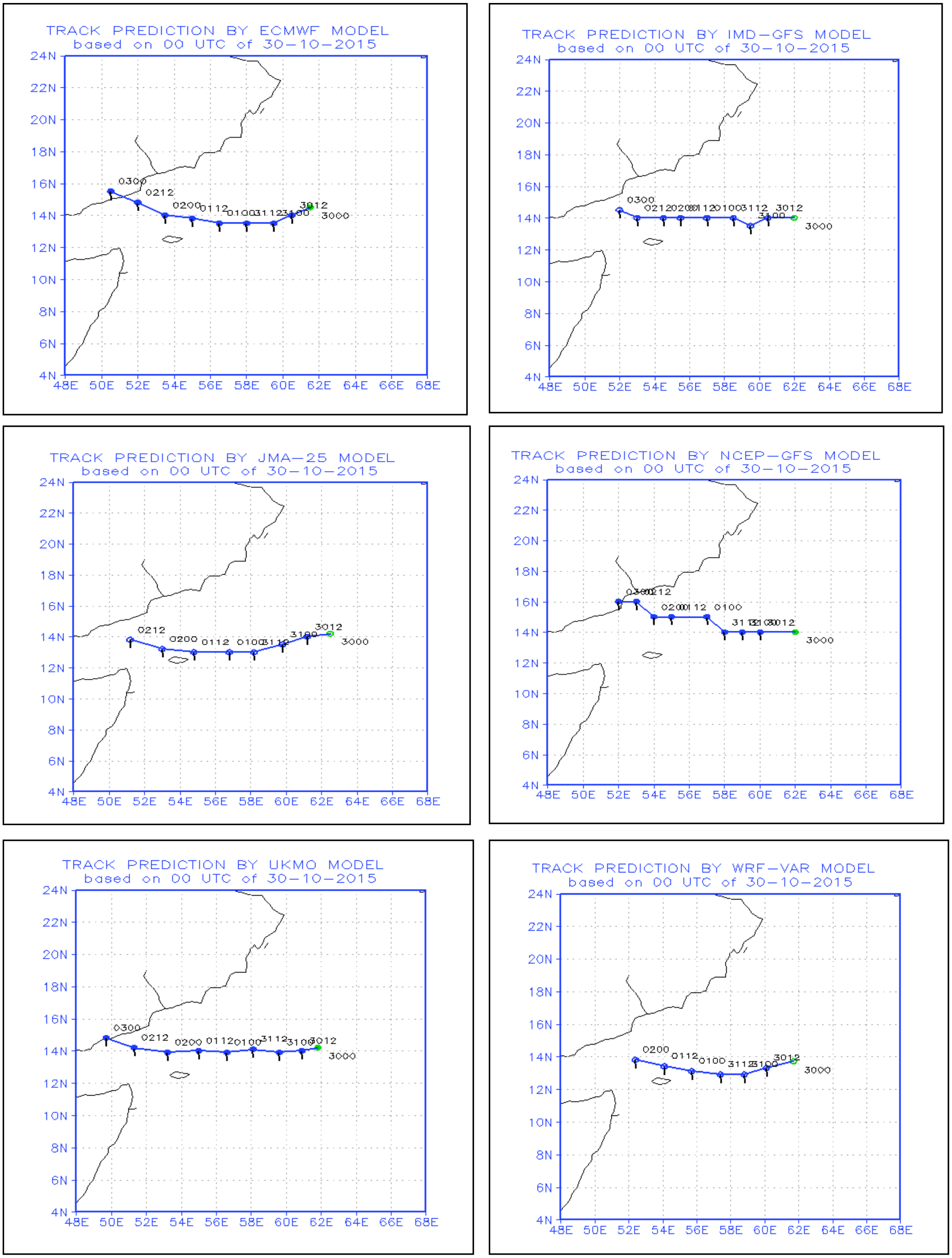


Fig. 3.16e Track prediction by NWP models based on 0000 UTC of 30.10.2015

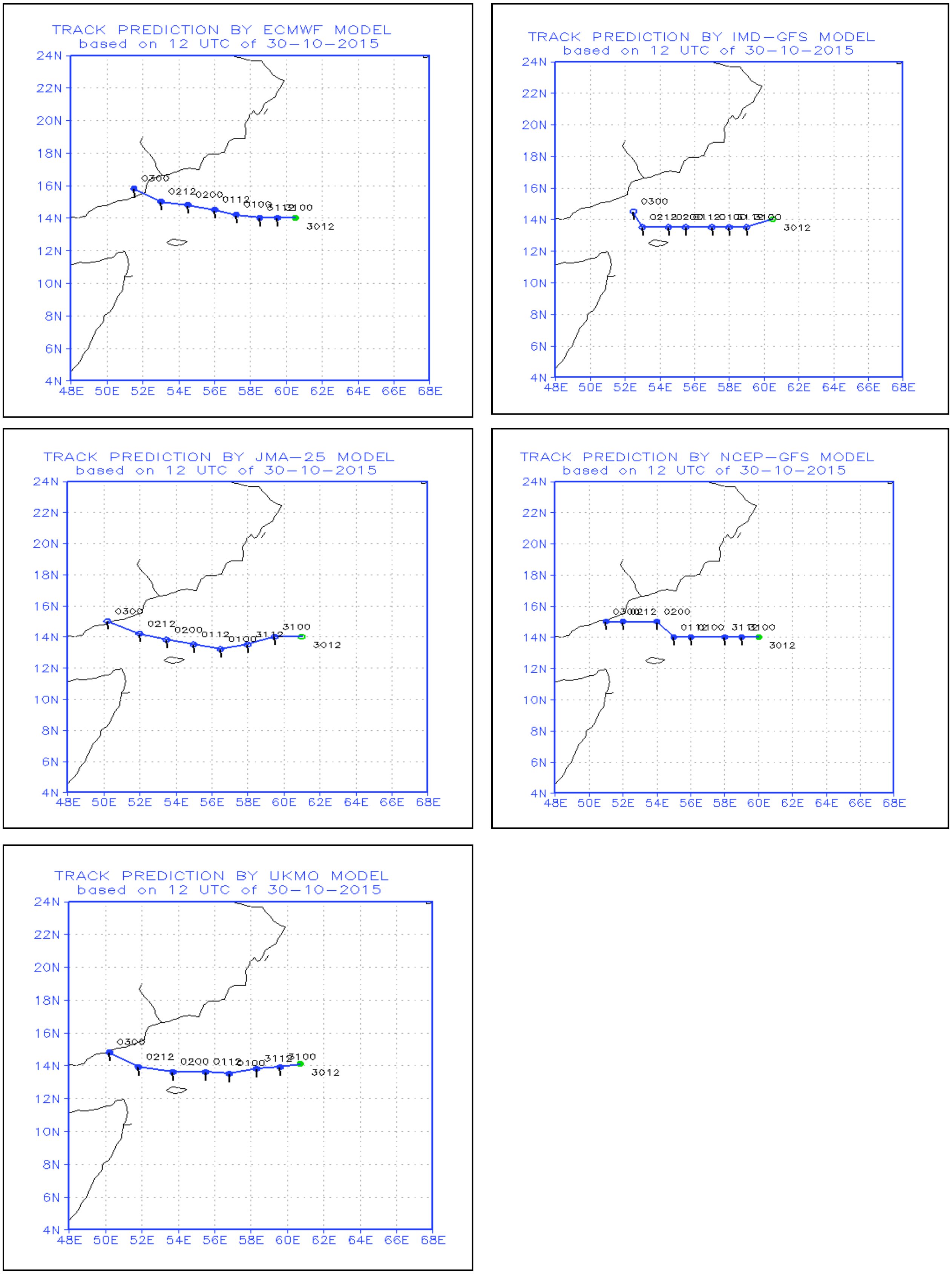


Fig. 3.16f Track prediction by NWP models based on 1200 UTC of 30.10.2015

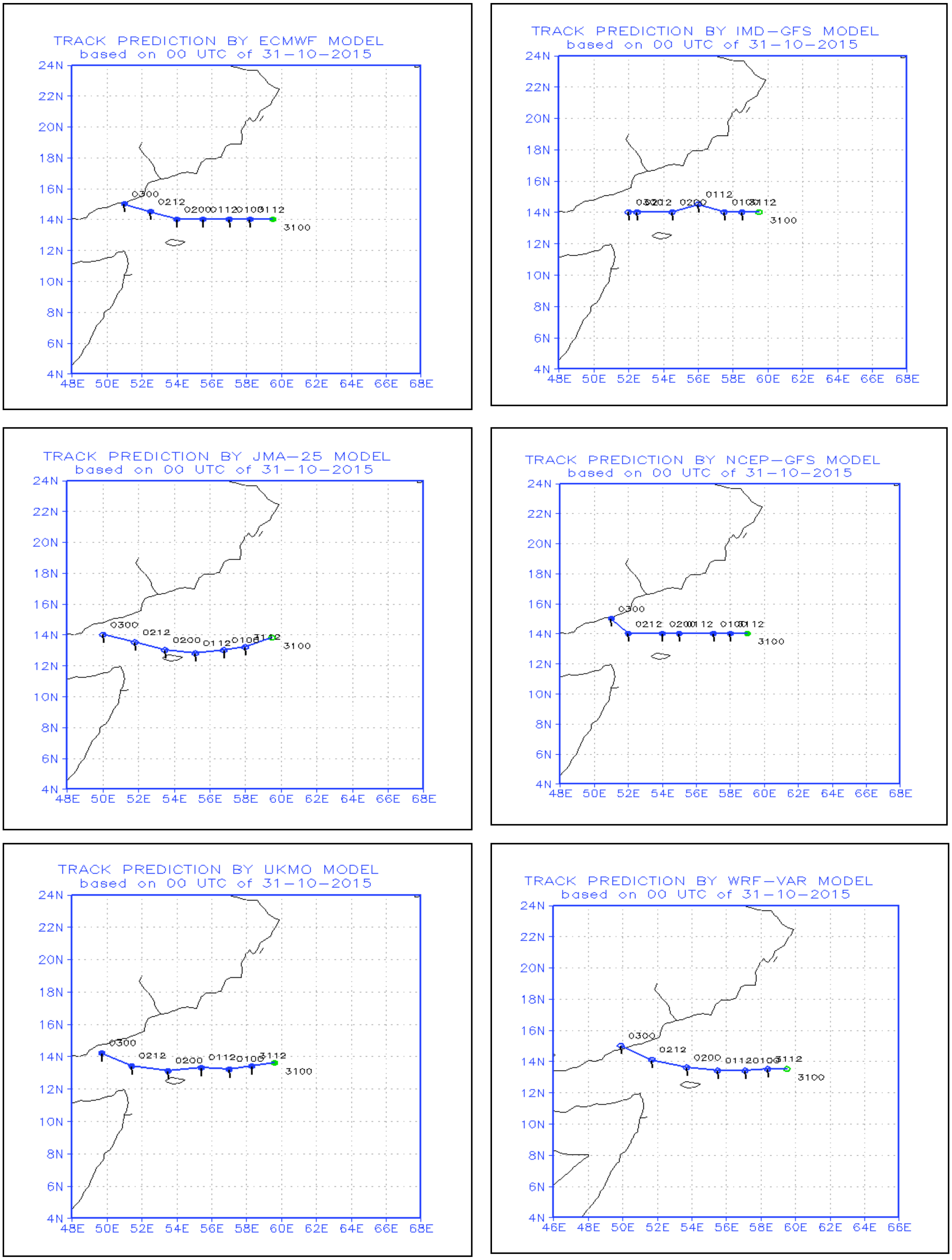


Fig. 3.16g Track prediction by NWP models based on 0000 UTC of 31.10.2015

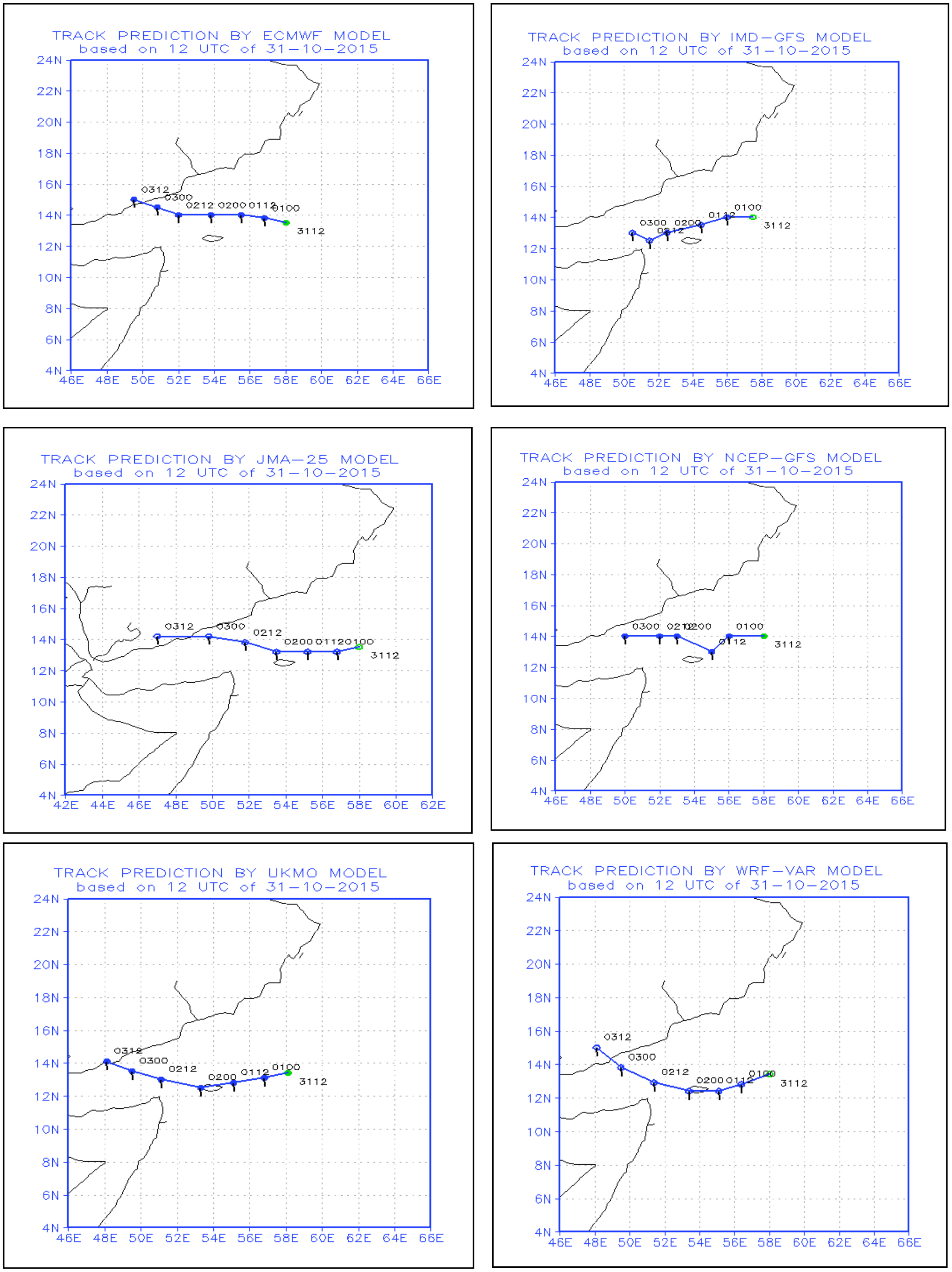


Fig. 3.16h Track prediction by NWP models based on 1200 UTC of 31.10.2015

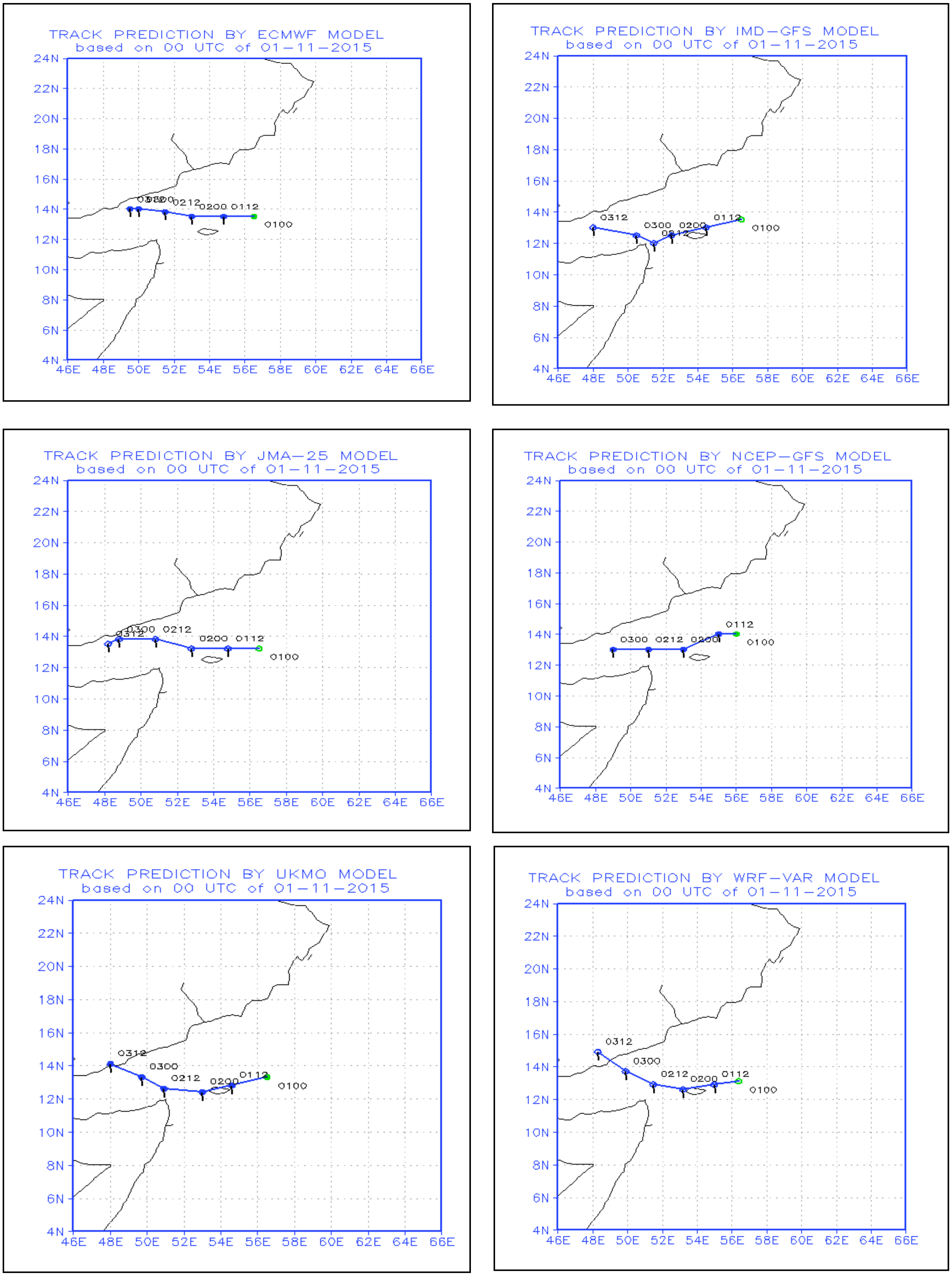


Fig 3.16i Track prediction by NWP models based on 0000 UTC of 01.11.2015

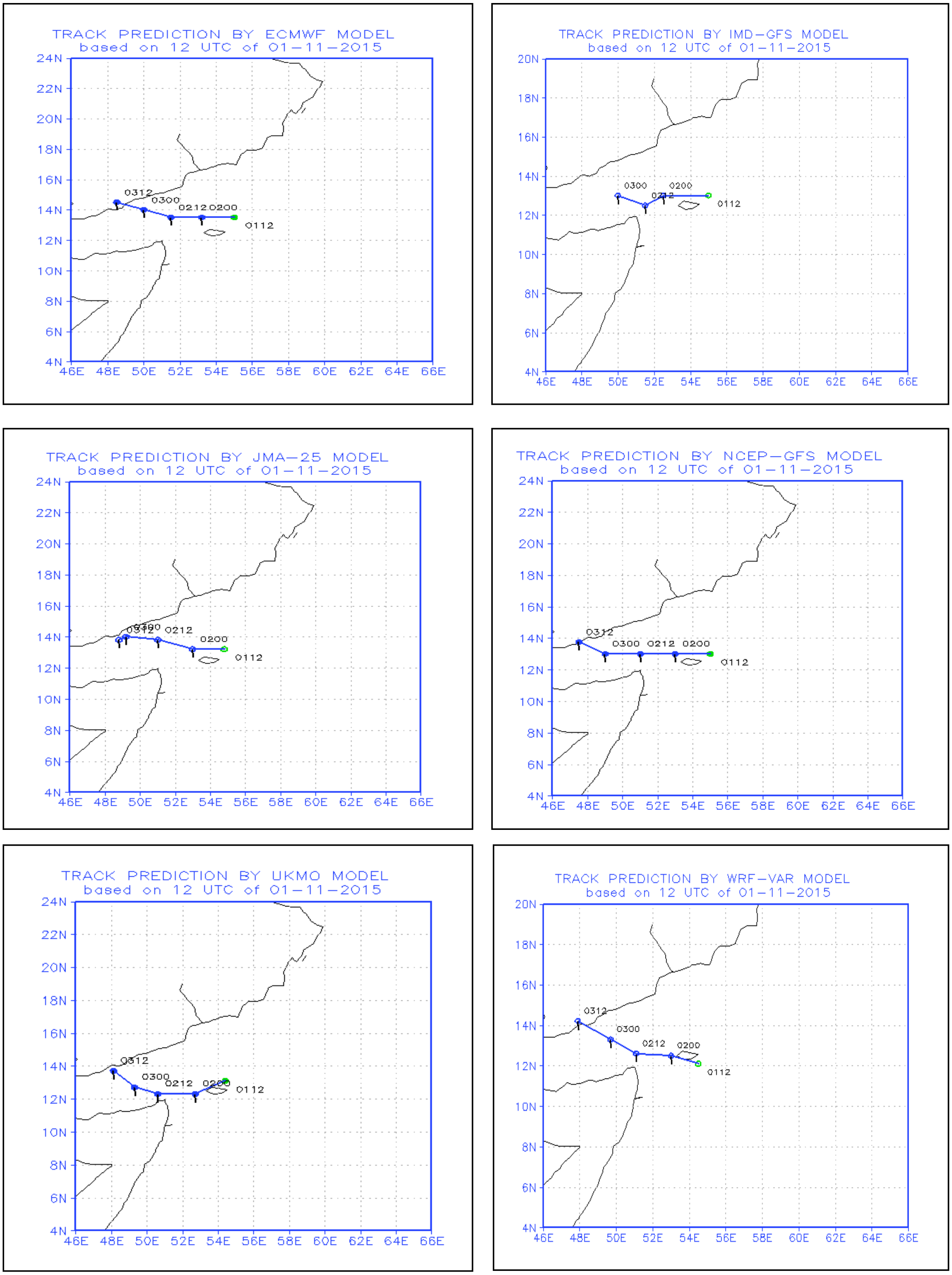


Fig 3.16j Track prediction by NWP models based on 1200 UTC of 01.11.2015

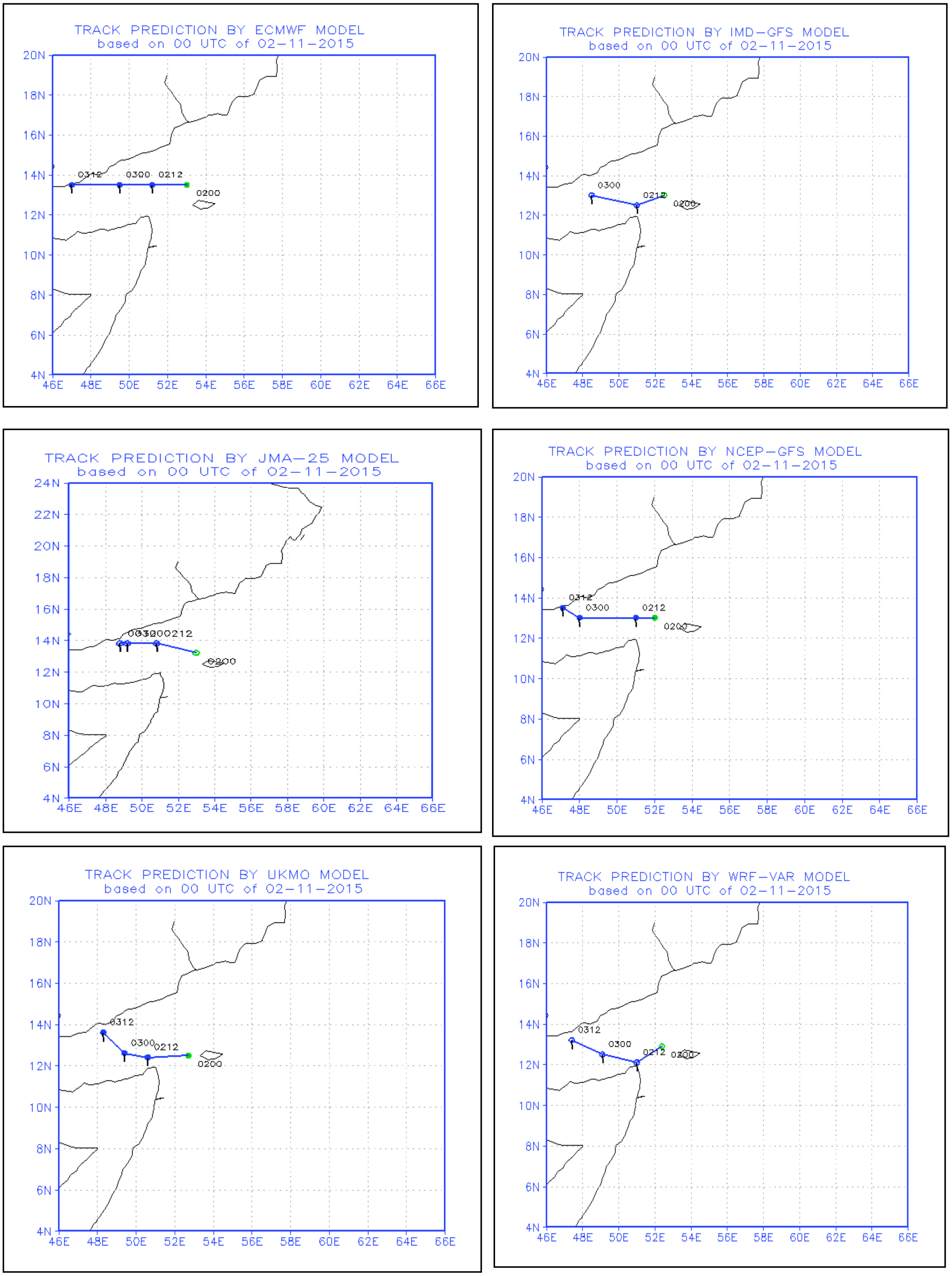


Fig 3.16k Track prediction by NWP models based on 0000 UTC of 02.11.2015

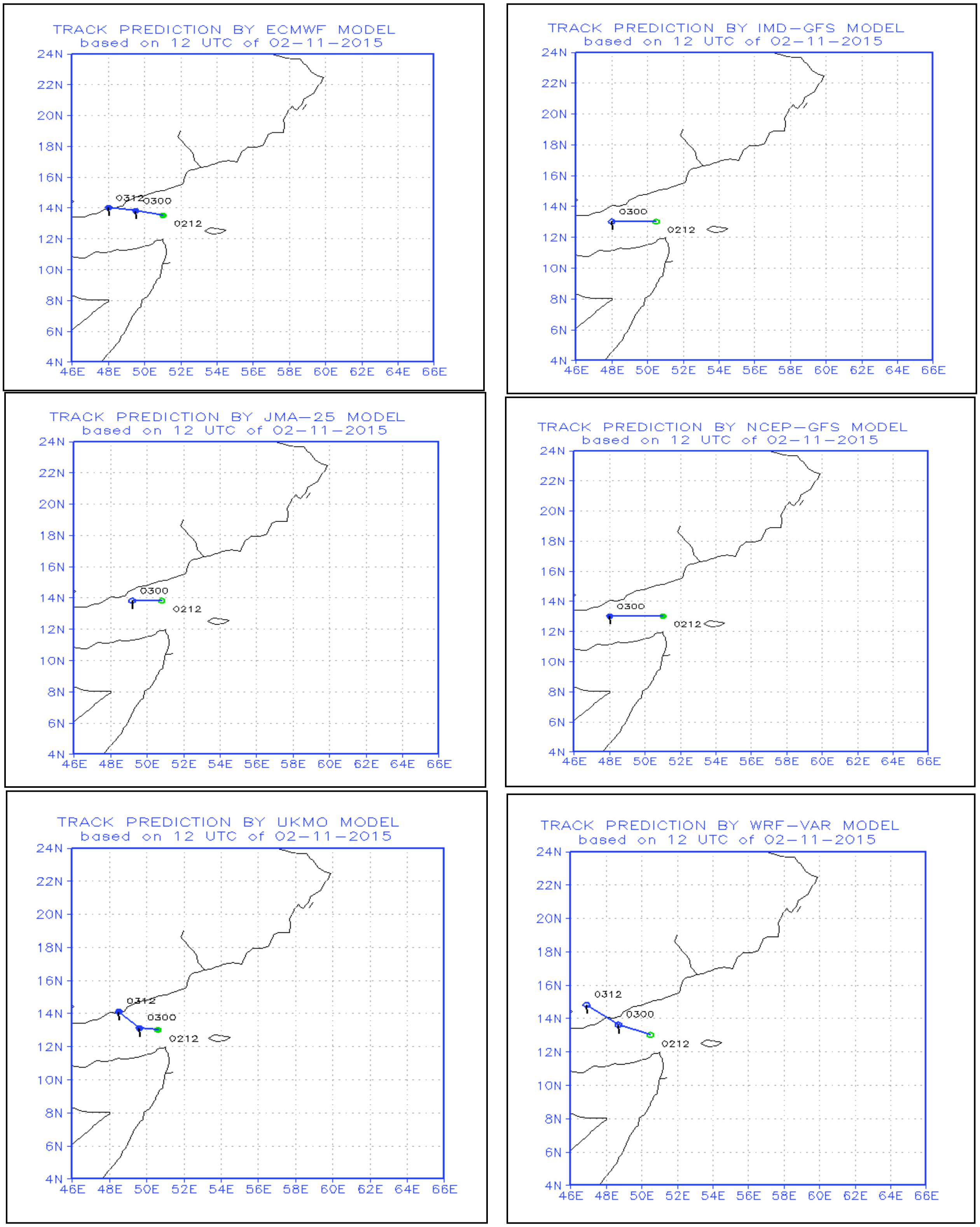
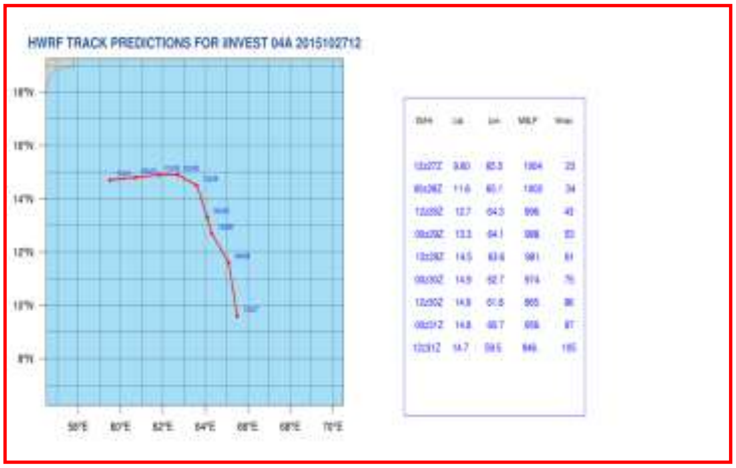
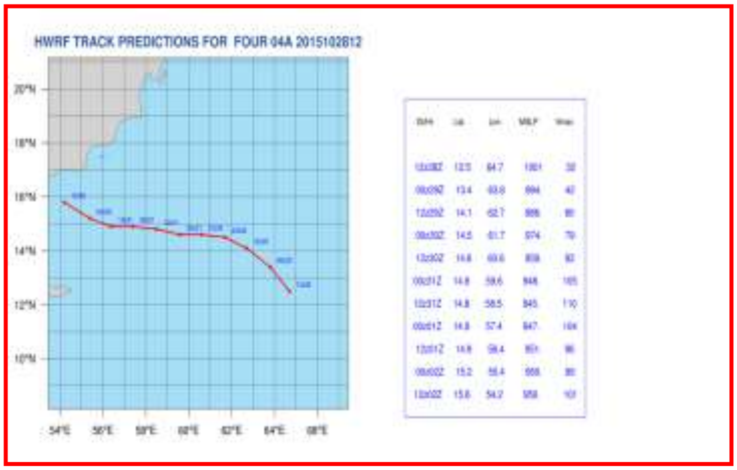
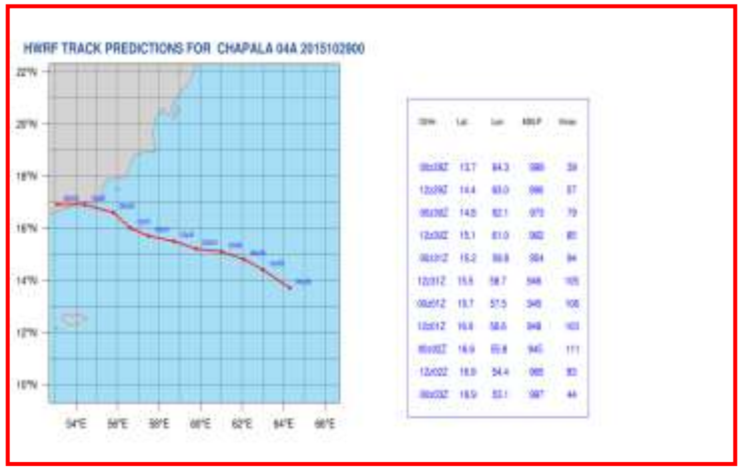


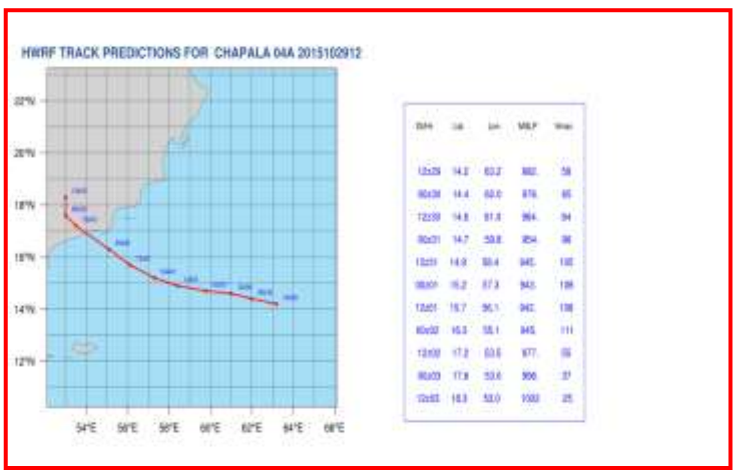
Fig 3.16l Track prediction by NWP models based on 1200 UTC of 02.11.2015

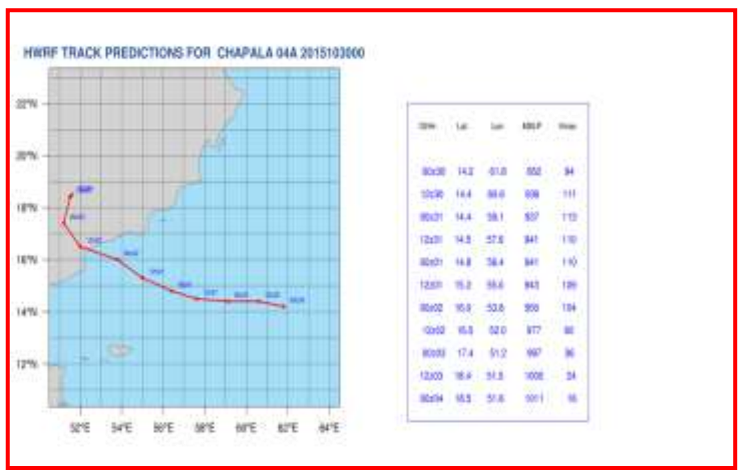

HWRF TRACK PREDICTIONS FOR INVEST 04A 2015102712

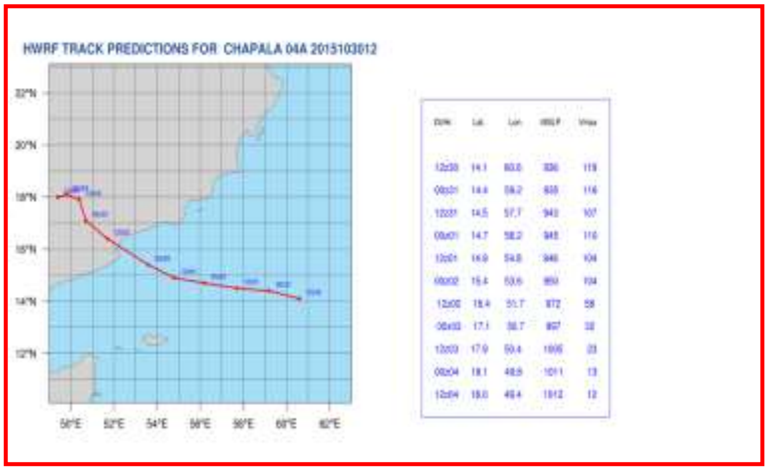

HWRF TRACK PREDICTIONS FOR INVEST 04A 2015102800

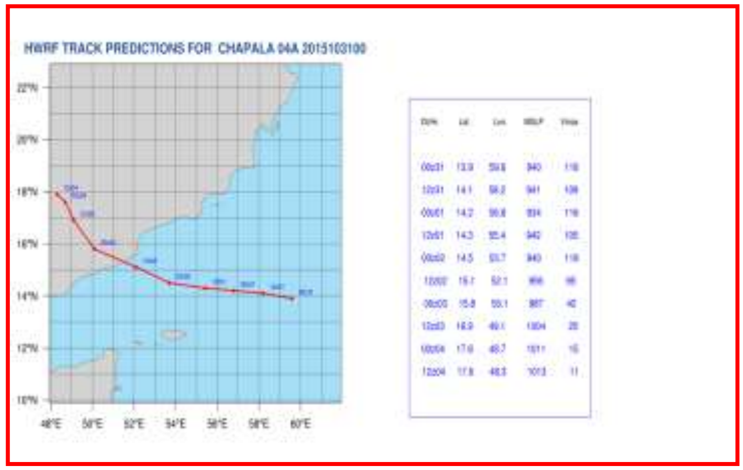

HWRF TRACK PREDICTIONS FOR FOUR 04A 2015102812

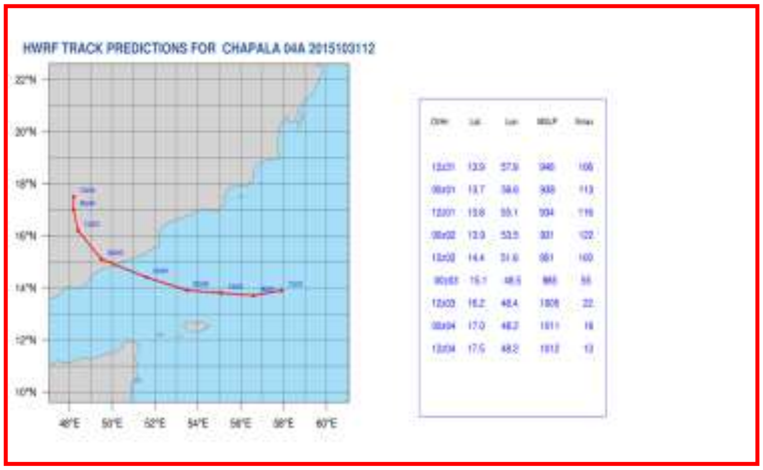

HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015102900

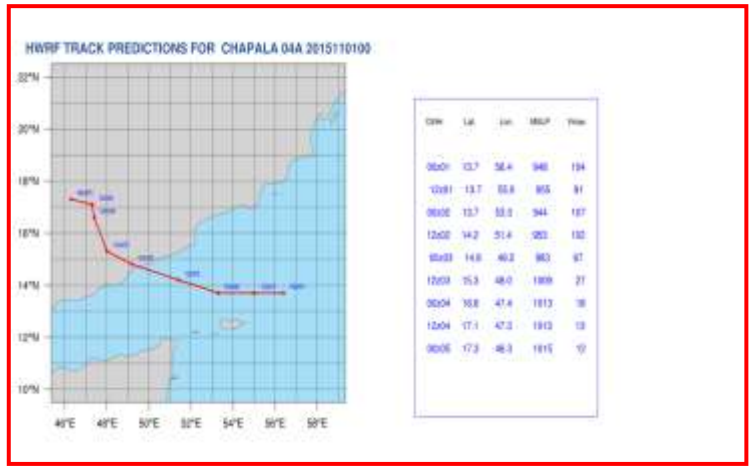

HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015102912

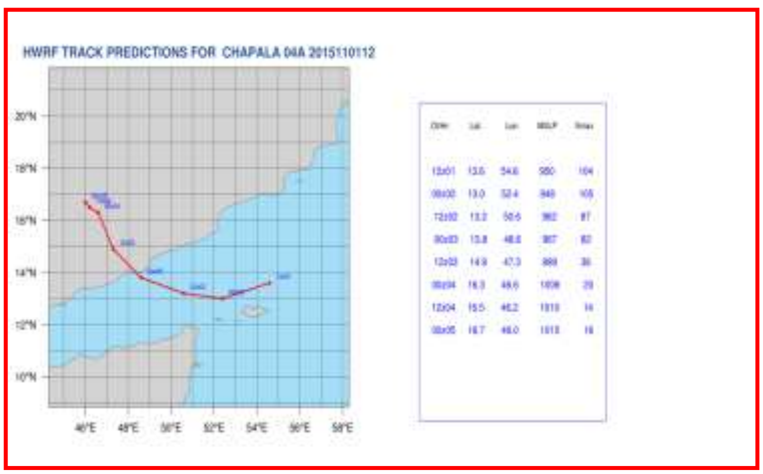

HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015103000

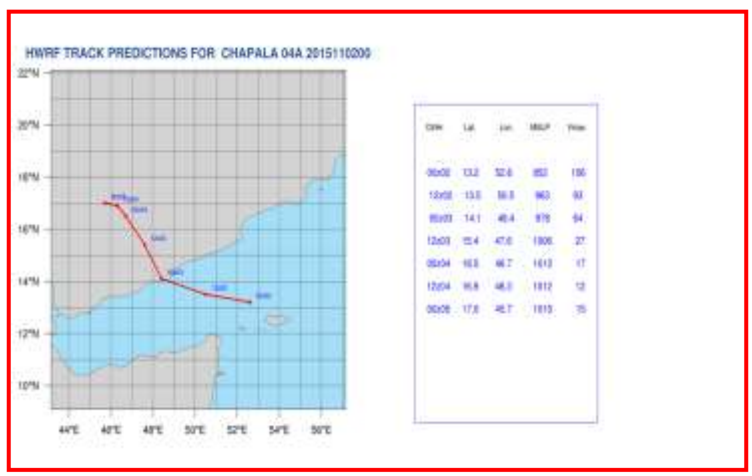

HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015103012


HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015103100


HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015103112


HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015110100


HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015110112


HWRF TRACK PREDICTIONS FOR CHAPALA 04A 2015110200

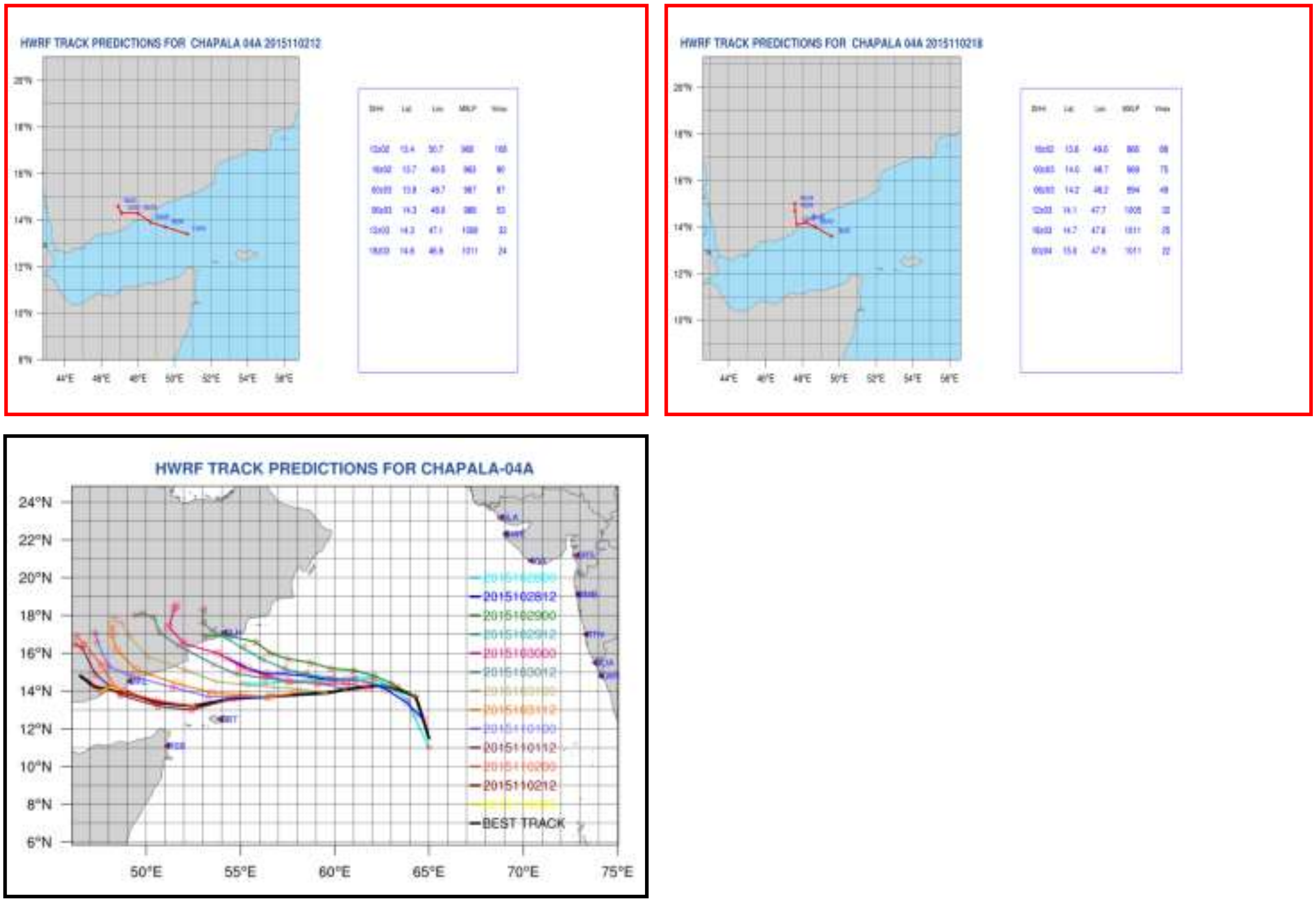


Fig. 3.17 Cluster Composite of HWRF tracks along with Best Track

Table 3.10 Average track forecast errors (Direct Position Error) in km (Number of forecasts verified is given in parentheses)

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
D-GFS	74(12)	36(11)	14(10)	166(9)	209(9)	301(7)	399(6)	517(5)	575(4)	376(3)
D-WRF	90(12)	13(12)	10(11)	01(10)	113(9)	147(8)	-	-	-	-
IA	57(12)	77(11)	99(11)	09(10)	110(9)	106(8)	128(6)	-	-	-
CEP	56(12)	31(11)	77(11)	21(10)	151(8)	201(7)	250(6)	318(5)	324(4)	339(3)
KMO	54(11)	34(11)	37(10)	87(9)	90(8)	105(7)	139(5)	148(4)	179(3)	289(2)
CMWF	42(12)	73(12)	95(11)	19(10)	164(9)	193(8)	233(6)	259(5)	341(4)	410(3)
D-HWRF	(22)	(22)	(20)	8(17)	2(15)	5(13)	1(11)	6(9)	8(7)	9(5)
D-MME	40(12)	52(12)	59(11)	39(10)	109(9)	127(8)	170(6)	234(5)	290(4)	350(3)

Table 3.11 Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead time (hour)	13hr	25hr	37hr	49hr	61hr	73hr	85hr	97hr	109hr	121hr
IMD-GFS	**	**	**	**	**	**	**	**	**	**
IMD-WRF	55	**	55	31	31	**	**	**	**	**
JMA	**	**	**	**	0	**	184	**	**	**
NCEP-GFS	**	175	113	**	**	261	261	431	431	**
UKMO	55	**	**	58	66	**	184	142	**	**
ECMWF	76	209	31	**	160	261	383	281	349	392
IMD-HWRF	2	7	0	18	91	36		74		30
IMD-MME	55	151	76	25	34	218	218	281	291	305

The average track forecast errors of different models are prepared in Table 3.10. The error is minimum in case of MME for 12 & 24 hrs forecasts, IMD-HWRF for 36 hrs. UKMO for 48-120 hrs forecasts. The landfall point & time forecast erors are presented in Table 3.11 & 3.12 respectively. The landfall point forecast is minimum in case of IMD-HWRF for 12-36 hrs, MME for 48 & 72 hrs forecast. The landfall time error for IMD-HWRF upto 60 hrs and for MME, ECMWF & NCEP-GFS for 72 hrs.

Table 3.12 Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead time (hour) →	13hr	25hr	37hr	49hr	61hr	73hr	85hr	97hr	109hr	121hr
MD-GFS	**	**	**	**	**	**	**	**	**	**
MD-WRF	+3	**	+9	+5	+4	**	**	**	**	**
MA	**	**	**	**	+4	**	-1	**	**	**
CEP-GFS	**	+11	+11	**	**	-1	-1	-3	-3	-3
KMO	+11	**	**	+11	+10	**	-1	-1	**	**
CMWF	+11	+11	+6	**	+6	-1	-5	-7	-10	-13
MD-HWRF	.5	.5	.5	.5	.5	.5		7.5		0.5
MD-MME	+11	+11	+11	+11	+5	-1	-3	-5	-4	-1

Intensity prediction (at stages of 12-h intervals) by statistical-dynamical model SCIP & HWRF models are is shown in Table 3.13 & 3.14 respectively.

Table 3.13 Average absolute errors (AAE) and Root Mean Square errors (RMSE) in knots of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
D-SCIP (AAE)	1.4(10)	6.4(10)	.9.1(9)	'2.5(8)	'3.0(7)	'4.6(5)	.7.0(4)	.6.7(3)	.7.0(2)	'1.0(1)
IMD-SCIP (RMSE)	14.2	24.0	28.1	27.6	25.8	27.4	18.5	19.4	17.0	21.0

Table 3.14 Average Absolute Error (INTENSITY) of IMD-HWRF Model (Number of forecasts verified is given in the parentheses)

ead Time	2 Hr	4 Hr	6 Hr	3 Hr	0 Hr	2 Hr	4 Hr	6 Hr	08 Hr	20 Hr
AE	3(22)	9(22)	0.9(20)	0(17)	7(15)	2.8(13)	6.8(11)	7.5(9)	1.2(7)	5.5 (5)
MSE	7(22)	0.3(22)	3.1(20)	1.9(17)	9(15)	5.9(13)	1.7(11)	0.7(9)	3.8(7)	6.6(5)

The error was less in case of HWRF for all forecast times. The error was quite high in case of SCIP model

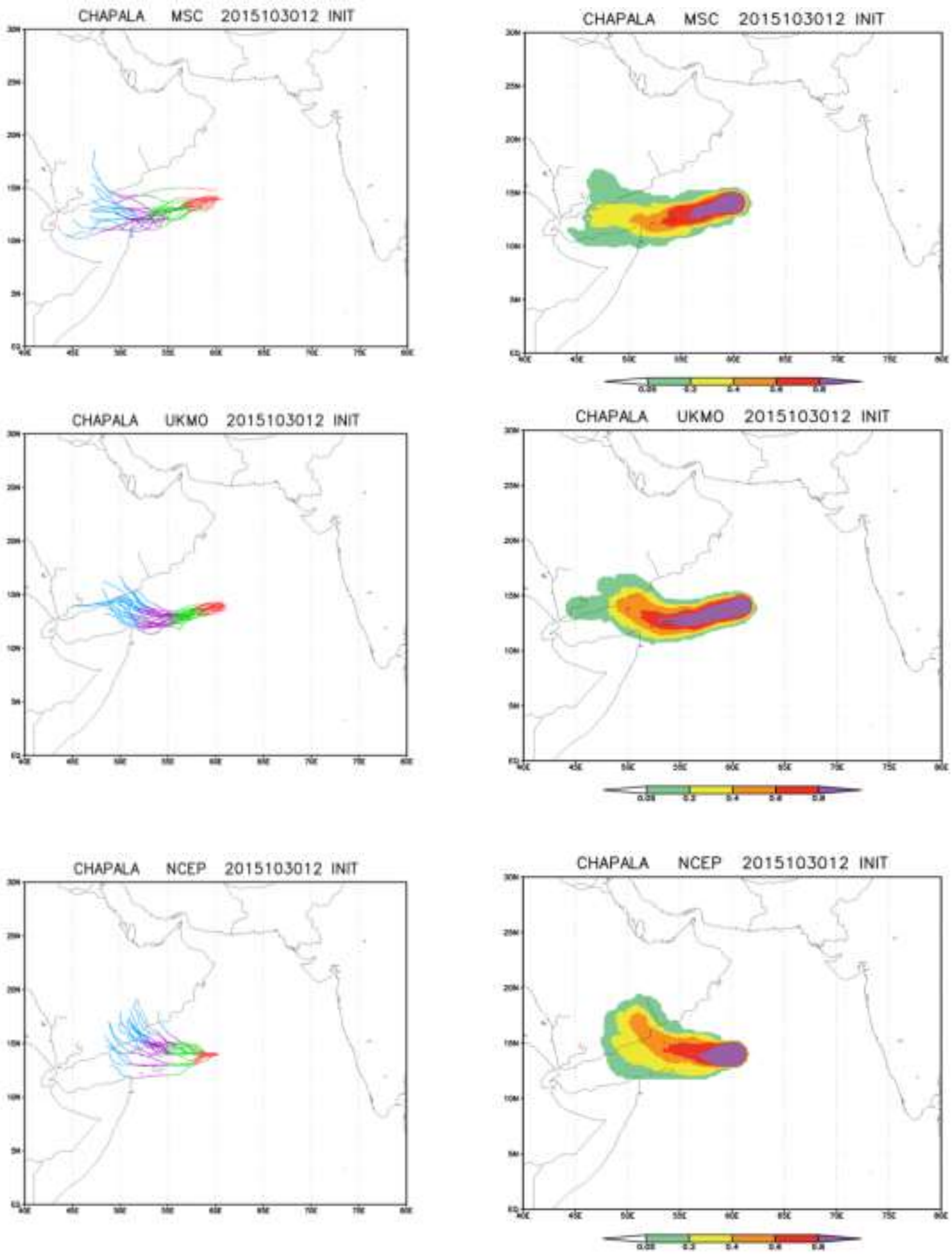


Fig. 3.18 (a) based on 12 UTC of 30.10.2015

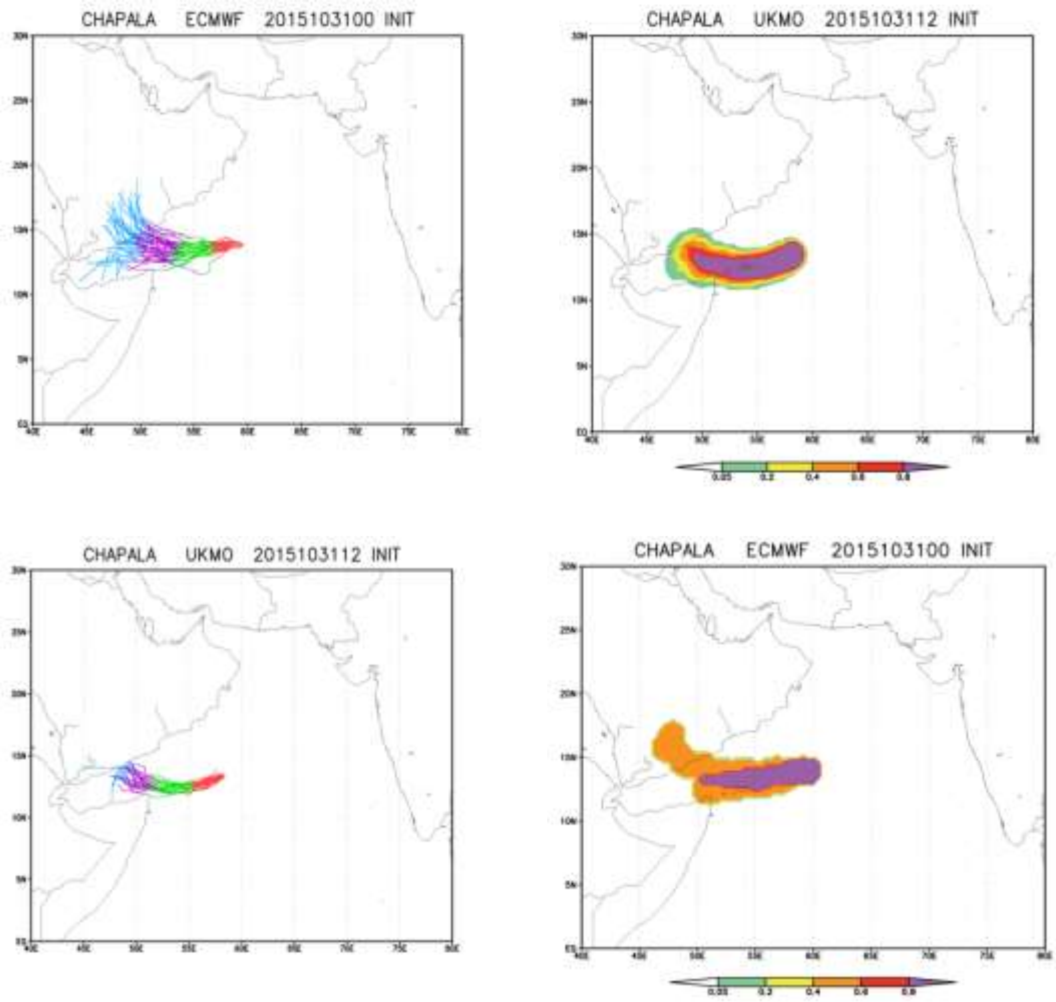


Fig. 3.18 (b) based on 00 & 12 UTC of 31.10.2015

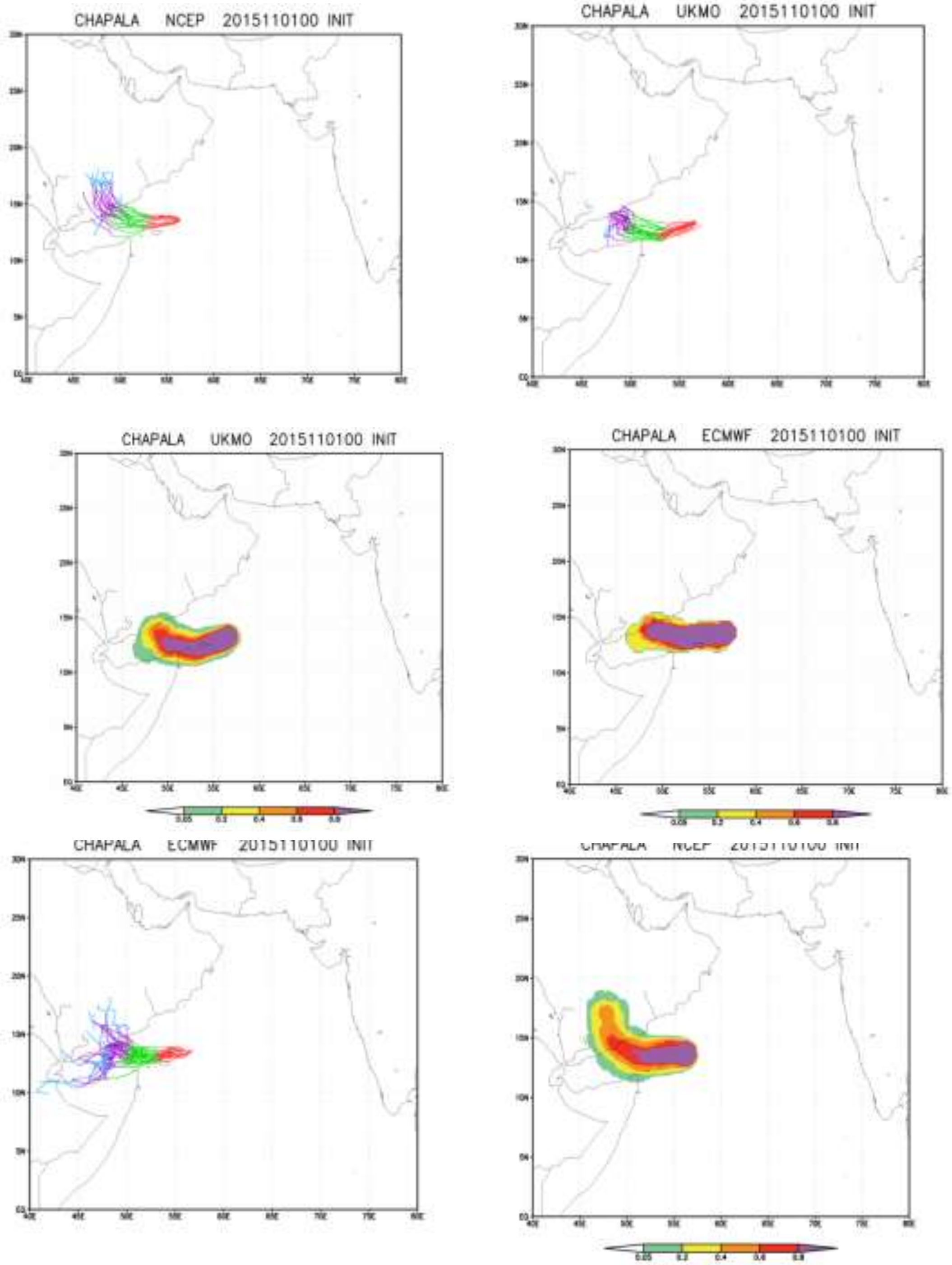


Fig. 3.18 (c) based on 00 UTC of 1.11.2015

3.6 Extremely severe cyclonic storm ‘MEGH’ over the Arabian Sea during 05-10 November, 2015

3.6.1. Grid point analysis and forecast of GPP

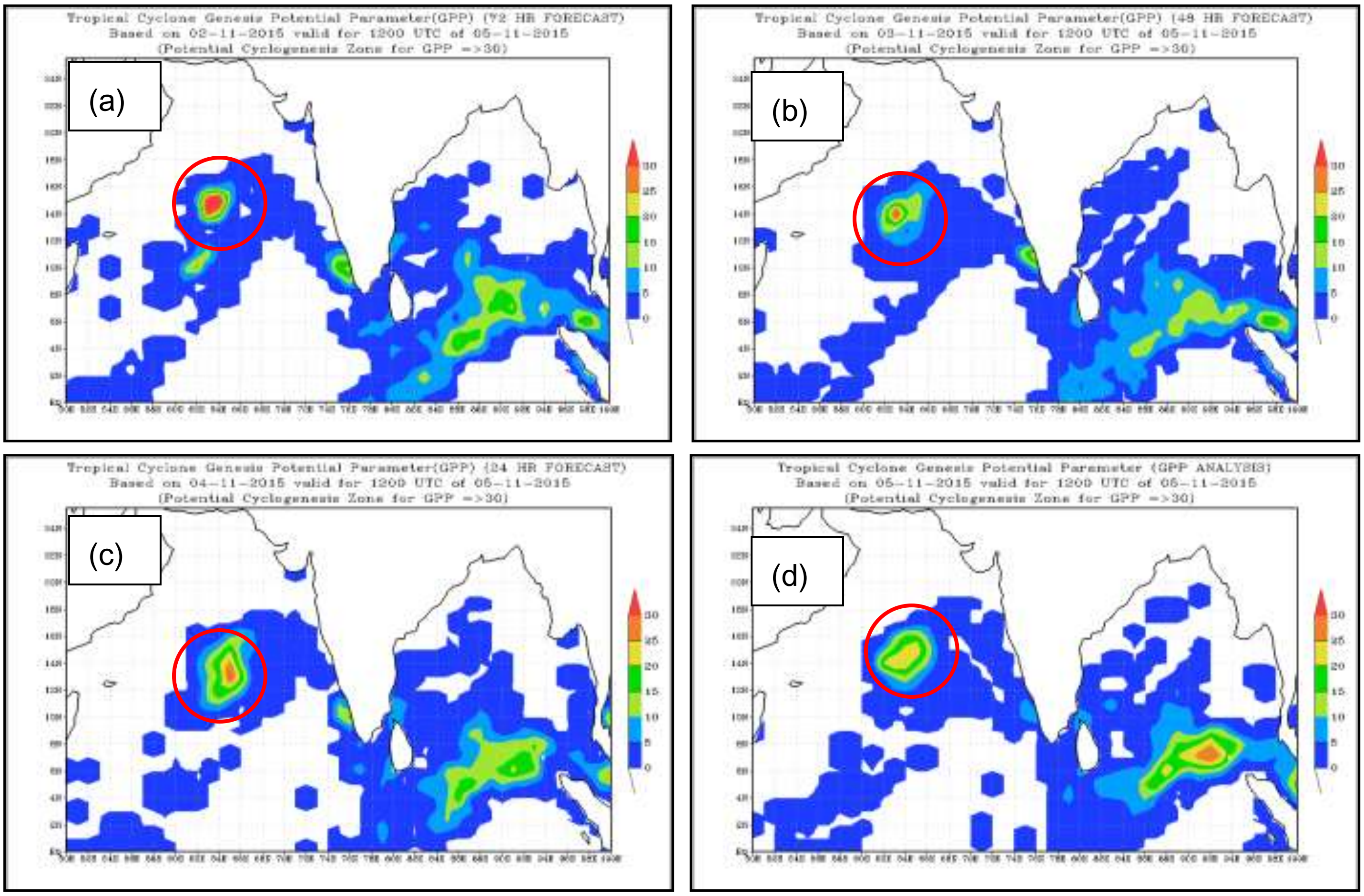


Fig. 3.19(a-d): Predicted zone of cyclogenesis.

Grid point analysis and forecasts of GPP (Fig.3.19(a-d)) shows a weak cyclogenesis zone 72 hrs before its formation.

3.6.2 Area average analysis of GPP

Conditions for genesis:

(i) Developed system (T3.0 or more): Threshold value of GPP ≥ 8.0 (ii) Non-developed system (T2.5 or less): Threshold value of GPP < 8.0

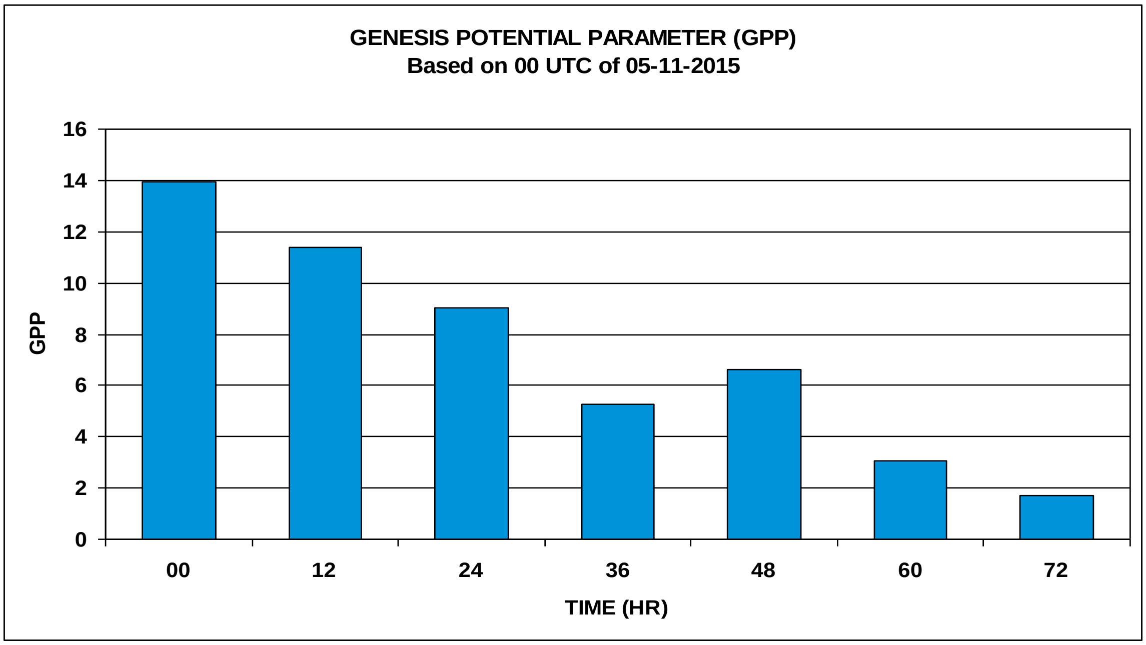
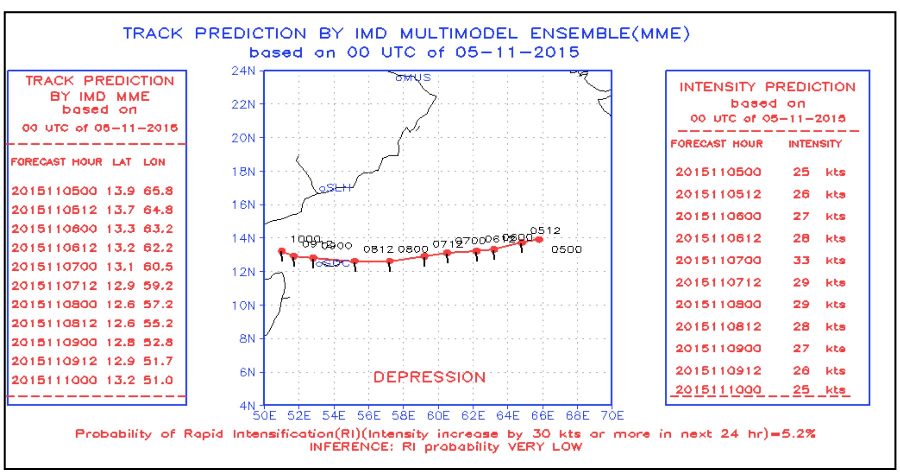


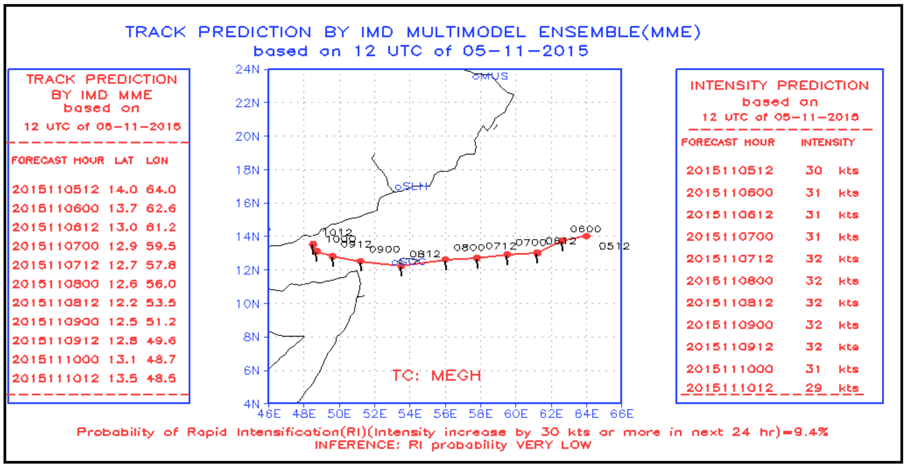
Fig. 3.20 Area average analysis and forecasts of GPP based on 0000 UTC of 05.11.2015 (T1.5)

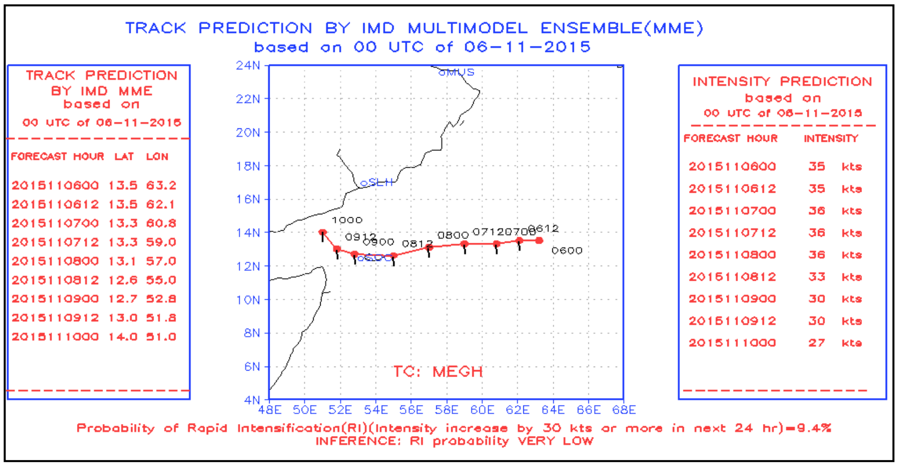
Inference: Analysis and forecasts of GPP (Fig.2) shows that GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone during next 24 hours but incorrectly showed weakening for subsequent hours up to 72 hours.

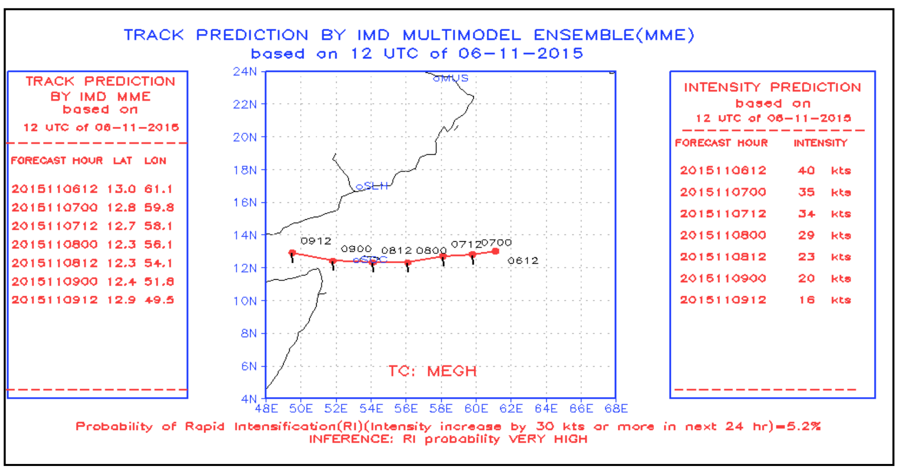
3.6.3 Track and intensity prediction

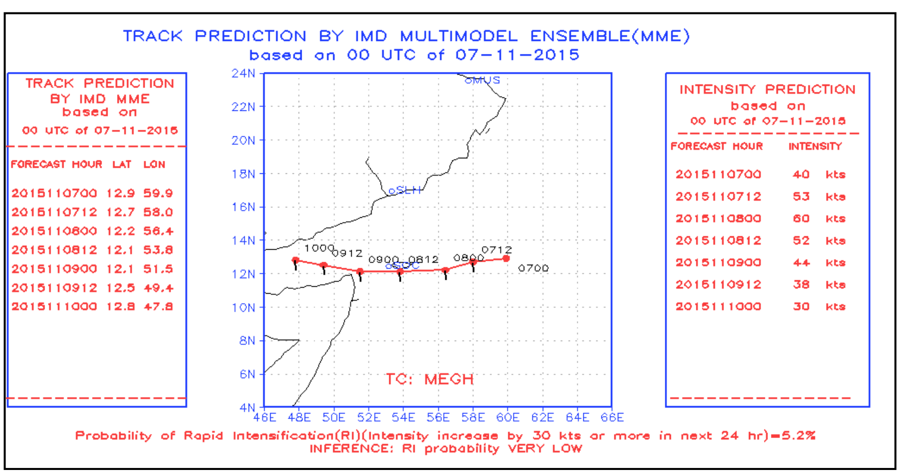
Consensus track prediction by MME and Intensity forecast by SCIP model are presented in Fig. 3.21. The track prediction by individual models is presented in Fig. 3.22. The track prediction by HWRF model is presented in Fig. 3.23




TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 12 UTC of 05-11-2015
TRACK PREDICTION BY IMD MME based on 12 UTC of 05-11-2015
FORECAST HOUR LAT LON
2015110512 14.0 64.0
2015110600 13.7 62.6
2015110612 13.0 61.2
2015110700 12.9 59.5
2015110712 12.7 57.8
2015110800 12.6 56.0
2015110812 12.2 53.5
2015110900 12.5 51.2
2015110912 12.8 49.6
2015111000 13.1 48.7
2015111012 13.5 48.5
TC: MEGH
INTENSITY PREDICTION based on 12 UTC of 05-11-2015
FORECAST HOUR INTENSITY
2015110512 30 kts
2015110600 31 kts
2015110612 31 kts
2015110700 31 kts
2015110712 32 kts
2015110800 32 kts
2015110812 32 kts
2015110900 32 kts
2015110912 32 kts
2015111000 31 kts
2015111012 29 kts
Probability of Rapid Intensification(RI)(Intensity increase by 30 kts or more in next 24 hr)=9.4%
INFERENCE: RI probability VERY LOW


TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 00 UTC of 06-11-2015
TRACK PREDICTION BY IMD MME based on 00 UTC of 06-11-2015
FORECAST HOUR LAT LON
2015110600 13.5 63.2
2015110612 13.5 62.1
2015110700 13.3 60.8
2015110712 13.3 59.0
2015110800 13.1 57.0
2015110812 12.6 55.0
2015110900 12.7 52.8
2015110912 13.0 51.8
2015111000 14.0 51.0
TC: MEGH
INTENSITY PREDICTION based on 00 UTC of 06-11-2015
FORECAST HOUR INTENSITY
2015110600 35 kts
2015110612 35 kts
2015110700 36 kts
2015110712 36 kts
2015110800 36 kts
2015110812 33 kts
2015110900 30 kts
2015110912 30 kts
2015111000 27 kts
Probability of Rapid Intensification(RI)(Intensity increase by 30 kts or more in next 24 hr)=9.4%
INFERENCE: RI probability VERY LOW


TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 12 UTC of 06-11-2015
TRACK PREDICTION BY IMD MME based on 12 UTC of 06-11-2015
FORECAST HOUR LAT LON
2015110612 13.0 61.1
2015110700 12.8 59.8
2015110712 12.7 58.1
2015110800 12.3 56.1
2015110812 12.3 54.1
2015110900 12.4 51.8
2015110912 12.9 49.5
TC: MEGH
INTENSITY PREDICTION based on 12 UTC of 06-11-2015
FORECAST HOUR INTENSITY
2015110612 40 kts
2015110700 35 kts
2015110712 34 kts
2015110800 29 kts
2015110812 23 kts
2015110900 20 kts
2015110912 16 kts
Probability of Rapid Intensification(RI)(Intensity increase by 30 kts or more in next 24 hr)=5.2%
INFERENCE: RI probability VERY HIGH


TRACK PREDICTION BY IMD MULTIMODEL ENSEMBLE(MME)
based on 00 UTC of 07-11-2015
TRACK PREDICTION BY IMD MME based on 00 UTC of 07-11-2015
FORECAST HOUR LAT LON
2015110700 12.9 59.9
2015110712 12.7 58.0
2015110800 12.2 56.4
2015110812 12.1 53.8
2015110900 12.1 51.5
2015110912 12.5 49.4
2015111000 12.8 47.8
TC: MEGH
INTENSITY PREDICTION based on 00 UTC of 07-11-2015
FORECAST HOUR INTENSITY
2015110700 40 kts
2015110712 53 kts
2015110800 60 kts
2015110812 52 kts
2015110900 44 kts
2015110912 38 kts
2015111000 30 kts
Probability of Rapid Intensification(RI)(Intensity increase by 30 kts or more in next 24 hr)=5.2%
INFERENCE: RI probability VERY LOW

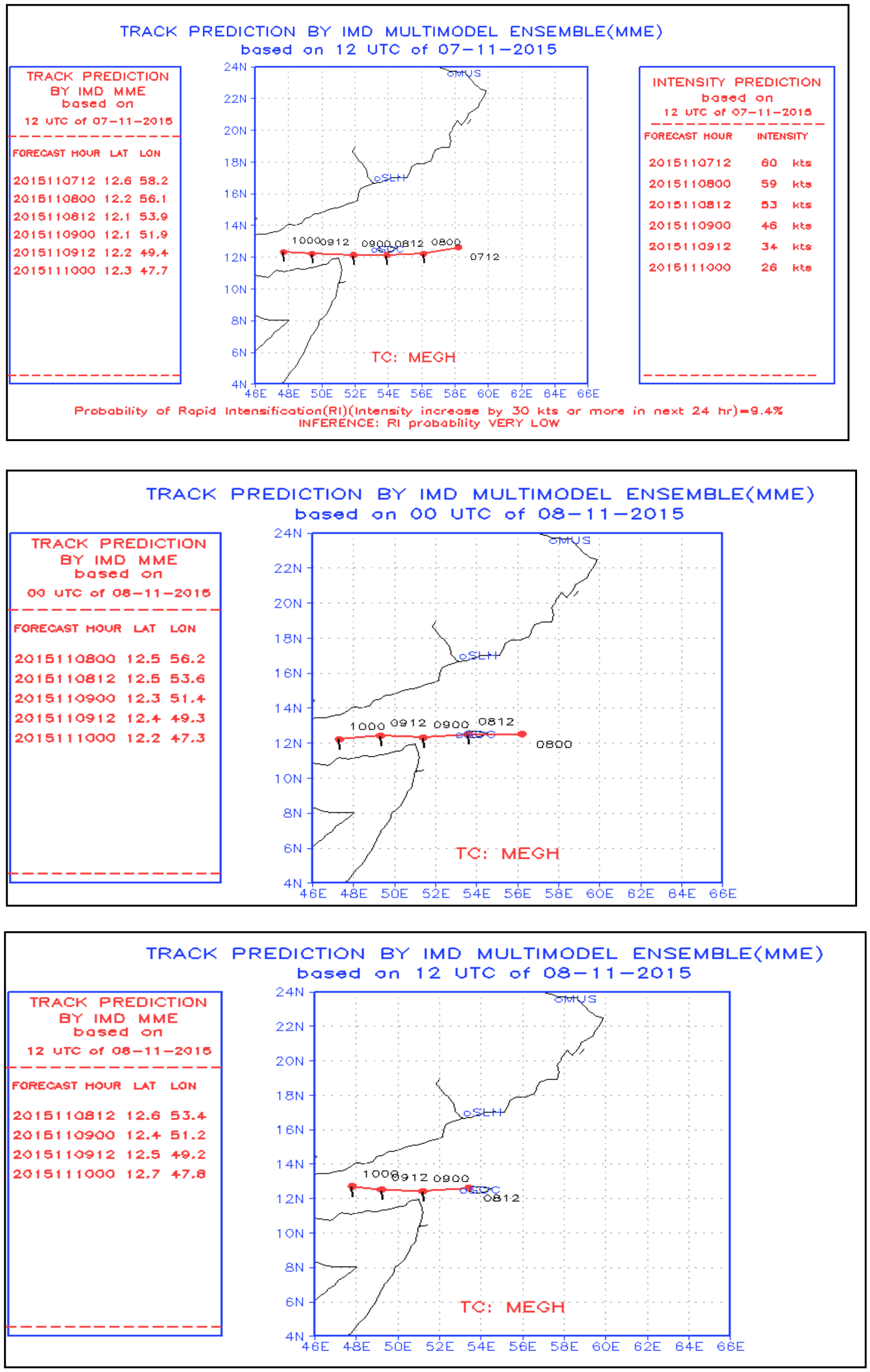


Fig. 3.21 Consensus track prediction by MME and Intensity forecast by SCIP model for ESCS, Megh

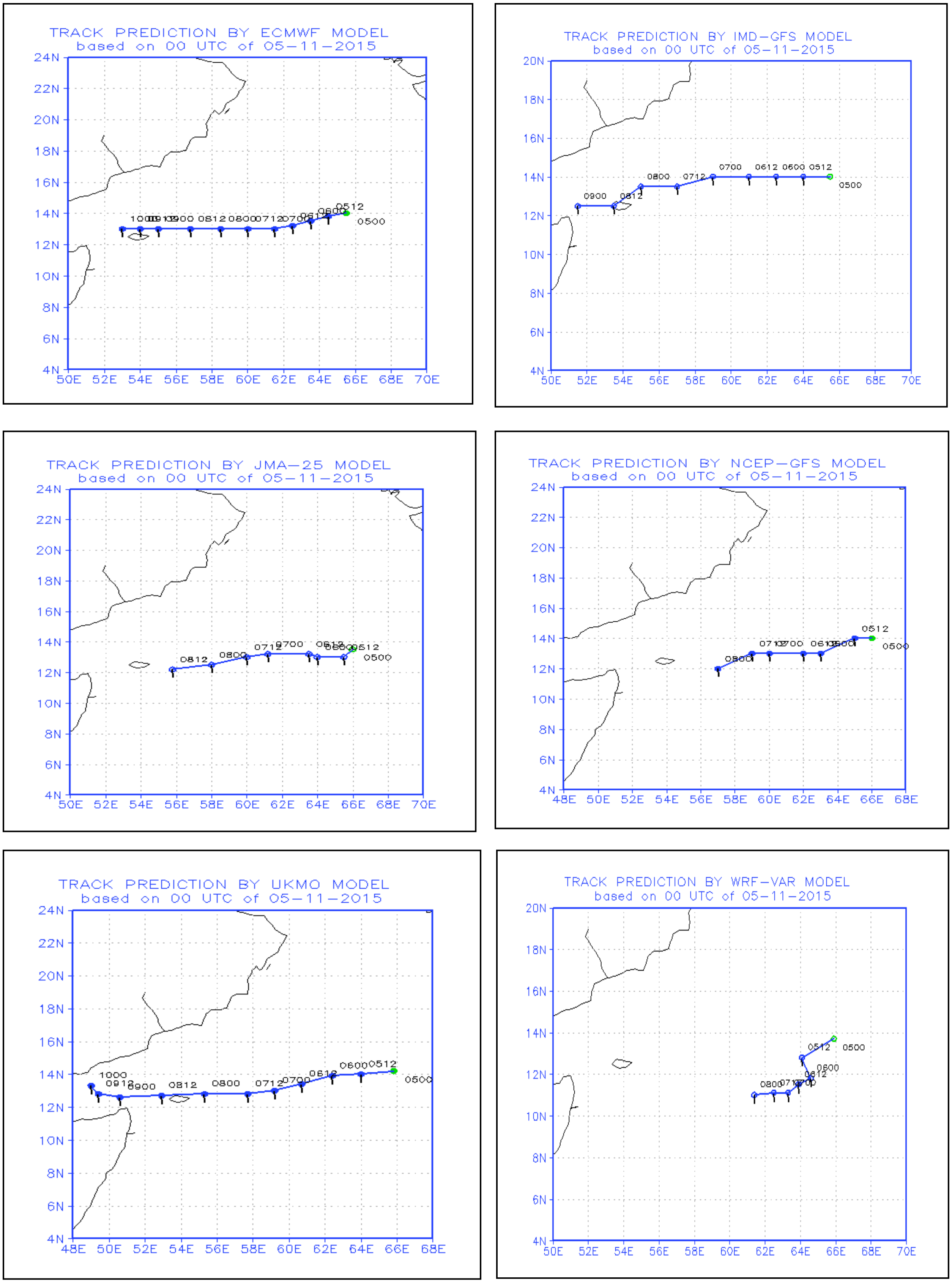


Fig 3.22 (a) Track prediction by NWP models based on 0000 UTC of 05.11.2015

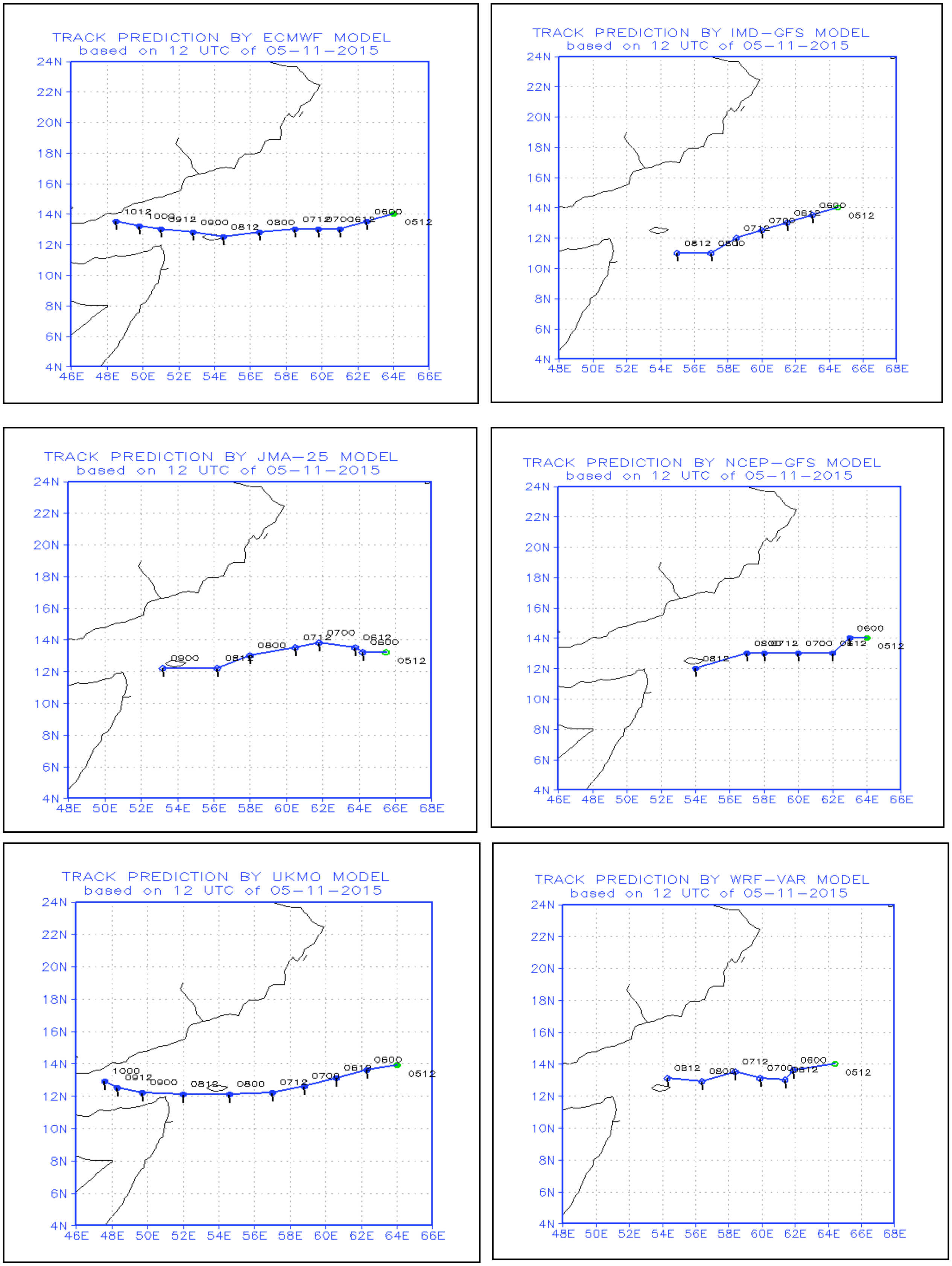


Fig 3.22(*b*) Track prediction by NWP models based on 1200 UTC of 05.11.2015

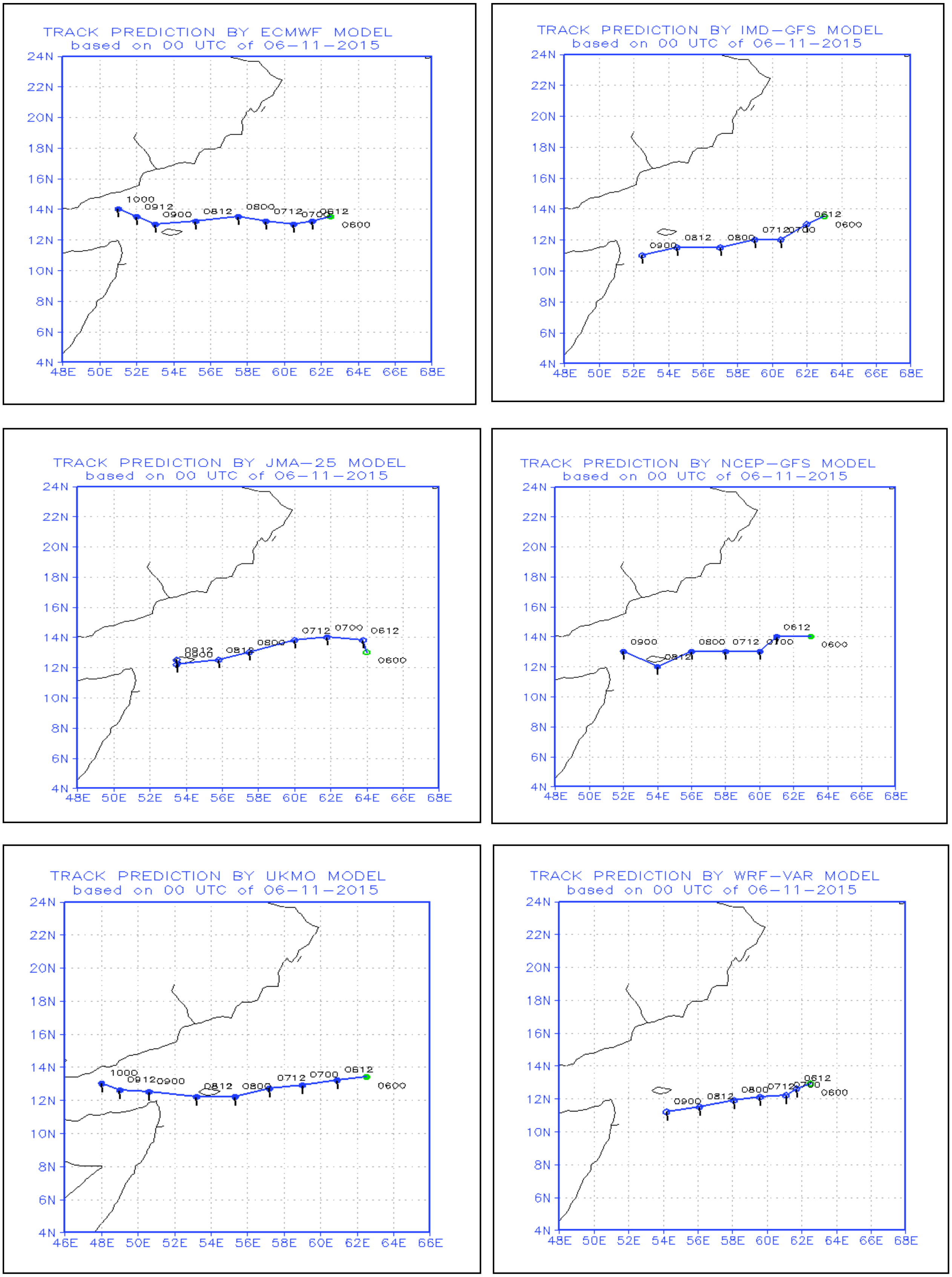


Fig 3.22(c) Track prediction by NWP models based on 0000 UTC of 06.11.2015

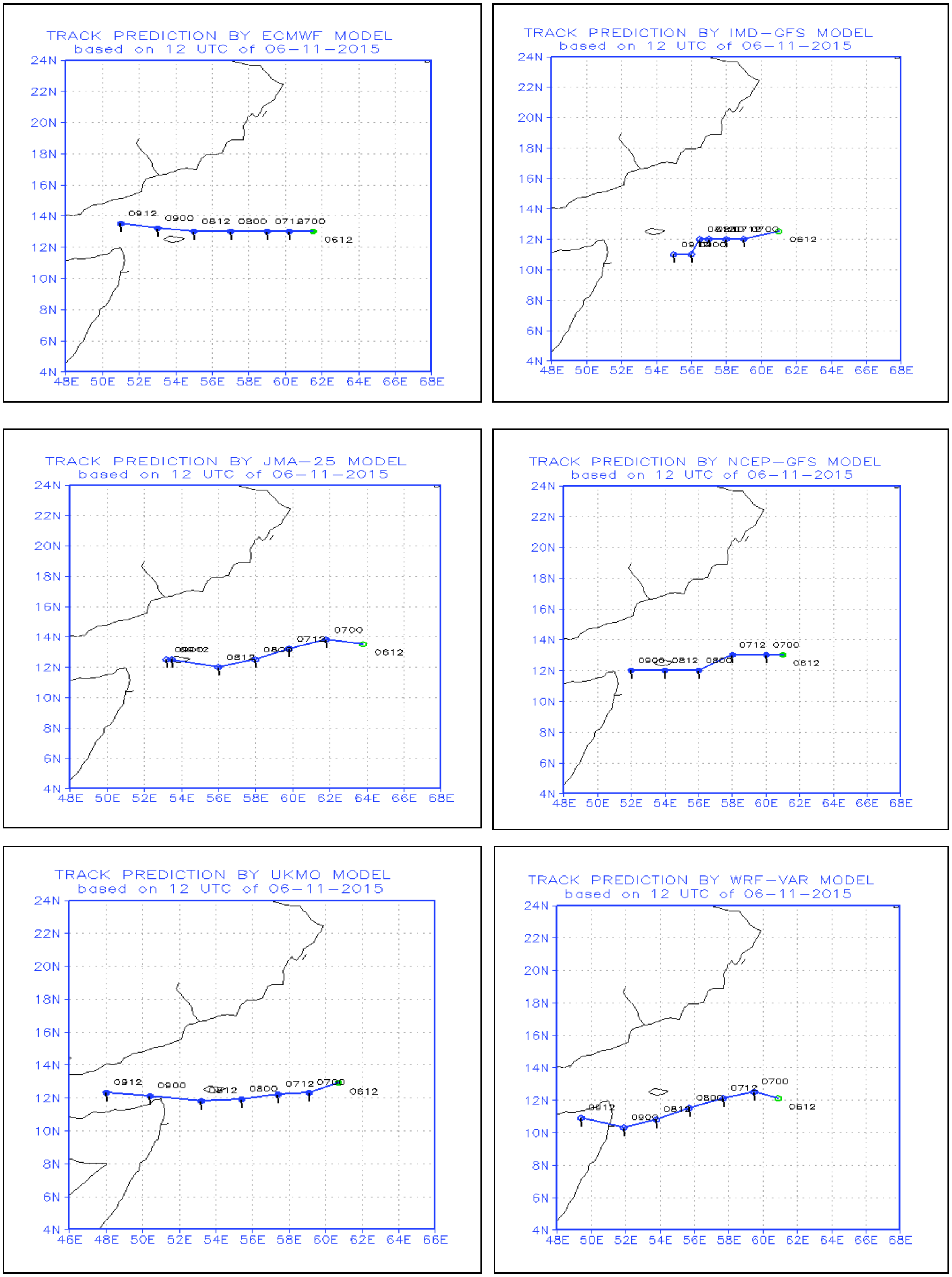


Fig. 3.22(d) Track prediction by NWP models based on 1200 UTC of 06.11.2015

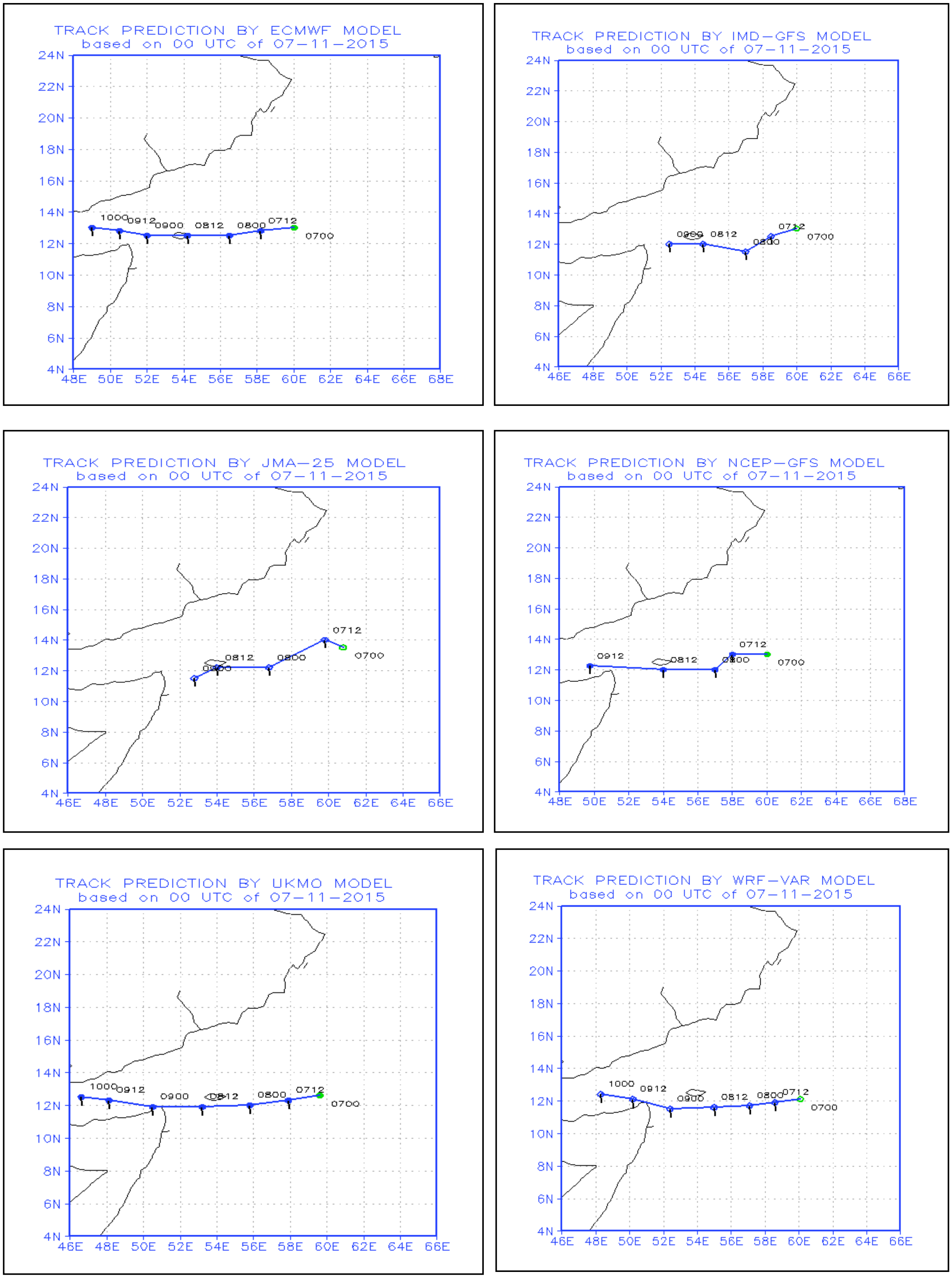


Fig 3.22(e) Track prediction by NWP models based on 0000 UTC of 07.11.2015

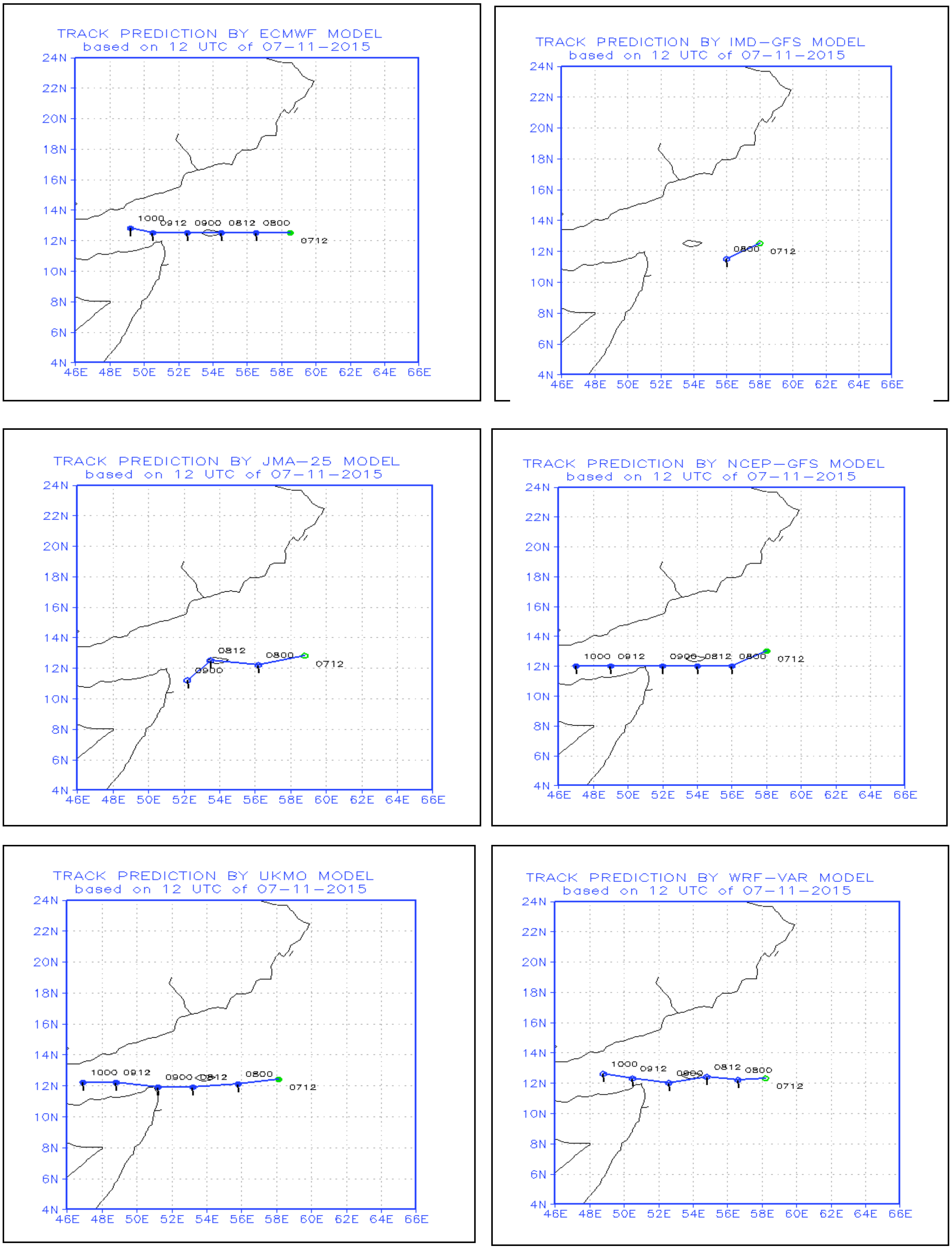


Fig. 3.22(f) Track prediction by NWP models based on 1200 UTC of 07.11.2015

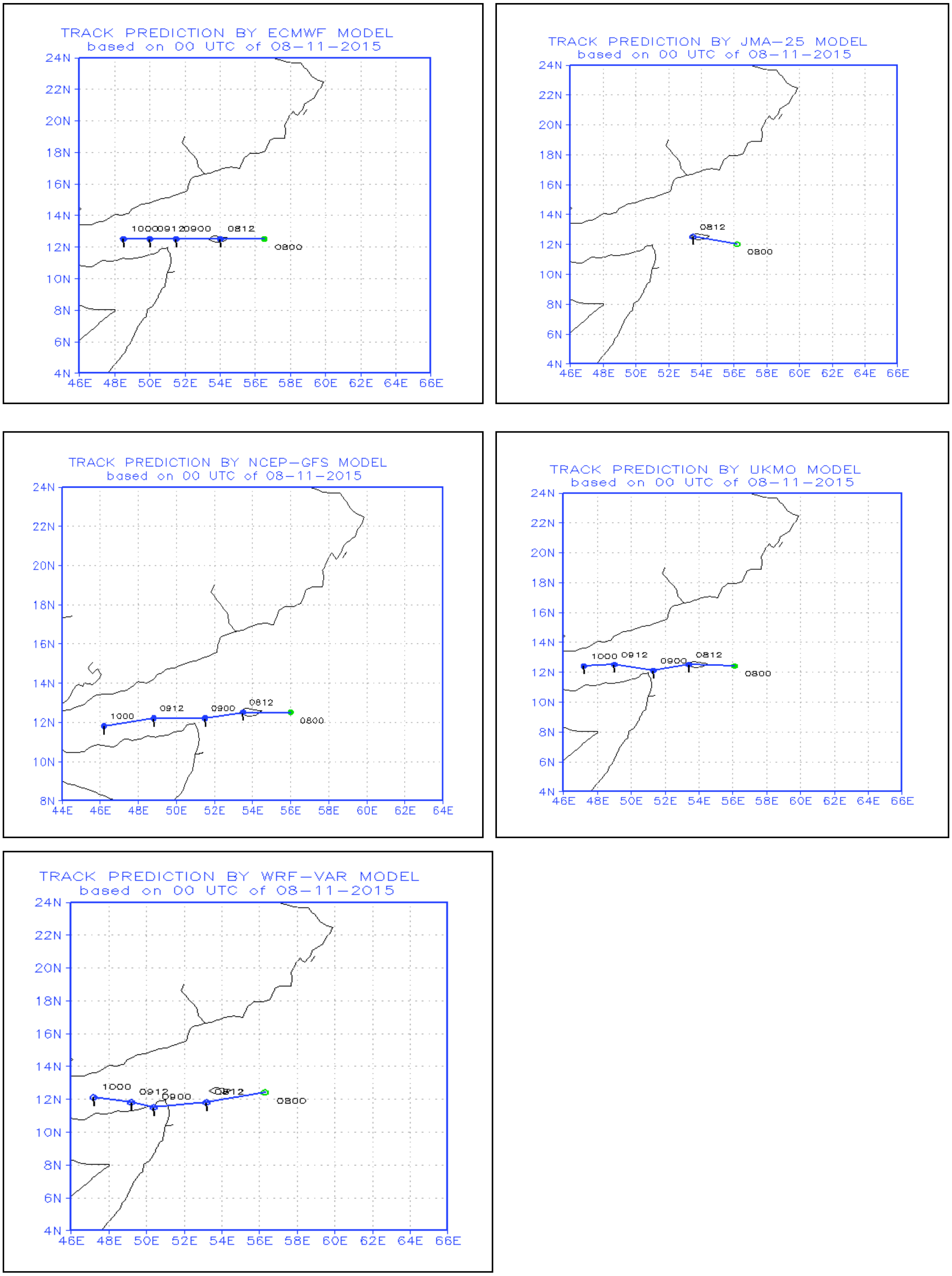


Fig. 3.22(g) Track prediction by NWP models based on 0000 UTC of 08.11.2015

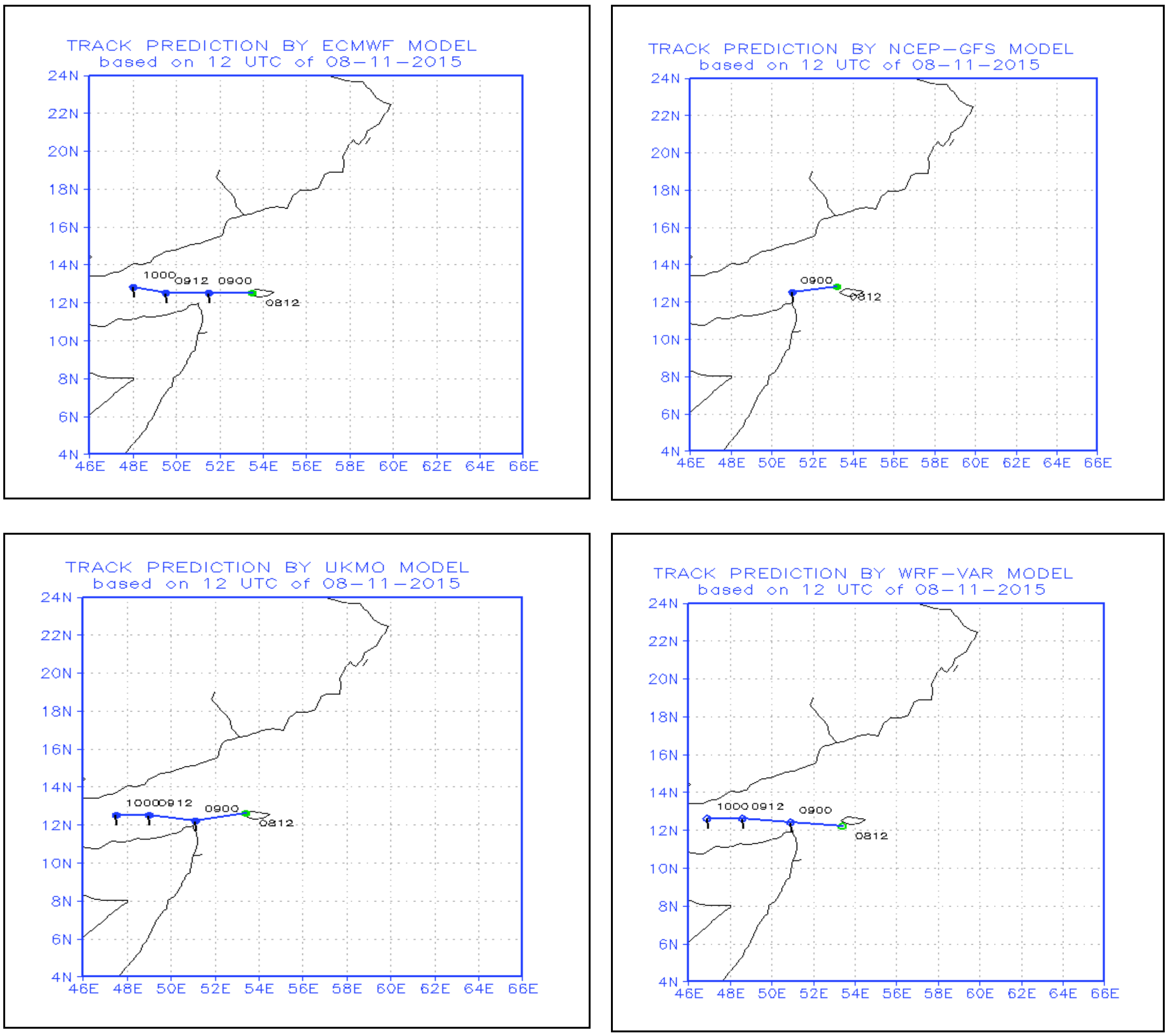
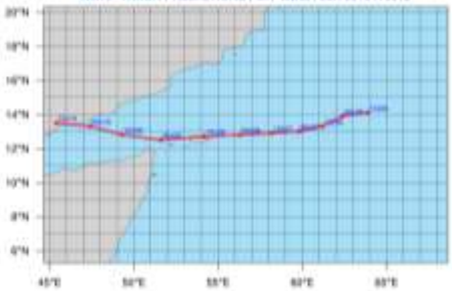


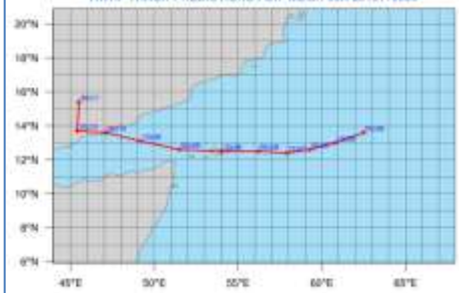
Fig. 3.22(h) Track prediction by NWP models based on 1200 UTC of 08.11.2015 for ESCS

HWRF TRACK PREDICTIONS FOR MEGH 05A 2015110512



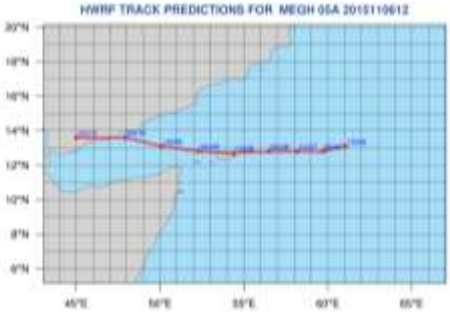
Dt/Hr	Lat	Lon	MSLP	Vmax
12z05	14.1	63.9	996.	33
00z06	13.9	62.4	999.	43
12z06	13.3	61.2	993.	55
00z07	13.0	59.8	978.	74
12z07	12.9	58.2	978.	79
00z08	12.8	56.3	973.	82
12z08	12.7	54.2	977.	73
00z09	12.5	51.6	981.	72
12z09	12.8	49.3	989.	58
00z10	13.3	47.4	998.	47
12z10	13.5	45.4	1007	20

HWRF TRACK PREDICTIONS FOR MEGH 05A 2015110600



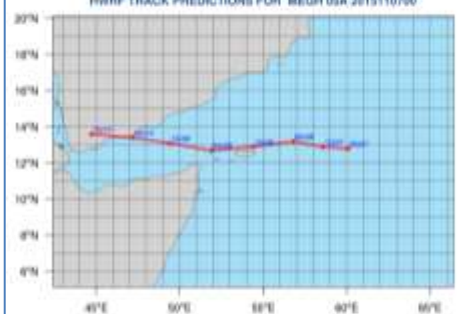
Dt/Hr	Lat	Lon	MSLP	Vmax
00z06	13.8	62.5	995.	38
12z06	13.0	60.8	992.	58
00z07	12.8	59.3	987.	58
12z07	12.4	57.9	977.	73
00z08	12.5	56.2	966.	90
12z08	12.5	54.0	972.	83
00z09	12.6	51.5	977.	79
12z09	13.1	49.2	990.	60
00z10	13.6	47.1	999.	49
12z10	13.7	45.4	1009	17
00z11	15.4	45.5	1011	16

HWRF TRACK PREDICTIONS FOR MEGH 05A 2015110612



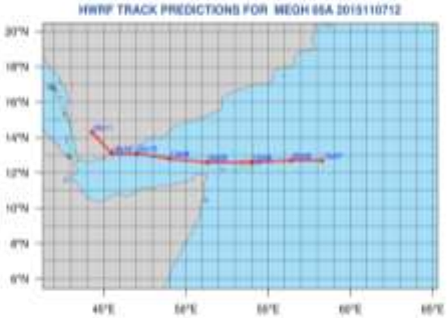
Dt/Hr	Lat	Lon	MSLP	Vmax
12z06	13.1	61.1	992	44
00z07	12.8	59.7	993	61
12z07	12.8	58.2	981	69
00z08	12.8	56.5	970	74
12z08	12.7	54.4	967	83
00z09	12.8	52.3	969	89
12z09	13.1	50.1	983	66
00z10	13.6	47.9	992	58
12z10	13.6	45.0	1007	17

HWRF TRACK PREDICTIONS FOR MEGH 05A 2015110700



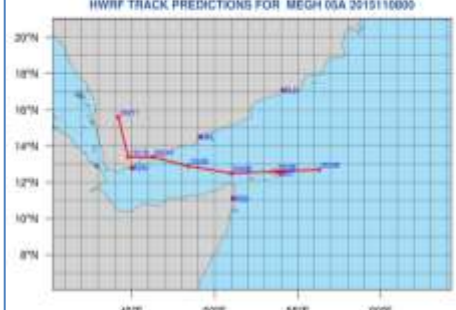
Dt/Hr	Lat	Lon	MSLP	Vmax
00z07	12.8	60.1	990.	46
12z07	12.9	58.6	984.	62
00z08	13.2	56.8	995.	58
12z08	12.9	54.4	980.	67
00z09	12.7	51.9	978.	76
12z09	13.1	49.4	989.	58
00z10	13.4	47.2	994.	53
12z10	13.6	44.7	1008	17

HWRF TRACK PREDICTIONS FOR MEGH 05A 2015110712



Dt/Hr	Lat	Lon	MSLP	Vmax
12z07	12.7	58.3	981.	57
00z08	12.7	56.4	983.	63
12z08	12.6	54.0	985.	66
00z09	12.8	51.3	988.	74
12z09	12.8	49.0	989.	57
00z10	13.1	47.3	993.	56
12z10	13.1	45.5	1006	28
00z11	14.3	44.5	1010	24

HWRF TRACK PREDICTIONS FOR MEGH 05A 2015110800



Dt/Hr	Lat	Lon	MSLP	Vmax
00z08	12.7	56.3	954.	92
12z08	12.6	53.7	972.	73
00z09	12.5	51.0	972.	84
12z09	12.9	48.4	988.	65
00z10	13.4	46.3	996.	50
12z10	13.4	44.8	1008	21
00z11	15.6	44.2	1009	14

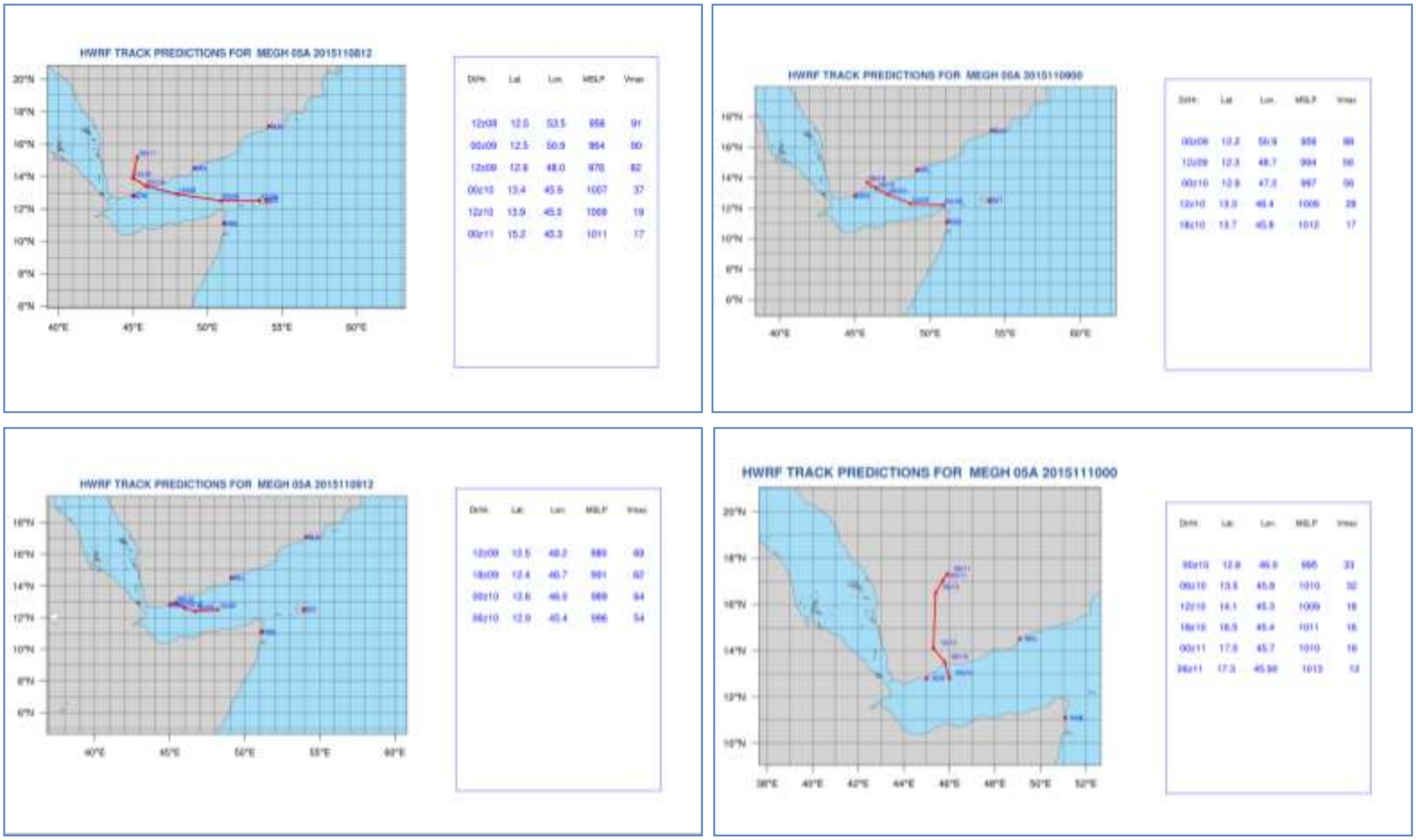


Fig. 3.23 Track and intensity prediction by IMD-HWRF model for ESCS, Megh

Table 3.15 Average track forecast errors (Direct Position Error) in km (Number of forecasts verified)

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
D-GFS	79(6)	88(5)	101(5)	185(5)	281(4)	349(4)	22(1)	59(1)	-	-
D-WRF	81(8)	132(8)	160(8)	215(7)	263(6)	304(5)	-	-	-	-
IA	172(7)	165(6)	194(6)	205(5)	219(4)	343(4)	364(3)	-	-	-
CEP	61(8)	80(7)	81(7)	81(7)	116(6)	118(3)	-	-	-	-
KMO	45(8)	80(8)	103(8)	105(7)	84(6)	77(5)	105(3)	87(3)	143(2)	285(1)
CMWF	44(8)	77(8)	128(8)	163(7)	205(6)	246(5)	336(3)	427(3)	511(2)	466(2)
D-HWRF	36(19)	47(17)	57(15)	55(13)	77(12)	09(10)	121(8)	130(6)	190(4)	229(3)
D-MME	52(8)	69(8)	101(8)	92(7)	111(6)	139(5)	210(3)	297(3)	327(2)	358(2)

The average track forecast errors are presented in Table 3.15. It was minimum in case of ECMWF for 12 hr, MME for 24 hr, NCEP-GFS for (36-48) hrs, UKMO for 60-72 hrs, IMD-GFS for 84-96 hrs, UKMO for 108 hrs and IMD-HWRF for 120 hrs forecast. Most of the models failed to predict landfall over Yemen except IMD-HWRF model.

Table 3.16 Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
IMD-SCIP (AAE)	12.7(6)	21.5(6)	31.3(6)	38.8(6)	43.7(6)	48.6(5)	51.7(3)	40.0(3)	32.5(2)	25.0(1)
MD-SCIP (RMSE)	14.2	23.3	34.5	42.4	46.3	50.7	52.4	42.5	34.5	25.0

Table 3.17 Average Absolute Error (INTENSITY) of IMD-HWRF Model
(Number of forecasts verified is given in the parentheses)

Lead Time	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	20hr
AAE	12 (19)	12 (17)	13(15)	11 (13)	12 (12)	13(10)	12(8)	14(6)	18(4)	12(3)
RMSE	13.5(19)	13.6(17)	15(15)	13.7(13)	14.4(12)	16.2(10)	16(8)	15.8(6)	20.8(4)	15(3)

The intensity forecast errors of SCIP and HWRF models are presented in Table 3.16 and 3.17 respectively. Like the case of Chapala, the performance of HWRF model was better than that of SCIP model. The error was very high in case of SCIP model.

The track prediction by EPS are presented in Fig. 3.24

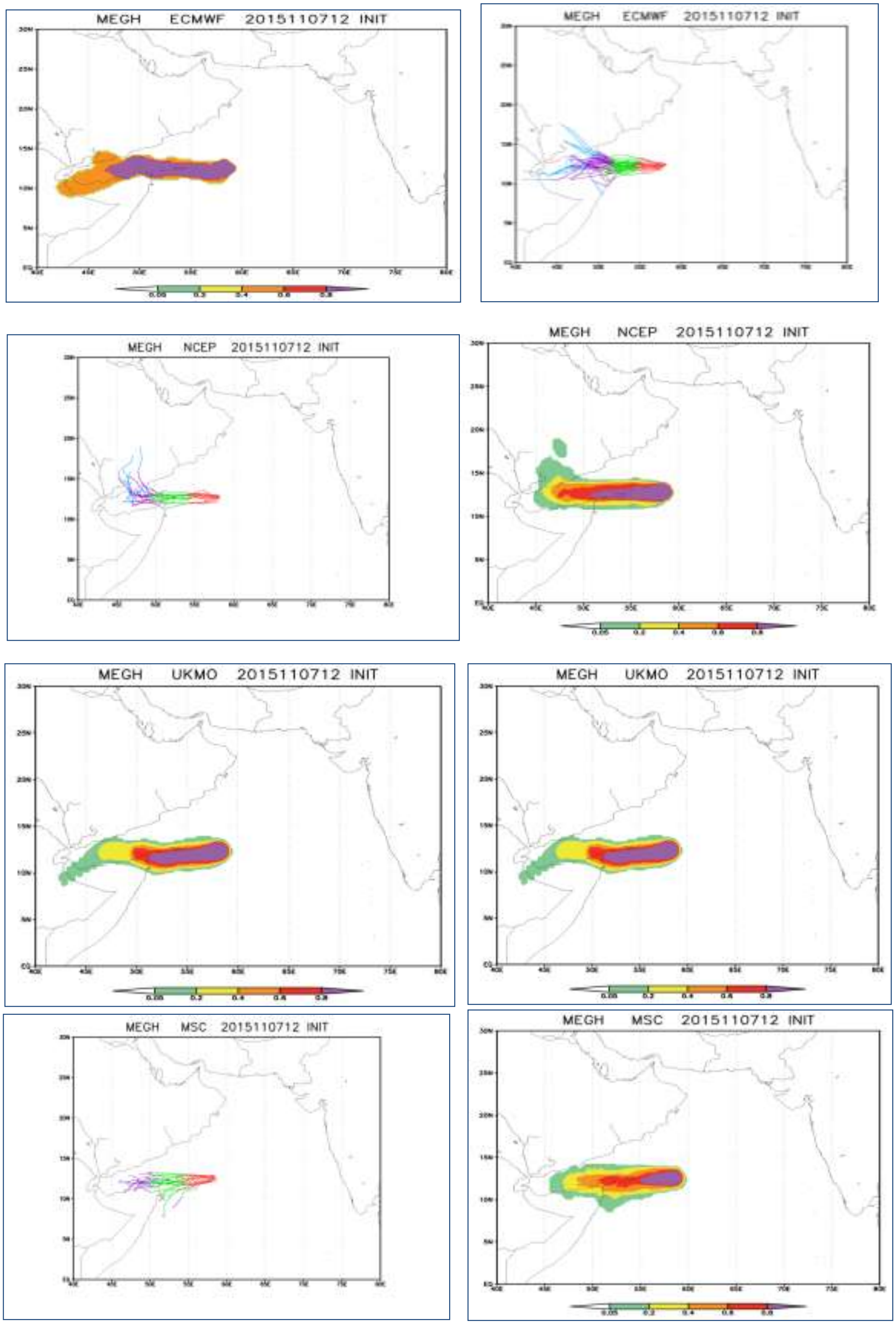


Fig. 3.24(a) based on 12 UTC of 07.11.2015

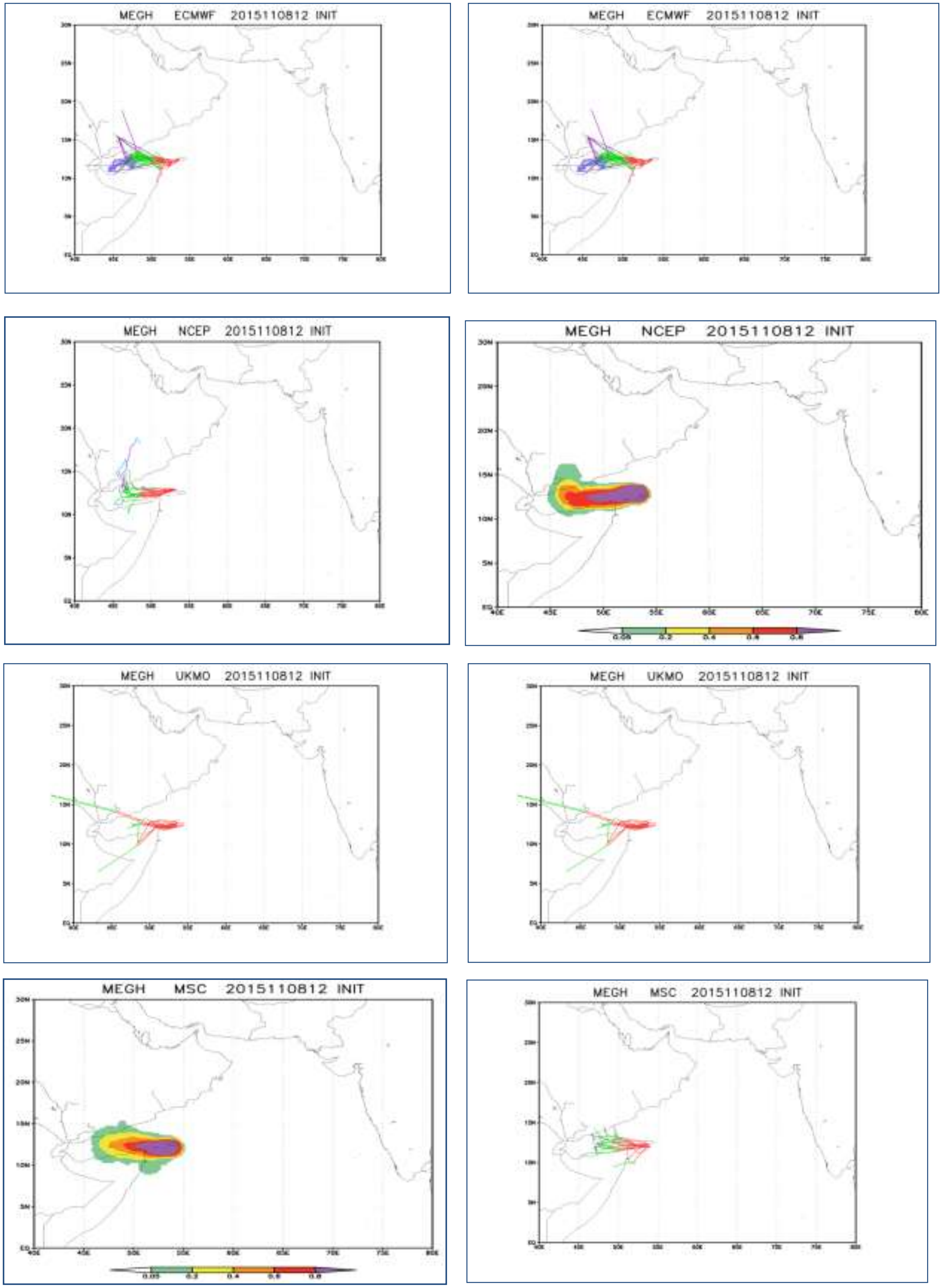


Fig 3.24(b) based on 12 UTC of 08.11.2015

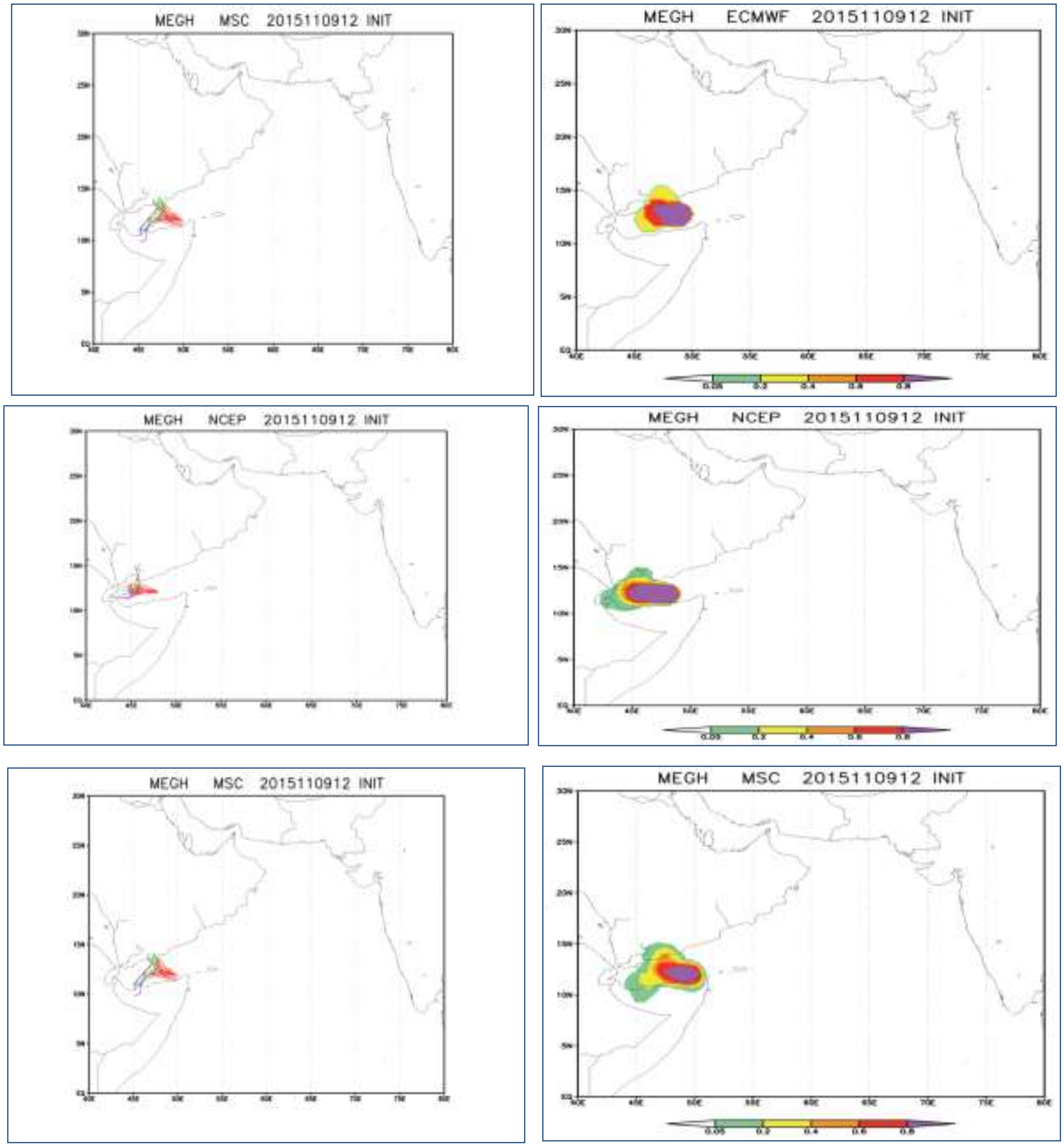


Fig 3.24(c) based on 12 UTC of 09.11.2015

3.7. Deep Depression over the Bay of Bengal during 08-10, November 2015

3.7.1. Grid point analysis and forecast of GPP

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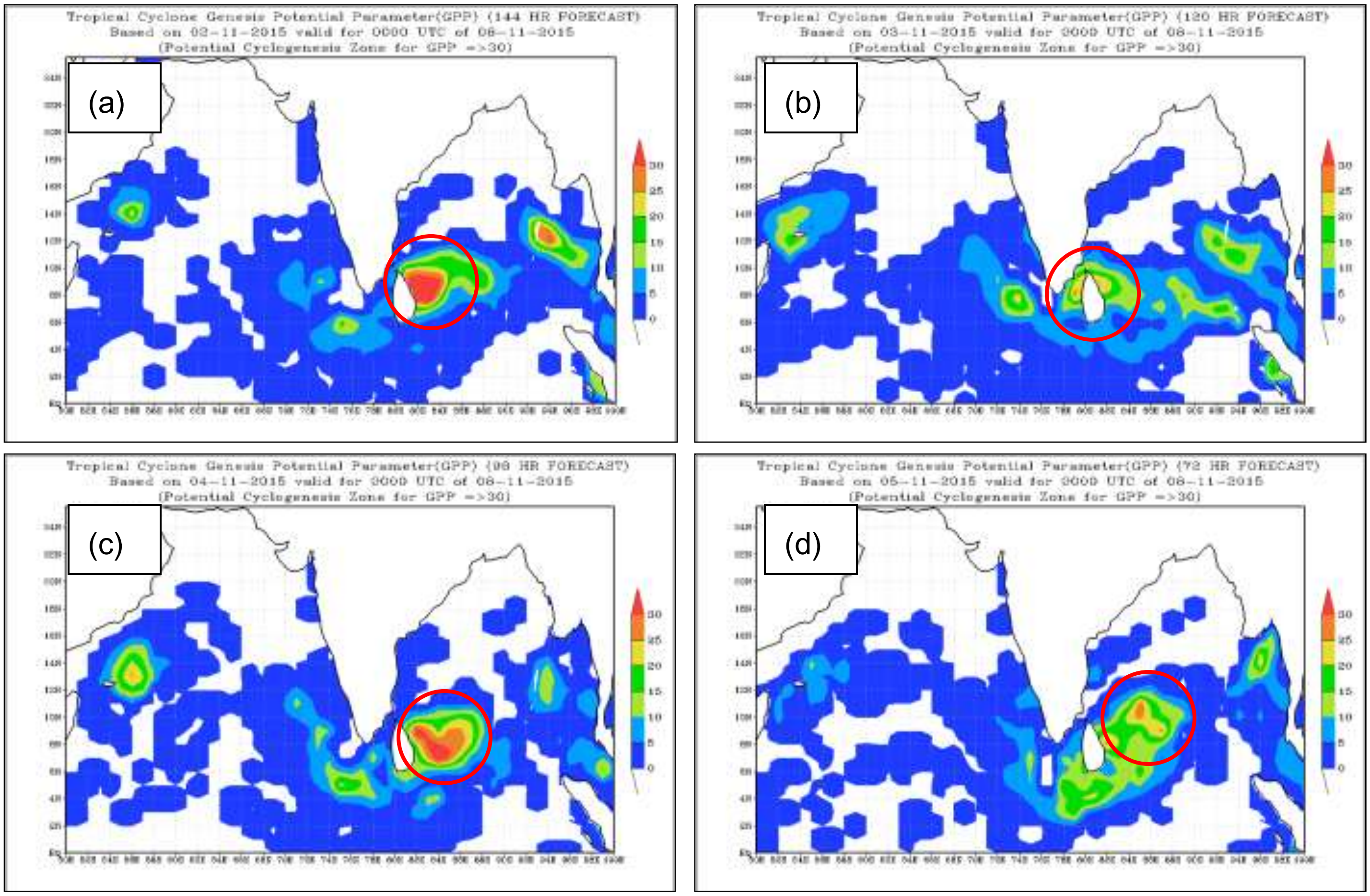

Fig. 3.25(a-d) Predicted zone of cyclogenesis based on 0000 UTC of 2-8 Nov. 2015

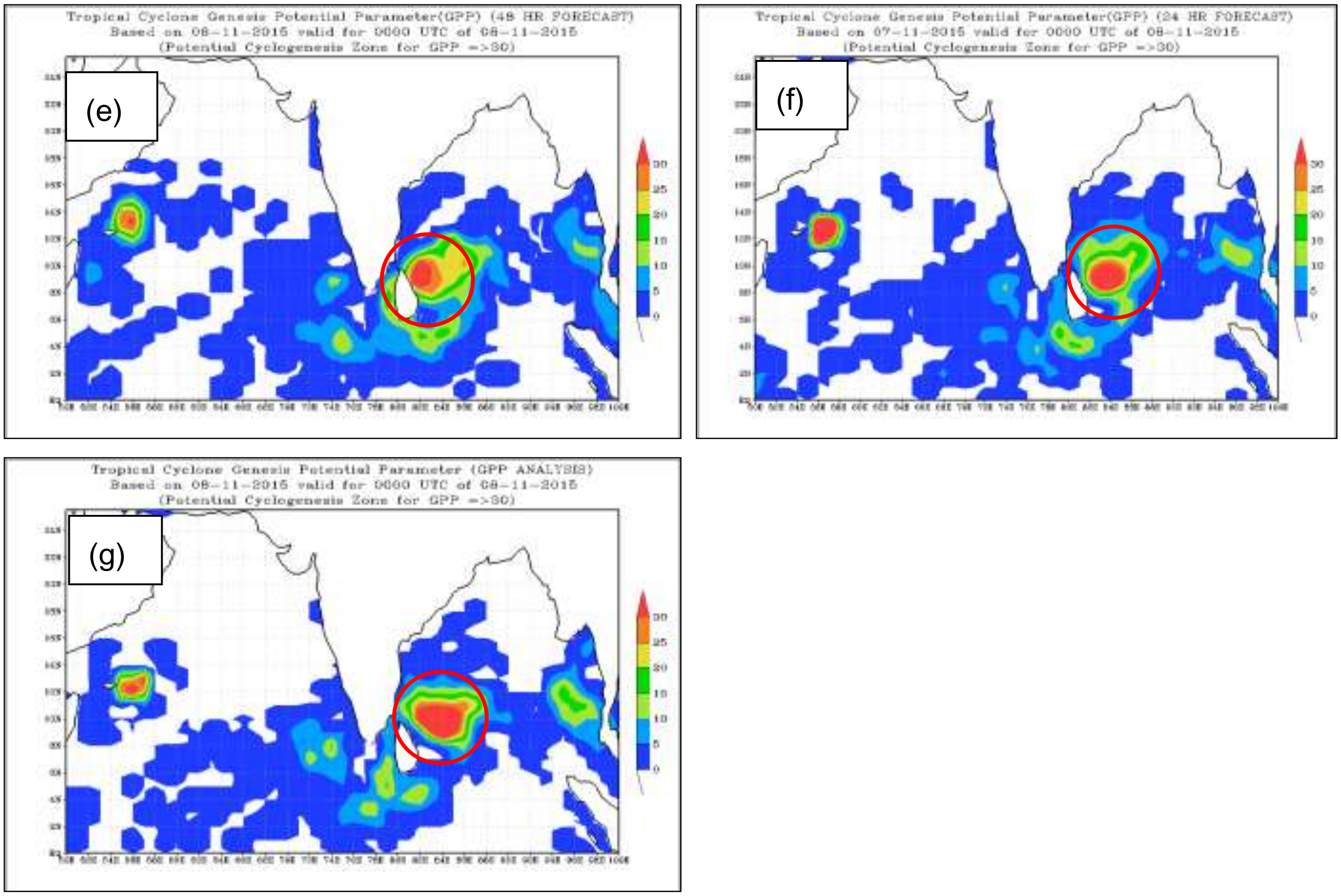

Fig. 3.25(e-g) Predicted zone of cyclogenesis based on 0000 UTC of 2-8 Nov. 2015

Grid point analysis and forecasts of GPP (Fig.3.25(a-g)) shows that it over predicted the intensity of the system.

3.7.2 Area average analysis of GPP

Conditions for genesis:

(i) Developed system (T3.0 or more): Threshold value of GPP ≥ 8.0 (ii) Non-developed system (T2.5 or less): Threshold value of GPP < 8.0

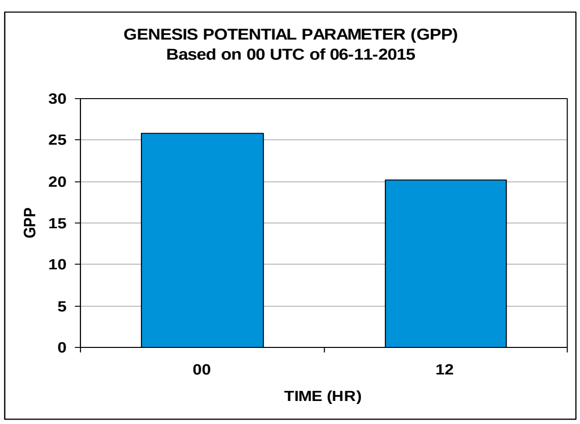

Fig. 3.26 Area average analysis and forecasts of GPP based on 0000 UTC of 06.11.2015 (T1.0)

Analysis and forecasts of GPP (Fig.3.26) indicated formation of cyclone at early stages of development (T.No. 1.0).

3.7.3 Track and intensity prediction

Consensus track prediction by MME and Intensity forecast by SCIP model are presented in Fig. 3.27. The track prediction by individual model is presented in Fig 3.28

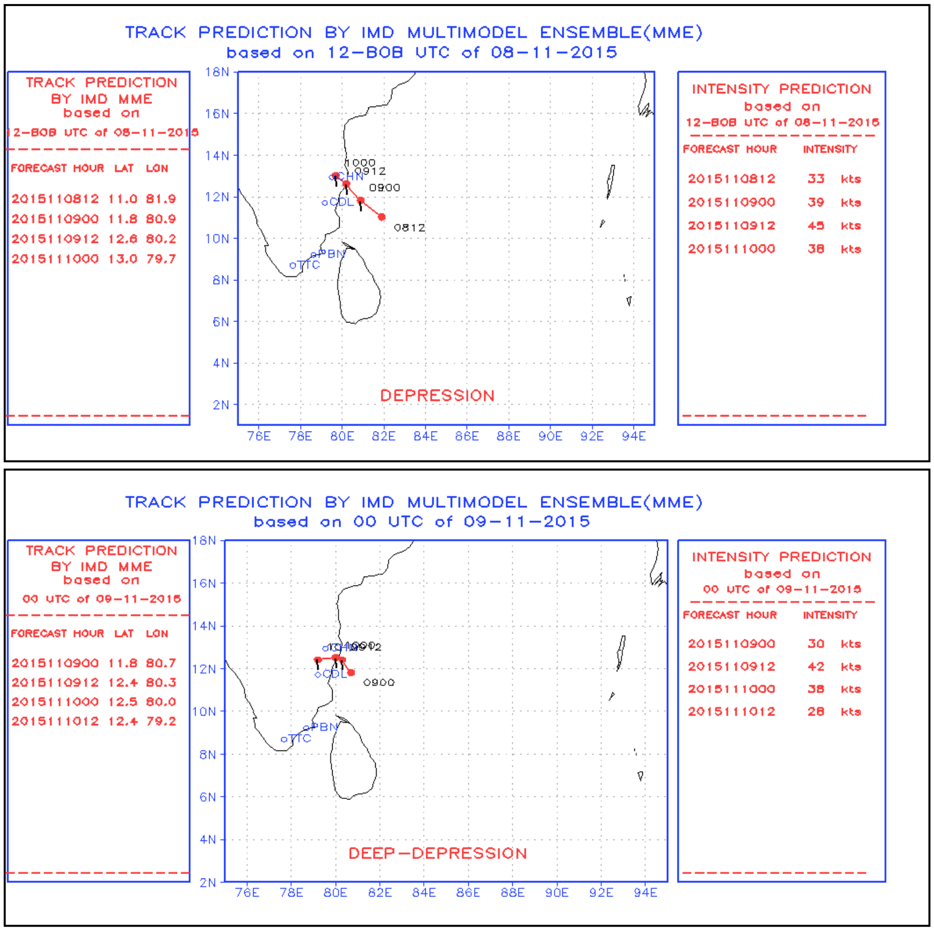

Fig. 3.27 Consensus track prediction by MME and Intensity forecast by SCIP model

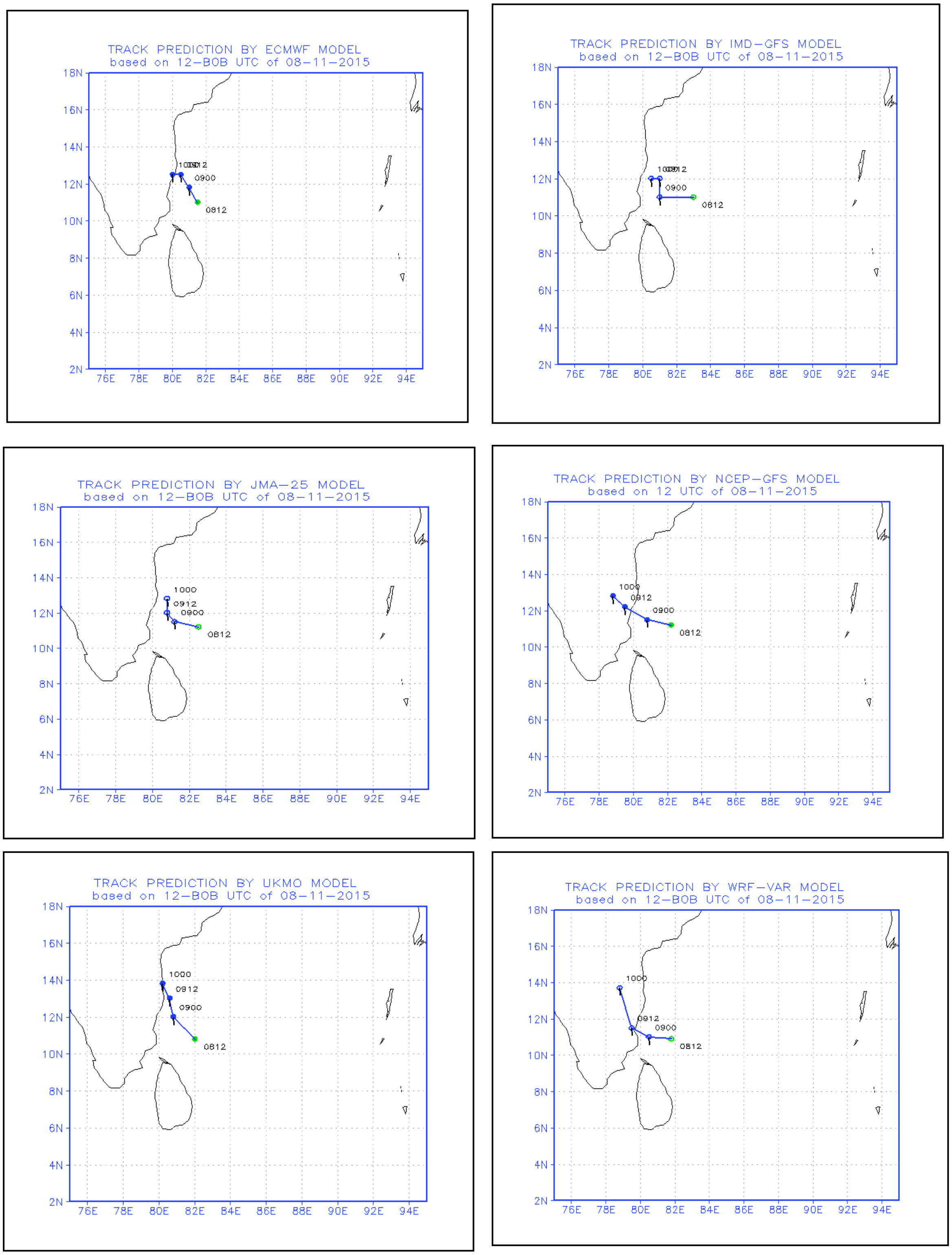

Fig 3.28(a) Track prediction by NWP models based on 1200 UTC of 08.10.2015

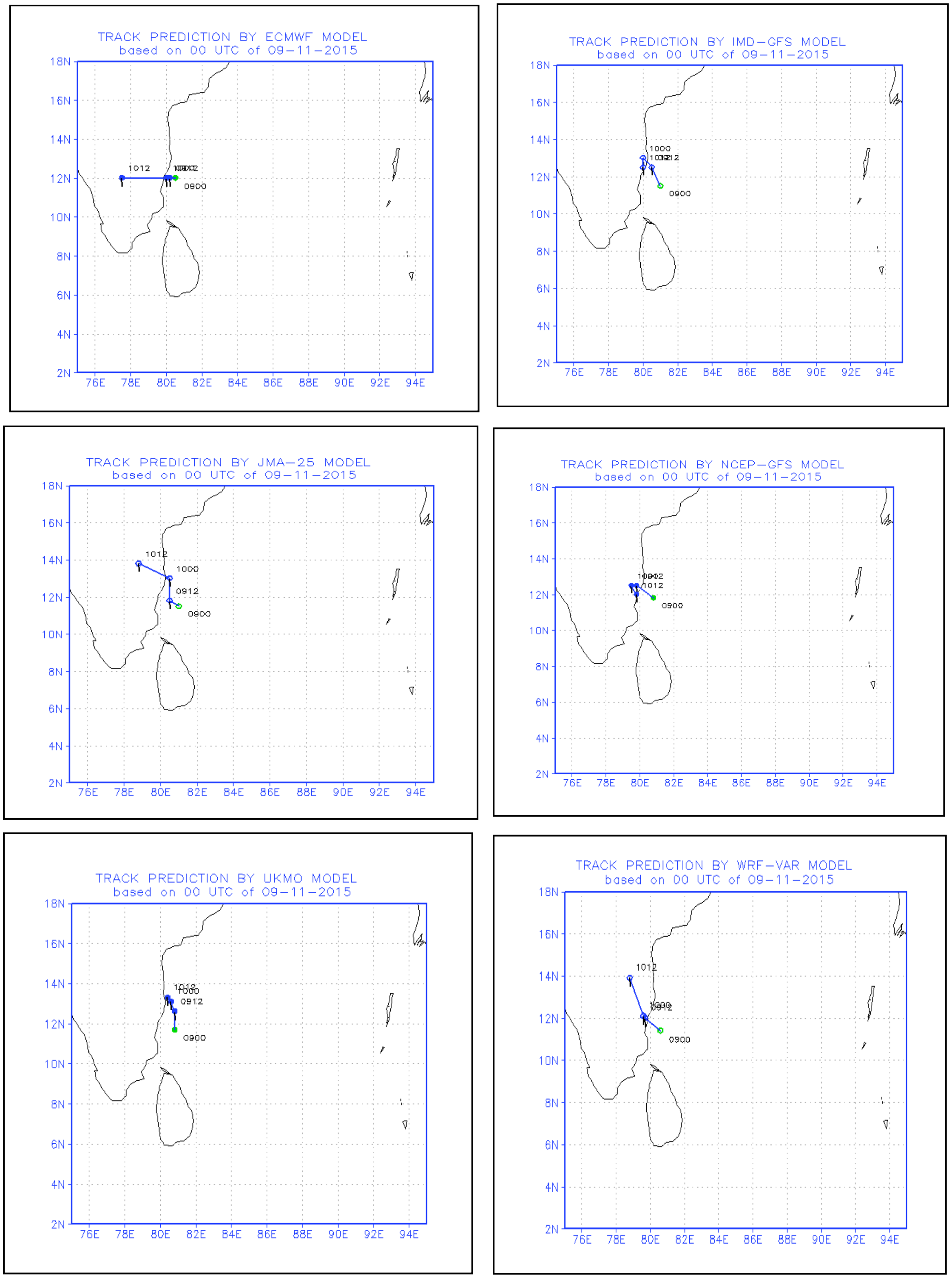

Fig 3.28(*b*) Track prediction by NWP models based on 0000 UTC of 09.10.2015

The track forecast errors of models are presented in Table 3.18. It was minimum in case of NCEP-GFS for 12 & 24 hrs forecasts and ECMWF for 36 hrs forecasts. The landfall point forecast error was minimum in case of ECMWF model and landfall time error in case of IMD-MME technique.

Table 3.18 Average track forecast errors (Direct Position Error) in km (Number of forecasts verified are given in parentheses)

Lead time	12 hr	24 hr	36 hr
IMD-GFS	63(2)	94(2)	107(1)
IMD-WRF	42(2)	60(2)	168(1)
JMA	60(2)	103(2)	138(1)
NCEP	33(2)	35(2)	97(1)
UKMO	85(2)	126(2)	169(1)
ECMWF	40(2)	66(2)	45(1)
IMD-MME	48(2)	52(2)	60(1)

Table 3.19 Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour)	14hr	26hr
IMD-GFS	70	**
IMD-WRF	31	114
JMA	91	**
NCEP-GFS	31	112
UKMO	113	81
ECMWF	25	33
IMD-MME	39	49

Table 3.20 Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	14hr	26hr
IMD-GFS	+4	**
IMD-WRF	-2	-3
JMA	+11	**
NCEP-GFS	-4	-5
UKMO	+24	+10
ECMWF	+10	+10
IMD-MME	-2	-2

The intensity forecast errors of SCIP model is presented in Table 3.21. It was about 8-12 knots for different forecast times upto 36 hrs.

Table 3.21 Average absolute errors (AAE) and Root Mean Square (RMSE) errors of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr
IMD-SCIP (AAE)	10.5(2)	11.5(2)	8.0(1)
IMD-SCIP (RMSE)	10.6	12.0	8.0

3.8 FORECAST SKILL OF GENESIS POTENTIAL PARAMETER (GPP), AVERAGE TRACK AND INTENSITY FORECAST ERRORS FOR CYCLONIC STORMS DURING 2015

3.8.1 Forecast Skill of Genesis potential parameter (GPP) during 2015

Since all low pressure systems do not intensify into cyclones, it is important to estimate the potential for intensification (into a cyclone) of a low pressure system at the early stages of development. Genesis potential parameter (GPP) used in real-time for distinguishing between developing and non-developing systems at their early stages (T-number 1.0, 1.5) of development.

Six metrics, such as the probability of detection (POD), the false alarm ratio (FAR), critical success index (CSI), equitable threat score (ETS), frequency bias (BIAS) and proportion correct (PC) have been computed to evaluate the skill of the GPP for genesis forecasts issued during 2015.

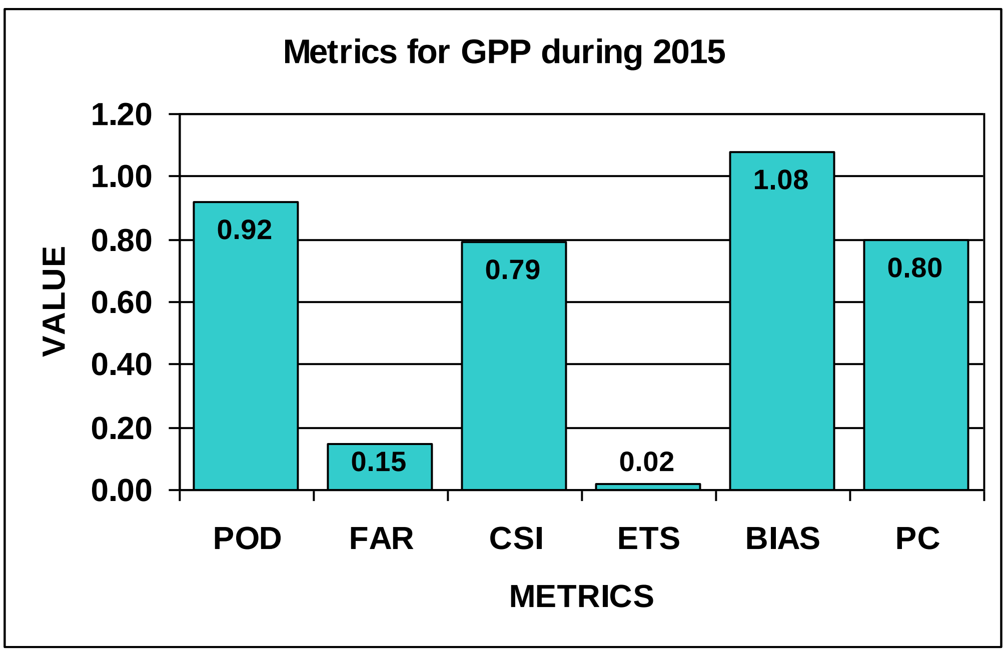

Fig. 3.29 POD, FAR, CSI, ETS, BIAS and PC for all genesis forecasts of GPP during 2015

Fig. 3.29 depicts the verification of the GPP forecasts for all cases during 2015. It can be seen from the figure that the POD of the GPP was 0.92, the FAR was 0.15, CSI was 0.79, ETS was 0.02, BIAS was 1.08 and PC was 0.80 for 59 forecast events during 2015. The results show that POD was much higher than FAR and near desirable value for BIAS and also high CSI and PC indicate that the GPP was skillful for cyclogenesis prediction. Forecast skill of GPP during the period 2008-2015 is depicted in the Fig. 3.30 below.

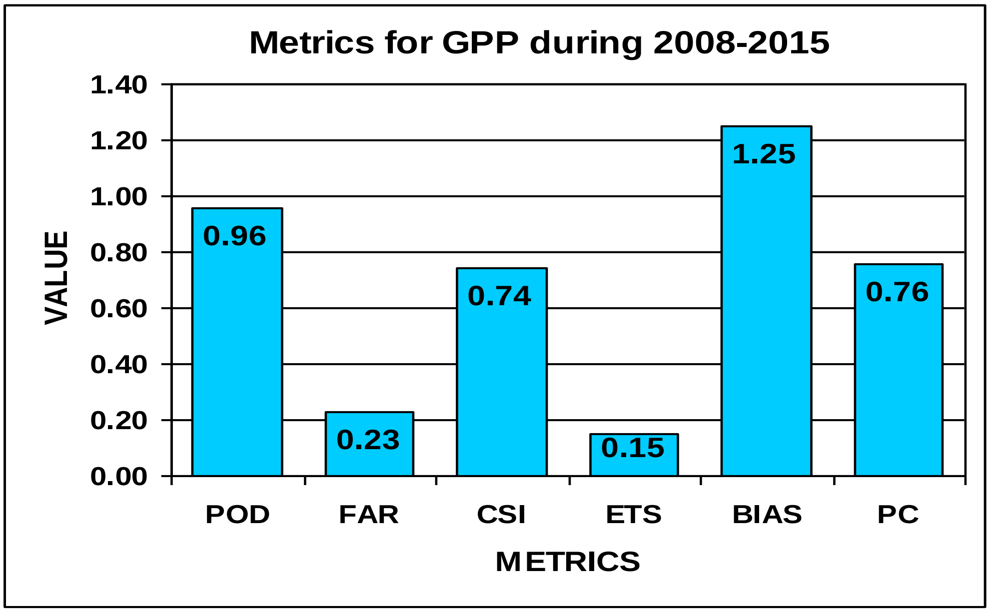

Fig. 3.30 POD, FAR, CSI, ETS, BIAS and PC for all genesis forecasts of GPP during 2008-2015

3.8.2 Mean track forecast error (km) – 2015

The annual average track forecast errors (Direct position error (DPE)) of various models for the systems ASHOBAA, KOMEN, DEEP DEPRESSION (9-12 October 2015 over Arabian Sea), CHAPALA, MEGH, and DEEP DEPRESSION (08-10, November 2015 over Bay of Bengal) over the North Indian Seas during the year 2015 are shown in Table 3.22. The 24 hr track forecast errors is less than 100 km for all models except IMDWRF, 48 hr track forecast errors is less than 150 km for all models except IMDGFS, IMDWRF and ECMWF, 72hr track forecast errors is more than 200 km except JMA, NCEP, UKMO, 96hr track forecast errors is more than 250 km for all models except IMDGFS, UKMO, and ECMWF, 120hr track forecast errors is more than 300 km for all models except for UKMO. Track forecast error of HWRF model ranged from 52 km at 12h to 429 km at 120h. Consensus track forecast error of MME ranged from 44 km at 12h to 353 km at 120h. Year wise MME track forecast error (km) during 2009-2015 is shown in Fig. 3.31 below. Mean MME track forecast error (km) during 2009-2015 (84h to 120h for the period 2013-2015) is presented I the Fig 3.32.

Table 3.22 Annual average track forecast errors (DPE) of various models for the year 2015 (Number of forecast verified given in the parentheses)

ad time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
D-GFS	1(22)	8(20)	18(18)	82(17)	31(14)	11(12)	45(7)	41(6)	75(4)	76(3)
D-WRF	1(36)	43(35)	71(31)	89(27)	0(22)9	38(19)	-	-	-	-
A	1(35)	8(32)	17(29)	36(25)	35(20)	75(18)	96(13)	-	-	-
EP	0(36)	75(33)	0(30)	05(27)	43(21)	87(16)	42(10)	17(7)	24(4)	39(3)
MO	7(35)	4(34)	2(30)	09(26)	24(21)	55(18)	22(12)	86(9)	64(5)	88(3)
MWF	8(36)	77(35)	13(31)	58(27)	12(22)	56(19)	28(13)	64(10)	98(6)	32(5)
D-HWRF	2(60)	73(56)	2(50)	31(41)	69(32)	18(26)	84(21)	36(17)	79(11)	29(8)
D-MME	4(36)	2(35)	78(31)	04(27)	30(22)	62(19)	33(13)	82(10)	02(6)	53(5)

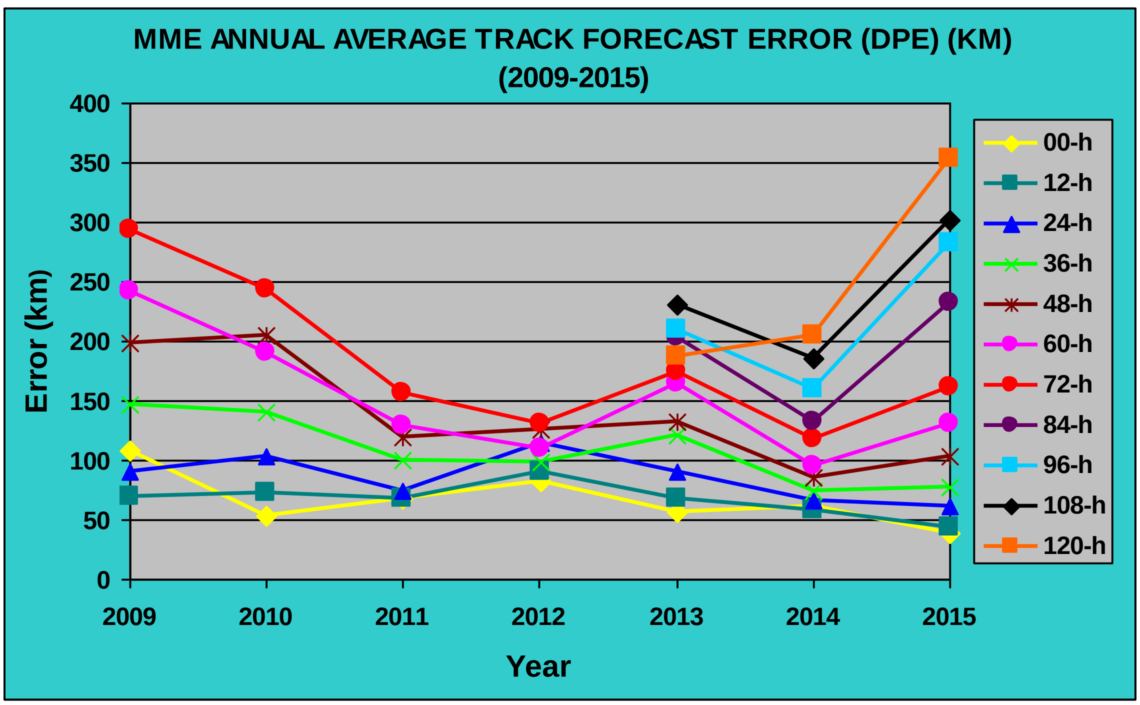

Fig. 3.31 Year wise MME track forecast error (km) during 2009-2015

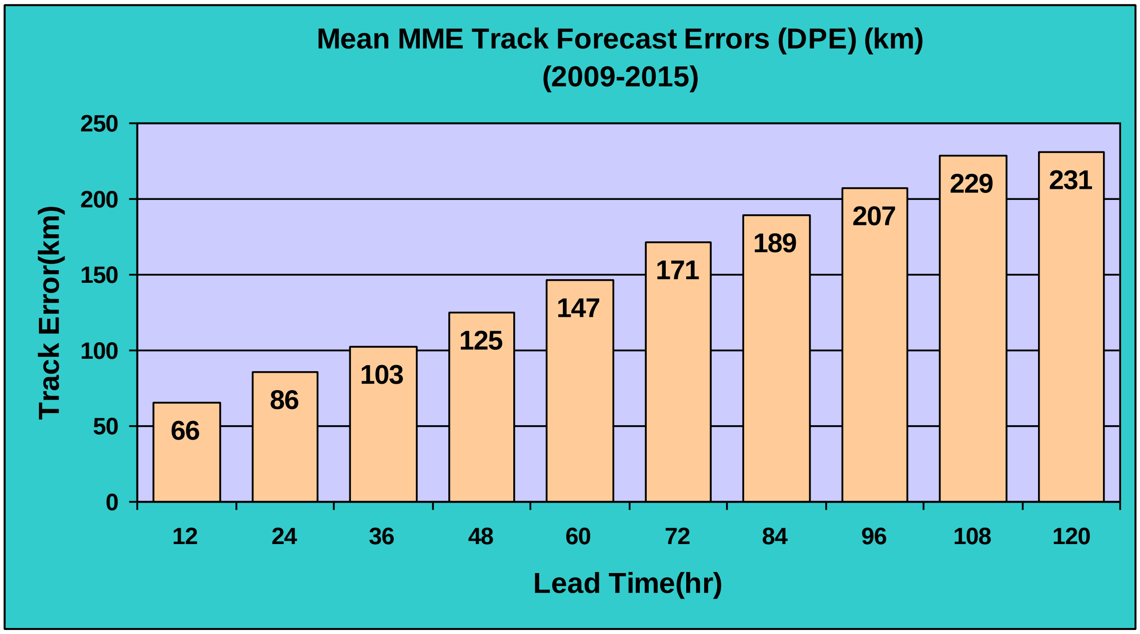

Fig. 3.32 Mean MME track forecast error (km) during 2009-2015 (84h to 120h for the period 2013-2015)

3.8.3 Mean Intensity forecast error (kt) -2015

I. SCIP model -2015

The annual average intensity forecast errors of SCIP model are shown in Table 3.23. The error is 12.6 kts at 24hr, 20.0 kts at 48hr and 25.5 kts at 72hr 22.9 kts at 96hr and 23.0 at 120 kts for all the systems (ASHOBAA, KOMEN, DEEP DEPRESSION (9-12 October 2015 over Arabian Sea), CHAPALA, MEGH, and DEEP DEPRESSION (08-10, November 2015 over Bay of Bengal) during 2015.

Table 3.23 The annual average intensity forecast errors (kt) of SCIP for all the systems during 2015 (Number of forecast verified given in the parentheses)

ead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
D-SCIP (AAE)	.5(32)	2.6(31)	5.8(27)	0.0(24)	3.8(20)	5.5(16)	3.2(11)	2.9(8)	4.8(4)	3.0(2)
IMD-SCIP (RMSE)	11.0	17.9	23.5	26.9	30.0	32.7	31.1	28.8	27.2	23.1

Year wise and mean intensity forecast error (kt) by SCIP model during 2008-2015 for 12h to 72h forecasts are presented in Fig 3.33 and Fig 3.34 below.

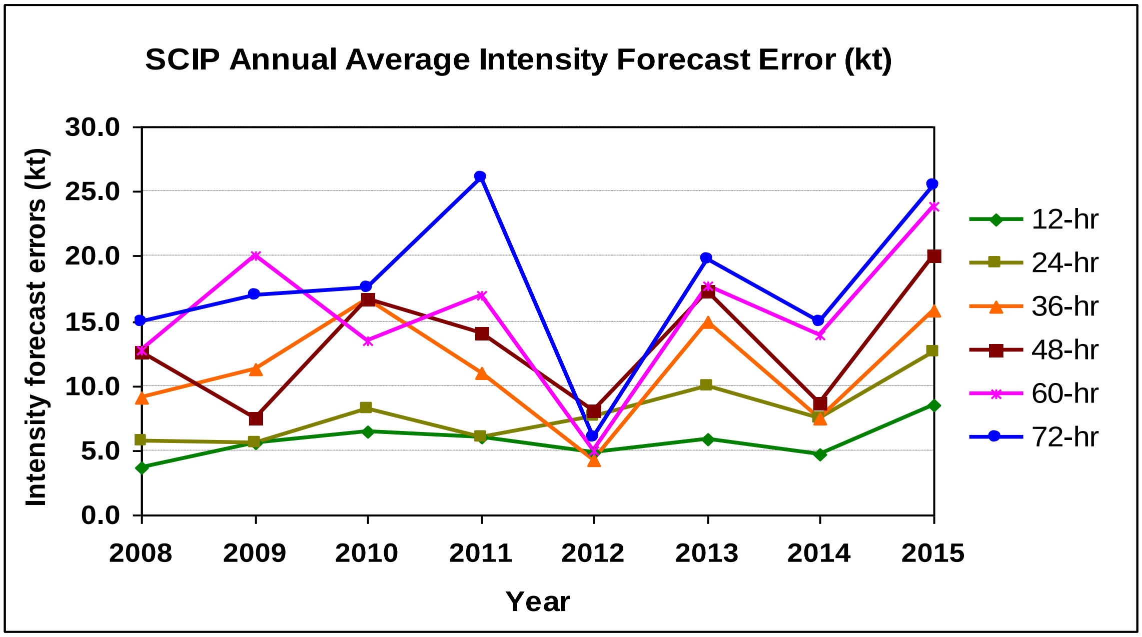

Fig. 3.33 Year wise intensity forecast error (kt) by SCIP model during 2008-2015 for 12h to 72h forecasts

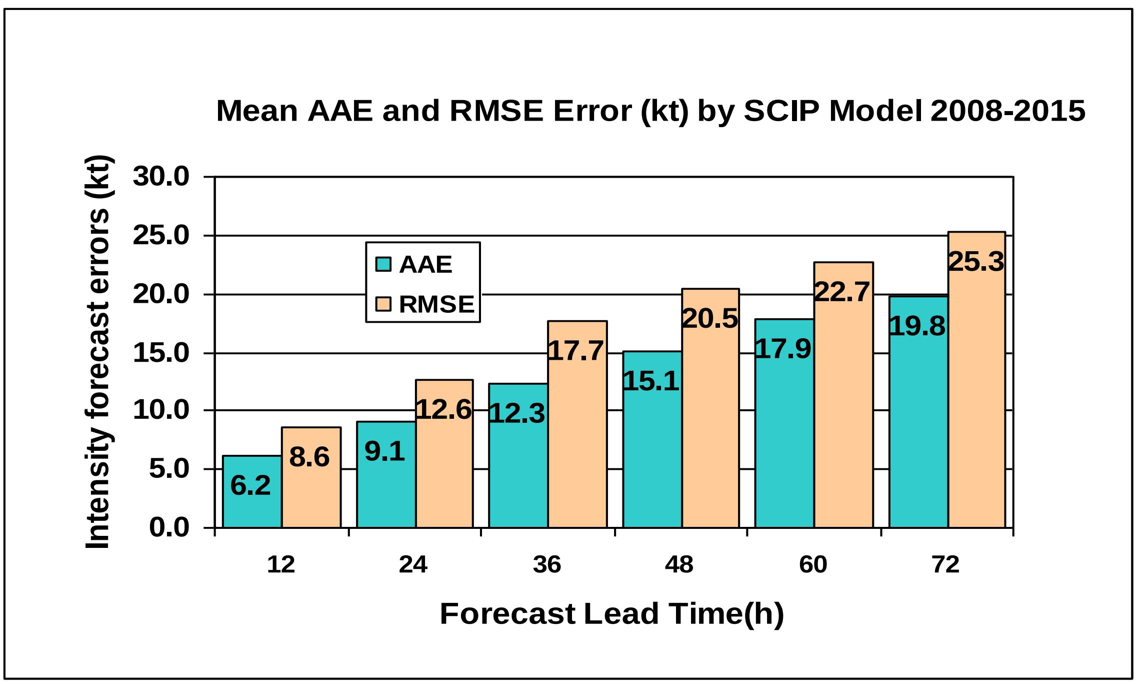

Fig. 3.34 Mean Intensity forecast error (kt) of SCIP model during 2008-2015

II. HWRF model -2015

The annual average intensity forecast errors (kt) of HWRF model for the systems (ASHOBAA, KOMEN, DEEP DEPRESSION (9-12 October 2015 over Arabian Sea), CHAPALA and MEGH) during 2015 are shown in Table 3.24.

Table 3.24 Average Absolute Error (kt) of INTENSITY of IMD-HWRF Model (Number of forecasts verified is given in the parentheses)

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr	120Hr
AAE	9.2(60)	9.1(56)	10.7(50)	10.2(41)	10.5(32)	13.2(26)	14.5(21)	14.4(17)	13.7(11)	14.2(8)
RMSE	11(60)	10.8(56)	12.6(50)	12.3(41)	12.6(32)	16.9(26)	18.8(21)	16.8(17)	16.4(11)	16(8)

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CHAPTER-IV

PERFORMANCE OF RSMC, NEW DELHI IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2015

4.1 Introduction

The Cyclone Warning Division/ Regional Specialized Meteorological Centre (RSMC)-Tropical Cyclone, IMD, New Delhi mobilized all its resources for monitoring and prediction of cyclonic disturbances over the north Indian Ocean during 2015. 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 Organization (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. The bulletins were also issued to Yemen and Somalia during the life period of cyclone Chapala and Megh which crossed Yemen coast during Nov, 2015. 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) to the Meteorological watch offices of Asia Pacific region and middle east countries. The TCAC bulletin was also sent to Aviation Disaster Risk Reduction (ADRR) centre of WMO at Hong Kong like previous years.

IMD continuously monitored, predicted cyclogenesis, track, intensity and structure of cyclones. The genesis forecast in probabilistic term was issued from 01 June 2015. Bulletins containing track & intensity forecast at +06, +12, +18, +24, +36, +48, +60, +72, +84, +96, +108 and +120. hrs or till the system weakened into a low pressure area warning issued regularly. The above structured track and intensity forecasts were issued from the stage of deep depression onwards. The cone of uncertainty in the track forecast was also given for all cyclones. The radius of maximum wind and radius of ≥ 34 kts, ≥ 50 kts and ≥ 64 kts wind in four quadrants of cyclone was also issued for every six hours. The graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were uploaded in the RSMC's website regularly. The storm surge guidance was provided as and when required to the member countries of WMO/ESCAP Panel based on IITD model. The prognosis and diagnosis of the systems were described in the special tropical weather outlook and tropical cyclone advisory bulletins since 2008.

The 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 2015 are analysed and discussed in sec.4.3.

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4.2 Bulletins issued by IMD

The following are the statistics of bulletins issued by IMD in association with the cyclonic disturbances during 2015

Bulletins issued during 'Ashobaa'

Bulletins for national disaster management agencies	:	21
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	38
Tropical cyclone advisory for international civil aviation	:	15

Bulletins issued during 'Komen'

Bulletins for national disaster management agencies	:	29
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	08
Tropical cyclone advisory for international civil aviation	:	05

Bulletins issued during ' Chapala'

Bulletins for national disaster management agencies	:	21
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	38
Tropical cyclone advisory for international civil aviation	:	15

Bulletins issued during 'Megh'

Bulletins for national disaster management agencies	:	18
Bulletin for WMO/ESCAP Panel counties (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	43
Tropical cyclone advisory for international civil aviation	:	21

Bulletins issued for all cyclones during 2015

Bulletins for national disaster management agencies	:	89
RSMC bulletin for WMO/ESCAP Panel member countries (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	127
TCAC bulletin for international civil aviation	:	56

***Bulletins issued for all cyclonic disturbances (depression and above) during 2015**

Bulletins for national disaster management agencies	:	110
RSMC bulletin for WMO/ESCAP Panel member countries: (Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	170
TCAC bulletin for international civil aviation	:	71

* It does not include the bulletins issued during monsoon depressions (June – September)

The number of bulletins issued during 2009-2015 for CDs (depression and above) over the NIO is shown in Fig.4.1 for comparison.

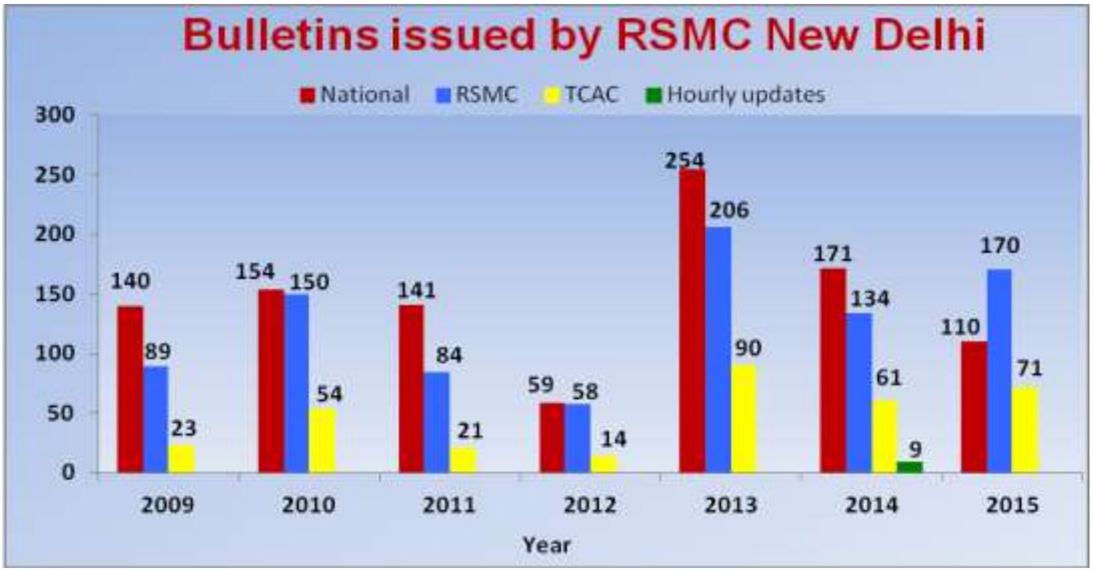


Fig 4.1: Total Number of bulletins issued by RSMC, New Delhi during 2009-15 for all CDs (depression and above)

4.3 Performance of Operational Track, intensity and landfall forecast

The performance of operational genesis, track, landfall and intensity forecasts issued by IMD, New Delhi for four cyclones and two deep depressions during 2015 are described below.

4.3.1 Cyclonic storm (CS) Ashobaa (07-12 June 2015)

Salient features of genesis, track, landfall and intensity forecast issued by RSMC, New Delhi are given below:

(i) **6th June:** Forecast for intensification of low pressure area into well marked low by 8th June and probability of cyclogenesis (LOW) during next 48-72 hours over southeast and adjoining east-central Arabian Sea.

(ii) **7th June/0300 UTC:** Depression formed in the morning of 7th June over east-central Arabian Sea and regular special bulletin commenced. Forecast was issued for further intensification into a deep depression within next 24 hours and north-northwestwards movement.

(i) **8th June/0000 UTC**: Deep Depression formed in the morning of 8th June and forecast was issued for its intensification into CS during next 24 hours. Forecast was issued that it would move north-northwestwards and intensify further into a cyclonic storm during next 24 hrs. The system intensified into a cyclonic storm at 0300 UTC of 8th.

(ii) **8th June/0300 UTC**: It would move initially north-northwestwards and intensify further into a severe cyclonic storm during next 36 hours.

(iii) **9th June/0300 UTC**: It would intensify further into a severe cyclonic storm, move initially northwestwards during next 24 hours and west-northwestwards towards Oman coast. Thereafter, it would cross Oman coast as a cyclonic storm between Sur and Mina Sultan Qaboos (Muscat) near latitude 23.0^{0}N and longitude 59.0^{0}E around night of 11 June 2015.

(iv) **9th June/1200 UTC**: It would intensify further into a severe cyclonic storm, move nearly northwestwards during next 24 hours and west-northwestwards towards Oman coast thereafter. The system would cross Oman coast between latitude 21.5^0 N and latitude 23.0^0 N near Ras Al Hadd (22.3^0 N/59.8^0 E) during the night of 11 June 2015.

(v) **11th June/0300 UTC:** Forecast was issued at 0000UTC of 11th that system would move west-southwestward and cross OMAN coast as a depression near lat. 20.5^0N around 0900 UTC of 12 June 2015.

(vi) **11th June/1800 UTC:** The system weakened into a deep depression and forecast was issued that the system would move nearly westwards and cross Oman coast as a depression near latitude 20.8^0N around 0900 UTC of 12 June 2015.

(vii) **12th June/0000 UTC:** The system weakened into a depression and the forecast was issued that the system would cross Oman coast as a well marked low pressure area.

(viii) **12th June/1200 UTC:** The system weakened into a well marked low pressure area over northwest AS and adjoining Oman coast at 1200 UTC of 12th June.

4.3.1.1 Average Track Forecast Error and Skill

Track forecast error is also known as direct position error. It is calculated for each six hourly forecasts valid upto 120 hrs for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hours lead period. The forecasts issued from the stage of deep depression onwards are verified against the actual best track upto the intensity of depression. The mean track forecast error is calculated based on all the six hourly forecasts for a cyclone. Similarly track forecast error based on reference model (Climatology & Persistence (CLIPER)) is calculated. It may be mentioned that CLIPER model is used as a reference model worldwide to verify the operational and numerical models forecast. Track forecast skill is the percentage error in operational track forecast w.r.t. CLIPER forecast error. Track forecast skill (%) = (CLIPER track forecast error-Operational track forecast error)/CLIPER track forecast error*100

The operational average track forecast errors and skills (compared to CLIPER forecasts) are shown in Table 4.1. The errors were higher than the long period average (LPA) based on 2010 - 2014 for all forecast time scales except the 12 hr forecast. They were significantly higher than the LPA for 48 hr forecast and beyond. The track forecast skill has also been less than the LPA for all forecast time scales except the 12 hr forecast.

Table 4.1 Operational Track Forecast Error (km) of CS, ASHOBAA

Lead Period (hrs)	N	Track forecast error (km)	Skill (%)	LPA (2010-14)	
		Operational		Track forecast error (km)	Skill (%)
12	16	61.6	40.5	61.8	39.2
24	14	120.8	31.3	106.8	46.1
36	12	127.6	57.7	132.4	56.6
48	10	225.1	46.3	164.6	62.3
60	8	246.8	63.2	188.9	67.1
72	6	296.1	62.9	230.1	68.1
84	4	347.8	60.4	-	-
96	2	375.9	58.5	-	-

- LPA not available beyond 72 hours.

- : Forecast could not be verified as the life period of the cyclone from deep depression stage was limited to 96 hrs only.

4.3.1.2 Intensity forecast error and skill

Intensity forecast error is calculated based on the forecast maximum sustained surface wind speed (MSW) and actual MSW. We calculate (a) absolute mean error and (ii) Root Mean Square (RMS) error. The data base used for this error calculation is same as that used for track forecast error, i.e. every six hourly forecasts with validity period of 120 hrs. The forecasts issued from the stage of deep depression onwards are verified against the actual best track upto the intensity of depression. Intensity forecast skills are calculated by comparing the operational intensity forecast errors with errors of reference model. For this purpose, the forecast based on persistence method is used as reference model. Thus we calculate errors and skill for 12, 24, 36, 48, 72, 84, 96, 108 and 120 hrs intensity forecast.

The operational intensity forecast error in terms of AE and RMSE and the forecast skills compared to persistence forecasts are presented in Table 4.2. The AE varied from about 4 to 10 kts in different time scales. The error was significantly less than the LPA error based on 2010-2015. The skill in intensity forecast compared to persistence forecast varied from 19% to 92% for different lead periods and has been higher as compared to LPA skill. Considering the RMSE, it varied from 05 to 11 kts for different forecast time scales and was significantly less than long period average RMSE. The skill varied from 14% to 90% and is higher than the LPA skills except for the 12, 72 and 84 hr forecasts.

Table 4.2 Operational Intensity forecast errors

Lead Period (hrs)	N	Operational Error (kts)		LPA Error (kts) (2010-14)		Operational skill against Persistence (%)		LPA Skill against Persistence (2010-14) (%)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	16	3.5	5.1	7.2	10.1	18.6	13.6	26.7	34.6
24	14	6.0	7.6	11.1	14.6	43.9	35.6	40.2	45.2
36	12	6.8	7.8	14.3	18.5	58.3	58.5	49.3	53.1
48	10	8.0	8.7	15.8	20.3	60.0	66.7	55.4	60.4
60	8	7.4	9.6	16.2	19.5	68.0	70.7	63.5	69.1
72	6	7.6	9.6	17.7	21.9	66.7	67.1	67.7	72.8
84	4	10.4	11.0	-	-	74.0	76.3	-	-
96	2	5.4	7.2	-	-	92.0	89.9	-	-

- LPA not available beyond 72 hours.
- : Forecast could not be verified as the life period of the cyclone from deep depression stage was limited to 96 hrs only. LPA not available beyond 72 hours.

4.3.2 CS Komen (25 July -02 August 2015)

Salient features of genesis, track, landfall and intensity forecast issued by RSMC, New Delhi are given below:

- **(i) 25th July:** Forecast for formation of depression over Bay of Bengal during next 24 hrs.
- **(ii) 26th July:** Depression formed over northeast Bay of Bengal at 0300 UTC of 26th. Forecast was issued for intensification into deep depression during next 48 hrs.

(iii) **29th July:** Deep depression formed over northeast Bay of Bengal and adjoining Bangladesh and West Bengal at 0000UTC of 29th. Forecast was issued that it would move nearly northwards and cross Bangladesh coast on 30th forenoon between longitude 90.5^{0}E and 91.5^{0}E. The CS formed at 1800 UTC of 29th July.

(iv) **30th July:** Forecast was issued at 0000 UTC that it would move north-northwestwards and cross Bangladesh coast between longitude 90.5°E and 91.0°E by afternoon of 30th July 2015. After landfall, it would move west-northwestwards and weaken gradually.

(v) **30th July**: Forecast was issued at 0300 UTC that Komen would cross Bangladesh coast around longitude 91.0°E by the afternoon of today, the 30th July 2015.

(vi) **30th July:** Komen crossed Bangladesh coast between Hatia and Sandwip near lat. 22.5^{0}N and long. 91.4^{0}E between 1400 and 1500 UTC as a cyclonic storm.

4.3.2.1 Operational landfall forecast error and skill

Landfall forecast error is calculated as landfall point forecast error and landfall time forecast error. Landfall point forecast error is defined as the direct position error between the forecast landfall point and the actual landfall point. Landfall time forecast error is defined as forecast landfall time and actual landfall time. Both actual error and absolute mean errors are calculated for each cyclone and for different lead periods.

The operational landfall forecast error was 41 km for 12 to 36 hrs lead period (Table 4.3). The landfall time error varied from 6 to 10 hrs for 12 to 36 hrs lead period. An example of forecast & actual track showing accurate prediction of landfall point & time is shown in Fig.4.2.

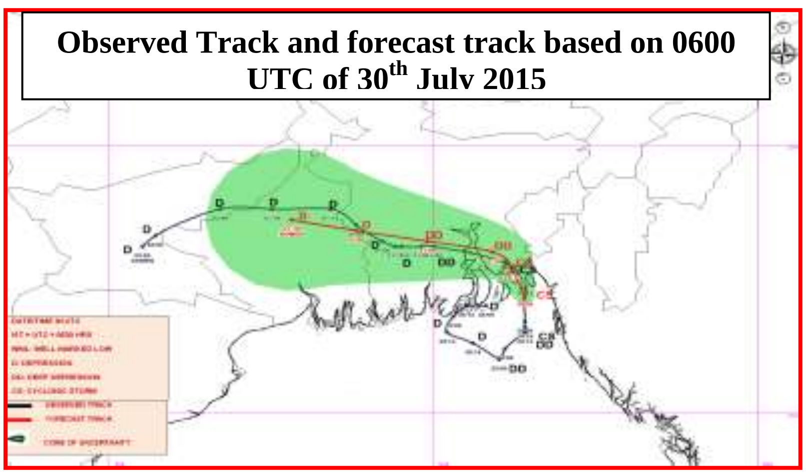


Fig.4.2 An example of forecast track along with cone of uncertainty issued at 00 UTC of 30th July 2015 and observed track

Table 4.3 Operational landfall point and time forecast errors of CS 'KOMEN'

Lead Time (Hrs)	Landfall Point Error (km)	Landfall Time Error (hrs)	Official LPA during 2010-14	
			Landfall Point Error (km)	Landfall Time Error (hrs)
12	41	-6	31.6	1.8
24	41	-10	58.5	3.4
36	41	-10	81.6	5.0

LPA: Long Period average

Landfall Point Error: Forecast Landfall Point - Actual Landfall Point
Landfall Time Error: Forecast Landfall Time - Actual Landfall Time

4.3.2.2 Operational track forecast error and skill

The operational average track forecast errors and skill are shown in Table 4.4. It was less than 100 km for all forecast time scales and significantly less than the LPA (2010-14) for lead period of 24 and 36 hrs. The track forecast skill varied from 19% to 44 % for various time scales.

Table 4.4 Operational Track Forecast Error (km) and Skill (%) of CS KOMEN

Lead Period (hrs)	No. of forecasts verified	Track forecast error (km)	Track forecast skill (%)	Official LPA based on 2010-14	
				Error (km)	Skill (%)
12	5	71.5	19.0	61.8	39.2
24	5	76.7	34.0	106.8	46.1
36	3	94.1	44.3	132.4	56.6

LPA: Long Period average

4.3.2.3 Operational intensity forecast error and skill

The operational intensity forecast error in terms of AE and RMSE are presented in Table 4.5. The AE and RMSE have been around 3.0 kts for various lead periods. The error was significantly less than the LPA error based on 2010-14. The skill in intensity forecast compared to persistence forecast based on AE varied from 25% to 78% for different lead periods and has been significantly higher for 24 and 36 hrs lead period as compared to long period average skill. Considering the skill in intensity based on RMSE, it varied between 43 to 80% for CS, KOMEN and has been higher than LPA for all lead periods.

Table 4.5 Operational Intensity forecast errors and skill

Lead Period (hrs)	N	Operational Error (kts)		LPA Error (kts) (2010-14)		Operational skill against Persistence (%)		LPA Skill against Persistence (2010-14) (%)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	5	3.0	3.1	7.2	10.1	25.0	43.6	26.7	34.6
24	5	2.9	3.3	11.1	14.6	67.8	72.5	40.2	45.2
36	3	2.9	3.3	14.3	18.5	78.2	80.4	49.3	53.1

LPA: Long Period average, AE- Absolute Error, RMSE: Root Mean Square Error

4.3.2.4 Heavy rainfall warning

The heavy rainfall warning issued by IMD alongwith the actual heavy rainfall is presented in Table 4.6. It is found that the heavy rainfall warning was predicted accurately and well in advance.

Table 4.6 Verification of Heavy Rainfall Forecast

<table>
<tr><th>Date & Time</th><th>Heavy rainfall warning issued</th><th>24-hour Heavy rainfall realised ending at 0300 UTC of date</th></tr>
<tr><td>26.07.2015 0300 UTC</td><td>Heavy rainfall at isolated places over Gangetic west Bengal during next 24 hours and heavy to very heavy during subsequent 24 hours. Heavy rainfall at isolated places over Odisha on 27th. Increase in rainfall intensity over Gangetic West Bengal and Odisha from 28th July 2015.</td><td rowspan="4"><u>27.07.2015:</u>
Heavy to very heavy rainfall at isolated places over Odisha and Gangetic West Bengal.
Heavy rainfall at isolated places over Nagaland, Manipur, Mizoram & Tripura and Jharkhand

<u>28.07.2015:</u>
Heavy to very heavy rainfall at isolated places over Odisha, Jharkhand and Gangetic West Bengal.
Heavy rainfall at isolated places over Bihar.

<u>29.07.2015:</u>
Heavy to very heavy rainfall at isolated places over Gangetic West Bengal, Odisha</td></tr>
<tr><td>27.07.2015 0300 UTC</td><td>Heavy to very heavy rainfall at isolated places over the Gangetic West Bengal during next 48 hours and heavy to very heavy at a few places during the subsequent 24 hours.
Heavy rainfall at isolated places over Odisha during next 48 hours and heavy to very heavy rainfall at a few places during subsequent 24 hours.</td></tr>
<tr><td>28.07.2015 0300 UTC</td><td>Heavy to very heavy rainfall at isolated places over the Gangetic West Bengal during next 48 hours and heavy to very heavy at a few places during the subsequent 24 hours.
Heavy rainfall at isolated places over Odisha during next 48 hours and heavy to very heavy rainfall at a few places during subsequent 24 hours.</td></tr>
<tr><td>29.07.2015 0300 UTC</td><td>Heavy to very heavy rainfall at a few places over the Gangetic West Bengal on 29 July; heavy to very heavy falls at a few places with isolated extremely heavy falls on 30 July and heavy to very heavy falls at a few places on 31 July.
Heavy rainfall at isolated places over Odisha on 29 & 30 July and heavy to very heavy rainfall at a few places with isolated extremely heavy falls on 31 July.</td></tr>
</table>

<table>
<tr>
<td>30.07.2015
0300 UTC</td>
<td>Heavy to very heavy rainfall at a few places and extremely heavy at isolated places over Gangetic West Bengal on 30 &31 July; heavy to very heavy falls at a few places on 01 August.
Heavy to very heavy rainfall at isolated places over Odisha on 30 and heavy to very heavy rainfall at a few places with isolated extremely heavy falls on 31 July & 01 August.
Heavy to very heavy rainfall at isolated places over Mizoram, Tripura and south Assam on 30 & 31 July.
Heavy to very heavy rainfall at isolated places over Jharkhand on 31 July & 01 August.</td>
<td rowspan="3">and Jharkhand.

<u>30.07.2015:</u>
Heavy to very heavy rainfall at isolated places over Gangetic West Bengal.

<u>31.07.2015:</u>
Heavy to very heavy rainfall at isolated places over Nagaland, Manipur, Mizoram & Tripura and Jharkhand.

<u>01.08.2015:</u>
Heavy to very heavy rainfall at isolated places over Assam & Meghalaya, Gangetic West Bengal,
Bihar and Jharkhand.
Heavy rainfall at isolated places over Nagaland, Manipur, Mizoram & Tripura.

<u>02.08.2015:</u>
Heavy to very heavy rainfall at isolated places over Gangetic West Bengal,
Odisha and Jharkhand.
Heavy rainfall at isolated places over Bihar.

<u>03.08.2015:</u>
Heavy to very heavy at isolated places over</td>
</tr>
<tr>
<td>31.07.2015
0300 UTC</td>
<td>Heavy to very heavy rainfall at a few places over the Gangetic West Bengal on 31 July and 01 August.
Heavy to very heavy rainfall at a few places with isolated extremely heavy falls on 31 July & 01 August over north Odisha and isolated heavy to very heavy rainfall over south Odisha during same period.
Heavy to very heavy rainfall at isolated places over sub-Himalayan West Bengal, Sikkim, Mizoram, Tripura, Meghalaya and south Assam on 31 July.
Heavy to very heavy rainfall at isolated places over Jharkhand on 31 July & 01 August.</td>
</tr>
<tr>
<td>01.08.2015
0300 UTC</td>
<td>Heavy to very heavy rainfall at a few places over the Gangetic West Bengal during next 24 hrs and isolated heavy to very heavy rainfall thereafter.
Heavy to very heavy rainfall at a few places with isolated extremely heavy falls over north Odisha and Jharkhand during next 24 hrs and heavy to very heavy rainfall at a few places over north Odisha and isolated heavy to very heavy rainfall over Jharkhand in subsequent 24 hrs. Isolated heavy to very heavy rainfall over south Odisha during same period.
Heavy to very heavy rainfall at isolated places over north Chhattisgarh and east Madhya Pradesh on 01 August and heavy to very heavy rainfall at few places with isolated extremely heavy falls on 02 August over north Chhattisgarh and on 03 August over east Madhya Pradesh.
Heavy to very heavy rainfall at isolated places over</td>
</tr>
</table>

	sub-Himalayan West Bengal, **Sikkim, Mizoram, Tripura, Meghalaya and south Assam** during next 24 hrs.	**Odisha, Jharkhand, East Madhya Pradesh and Chattisgarh.** Heavy rainfall at isolated places over **Arunachal Pradesh.** **<u>04.08.2015:</u>** Heavy to very heavy at isolated places over **East Madhya Pradesh.** Heavy rainfall at isolated places over **Chhattisgarh.** **<u>05.08.2015</u>** Extremely heavy at isolated places with Heavy to very heavy rainfall at few places over **west Madhya Pradesh**. Heavy rainfall at isolated places over **east Madhya Pradesh**. Extremely heavy at isolated places with Heavy to very heavy rainfall at many places over **Vidarbha**.
02.08.2015 0300 UTC	Heavy to very heavy rainfall at isolated places over the **Gangetic West Bengal** during next 24 hrs and isolated heavy rainfall during subsequent 24 hrs. Heavy to very heavy rainfall at isolated places over **Jharkhand, Odisha** and **Chhattisgarh** during next 48 hrs. Heavy to very heavy rainfall over **east Madhya Pradesh** on 03 and 04 August. Heavy rainfall at isolated places over **sub-Himalayan West Bengal**, **Bihar and Sikkim** during next 24 hrs.	

Based on the Table 4.6, contingency Table for verification of 24 and 48 hr forecast are prepared as shown in Table 4.7 (a & b) and skill scores are calculated (Table 4.8).

Table 4.7(a) Contingency Table for verification of 24 hr Heavy rainfall forecast

24 hour heavy rainfall forecast verification			
Observed	**Forecast**		
	Yes	No	Total
Yes	21	3	24
No	12	3	15
Total	33	6	39

Table 4.7(b) Contingency Table for verification of 24 hr Heavy rainfall forecast

48 hour heavy rainfall forecast verification			
Observed	Forecast		
	Yes	No	Total
Yes	20	3	23
No	6	14	20
Total	26	17	43

Table 4.8 Skill scores for 24 and 48 hr heavy rainfall forecast

Skill parameter	**24 hr forecast**	**48 hr forecast**
Probability of detection(POD)	0.9	0.9
False alarm rate (FAR)	0.4	0.2
Missing rate (MR)	0.1	0.1
Correct non-occurrence (C-NON)	0.2	0.7
Critical success index (CSI)	0.6	0.7
Bias for occurrence	1.4	1.1
Percentage correct (PC)	61.5	79.1
Heidke skill score (HSS)	0.1	0.6

4.3.2.5 Gale wind warning

The gale wind warning issued by IMD alongwith the actual wind is presented in Table 4.9. It is found that the gale wind warning was predicted accurately and well in advance.

Table 4.9 Verification of Gale Wind Forecast

<table>
<tr><th>Date/ Time(UTC)</th><th>Gale wind Forecast</th><th>Recorded wind speed</th></tr>
<tr><td>30.07.15
0000</td><td>Squally wind speed reaching 50-60 kmph gusting to 70 kmph along and off West Bengal & north Odisha coasts during next 48 hours.
Squally wind speed reaching 40-50 kmph gusting to 60 kmph over Mizoram and Tripura commencing from today evening for next 24 hours and over Gangetic West Bengal from tomorrow morning.</td><td rowspan="3">60-70 kmph at the time of landfall.

Chittagong reported 44 kmph at 1735 UTC of 30th July.

30 - 40 kmph around the system centre reported at the inland stations</td></tr>
<tr><td>30.07.15
1200</td><td>Squally wind speed reaching 50-60 kmph gusting to 70 kmph along and off West Bengal & north Odisha coasts during next 48 hours.
Squally wind speed reaching 40-50 kmph gusting to 60 kmph over Mizoram and Tripura commencing from today evening for next 24 hours and over Gangetic West Bengal from tomorrow morning.</td></tr>
<tr><td>31.07.15</td><td>Squally wind speed reaching 45-55 kmph gusting to</td></tr>
</table>

0000	65 kmph along and off West Bengal & north Odisha coasts during next 24 hours. Squally wind speed reaching 40-50 kmph gusting to 60 kmph over Mizoram and Tripura during next 12 hours and over Gangetic West Bengal during next 24 hours.	over West Bengal, Odisha and Jharkhand
31.07.15 1200	Squally wind speed reaching 35-45 kmph gusting to 55 kmph along and off West Bengal & north Odisha coasts during next 24 hours. Strong wind speed reaching 30-40 kmph gusting to 50 kmph over Mizoram, Tripura and Gangetic West Bengal during next 12 hours	
01.08.15 0000	Squally wind speed reaching 35-45 kmph gusting to 55 kmph along and off West Bengal & north Odisha coasts during next 24 hours. Strong wind speed reaching 30-40 kmph gusting to 50 kmph over Gangetic West Bengal during next 12 hours.	
01.08.15 1200	Strong wind speed reaching 30-40 kmph gusting to 50 kmph over Gangetic West Bengal around the Depression centre during next 24 hours.	
02.08.15 0000	Strong wind speed reaching 30-40 kmph gusting to 50 kmph around the Depression centre over Jharkhand and adjoining West Bengal during next 24 hours.	

4.3.2.6 Storm surge warning

The storm surge warning issued by IMD alongwith the actual storm surge is presented in Table 4.10. It is found that the storm surge warning was predicted accurately and well in advance.

Table 4.10 Verification of Storm Surge Forecast issued by IMD

Forecast Storm surge above astronomical tide and area to be affected	**Actual Storm Surge**
30.08.15-0300/0600/0900 UTC Tidal Wave (storm surge + astronomical tide) of about 2 meters would inundate low lying areas of Bangladesh coast around the time of landfall. (12 Oct 2015/ Around noon)	Chittagong (Bangladesh) reported Storm Surge of 1-2 metre

4.3.3 Deep Depression (09-12 October 2015)

Salient features of genesis, track, landfall and intensity forecast issued by RSMC, New Delhi are given below:

- **(i)** **6th & 7th Oct/0300 UTC:** Forecast of cyclogenesis over AS on 9th October.
- **(ii)** **8th Oct/0300 UTC**: Forecast of cyclogenesis over AS on 9th October with **HIGH confidence**.
- **(iii)** **9th Oct/0300 UTC:** Depression formed at 0300 UTC of 9th over eastcentral AS. Forecast of intensification into DD during next 24 hours.

(iv) **10th Oct/0300 UTC:** DD formed over eastcentral AS at 1800 UTC of 9th. Forecast of its intensification to marginal cyclonic storm during next 24 hours was issued at 0600 UTC of 10th. It would move northwestwards and weaken gradually from 12th.

(v) **11th Oct/0300 UTC:** DD would weaken due to dry air intrusion from northwest and slow movement of the system. It would move north-westnorthwards during next 24 hours and west-northwestwards thereafter. The system weakened into a depression at 0300 UTC of 11th.

(vi) **12th Oct/0300 UTC:** The system would move west-northwestwards & weaken into a well marked low (WML) during next 12 hours. System weakened into WML at 0300 UTC of 12th.

4.3.3.1 Operational track forecast error and skill

The operational average track forecast errors and skills (compared to CLIPER forecasts) are shown in Table 4.12. The track forecast errors for 12, 24 and 36 hours lead period have been 46.1, 115 and 172 km respectively. The skill in track forecast error varied between 33 to 49% for various lead periods. Forecast has been verified upto 36 hours lead period due to short life of the system.

Table 4.12 Track Forecast Error (km) and skill for DD (09-12 October 2015)

Lead Period (hrs)	N	Track forecast		
		Official Error (km)	Cliper Error (km)	Skill (%)
12	6	46.1	89.8	48.7
24	4	115 0	173.3	33.6
36	2	172.0	291.0	40.9

N: Number of six hourly forecasts verified.

4.3.3.2 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of AE and RMSE are presented in Table 4.13.

The intensity forecast error based on AE from 12 to 36 hours lead period varied from 05 to 18 kts. The intensity forecast error has been slightly higher for 24 and 36 hours lead period mainly because it was a weak system and it rapidly dissipated over the sea. Further, the maximum intensity of the system was predicted as a marginal CS (40 kts), though it intensified upto DD (30 kts) only.

Table 4.13: Intensity forecast errors (kts) and skill (%) for DD (09-12 October 2015)

Lead period (hrs)	**Operational intensity error (kts)**	
	AE	**RMSE**
12	4.8	6.3
24	12.7	13.6
36	18.0	18.2

4.3.4 Extremely Severe Cyclonic Storm (ESCS) Chapala (28 October-04 November 2015)

Salient features of genesis, track, landfall and intensity forecast issued by RSMC, New Delhi are given below:

(i) **25th Oct/0300 UTC:** Forecast for formation of depression over Bay of Bengal during next 48 hrs.

(ii) **26th Oct/0300 UTC:** Forecast for formation of depression over Bay of Bengal during next 48-72 hrs.

(iii) **28th Oct/0300 UTC:** Depression formed over southeast Arabian Sea at 0300 UTC of 28th Oct. Forecast was issued for intensification into deep depression during next 24 hrs and into a cyclonic storm during subsequent 24 hrs.

(iv) **29th Oct/0000 UTC:** Depression intensified into a Deep Depression at 1200 UTC of 28th Oct. and further intensified into a Cyclonic Storm (CS) at 0000 UTC of 29th Oct. Forecast was issued for further intensification into a Severe Cyclonic Storm (SCS) during next 24 hrs and into a Very Severe Cyclonic Storm (VSCS) in subsequent 12 hrs.

(v) **29th Oct/0600 UTC:** Forecast was issued that the system would cross north Yemen coast and adjoining Oman coast between 15°N and 17°N around 1800 UTC of 2 Nov. as VSCS

(vi) **29th Oct/1200 UTC:** The Cyclonic Storm intensified into Severe Cyclonic Storm at 1200 UTC of 29th Oct. Forecast was issued for intensification into a Very Severe Cyclonic Storm during next 12 hrs. The crossing forecast was maintained.

(vii) **29th Oct./1800 UTC:** The Severe Cyclonic Storm intensified into Very Severe Cyclonic Storm at 1800 UTC of 29th Oct. The crossing forecast was maintained.

(viii) **30th Oct./0000 UTC:** Forecast was given that VSCS would intensify into Extremely Severe Cyclonic Storm (ESCS) during next 12 hours. The coastal crossing forecast was maintained but between 15°N and 16°N.

(ix) **30th Oct./0300 UTC:** The Very Severe Cyclonic Storm intensified into an Extremely Severe Cyclonic Storm at 0300 UTC of 30th Oct. The forecast was given that the system would intensify into a Super Cyclonic Storm (SuCS) during next 48 hours. Though the intensity at the time of crossing was maintained as VSCS, the landfall time was changed to midnight of 2nd Nov.

(x) **31th Oct./0000 UTC:** The crossing point was changed to near Lat. 15°N. The forecast was given that ESCS would gradually weaken into VSCS during next 24 hrs and into SCS during subsequent 24 hrs.

(xi) **01st Nov./0000 UTC:** The forecast was given that ESCS would gradually weaken into VSCS during next 24 hrs. The forecast for landfall time was changed to 2100 UTC of 02 Nov.

(xii) **02nd Nov./0000 UTC:** The forecast was given that ESCS would gradually weaken into VSCS during next 12 hrs. The forecast for crossing time was changed to 0600 UTC of 03 Nov.

(xiii) **02nd Nov./1200 UTC:** The ESCS weakened into VSCS at 1200 UTC of 2 Nov. Forecast was given for further weakening

(xiv) **03rd Nov./0300 UTC:** The VSCS crossed Yemen coast near 14.1/48.65 during 0100-0200 UTC of 3rd Nov. The system weakened into a SCS after crossing the coast. The forecast was given for rapid weakening into a CS and further into a Deep Depression (DD) during next 12 hrs.

(xv) **03rd Nov./0600 UTC:** The SCS weakened into CS at 0600 UTC and into a DD at 1800 UTC of 3rd Nov. Forecast was given that the DD would weaken into a Depression (D) during next 12 hrs.

(xvi) **04th Nov./0000 UTC:** The Deep Depression weakened into a Depression at 0000 UTC of 4th Nov.

4.3.4.1 Operational landfall forecast error and skill

The operational landfall forecast errors and skill are presented in Table 4.14. The landfall point error (LPE) has been about 123, 181 and 261 km against LPA of 59, 86 and 109 km for 24, 48 and 72 hours lead period respectively. The LPE has been significantly higher than the LPA as initially, it was predicted that the system would cross Yemen coast near 16.0^0N and the system crossed near 14.1^0N. Though there is a difference of 2^0 in latitude, there is a difference of about 4^0 in longitude due to west-southwest to east-northeast oriented coastline. The landfall time error (LTE) has been 4.5, 2.5 and 4.5 hours against the LPA of 3.4, 4.4 and 1.8 hours for 24, 48 and 72 hours lead period respectively. An example of forecast track along with cone of uncertainty issued at 1800 UTC of 28th October 2015 and observed track is presented in Fig.4.3.

Table 4.14 Landfall Point and Time Error in association with ESCS Chapala

Lead Period (hrs)	Base Date/ Time	Landfall Point (degrees)		Landfall Time (hours)		Operational Error		LPA error (2010-14)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hrs)	LPE (km)	LTE (hrs)
12	02/1200	14.0^0N/48.10^0E	14.1^0N/48.65^0E	03/0500	03/0130	61.5	+3.5	31.6	1.8
24	02/0000	13.8^0N/47.57^0E	14.1^0N/48.65^0E	03/0600	03/0130	123.3	+4.5	58.5	3.4
36	01/1200	14.66^0N/49.3^0E	14.1^0N/48.65^0E	02/2330	03/0130	94.4	-2.0	81.6	5.0
48	01/0000	14.87^0N/50.1^0E	14.1^0N/48.65^0E	02/2300	03/0130	180.6	-2.5	85.7	4.4
60	31/1200	15.17^0N/51.0^0E	14.1^0N/48.65^0E	02/1900	03/0130	284.0	-6.5	76.9	3.5
72	31/0000	15.1^0N/50.8^0E	14.1^0N/48.65^0E	02/2100	03/0130	260.8	-4.5	108.5	1.8
84	30/1200	15.18^0N/51.0^0E	14.1^0N/48.65^0E	02/1900	03/0130	284.5	-6.5	-	-
96	30/0000	15.14^0N/50.9^0E	14.1^0N/48.65^0E	02/1700	03/0130	272.7	-8.5	-	-
108	29/1200	15.6^0N/52.0^0E	14.1^0N/48.65^0E	02/1800	03/0130	403.8	-7.5	-	-
120	29/0000	15.9^0N/52.18^0E	14.1^0N/48.65^0E	02/2100	03/0130	435.9	-4.5	-	-

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point, LTE= Forecast Landfall Time-Actual Landfall Time, LPA not available for 84-120 hr forecasts, as this forecast was introduced from 2013 only.

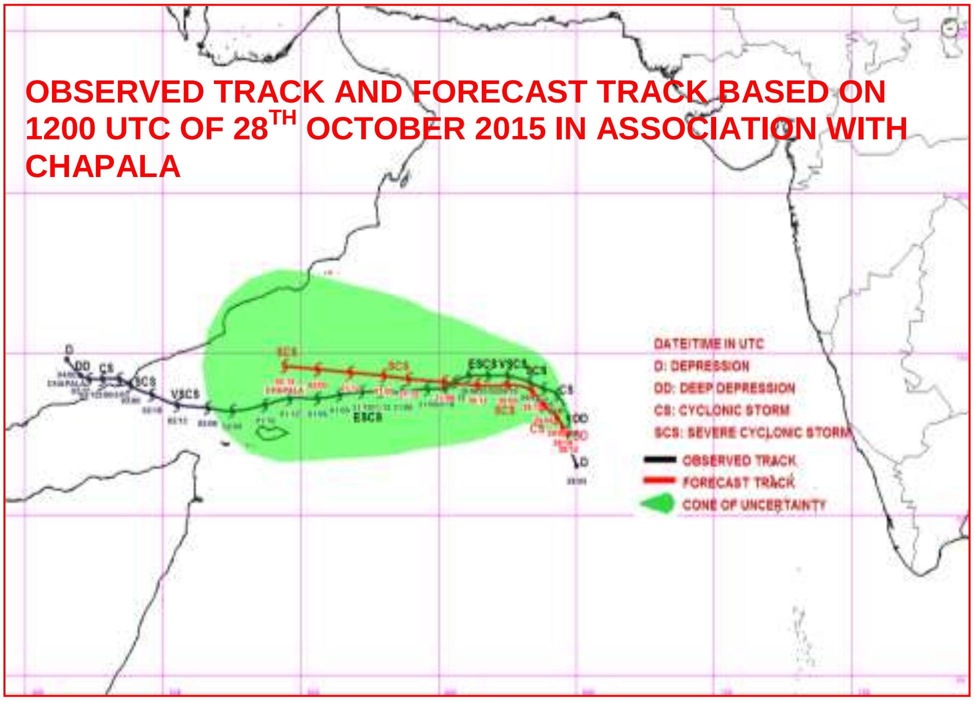


Fig.4.3 An example of forecast track along with cone of uncertainty issued at 1800 UTC of 28th October 2015 and observed track

4.3.4.2 Operational track forecast error and skill

The operational average track forecast errors (skill compared to CLIPER forecasts) are shown in Table 4.15. The track forecast errors for 24, 48 and 72 hours lead period have been 79, 125 and 198 km against the long period average (LPA) of 107, 165 and 230 km respectively. The track forecast errors have been significantly lower than the LPA. The skill has been about 45, 56 and 57 % against LPA of 46, 62 and 68% for 24, 48 and 72 hours lead period.

Table 4.15 Track forecast errors and skill in association with ESCS Chapala

Lead Period (hrs)	N	Track forecast error (km)		Skill (%)	LPA (2010-14)	
		Operational	CLIPER		Track forecast error (km)	Skill (%)
12	25	44.9	63.9	29.8	61.8	39.2
24	23	79.1	142.8	44.6	106.8	46.1
36	21	99.7	207.4	51.9	132.4	56.6
48	19	124.8	282.2	55.8	164.6	62.3
60	17	156.3	343.3	54.5	188.9	67.1
72	15	198.3	460.1	56.9	230.1	68.1
84	13	239.1	624.3	61.7	-	-
96	10	275.3	833.9	67.0	-	-
108	8	326.4	1075.9	69.7	-	-
120	6	398.6	1283.1	68.9	-	-

N: No. of forecasts verified, LPA: Long Period Average

- : LPA not available for 84-120 hr forecasts, as it was introduced from 2013.

4.3.4.3 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of AE and RMSE are presented in Table 4.16. The operational AE in intensity forecast has been about 18, 19 and 12 kts against LPA of 11, 16 and 18 kts for 24, 48 and 72 hours lead period. The forecast error has been slightly higher than LPA for 24 and 48 hours and less for 72 hours lead period. Similarly, operational RMSE in intensity forecast has been about 20, 25 and 21 kts against LPA of 15, 20 and 22 kts for 24, 48 and 72 hours lead period respectively. Slightly higher errors in 24 and 48 hours lead period is mainly attributed to rapid intensification of the system on 29th & 30th November, which could not be predicted operationally as well as by the numerical models. Also, the Rapid Intensification (RI) index developed by IMD could not predict the rapid intensification.

Considering the variation of intensity error w.r.t. the lead periods, the AE gradually increased with increase in lead period from 12 hours (10 kts) to 48 hours (20 kts) lead period. It then decreased gradually with increase in lead period upto 120 hours (13 kts). Similarly, the RMSE increased from 12 hours (13 kts) to 48 hours (25 kts) and then decreased towards 120 hours (15 kts) lead period. This is mainly due to the fact that IMD could very well predict the trend in intensification and as well as the weakening of the system while moving towards Oman coast. But the forecast for rapid intensification could not be predicted satisfactorily leading to higher errors in 36-48 hours lead period.

Comparing the forecast errors with the performance of dynamical statistical cyclone intensity prediction (SCIP) model and rapid intensification index (RI) model developed by IMD, it is observed that both these models failed to predict the rapid intensification of the system. It is worth mentioning that both these models consider external dynamical features/ environmental parameters and do not consider the internal dynamics of the system. Hence, this analysis confirms that intensity forecast can be improved significantly by considering both external and internal dynamics in the numerical weather prediction (NWP) models and dynamical statistical models. For this purpose, therefore there is need for observations from the core of the system for assimilation in numerical models.

Considering the individual deterministic models, the performance of high resolution Hurricane Weather Research Forecast (HWRF) model was better in predicting the intensification of the system. Hence there is scope to improve intensity forecast by HWRF model with more data assimilation, high resolution and ocean atmosphere coupling.

Skill in operational intensity forecast error in terms of AE has been 23, 65 and 86 % against LPA of 40, 55 and 68% for 24, 48 and 72 hours lead period. In terms of RMSE, it was 36, 64 and 82% against LPA of 45, 60 and 72% for 24, 48 and 72 hours lead period. As discussed in previous paragraph, the skill has been slightly less than the LPA for 24 to 36 hours lead period due to lower accuracy in prediction of rapid intensification of the system.

Table 4.16 Intensity forecast errors and skill in association with ESCS Chapala

Lead Period (hrs)	N	Operational Error (kts)		LPA Error (kts) (2010-14)		Operational skill against Persistence (%)		LPA Skill against Persistence (2010-14) (%)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	25	10.1	13.2	7.2	10.1	14.5	14.7	26.7	34.6
24	23	17.8	20.4	11.1	14.6	22.6	36.4	40.2	45.2
36	21	19.8	24.9	14.3	18.5	38.5	51.4	49.3	53.1
48	19	19.2	25.4	15.8	20.3	65.0	64.0	55.4	60.4
60	17	15.3	25.4	16.2	19.5	79.1	73.1	63.5	69.1
72	15	11.8	20.8	17.7	21.9	85.5	81.8	67.7	72.8
84	13	13.8	17.5	-	-	86.6	88.0	-	-
96	10	13.4	18.9	-	-	91.3	90.7	-	-
108	8	12.2	17.5	-	-	92.3	92.0	-	-
120	6	13.1	15.0	-	-	88.2	89.7	-	-

N: No. of forecasts verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average,

-: LPA not available for 84-120 hr forecasts, as this forecast was introduced from 2013

4.3.4.4. Adverse weather forecast verification

No adverse weather like heavy rainfall, gale wind and storm surge was likely over the west coast of India, hence no warning was issued. No observations were available from Yemen to verify the gale winds forecast at the time of landfall. However, the forecast of gale winds issued by IMD is verified with best track intensity mainly based on the satellite T. No at the time of landfall and is given in Table 4.17.

Table 4.17 Verification of Gale Wind Forecast at the time of landfall

Date/ Time(UTC)	Lead period	Gale wind Forecast for Yemen coast	Estimated wind speed at the time of landfall	Error (knots)	
				MSW	Gustiness
02.11.15/1200	12	120-130 kmph gusting to 145 kmph	120 kmph gusting to 140 kmph	+2.7	+2.7
02.11.15/0000	24	120-130 kmph gusting to 145 kmph		+2.7	+2.7
01.11.15/1200	36	115-125 kmph gusting to 140 kmph		0	0
01.11.15/0000	48	120-130 kmph gusting to 145 kmph		+2.7	+2.7
31.10.15/1200	60	110-120 kmph gusting to 135 kmph		-2.7	-2.7
31.10.15/0000	72	100-110 kmph gusting to 115 kmph		-8.0	-13.5

Error has been calculated by considering the middle value of the forecast MSW and actual MSW.

4.3.5 ESCS Megh (05-10 November 2015)

Salient features of genesis, track, landfall and intensity forecast issued by RSMC, New Delhi are given below:

i. **4th November/0300 UTC:** Forecast of formation of depression during next 24 hours. Depression formed over eastcentral AS at 0000 UTC of 5th November.

ii. **5th November/0000 UTC**: The system would move west-northwestwards and intensify into a DD during next 24 hours. No Indian coast would be affected by this system.

iii. **5th November/0600 UTC**: Intensification into CS during next 12 hours and thereafter it would move west-southwestwards towards Gulf of Aden. No Indian coast would be affected by the system. The system intensified into a CS at 1200 UTC of 5th.

iv. **5th November/1200 UTC:** Intensification into SCS during next 24 hours and movement towards Gulf of Aden. System intensified into SCS on 0900 UTC of 7th.

v. **6th November/0000 UTC:** Forecast of west-southwestwards movement and intensification into an SCS during next 24 hrs. It would continue to move west-southwestwards towards Gulf of Aden. System intensified into SCS at 0900 UTC of 7th.

vi. **7th November/0600 UTC:** The system would move west-northwestwards towards Gulf of Aden, reaching close to northern tip of Somalia around 0600 UTC of 9th November. The system would intensify further into a severe cyclonic storm during next 12 hours. It would maintain its intensity till 0000 UTC of 8th November and weaken gradually thereafter. It would cross Yemen coast near 13.4^0N/46.5^0E around 0600 UTC of 11th November as a depression. The system crossed Yemen coast near 13.4^0N/46.1^0E around 0900 UTC of 9th November.

vii. **7th November/0900 UTC:** Intensification into VSCS during next 12 hours. It would maintain its intensity till 0600 UTC of 8th November and weaken gradually thereafter. The system intensified into VSCS at 1500 UTC of 7th and started weakening from 1200 UTC of 8th November.

viii. **8th November/0000 UTC**: It would cross Yemen coast between latitude 13 and 14 degree north around 1200 UTCof 10th November.as a CS.

ix. **9th November/0300 UTC:** It would move west-southwestwards initially & then west-northwestwards across Gulf of Aden, weaken gradually and cross Yemen coast between latitude 13 & 14 degree north around 1200 UTC of 10th November as an **SCS**.

x. **10th November/0300 UTC:** It would cross Yemen coast near 13.2 degree north around 0600 UTC of 10th November.as a CS. The system crossed Yemen coast as a DD near 13.4 degree North/ 46.1 degree East at 0900 UTC of 10th November.

4.3.5.1 Operational landfall forecast error and skill

The operational landfall forecast errors and skill are presented in Table 4.18. The landfall point error (LPE) has been about 78, 78 and 70 km against LPA of 59, 86 and 109 km for 24, 48 and 72 hours lead period respectively. The LPE has been significantly lower than the LPA as for all lead periods beyond 24 hours. Upto 24 hours lead period, the LPE was slightly higher than the LPA. The landfall time error (LTE) has been 2.0, 3.0 and 3.0 hours against the LPA of 3.4, 4.4 and 1.8 hours for 24, 48 and 72 hours lead period respectively. LTE had been slightly lower for 24 and 48 hours lead period and higher than LPA for 72 hours lead period. An example of forecast track along with cone of uncertainty issued on 0600 UTC of 7th November and observed track is presented in fig.4.4.

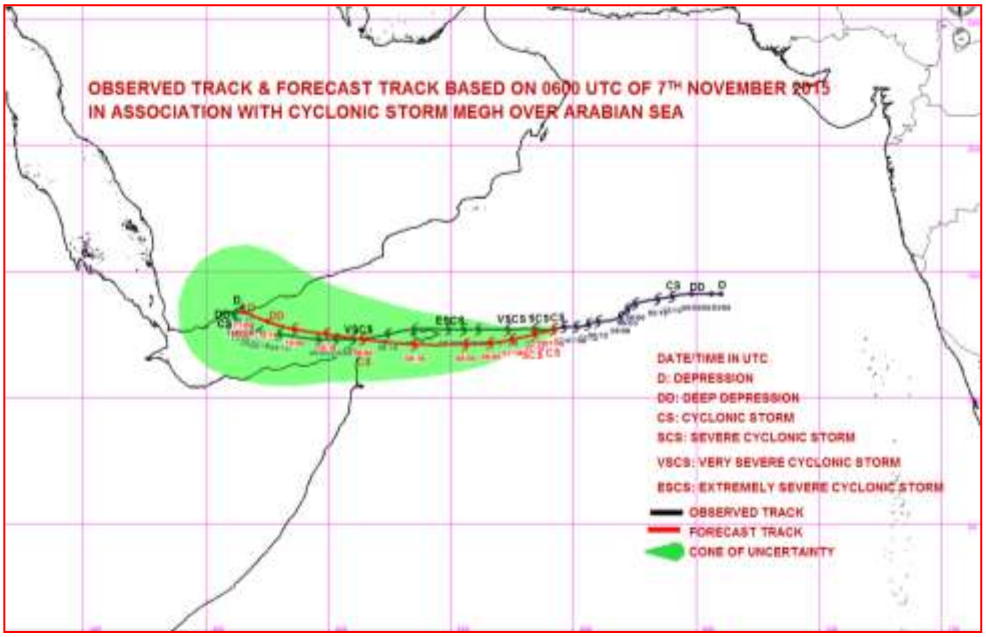


Fig.4.4 An example of forecast track along with cone of uncertainty issued at 0600 UTC of 7^{th} November 2015 and observed track

Table 4.18 Landfall Point and Time Error in association with ESCS Megh

Lead Period (hrs)	Base Date/ Time	Landfall Point (degrees)		Landfall Time (hours)		Operational Error		LPA error (2010-14)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	Absolute LTE (hours)
12	09/1800	13.2^{0}N/ 45.5^{0}E	13.4^{0}N/ 46.1^{0}E	10/0500	10/0900	44.0	-4.0	31.6	1.8
24	09/0600	13.3^{0}N/ 45.6^{0}E	13.4^{0}N/ 46.1^{0}E	10/0700	10/0900	77.8	-2.0	58.5	3.4
36	08/1800	13.5^{0}N/ 46.8^{0}E	13.4^{0}N/ 46.1^{0}E	10/0900	10/0900	11.0	0.0	81.6	5.0
48	08/0600	13.4^{0}N/ 46.2^{0}E	13.4^{0}N/ 46.1^{0}E	10/1200	10/0900	77.8	+3.0	85.7	4.4
60	07/1800	13.5^{0}N/ 46.8^{0}E	13.4^{0}N/ 46.1^{0}E	10/0900	10/0900	56.1	0.0	76.9	3.5
72	07/0600	13.4^{0}N/ 46.5^{0}E	13.4^{0}N/ 46.1^{0}E	10/1200	10/0900	69.6	+3.0	108.5	1.8

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point
LTE= Forecast Landfall Time-Actual Landfall Time

4.3.5.2 Operational track forecast error and skill

The operational average track forecast errors and skills (compared to CLIPER forecasts) are shown in Table 4.19. The track forecast errors for 24, 48 and 72 hours lead period have been 98, 133 and 169 km against the long period average (LPA) of 107, 165 and 230 km respectively. The track forecast errors have been significantly lower than the LPA for all lead periods.

Table 4.19 Track forecast errors and skill in association with ESCS Megh

Lead Period (hrs)	N	Track forecast error (km)		Skill (%)	LPA (2010-14)	
		Operational	CLIPER		Track forecast error (km)	Skill (%)
12	20	57.4	82.0	30.0	61.8	39.2
24	18	98.3	146.2	32.8	106.8	46.1
36	16	128.5	198.1	35.1	132.4	56.6
48	14	133.2	244.8	45.6	164.6	62.3
60	12	153.3	321.2	52.3	188.9	67.1
72	9	169.2	332.8	49.2	230.1	68.1
84	5	174.9	501.7	65.1	-	-
96	5	262.4	526.8	50.2	-	-
108	4	257.7	667.1	61.4	-	-
120	2	228.1	828.0	72.5	-	-

N: No. of forecasts verified, LPA: Long Period Average: LPA not available for 84-120 hr forecasts, as this forecast was introduced from 2013 only

4.3.5.3 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of AE and RMSE are presented in Table 4.20. The operational AE in intensity forecast has been about 17, 31 and 40 kts against LPA of 11, 16 and 18 kts for 24, 48 and 72 hours lead period. The forecast error has been higher than LPA for 24, 48 and 72 hours lead period. Similarly, operational RMSE in intensity forecast has been about 23, 38 and 42 kts against LPA of 15, 20 and 22 kts for 24, 48 and 72 hours lead period respectively. Higher errors in intensity forecast is mainly attributed to rapid intensification of the system on 07th November, which could not be predicted operationally as well as by the numerical models. The Rapid Intensification (RI) index developed by IMD could not predict the RI.

Considering the variation of intensity error w.r.t. the lead periods, the AE gradually increased with increase in lead period from 12 hours (8 kts) to 96 hours (30 kts) lead period. It then decreased gradually with increase in lead period upto 120 hours (8 kts). Similarly, the RMSE increased from 12 hours (10 kts) to 96 hours (38 kts) and then decreased towards 120 hours (4 kts) lead period. This is mainly due to the fact that IMD could very well predict the trend in intensification and as well as the weakening of the system while moving towards Yemen coast. But the forecast for rapid intensification could not be predicted satisfactorily leading to higher errors in 48-96 hours lead period.

Comparing the forecast errors with the performance of dynamical statistical cyclone intensity prediction (SCIP) model and RI model developed by IMD, it is observed that both these models failed to predict the rapid intensification of the system. It is worth mentioning that both these models consider external dynamical features/ environmental parameters and do not consider the internal dynamics of the system. Hence, this analysis confirms that intensity forecast can be improved significantly by considering both external and internal dynamics in the numerical weather prediction (NWP) models and dynamical statistical models. For this purpose, therefore there is need for observations from the core of the system for assimilation in numerical models.

Considering the individual deterministic models, the performance of high resolution Hurricane Weather Research Forecast (HWRF) model was better in predicting the intensification of the system. Hence there is scope to improve intensity forecast by HWRF model with more data assimilation, high resolution and ocean atmosphere coupling.

Skill in operational intensity forecast error in terms of AE has been 31, 46 and -03% against LPA of 40, 55 and 68% for 24, 48 and 72 hours lead period. In terms of RMSE, it was 22, 48 and 18% against LPA of 45, 60 and 72% for 24, 48 and 72 hours lead period. As discussed in previous paragraph, the skill has been less than the LPA for all forecast times due to lower accuracy in prediction of rapid intensification of the system.

Table 4.20 Intensity forecast errors and skill in association with ESCS Megh

Lead Period (hrs)	N	Operational Error (kts)		LPA Error (kts) (2010-14)		Operational skill against Persistence (%)		LPA Skill against Persistence (2010-14) (%)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	20	8.0	10.3	7.2	10.1	13.1	15.2	26.7	34.6
24	18	17.2	22.7	11.1	14.6	30.6	22.1	40.2	45.2
36	16	25.1	32.1	14.3	18.5	14.0	35.6	49.3	53.1
48	14	31.1	38.1	15.8	20.3	45.6	47.5	55.4	60.4
60	12	35.9	38.1	16.2	19.5	31.7	47.5	63.5	69.1
72	9	40.1	41.7	17.7	21.9	-3.0	18.3	67.7	72.8
84	5	43.9	43.8	-	-	-9.9	0.8	-	-
96	5	30.4	32.4	-	-	50.2	52.0	-	-
108	4	16.8	20.8	-	-	84.5	81.5	-	-
120	2	3.2	4.0	-	-	97.6	96.9	-	-

N: No. of forecasts verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average

- : LPA not available for 84-120 hr forecasts, as this forecast was introduced from 2013

4.3.5.4 Adverse weather forecast verification

No adverse weather like heavy rainfall, gale wind and storm surge was expected over the west coast of India, hence no warning was issued. No observations were available from Yemen to verify the gale winds forecast at the time of landfall. However, the forecast of gale winds issued by IMD is verified with the satellite T. No at the time of landfall and is given in Table 4.21.

Table 4.21 Verification of wind forecast at the time of landfall

Date/ Time(UTC)	Lead period	Maximum Sustained Wind at the time of landfall (kmph)		Error (knots)	
		Forecast	Actual	MSW	Gustiness
09/1800	12	80-90 gusting to 100	50-60 gusting to 70	+15	+10
09/0600	24	100-110 gusting to 120	50-60 gusting to 70	+27	+25
08/1800	36	95-105 gusting to 120	50-60 gusting to 70	+24	+22
08/0600	48	95-105 gusting to 115	50-60 gusting to 70	+24	+22
07/1800	60	55-65 gusting to 75	50-60 gusting to 70	+2	-2
07/0600	72	55-65 gusting to 75	50-60 gusting to 70	+2	-2

The middle value of the forecast range of wind is considered for forecast verification,
Error = Forecast Wind-Actual Wind

4.3.6 Deep Depression (08-10 November 2015) over Bay of Bengal

Salient features of genesis, track, landfall and intensity forecast issued by RSMC, New Delhi are given below:

(i) 7th November/0300 UTC:

Forecast for formation of a depression by 8th November over southwest Bay of Bengal and subsequent intensification and movement towards Tamil Nadu coast by 07th.

(ii) 8th November/0300 UTC:

(a) Depression formed in the morning of 8th November over southwest Bay of Bengal. Forecast was issued for further intensification into a deep depression within 24 hours and further into a cyclonic storm and cross north Tamil Nadu coast between Karaikal and Chennai near Puducherry by 09th mid-night.

(b) Warning for heavy to very heavy rainfall occurrence over north Tamil Nadu and Puducherry with isolated extremely heavy rainfall on 09th was issued.

(c) Squally wind warning for north Tamil Nadu, Puducherry and adjoining Pudukkottai and Ramanathapuram districts of south Tamil Nadu coasts with speed reaching 40-50 kmph gusting to 60 kmph during next 24 hrs 55-65 kmph gusting to 75 kmph during the subsequent 24 hrs was issued.

4.3.6.1 Operational landfall forecast error

Operational forecast errors in landfall location and time for 12, 24 and 36 hr lead times are shown in Table 4.22.The operational landfall forecast point error (LPE) was about 50 km and landfall time error (LTE) was -6 hrs. Delay in the landfall time than the one predicted was due to the northward movement of the system close to the coast from 0600 UTC of 09th until the landfall around 1400 UTC of 09th. An example of forecast & actual track showing prediction of landfall point & time is shown in Fig.4.5.

Table 4.22 Operational landfall point and landfall time forecast errors

Lead Period (hrs)	Base Date/Time	Landfall Point (degrees)		Landfall Time (hours)		Operational Error	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)
12	09/0000	11.8^0N/ 79.8^0E	12.2^0N/ 80.0^0E	09/0800	09/1400	49	-6.0
24	08/1200	11.9^0N/ 79.8^0E	12.2^0N/ 80.0^0E	09/1630	09/1400	40	+2.0
36	08/0000	11.9^0N/ 79.8^0E	12.2^0N/ 80.0^0E	09/1830	09/1400	40	+4.5

LTE : Landfall forecast time – Actual landfall time,
LPE : Landfall forecast point – Actual landfall point, N: No. of forecasts verified

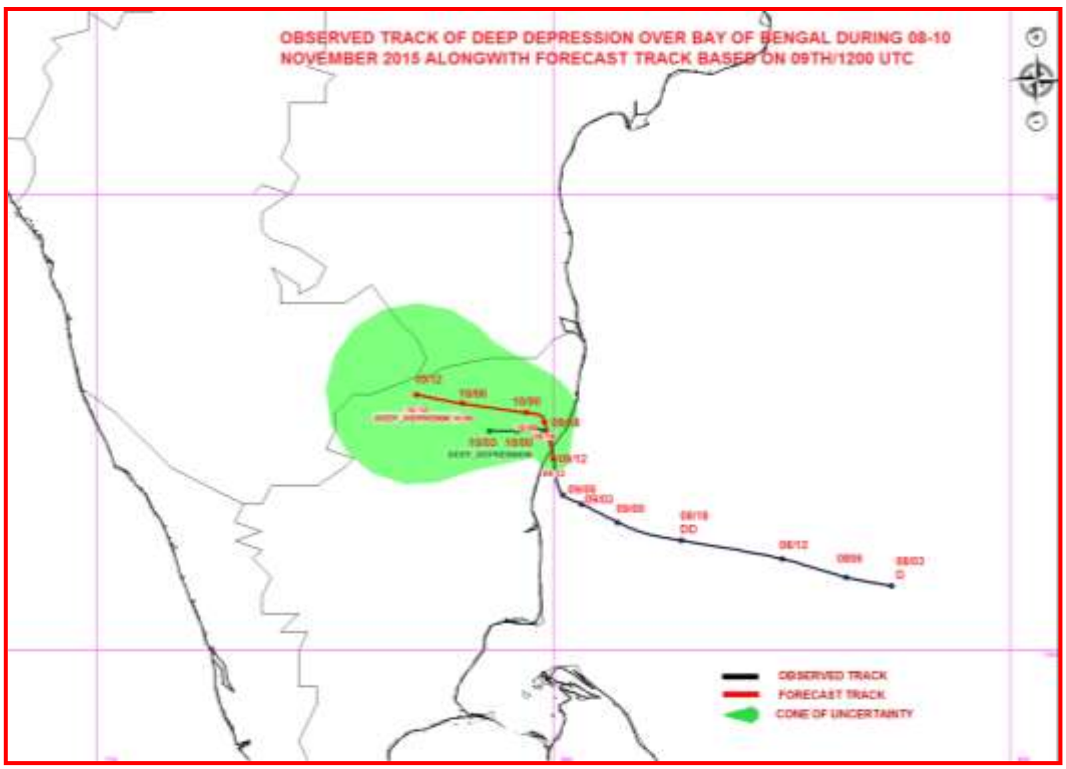


Fig.4.5 Actual track of the Deep Depression (08-10 November 2015) and the forecast track along with cone of uncertainty based at 1200 UTC of 9th November 2015.

4.3.6.2 Operational track forecast error and skill

The operational average track forecast errors are shown in Table-4.23. The track forecast for 12- and 24-hr forecasts were skilful as seen from the Table.

Table 4.23 Operational Track Forecast Error and Skill

Lead Period (hrs)	N	Direct Positional Error (km)		Skill (%)
		Operational	CLIPER	
12	3	83.8	135.1	38.0
24	1	187.3	308.2	39.2

N: No. of forecasts verified

4.3.6.3 Operational Intensity forecast error and skill

The operational intensity forecast errors are presented in Table 4.24. 24-hr intensity forecast performance was quite good with 70% skill against persistence forecast.

Table 4.24 Operational Intensity forecast errors and skill

Lead Period (hrs)	N	Operational Error (knot)		Persistence based Error (knot)		Operational skill against Persistence forecast (%)	
		AE	RMSE	AE	RMSE	AE	RMSE
12	3	1.7	2.0	1.7	2.9	0	31.0
24	1	3.0	3.0	10.0	10.0	70.3	70.3

N: No. of forecasts verified; AE: Absolute Error; RMSE: Root Mean Square Error

4.4 Annual Performance cyclone landfall, track and intensity forecast

4.4.1 Track Forecast

Annual average track forecast error is calculated by considering the track forecast errors of all the cyclones during the year. The mean error of each cyclone is weighted by number of forecasts verified to calculate the annual average track forecast errors as mentioned below. This is calculated for 12, 24, 36, 48, 60, 72, 84, 96, 108, 120 hr forecasts.

Annual average track forecast error= (n1*E1+n2*E2+n3*E3+....)/(n1+n2+n3+...)

where n1, n2, n3... are number of six hrly forecasts verified for cyclone 1, 2, 3. and E1, E2, E3... are the average track forecast errors for cyclone n1, n2, n3.

Similarly, annual average CLIPER model based track forecast errors are calculated. Subsequently, skill is calculated for a given cyclone by comparing the six hourly operational track forecast errors with track forecast errors of a reference model.

Track forecast skill (%) = (CLIPER track forecast error-Operational track forecast error)/ CLIPER track forecast error*100

The annual average track forecast error (Fig.4.6) has been 94 km, 151 km and 209 km, respectively for 24, 48 and 72 hrs against the LPA error of 107, 164 and 230 km based on data of 2010-2014 (Table 4.25). The 96 and 120 hr track forecast errors during 2015 are 283 and 356 km respectively. Also the track forecast skills compared to CLIPER forecast during 2015 are 37%, 50% and 57% respectively for the 24, 48 and 72 hrs lead period which is lower than LPA of 2010-2014 (46%, 62% & 68% respectively) by about 10%. Official track forecast errors during 2015 were 7-13% less as compared to 2010-14 upto 72 hours lead period and 17-30 % more beyond that. There has been reduction in track forecast error by about 12%, 8% and 9% for 24, 48, 72 hr lead period respectively (Table 4.28) relative to the LPA based on 2010-14.

During 2015 CLIPER errors were more than official errors for all lead periods. CLIPER is a measure of the forecast difficulty level for a basin. Despite increased difficulty level and limited data availability over AS, there was improvement in track forecast error during 2015 upto 72 hours lead period.

4.4.2 Landfall Forecast

The annual average landfall forecast error is average landfall forecast error of all the landfalling cyclones in a year. It is calculated for 12, 24, 36, 48, 60 and 72 hours lead period w.r.t. position and time respectively.

The landfall point forecast error during 2015 has been 81, 129 and 165 km against LPA of 59, 86 and 109 km for 24, 48 and 72 hrs lead period and the landfall time forecast error has been 5.5, 2.8 and 3.8 hours against LPA of 3.4, 4.4 and 1.8 hours for 24, 48 and 72 hrs lead period (Fig. 4.7). Official landfall point forecast errors were 38, 51 and 52% more as compared to LPA during 2010-14 for 24, 48 and 72 hours lead period (Table 4.26).

4.4.3 Intensity Forecast

The annual average intensity forecast error based on AE is the weighted mean of the absolute error for each cyclone. Similarly, the annual average error is calculated by persistence method. Based on these two errors, the intensity forecast skill with reference to absolute error is calculated. Errors and skills are calculated for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hour forecasts.

The annual average intensity forecast error based on RMSE is calculated by taking square root of the average of squared error between the forecast and observed intensity values for 12, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hours forecast period for every six hourly forecast. Similarly, RMSE error based on persistence is calculated and hence the skill.

The annual average intensity forecast error during 2015 based on AE (Fig.4.8) has been 14, 20 and 19 kts respectively for 24, 48 and 72 hrs lead period of forecast against the LPA of 11, 16 and 18 kts (Table 4.27). The annual average intensity forecast error based on RMSE has been 18, 28 and 28 kts respectively for 24, 48 and 72 hrs lead period of forecast against the LPA of 15, 20 and 22 kts (Table 4.28).

The skill compared to persistence forecast during 2015 based on AE (Fig.4.9) has been 30%, 57% and 66% for 24, 48 and 72 hours lead period respectively against the LPA (2010-14) of 40%, 55% and 68% respectively (Table 4.27). The skill compared to persistence forecast based on RMSE has been 33%, 58% and 68% respectively against the LPA (2010-14) of 45%, 60% and 73% respectively for 24, 48 and 72 hours lead period (Table 4.28). The intensity forecast errors during 2015 have been higher than LPA (2010-14) upto 84 hrs lead period (Table 4.29 & 4.30) and less beyond that. Persistence based intensity forecast errors have been significantly higher for all lead periods indicating increased difficulty level in intensity forecast during 2015.

During 2015, in general the errors have been higher and skill less for intensity mainly due to the fact that:

i. Out of total of **4** cyclones**, 3** developed over the AS and errors are in general higher for the systems developing over AS than those over BoB. It has been demonstrated in research paper on evaluation of track, intensity and landfall forecast by Mohapatra etal, 2013 (a&b) and 2015. This is mainly due to the fact that AS and adjoining land areas are data sparse regions. As a result the amount of data assimilated in the numerical models is relatively less.

ii. Also the errors in intensity forecast are higher for higher intensity systems. Year 2015 witnessed development of **2** extremely severe cyclones Chapala and Megh.

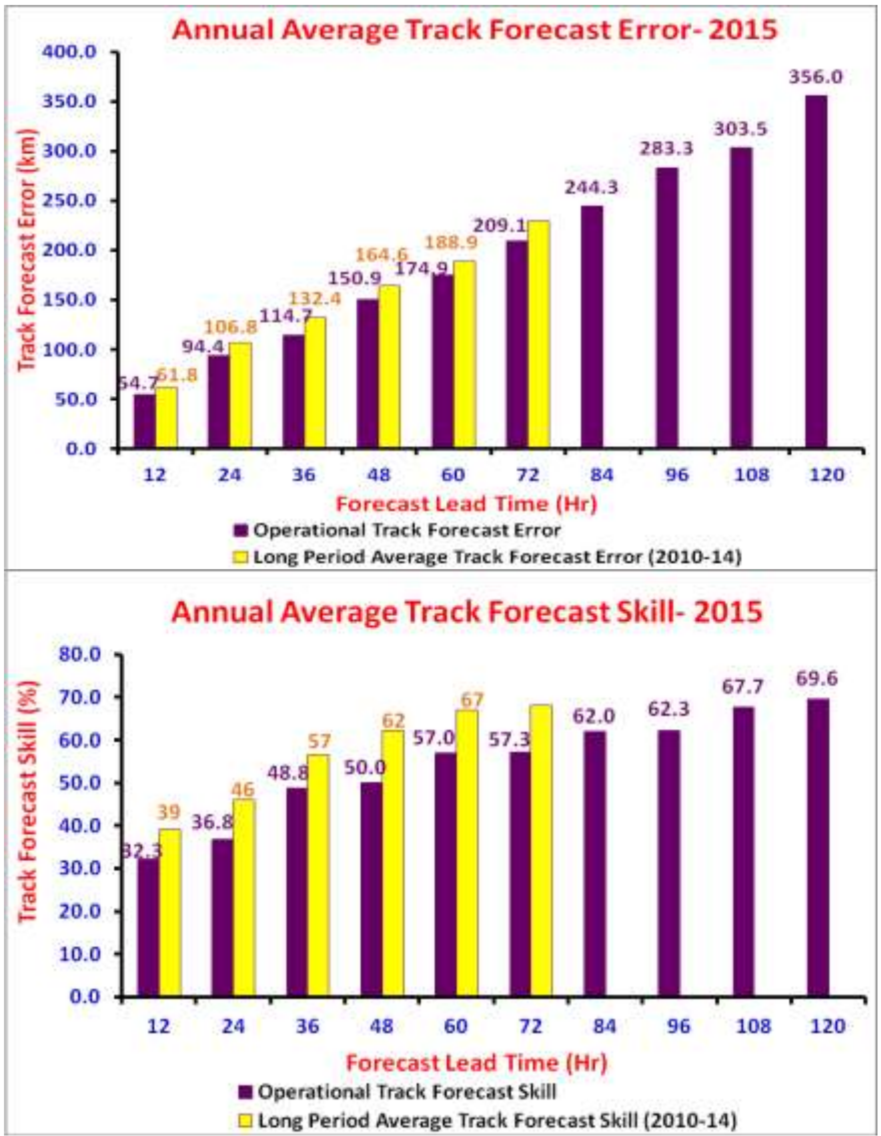


Fig.4.6 Annual Average Track Forecast Error and Skill -2015

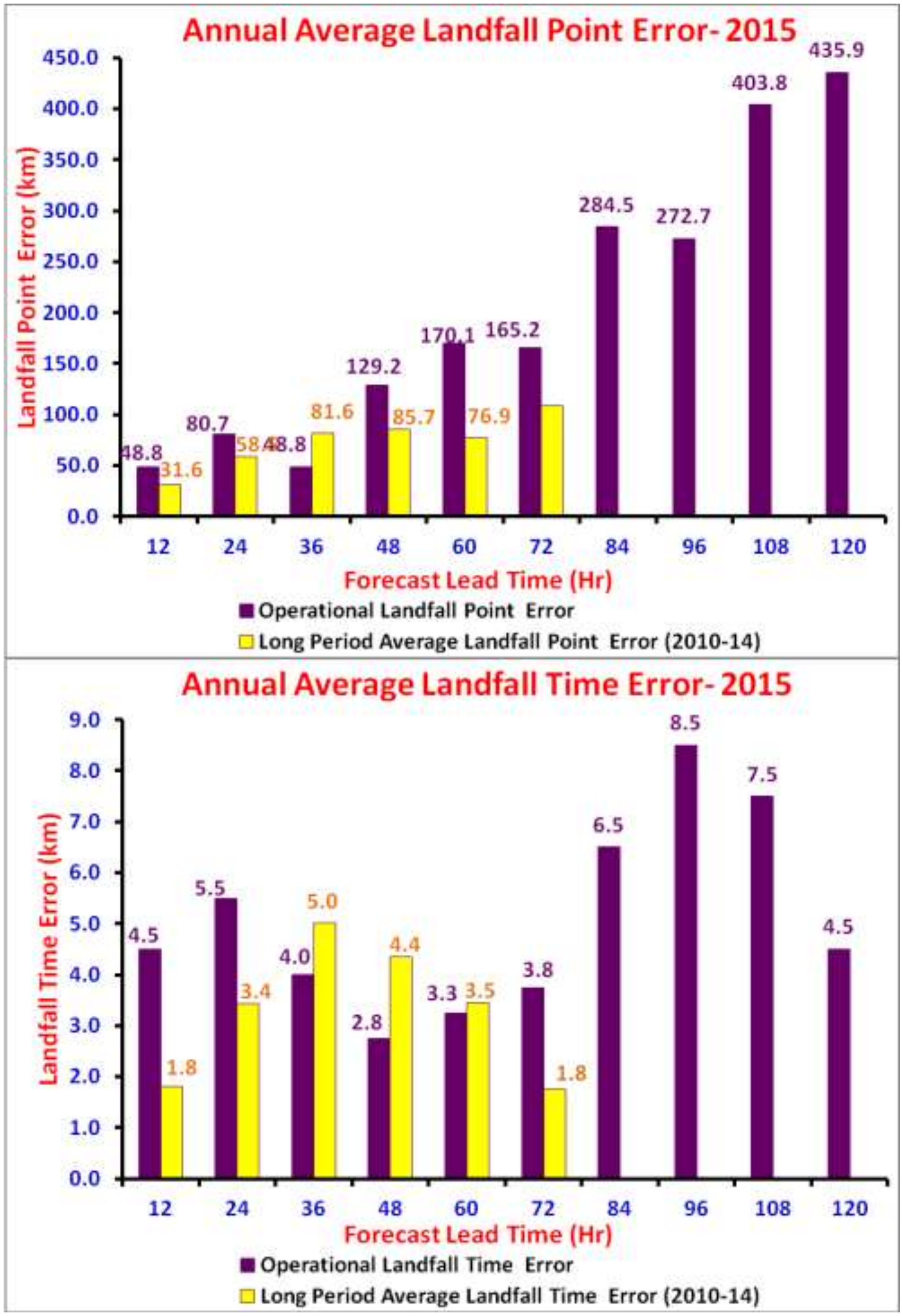


Fig.4.7 Annual Average Landfall Point and Landfall Time Forecast Error -2015

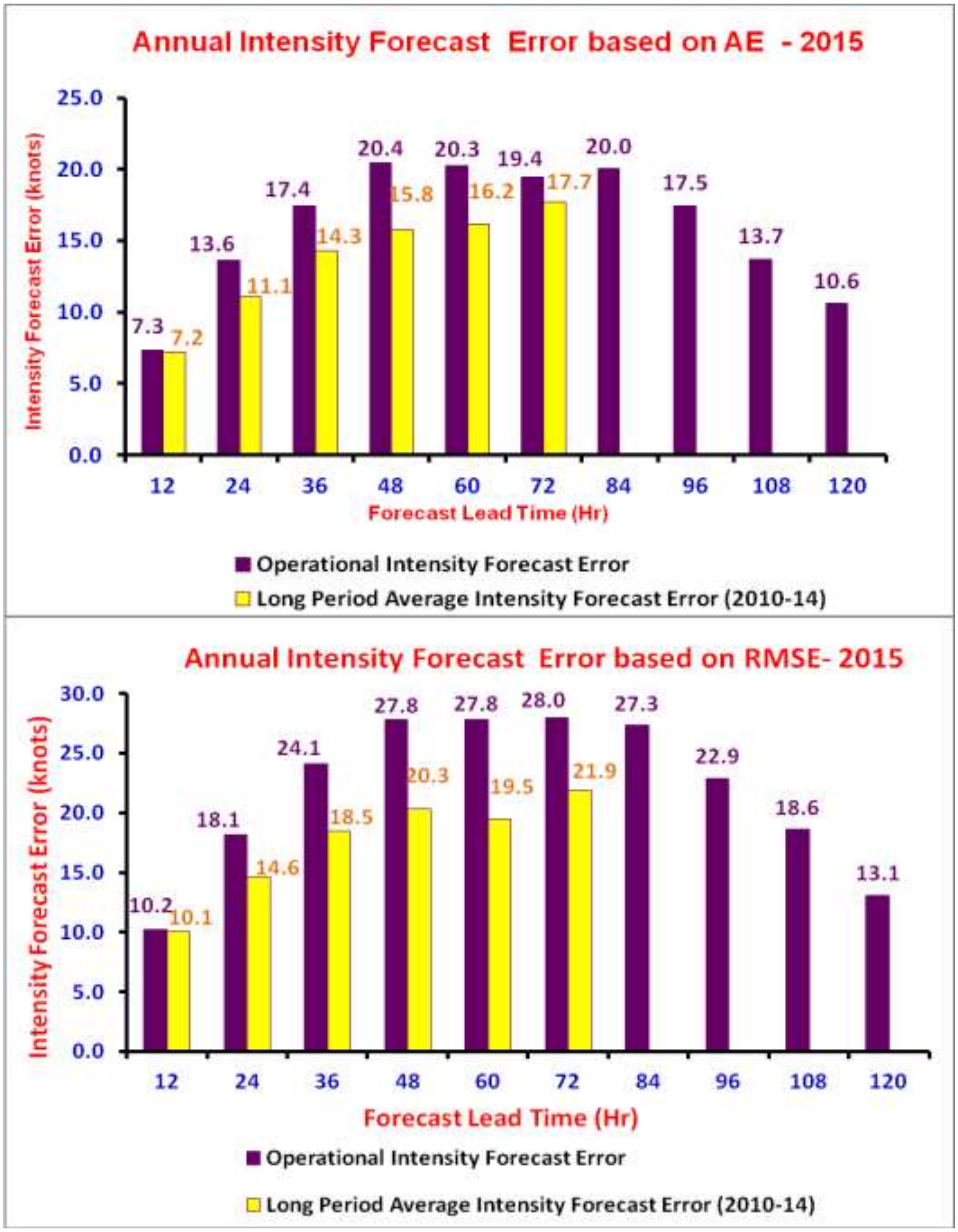


Fig.4.8 Annual Intensity Forecast Error based on AE and RMSE -2015

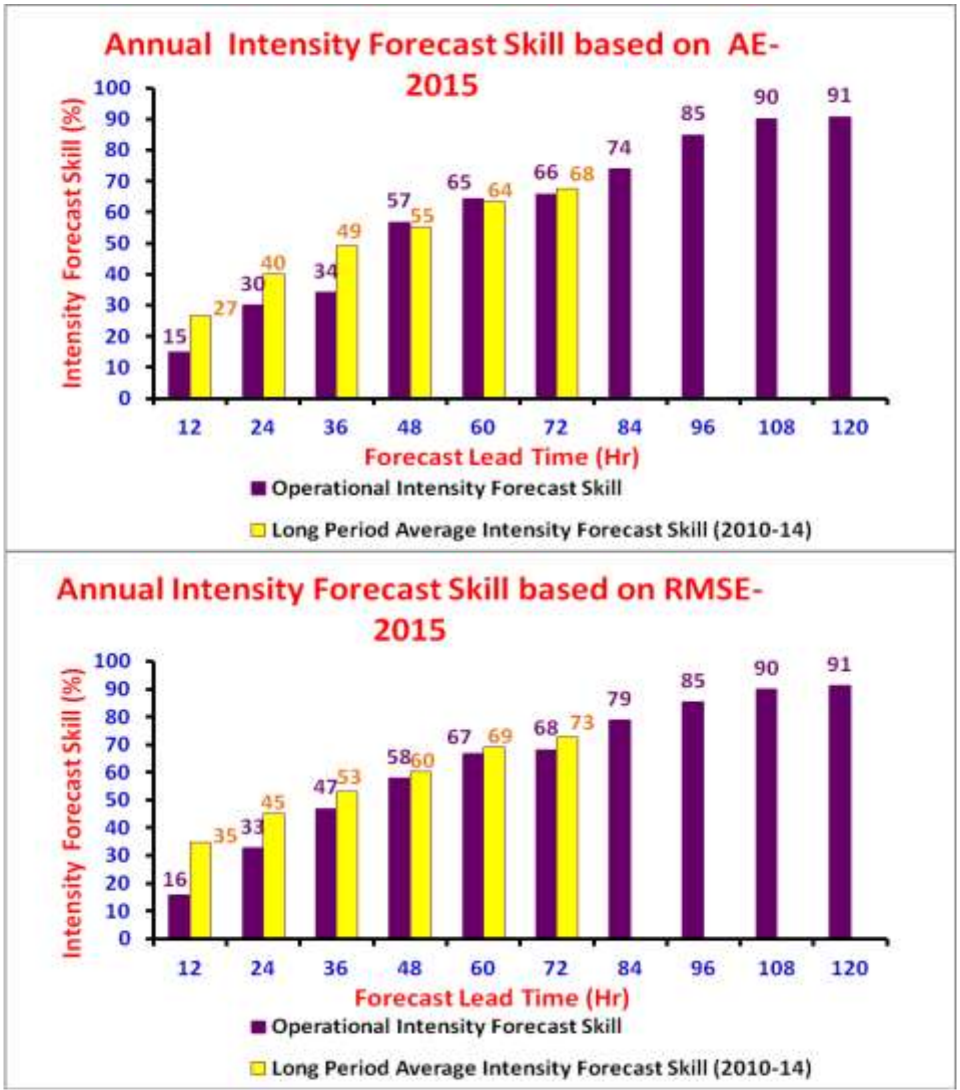


Fig.4.9 Annual Intensity Forecast Skill based on AE and RMSE -2015

Table 4.25 Homogeneous comparison of Official (OFCL) & CLIPER Trak Forecast Errors over north Indian Ocean in 2015 as compared to 2010-14 and 2005-14

Parameter		**Forecast Period (hr)**								
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2015 Mean OFCL Forecast Error (km)	54.7	94.4	114.7	150.9	174.9	209.1	244.3	283.3	303.5	356.0
2015 Mean CLIPER Error (km)	82.0	149.3	224.1	301.8	406.8	489.5	642.7	752.1	939.6	1169.3
2015 Mean OFCL Skill wrt CLIPER (%)	32.3	36.8	48.8	50.0	57.0	57.3	62.0	62.3	67.7	69.6
2015 No. of cases	66	60	52	43	37	30	22	17	12	8
2010-14 Mean OFCL Forecast Error (km)	61.7	106.8	132.4	164.6	188.9	230.1	185.6	219.0	259.1	276.4
2010-14 Mean CLIPER Error (km)	101.6	198.1	305.2	437.2	573.9	721.5	808.2	943.3	998.3	1171.1
2010-14 Mean OFCL Skill wrt CLIPER (%)	39.2	46.1	56.6	62.3	67.1	68.1	77.0	76.8	74.0	76.4
2010-14 No. of cases	236	208	172	146	117	92	48	36	24	14
2005-14 Mean OFCL Forecast Error (km)	70.9	119.2	145.8	177.9	204.2	235.5	185.6	219.0	259.0	276.4
2005-14 Mean CLIPER Error (km)	99.5	193.9	301.9	436.6	571.3	716.5	808.2	943.3	998.3	1171.1
2005-14 Mean OFCL Skill wrt CLIPER (%)	28.7	38.5	51.7	59.3	64.3	67.1	77.0	76.8	74.0	76.4
2005-14 No. of cases	376	319	188	154	123	94	48	36	24	14
2015 OFCL error relative to 2010-14 mean (%)	-11.4	-11.6	-13.4	-8.3	-7.4	-9.1	31.6	29.3	17.2	28.8
2015 CLIPER error relative to 2010-14 mean (%)	-20.4	-24.6	-26.6	-30.9	-29.1	-32.1	-20.5	-20.2	-5.9	-0.2

The track forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs during 2013-15

Table 4.26 Homogeneous comparison of Official (OFCL) Landfall Forecast Errors over north Indian Ocean in 2015 as compared to 2010-14 and 2005-14

Parameter		**Forecast Period (hr)**				
	12	**24**	**36**	**48**	**60**	**72**
2015						
Mean OFCL Landfall Point Error (km)	48.8	80.7	48.8	129.2	170.1	165.2
Mean OFCL Landfall Time Error (hr)	4.5	5.5	4.0	2.8	3.3	3.8
No. of cases	3	3	3	2	2	1
2010-14						
Mean OFCL Landfall Point Error (km)	31.6	58.5	81.6	85.7	76.9	108.5
Mean OFCL Landfall Time Error (hr)	1.8	3.4	5.0	4.4	3.5	1.8
No. of cases	14	14	13	12	11	8
2005-14						
Mean OFCL Landfall Point Error (km)	53.2	84.9	89.9	91.3	76.9	108.5
Mean OFCL Landfall Time Error (hr)	3.5	5.7	7.4	6.7	3.5	1.8
No. of cases	31	28	17	15	11	8
2015 OFCL Landfall Point Error relative to 2010-14 mean (%)	54.6	37.9	-40.2	50.8	121.7	52.3
2015 OFCL Landfall Time Error relative to 2010-14 mean (%)	148.0	60.0	-20.2	-36.8	-5.9	114.3

Table 4.27 Homogeneous comparison of Official (OFCL) & Persistence intensity forecast errors based on AE over NIO in 2015 as compared to 2010-14 and 2005-14

Parameter		Forecast Period (hr)								
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2015 Mean OFCL Forecast Error (kts)	7.3	13.6	17.4	20.4	20.3	19.4	20.0	17.5	13.7	10.6
2015 Mean Persistence Error (kts)	8.6	20.2	35.1	47.4	57.2	57.0	77.3	116.2	141.3	115.6
2015 Mean OFCL Skill wrt Persistence (%)	14.9	30.1	34.2	56.9	64.5	65.9	74.1	85.0	90.3	90.8
2015 No. of cases	66	60	52	43	37	30	22	17	12	8
2010-14 Mean OFCL Forecast Error (kts)	7.3	11.1	14.3	15.8	16.2	17.7	18.2	18.3	16.5	13.9
2010-14 Mean Persistence Error (kts)	9.9	18.6	28.2	35.5	44.3	54.8	67.1	74.2	77.1	76.1
2010-14 Mean OFCL Skill wrt Persistence (%)	26.7	40.2	49.3	55.4	63.5	67.8	72.9	75.3	78.7	81.7
2010-14 No. of cases	235	209	175	145	117	91	44	34	24	14
2005-14 Mean OFCL Forecast Error (kts)	7.3	11.6	13.9	15.2	15.6	17.5	18.2	18.3	16.5	13.9
2005-14 Mean Persistence Error (kts)	9.7	18.0	27.7	35.4	44.4	54.5	67.1	74.2	77.1	76.1
2005-14 Mean OFCL Skill wrt Persistence (%)	24.7	35.7	49.9	56.9	64.9	67.9	72.9	75.3	78.7	81.7
2005-14 No. of cases	374	315	193	156	122	92	44	34	24	14
2015 OFCL error relative to 2010-14 mean (%)	0.8	22.4	21.8	28.8	26.5	9.9	9.4	-4.2	-16.7	-23.8
2015 Persistence error relative to 2010-14 mean (%)	18.4	82.3	24.6	33.7	28.9	4.1	15.2	56.5	83.2	51.9

The intensity forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs during 2013-15

Table 4.28 Homogeneous comparison of Official (OFCL) & Persistence intensity forecast errors based on RMSE over NIO in 2015 as compared to 2010-14 and 2005-14

Parameter	Forecast Period (hr)									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2015 Mean OFCL Forecast Error (kts)	10.2	17.1	24.1	27.8	27.8	28.0	27.3	22.9	18.6	13.1
2015 Mean Persistence Error (kts)	12.1	26.7	44.7	63.8	82.5	86.3	116.3	162.1	190.4	141.9
2015 Mean OFCL Skill wrt Persistence (%)	15.8	32.7	46.9	57.8	66.9	68.2	78.8	85.5	89.9	91.4
2015 No. of cases	66	60	52	43	37	30	22	17	12	8
2010-14 Mean OFCL Forecast Error (kts)	9.9	14.6	18.2	20.0	19.2	21.5	22.2	21.3	17.5	15.0
2010-14 Mean Persistence Error (kts)	15.5	26.7	39.4	51.2	63.3	80.2	94.3	96.5	94.9	98.4
2010-14 Mean OFCL Skill wrt Persistence (%)	34.6	45.2	53.1	60.4	69.1	72.8	76.3	77.9	81.5	84.7
2010-14 No. of cases	235	209	175	145	117	91	48	36	24	14
2005-14 Mean OFCL Forecast Error (kts)	9.8	14.8	17.6	19.4	18.5	21.3	22.2	21.3	17.5	15.0
2005-14 Mean Persistence Error (km)	14.8	26.3	38.4	50.3	62.8	79.8	94.3	96.5	94.9	98.4
2005-14 Mean OFCL Skill wrt Persistence (%)	30.8	42.3	53.1	60.7	69.5	72.8	76.3	77.9	81.5	84.7
2005-14 No. of cases	374	315	193	156	122	92	48	36	24	14
2015 OFCL error relative to 2010-14 mean (%)	3.1	24.9	32.4	38.9	44.8	30.5	23.1	7.7	6.5	-12.5
2015 Persistence error relative to 2010-14 mean (%)	-18.5	0	13.3	24.6	30.4	7.6	23.3	68.0	100.7	44.1

The intensity forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs during 2013-15

The average landfall, track and intensity forecast errors during 2011-15 are given in Tables 4.29-4.30.

Table 4.29 Average landfall point and time error during 2011-15

Lead Period (hrs)	N	Landfall Point Error (km)	Landfall Time Error (hrs)
12	12	36.5	2.5
24	12	56.3	4.2
36	12	60.6	4.7
48	11	93.5	4.7
60	10	95.2	3.9
72	6	105.7	2.4
84	-	-	-
96	-	-	-
108	-	-	-
120	-	-	-

N: Number of landfalling cyclones

Table 4.30 Average Track forecast error & skill compared to CLIPER error and Intensity forecast error & skill based on AE & RMSE compared to persistence during 2011-15

Lead Period (hrs)	N	Track forecast		Average Intensity forecast error (kts)		Gain in Skill (%) against Persistence	
		Error (km)	Skill (%)	AE	RMSE	AE	RMSE
12	246	59.1	41.4	7.1	9.5	20.9	27.9
24	220	97.5	48.5	11.5	15.1	36.4	40.1
36	186	120.0	58.1	14.8	19.6	49.4	52.0
48	160	145.5	62.7	16.9	22.1	55.8	59.6
60	131	160.4	67.8	17.7	22.6	62.3	67.0
72	103	183.2	69.3	17.6	22.5	67.3	72.0
84	70	204.2	71.3	18.8	24.0	73.4	76.4
96	53	239.6	70.4	18.0	21.8	79.5	82.0
108	36	273.9	69.2	15.5	17.9	84.2	86.7
120	22	305.3	70.8	12.7	14.4	86.0	87.6

N: Number of six hourly forecasts verified

4.5 Errors and skill during 2011-15 compared to that during 2006-10

Significant improvement in landfall forecast error was observed during 2011-15 compared to that during 2006-10 due to implementation of modernisation programme in IMD in 2009. The landfall point error during 2011-15 has been 56 and 94 km against 99 and 100 km during 2006-10 (Fig.4.10 a). 33-49% improvement in landfall point error was observed during 2011-15 compared to 2006-10 upto 36 hours lead period. 6% for 48 hours lead period. Landfall time error dropped significantly during 2011-15 upto 48 hours lead period (Fig.4.10 b) and has been 4.2 and 4.7 hrs against 6.9 and 9.0 hrs during 2006-10 for 24, 48 hrs lead period respectively. The landfall forecast error for 60 and 72 hrs during 2011-15 could not be compared with that during 2006-10, as the number of forecasts for these lead periods during 2006-10 is very less.

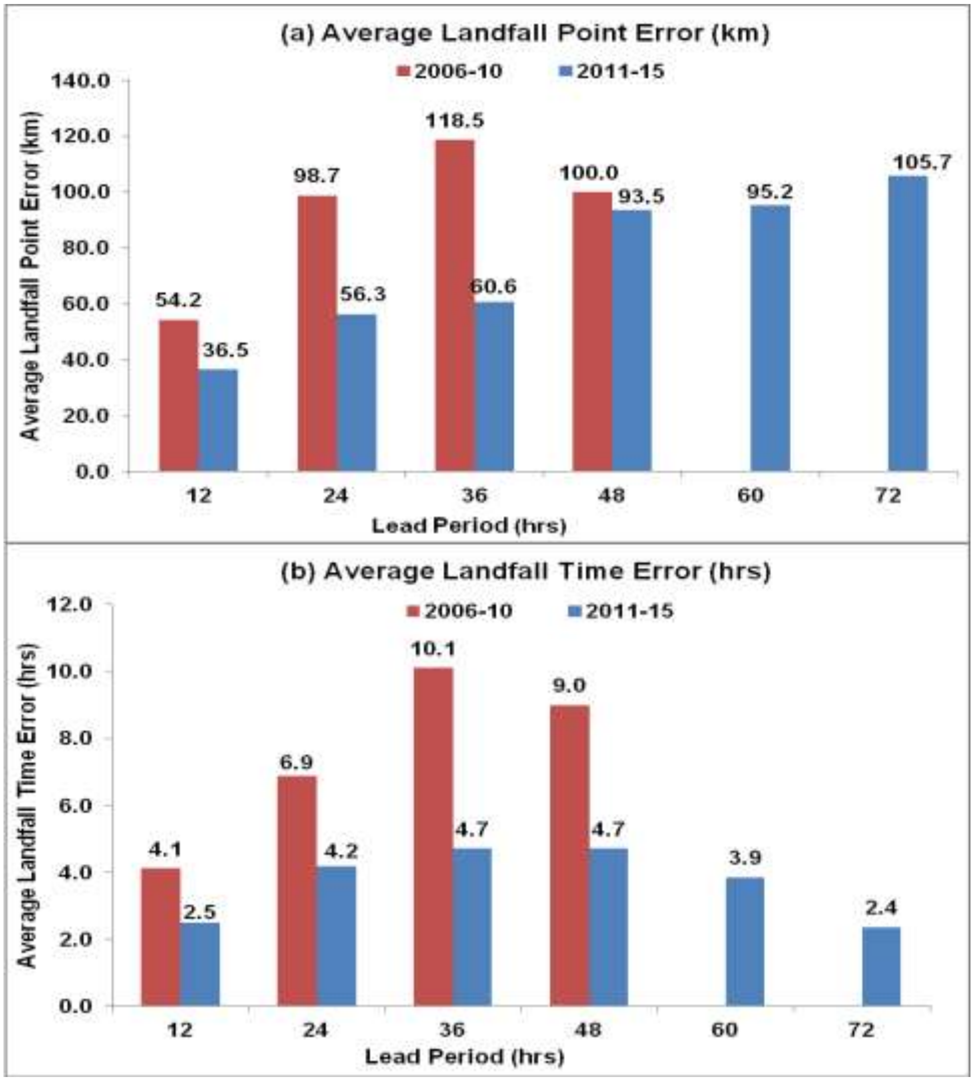


Fig.4.10 Average landfall (a) point error (km) and (b) time error (hrs) during 2006-10 and 2011-15.

The track forecast error during 2011-15 has been 98, 146, 183 km against 141, 287, 454 km during 2006-10 for 24, 48 and 72 hrs lead period respectively. The period during 2011-15 registered a decrease in track forecast error by 30, 50 & 60% as compared to 2006-10 for 24, 48 and 72 hours lead period respectively. Similarly skill also improved significantly during 2011-15 (Fig.4.11) and has been

49, 63 & 69 % during 2011-15 against 24, 31 & 40% during 2006-10 for 24, 48 and 72 hrs lead period respectively.

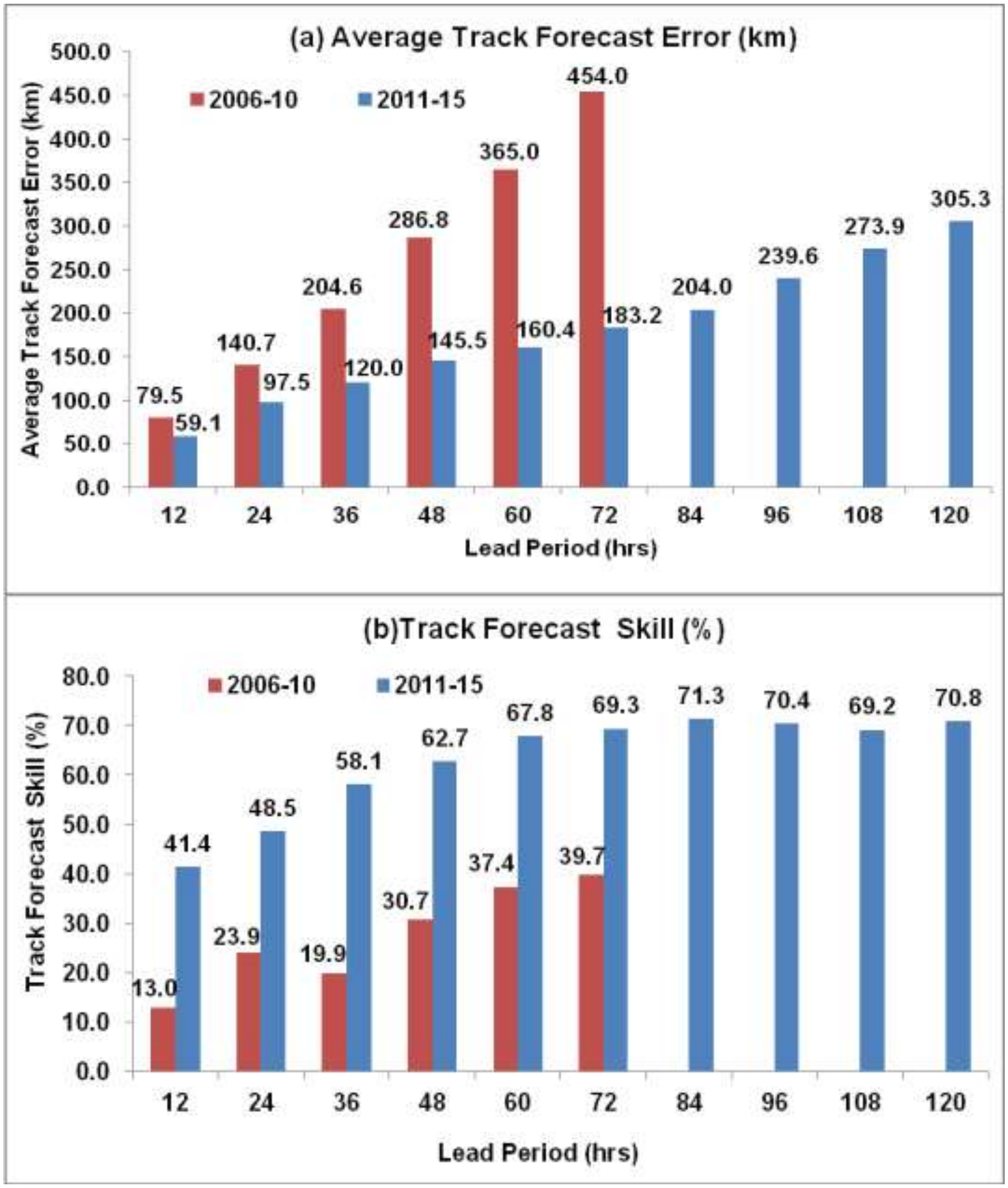


Fig.4.11 Average track forecast (a) error (km) and (b) skill (%) during 2006-10 and 2011-15.

Comparative analysis of intensity forecast errors and skill based on AE & RMSE relative to persistence error is shown in Fig. 4.12 & 4.13. Intensity forecast errors based on AE during 2011-15 has been 11.5, 16.9 & 17.6 kts against 12.2, 14.0 & 19.7 kts during 2006-10 for 24, 48 and 72 hrs lead period respectively. Improvement in intensity forecast errors have been observed for 12, 24 & 72 hrs lead period during 2011-15. Skill in Intensity forecast error based on AE has been 36.4, 55.8 and 67.3% during 2011-15 against 39.1, 61.9 and 67.5% during 2006-10 for 24, 48 and 72 hr lead period. There has been marginal improvement of skill in intensity forecast based on AE for all lead period. The rate of improvement is relatively less as compared to track & landfall forecast errors during the same period.

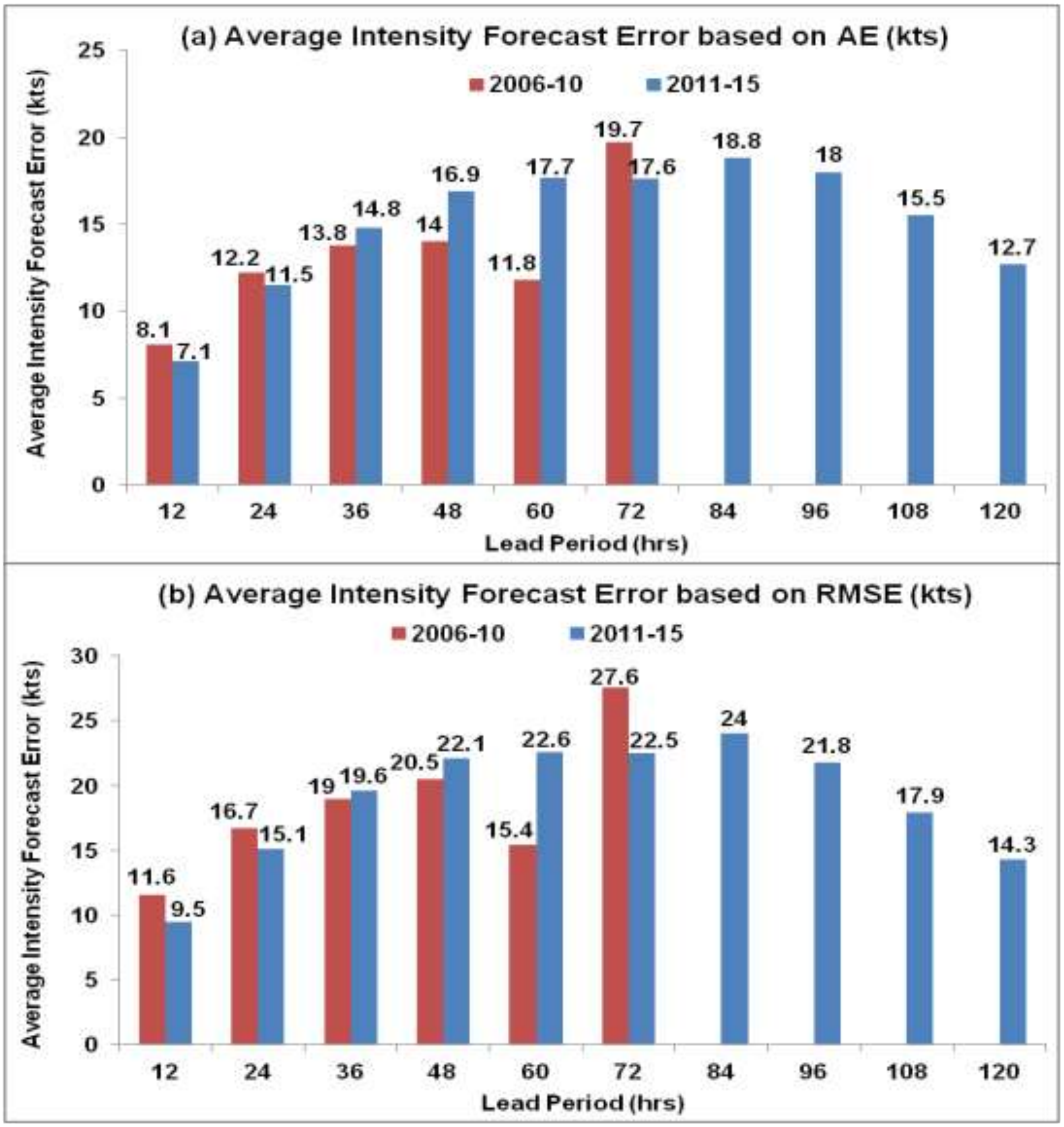


Fig.4.12 Average intensity forecast error (kts) based on (a) AE and (b) RMSE during 2006-10 and 2011-15.

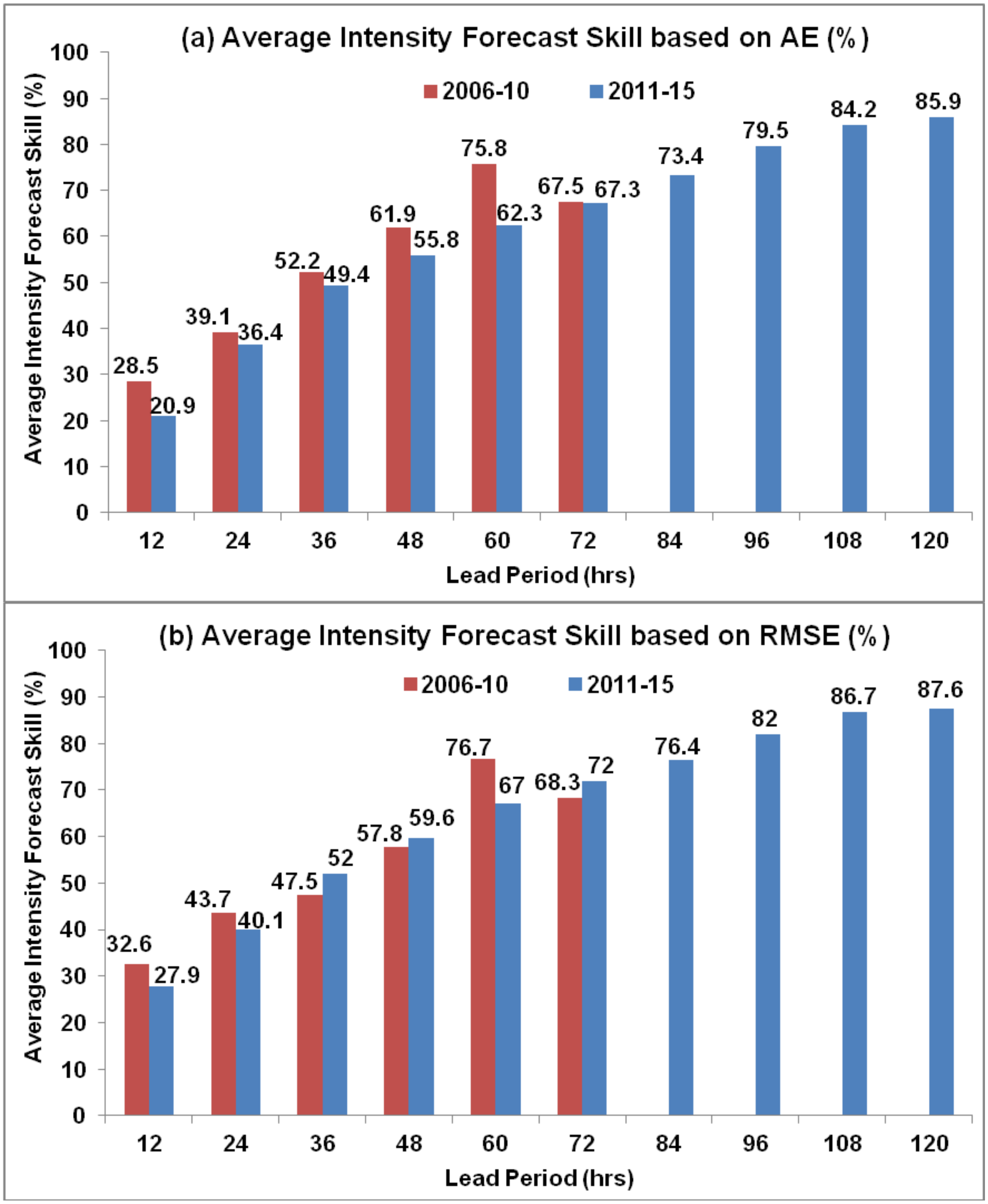


Fig.4.13 Average intensity forecast skill (%) based on (a) AE and (b) RMSE compared to persistence during 2006-10 and 2011-15.

4.6 Interannual variation

The landfall point and time forecast errors of cyclones over north Indian Ocean during 2003-15 are shown in fig.4.14. The track forecast errors and skill as compared to climatology and persistence (CLIPER) model based forecast errors of cyclones over north Indian Ocean during 2003-15 are shown in fig 4.15. The intensity forecast errors and skill as compared to persistence based forecast errors of cyclones over north Indian Ocean are shown in fig.4.16. It is observed that the errors are significantly less and skills are higher in recent years (2009 onwards) for all types of forecasts including track, intensity and landfall. It is mainly due to the modernization programme of Ministry of Earth Sciences and India Meteorological Department leading to enhanced observation, modeling, analysis tools and techniques and computation system. However, the rate of improvement has been highest in case of landfall point forecasts followed by track forecast. The rate of improvement in the intensity forecasts is relatively less like the other Ocean basins.

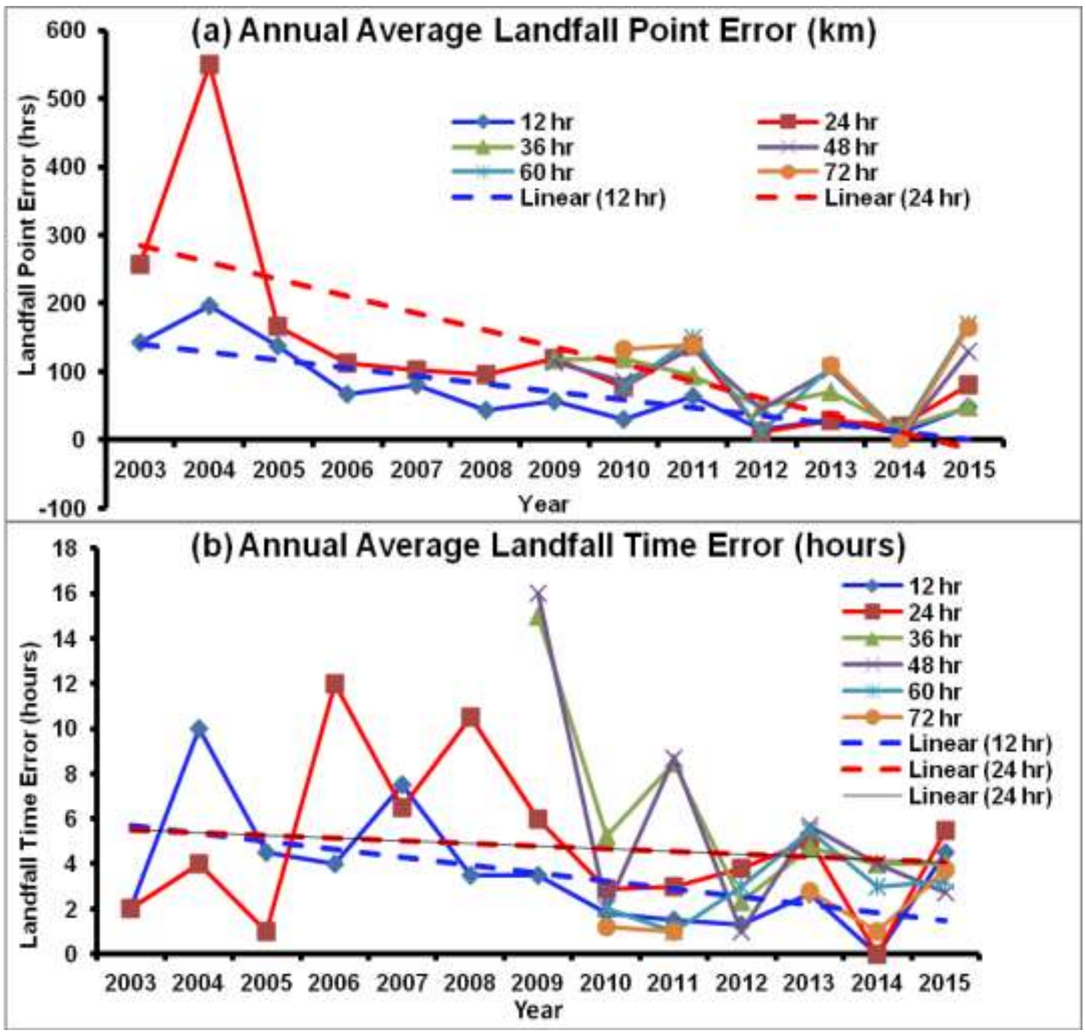


Fig. 4.14 Annual Average (a) Landfall Point Error (km) and (b) Landfall Time Error (hours)

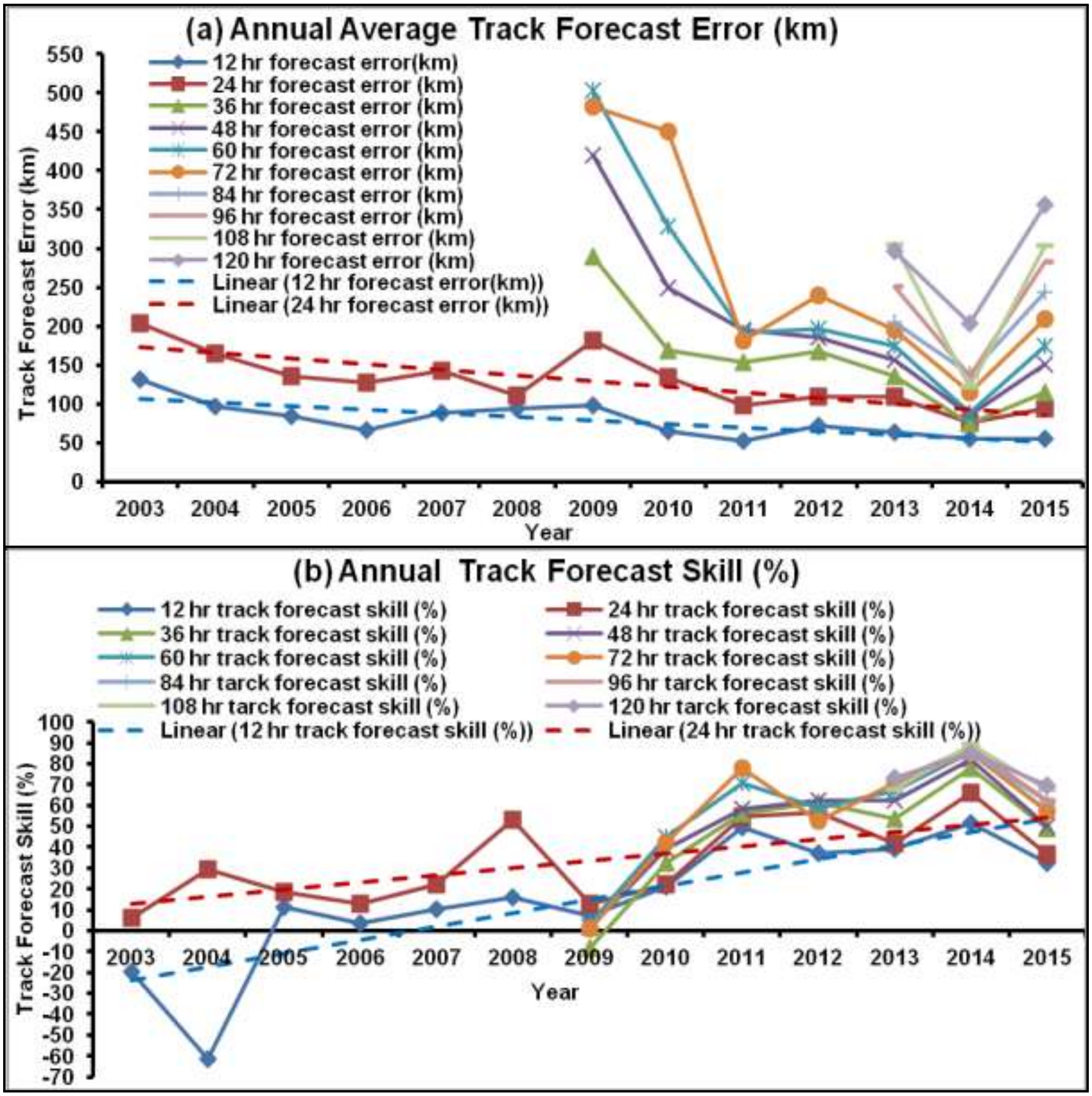


Fig.4.15 Annual Average (a) Track Forecast Error (km) and (b) Track Forecast Skill (%)

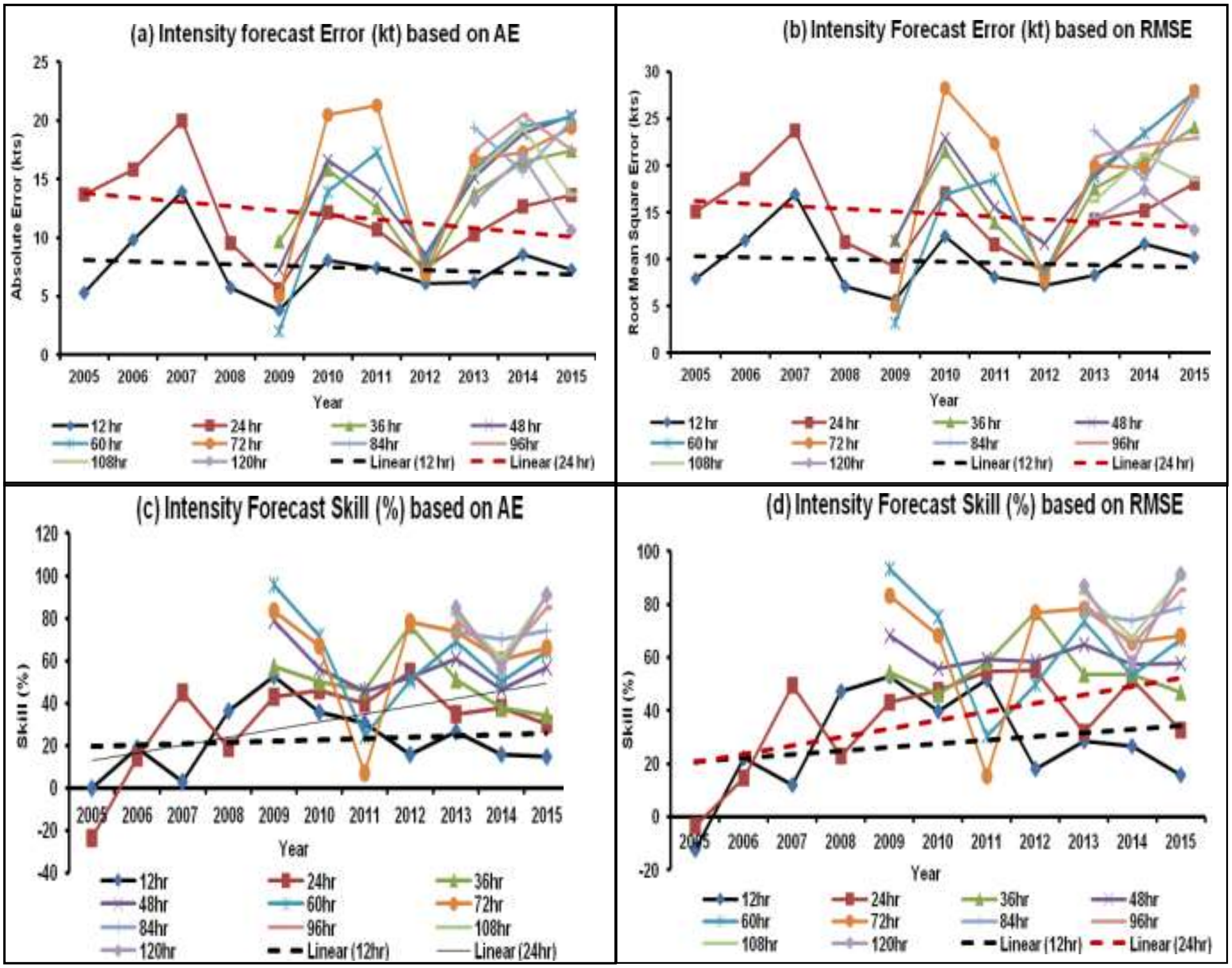
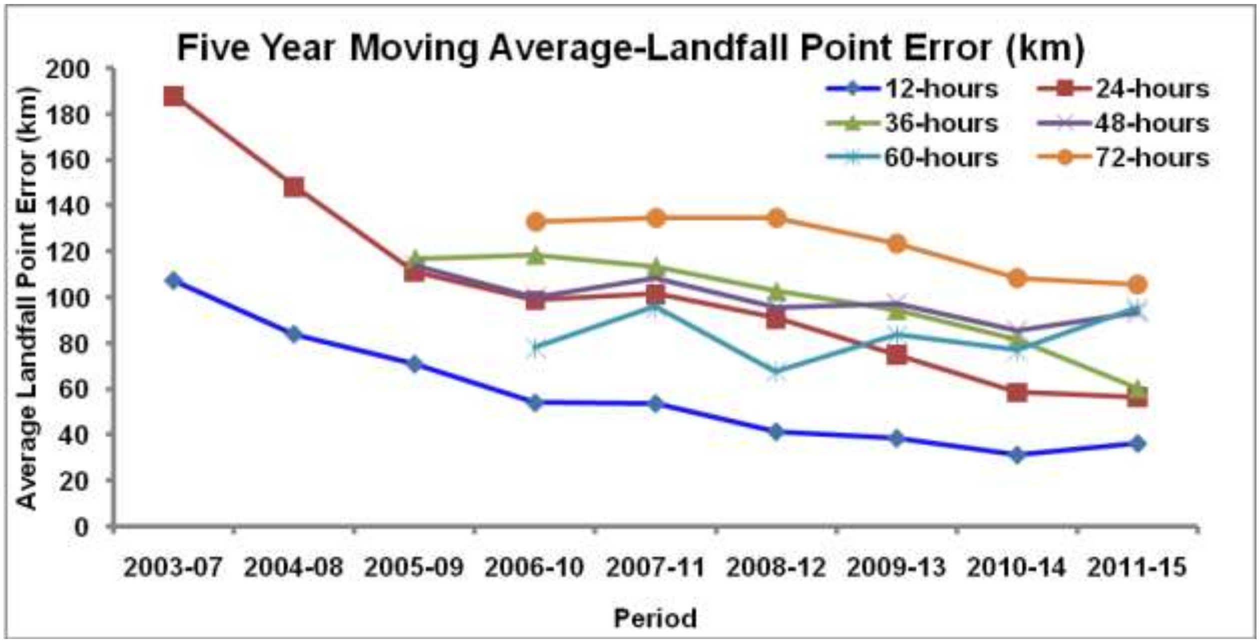


Fig. 4.16 Annual Average Intensity Forecast Error (kts) based on (a) AE & (b) RMSE and Intensity Forecast Skill (%) based on (c) AE & (d) RMSE

4.7. Five year moving averages of errors and skill

It can be seen from Fig. (4.17-4.20) that there has been continuous improvement in forecast accuracy with decrease in error and increase in skill over the years. However, due to modernization programme of IMD and other initiatives of MoES, the improvement has been more significant since 2009.



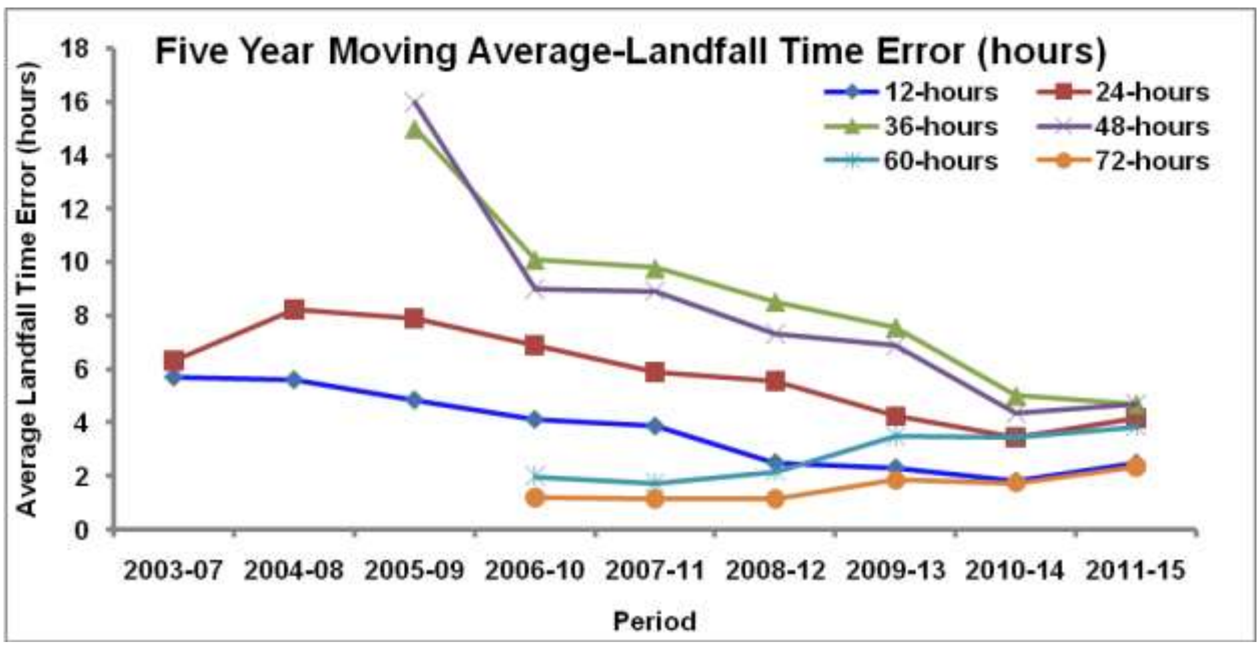


Fig. 4.17 Five Year Moving Average (a) Landfall Point Error (km) and (b) Landfall Time Error (hours)

As the 36-72 hours forecasts commenced from 2009, the five year period of 2005-09, 2006-10, 2007-11, 2008-12 for these forecast times contain only 1,2,3 and 4 years of data respectively.

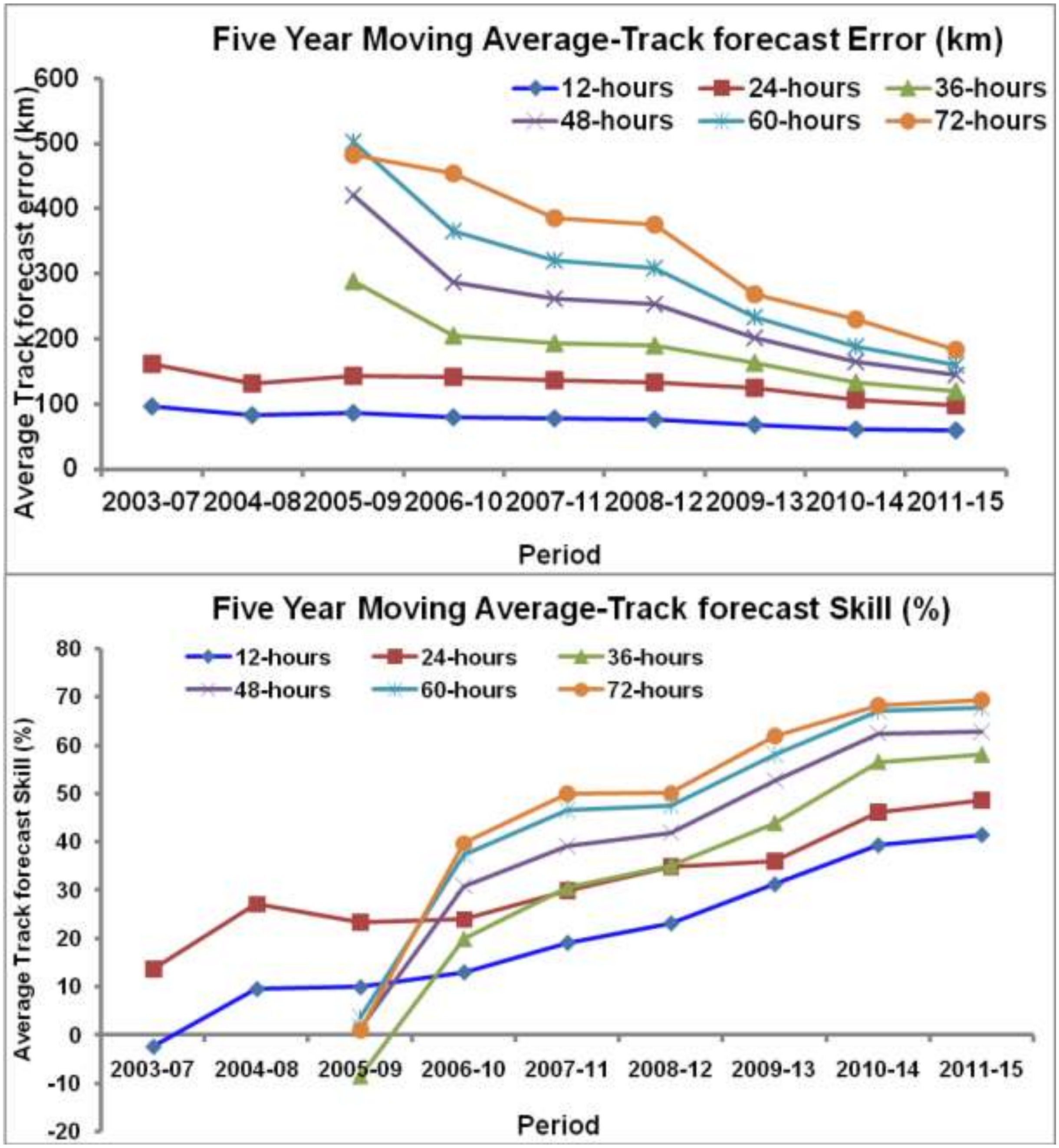


Fig.4.18 Five Year Moving Average (a) Track Forecast Error (km) and (b) Track Forecast Skill (%)

As the 36-72 hours forecasts commenced from 2009, the five year period of 2005-09, 2006-10, 2007-11, 2008-12 for these forecast times contain only 1,2,3 and 4 years of data respectively.

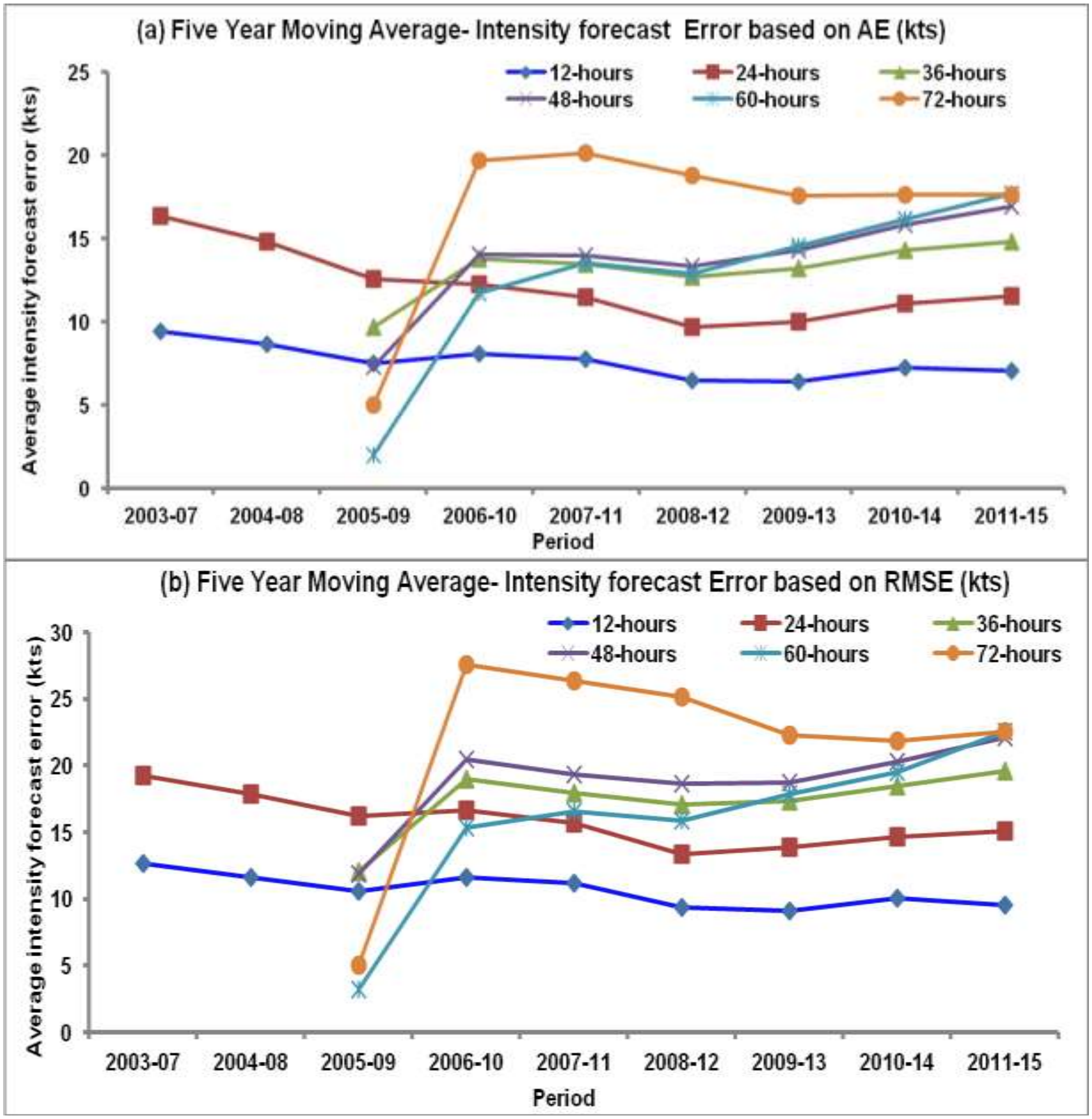


Fig.4.19 Five Year Moving Average Intensity Forecast Error based on (a) AE and (b) RMSE

As the 36-72 hours forecasts commenced from 2009, the five year period of 2005-09, 2006-10, 2007-11, 2008-12 for these forecast times contain only 1,2,3 and 4 years of data respectively.

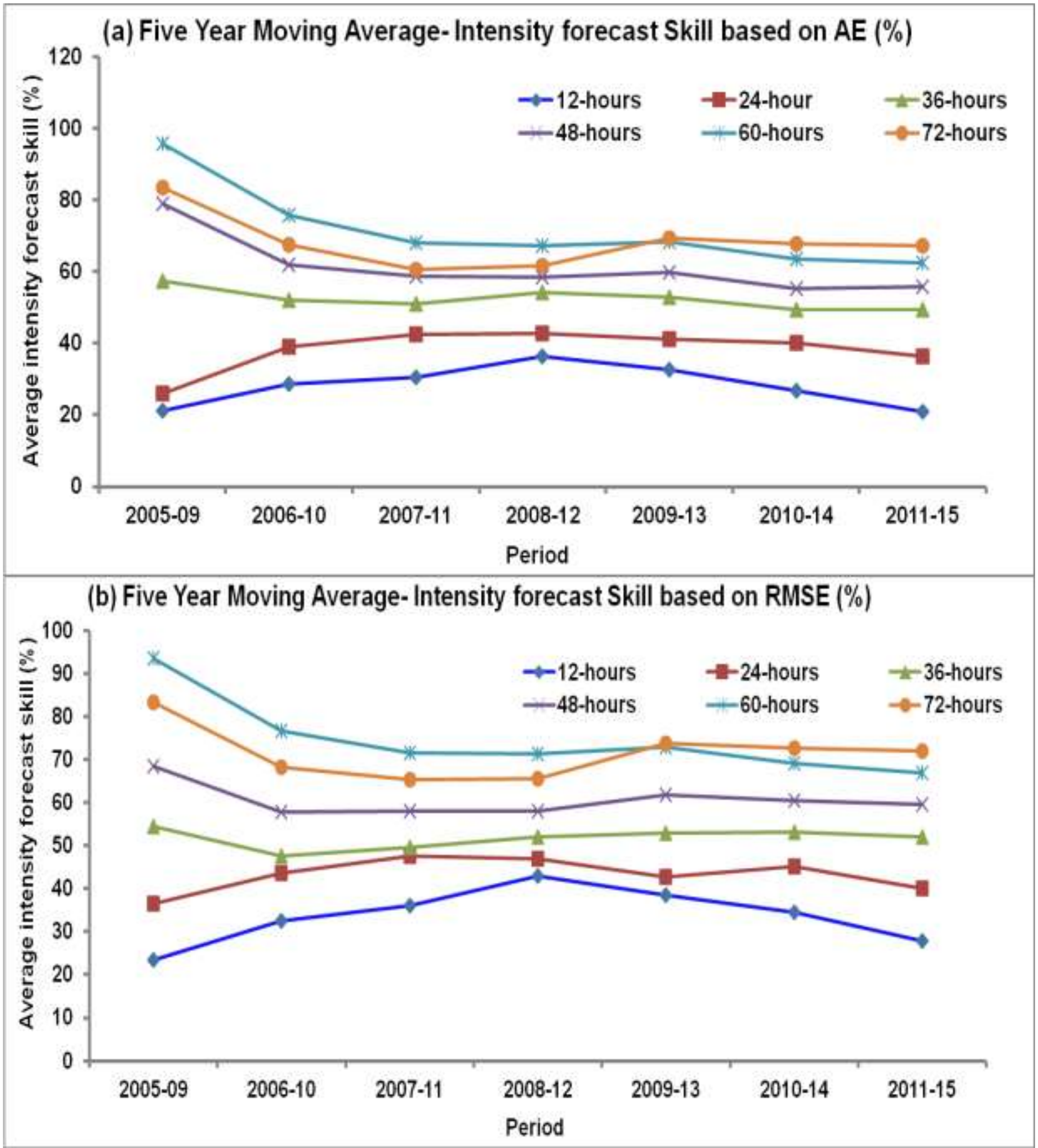


Fig.4.20 Five Year Moving Average Intensity Forecast skill based on AE compared to persistence forecast

As the 36-72 hours forecasts commenced from 2009, the five year period of 2005-09, 2006-10, 2007-11, 2008-12 for these forecast times contain only 1, 2, 3 and 4 years of data respectively.

DAMAGE DUE TO EXTREMELY SEVERE CYCLONIC STORM ‘CHAPALA’ OVER YEMEN