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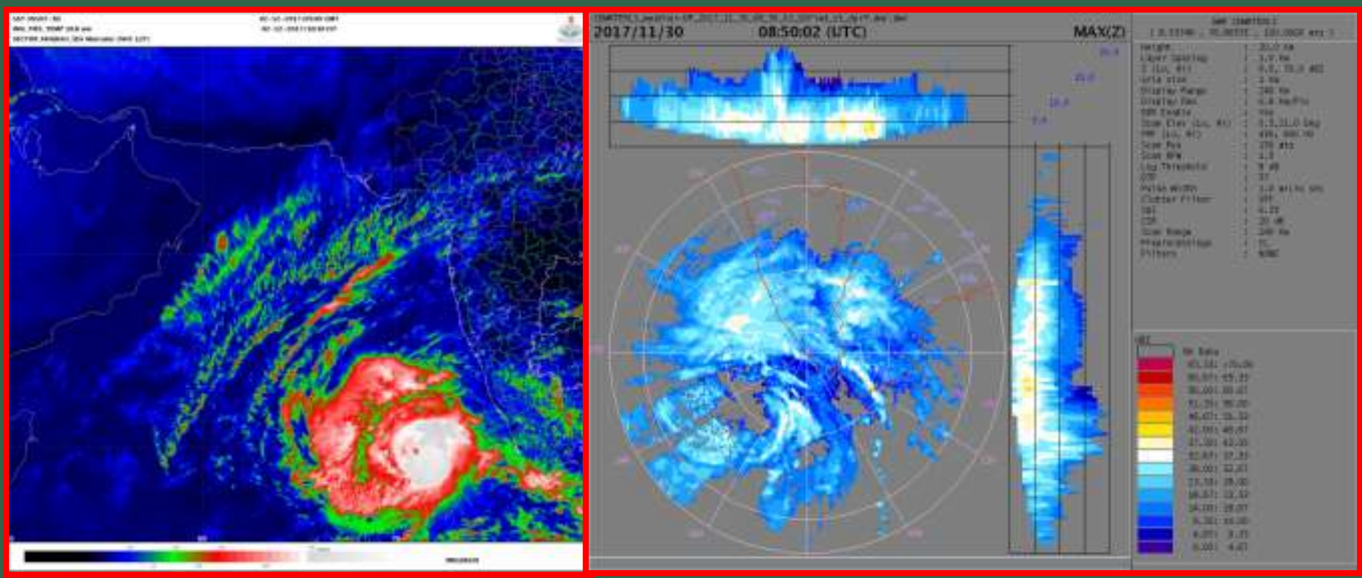
REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2017



SATELLITE AND RADAR IMAGERY OF VERY SEVERE CYCLONIC STORM, “OCKHI"

RSMC-TROPICAL CYCLONES, NEW DELHI

APRIL 2018

WMO

INDIA METEOROLOGICAL DEPARTMENT

RSMC- TROPICAL CYCLONES, NEW DELHI

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13.	Abstract	The activities of Regional Specialised Meteorological Centre (RSMC) – Tropical Cyclone New Delhi are briefly presented alongwith the current state of art for monitoring and prediction of cyclonic disturbances over the north Indian Ocean. This report further describes the characteristics of cyclonic disturbances formed over the north Indian Ocean during 2017. 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, Thailand and Yemen. 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, Thailand and Yemen as shown in Fig. 1.1.

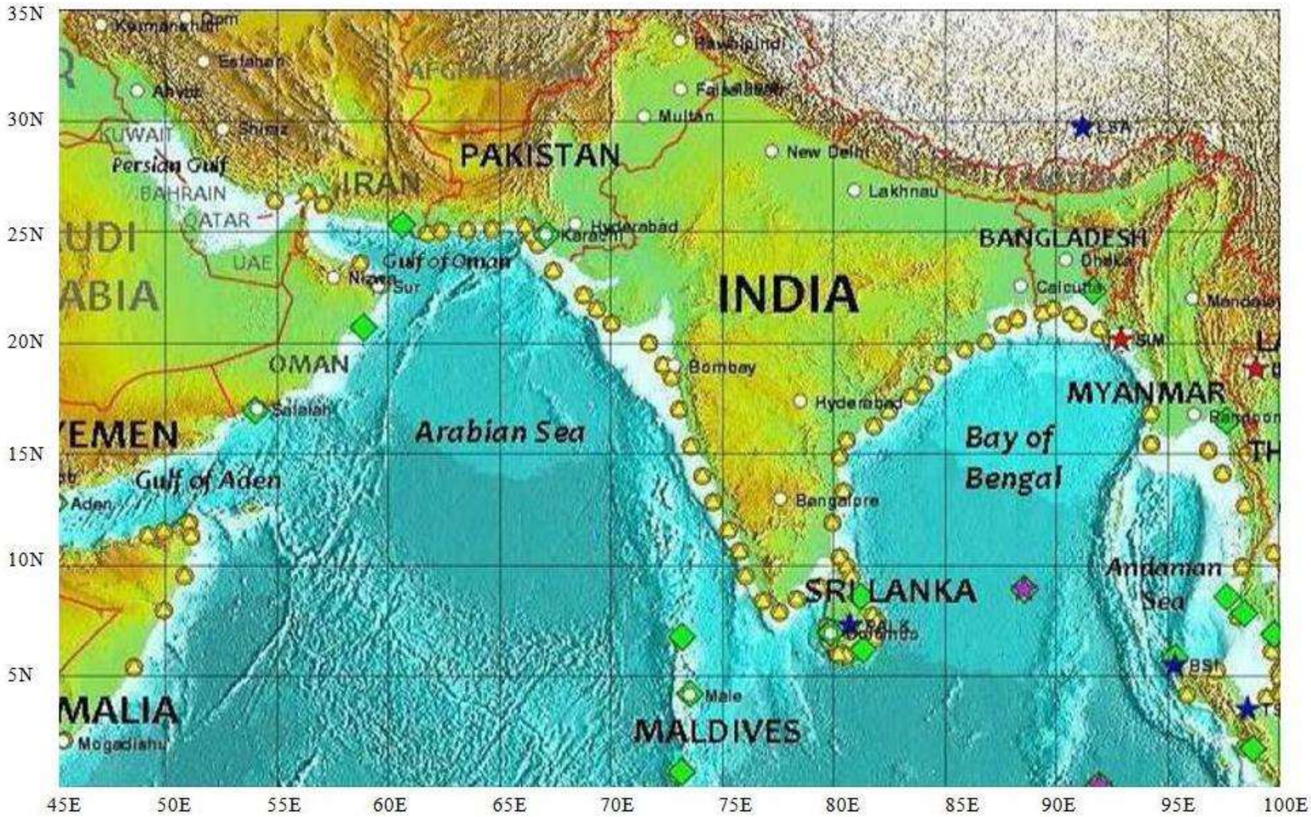


Fig. 1.1 Area of responsibility of RSMC- Tropical Cyclone, New Delhi

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, 46 names have been utilized till the end of year 2016.

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.

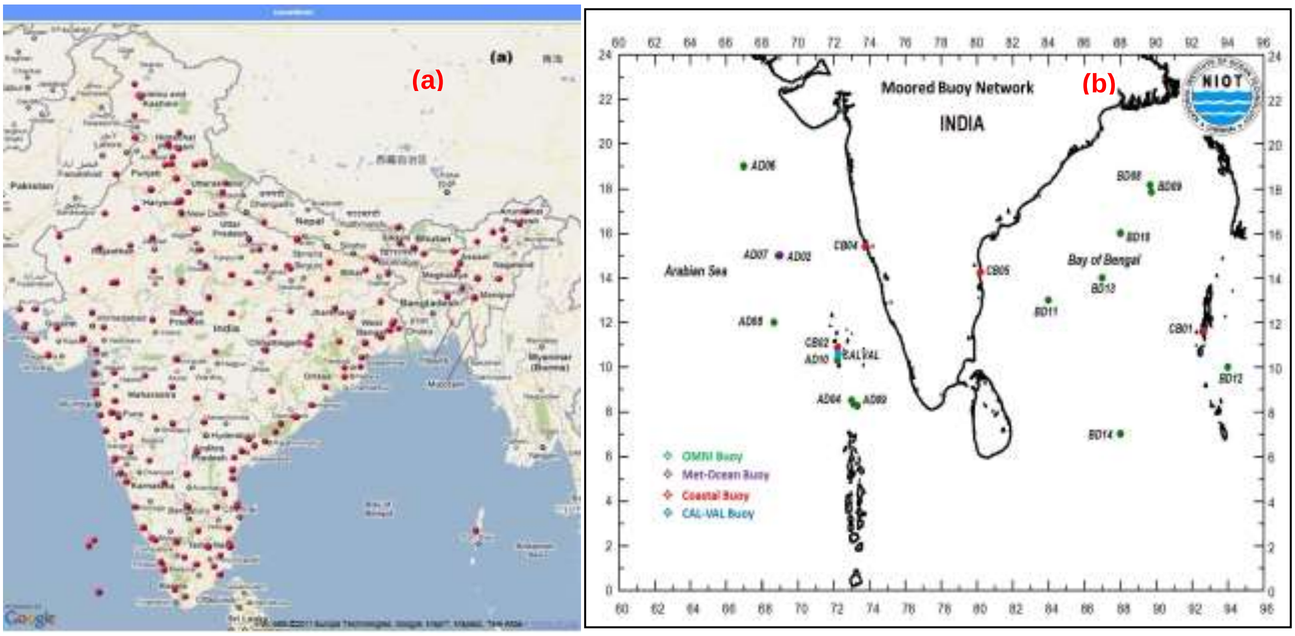


Fig.1.2. (a) The surface Observatory Network of IMD (b) Buoy network of NIOT

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 Fig. 1.3 is now available for operational utilization. In addition to AWS, a network of 1350 Automatic Rain Gauge (ARG) Stations has been established in different states.

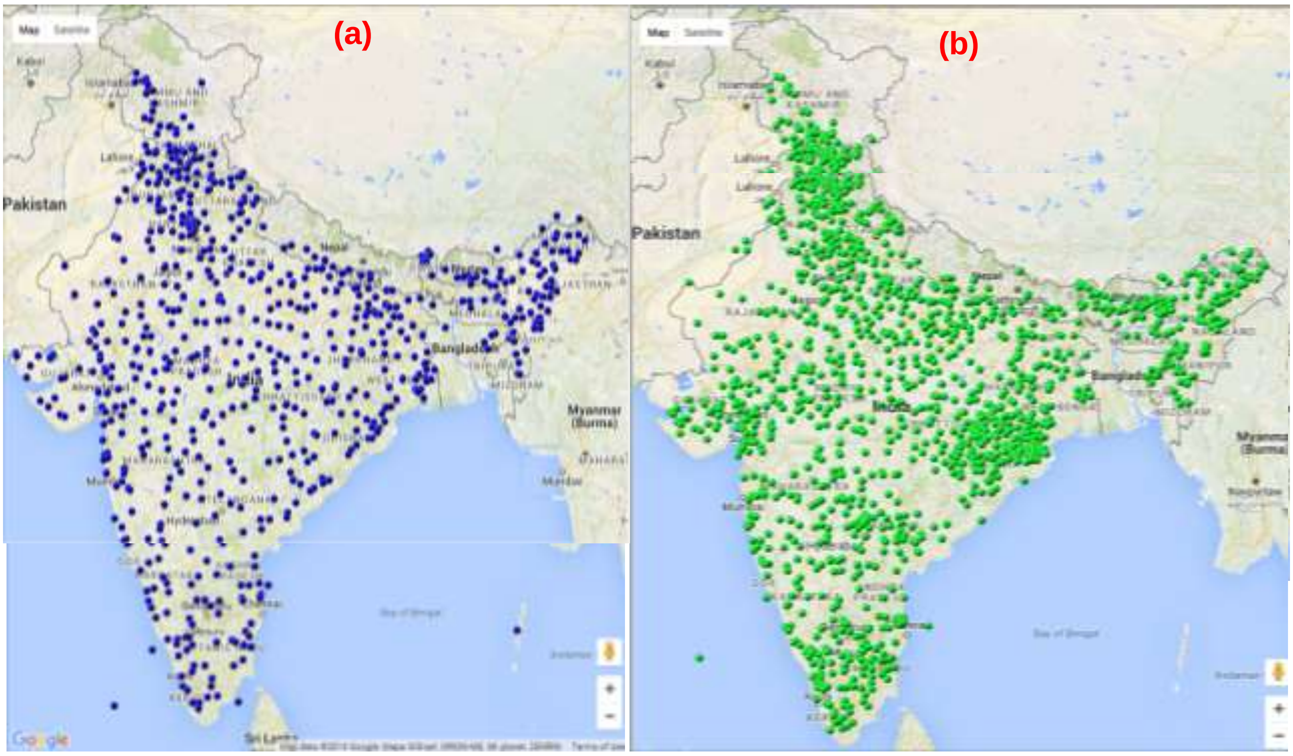


Fig. 1.3 (a) Network of 675 AWS and (b) 135 ARGs.

1.3.2 Upper Air Observatories

There are at present 62 Pilot Balloon Observatories, 43 Radiosonde/ Radio wind observatories. All the 43 stations are latest of the art- GPS based observatories. Out of 43 6 RS/RW stations at Regional Meteorological Centre's (New Delhi, Mumbai, Kolkata, Chennai, Guwahati and Nagpur) are of WMO-GUAN (Global Climatological Observations System Upper Air Network) standards. Formal request for inclusion of these stations into GUAN network has been made with GCOS secretariat through Secretary General WMO. The pilot balloon observation network and RS/RW network of IMD is shown in Fig 1.4

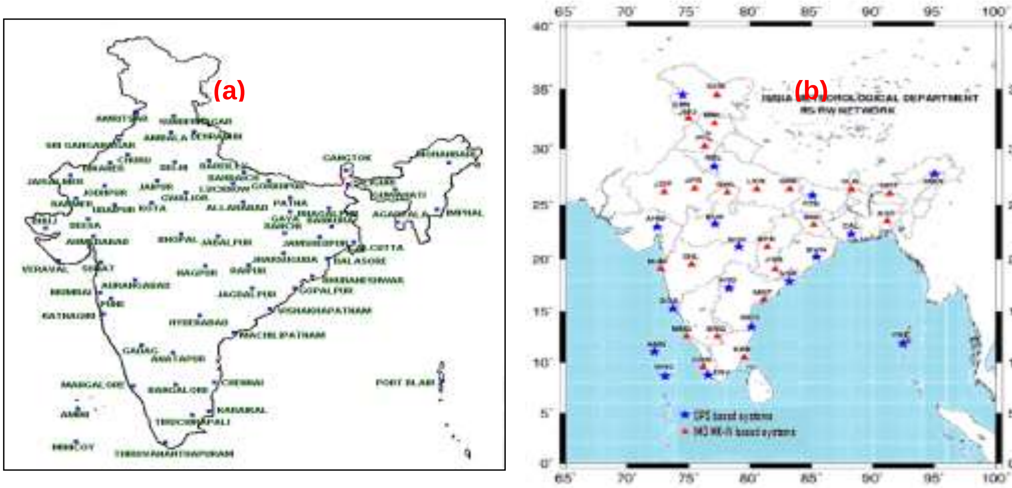


Fig.1.4 (a) Network of Pilot Balloon Observatories and (b) Network of Radiosonde/ Radio wind observatories

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.

1.3.3 Radars

1.3.3.1 Current status

Weather radar network of India is managed by IMD, and consists of twenty one Doppler weather radars presently spreading across the country. There are twenty three sites with Doppler Weather Radars (DWR), including eighteen sites operating in S-band and two sites with C-band Polarimetric DWRs and one in X-band. Nine more sites have analogue non Doppler Weather Radars. Two indigenously manufactured S-band polarimetric DWRs have been installed at Kochi and Gopalpur.

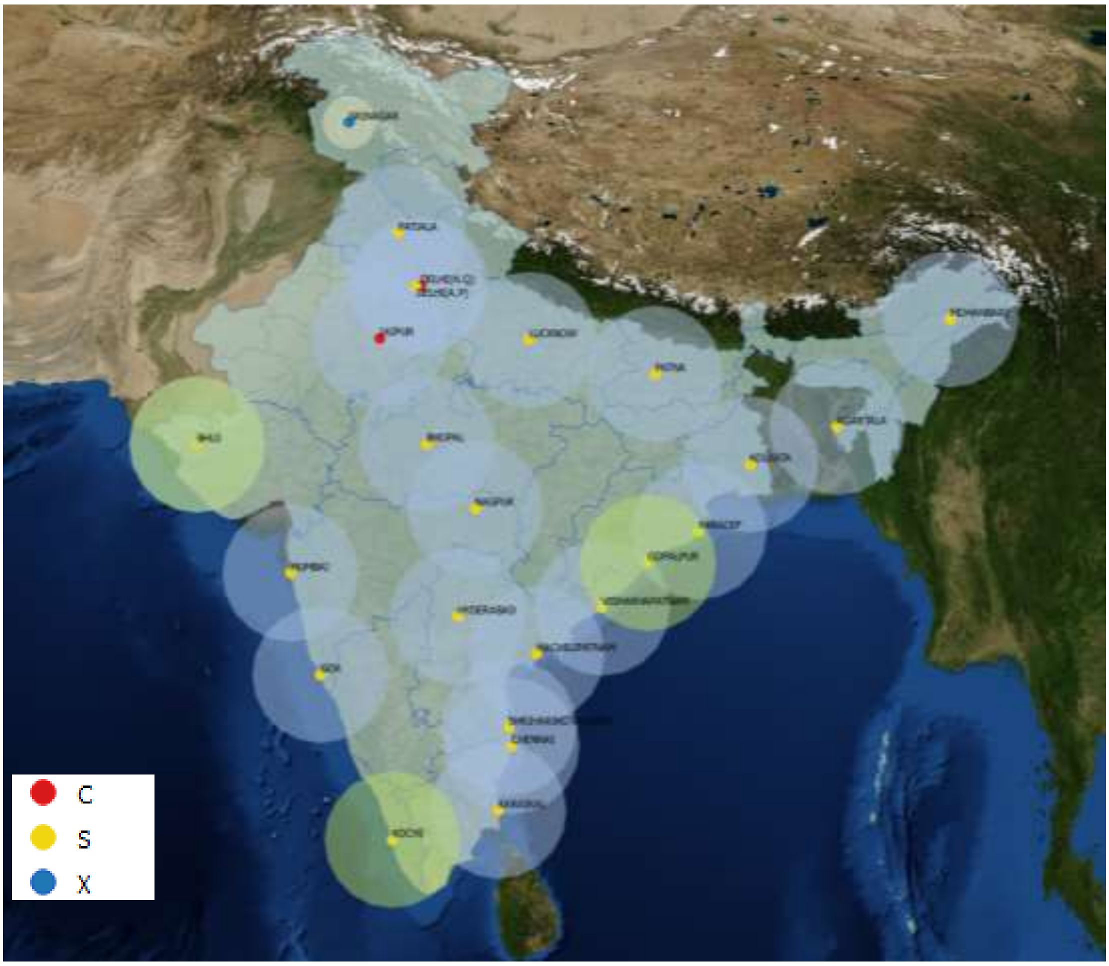


Fig. 1.5 Network of Radar

S-band DWRs are installed at Agartala, Bhopal, Chennai, Hyderabad, Kolkata, Lucknow, Machilipatnam, Mohanbari, Goa, Karaikal, Paradeep, Nagpur, New Delhi, Patna, Patiala, Gopalpur, Kochi, Mumbai, Bhuj, Sriharikota and Visakhapatnam. C-band Polarimetric DWRs are installed at Jaipur and New Delhi. One X-Band transportable radar has been installed at Srinagar.

Analogue 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 and hydrological products derived from DWR data using software algorithms are extremely useful to the forecasters for estimating the storm's center and intensity as well as structure. The existing DWRs have also been networked to super computers for numerical weather prediction (NWP) models for short range forecasting. 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.

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 two Indian satellites namely INSAT-3D & INSAT-3DR. INSAT-3D launched on 26 July 2013 is positioned at 82°E and INSAT 3DR launched on 28th Aug 2016 is located at 74°E. INSAT-3D and INSAT-3DR have 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 INSAT-3D and INSAT-3DR. *Images from imager data are available every 15 minutes and Sounder multi-level imagery is obtained half hourly from the sounder channels of INSAT-3D and INSAT-3DR satellites in staggered mode.* 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-3D and INSAT3-DR that 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. Enhanced grey scale imagery of cyclone.
2. Enhanced coloured imagery of cyclone.
3. Lower level Vorticity
4. Upper level Divergence.
5. Lower level convergence.
6. Vertical wind shear.
7. Wind shear tendency.
8. Outgoing Long wave Radiation (OLR) at 0.250X0.250 resolution
9. Quantitative Precipitation Estimation (QPE) at 10 /10 resolution
10. Sea Surface Temperature (SST) at 10 /10 resolution
11. Cloud Motion Vector (CMV)
12. Water Vapour Wind (WVW)
13. Upper Tropospheric Humidity (UTH)
14. Temperature, Humidity profile
15. 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.1.6.

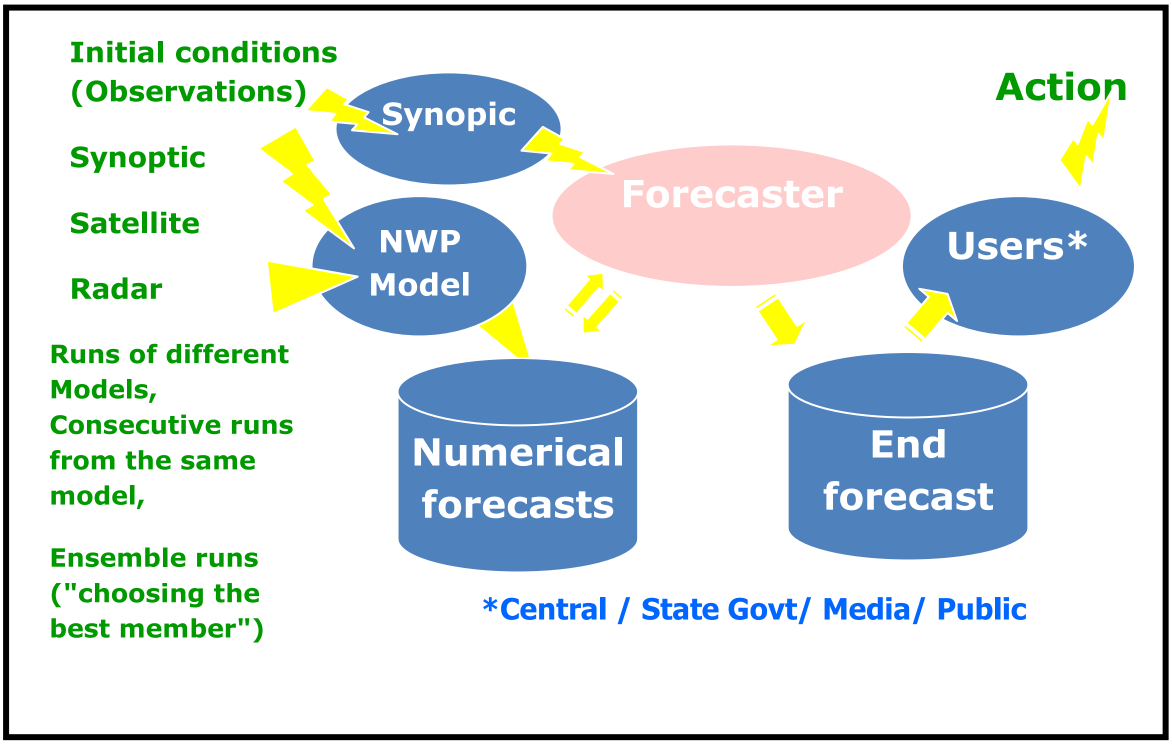


Fig.1.6. Strategy adopted for cyclone analysis and forecasting

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 from 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 2017

1.5.1. Global Forecast System

The Global Forecast System (GFS), adopted from National Centre for Environmental Prediction (NCEP) was implemented at India Meteorological Department (IMD), New Delhi on IBM based High Power Computing Systems (HPCS) at T1534 (~ 12 km in horizontal over the tropics) with ENKF based Grid point Statistical Interpolation (GSI) scheme as the global data assimilation for the forecast up to 10 days. The model is run twice in a day (00 UTC and 12 UTC). The real-time outputs are made available to the national web site of IMD (http://www.imd.gov.in/section/nhac/dynamic/nwp/welcome.htm).

1.5.2. Regional Forecast System

IMD operationally runs three regional models WRFDA-WRFARW (v3.6), 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 3.6) 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 18 km, 6 km and 2 km horizontal resolution and 61 vertical levels with outer domain covering the area of 80X80, 24X24 and innermost domain 7X7 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 during the 2011 cyclone season as an experimental forecast in real-time. In these runs only the atmospheric model (HWRF) was tested. The Ocean Model (POM-TC) and Ocean coupler requires the customization of Ocean Model for Indian Seas. In this regards, IMD is working in collaboration with INCOIS, Hyderabad which is running the Ocean Models (POM)/Hybrid co-ordinate ocean model (HYCOM) to support in porting the Ocean Model with Indian Ocean climatology and real time data of SST over Indian Seas. The model is run on real time 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-T1534L64 analysis/forecast as first guess.

1.5.3. NWP based Objective Cyclone Prediction System (CPS)

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

1.5.3.1 Genesis Potential Parameter (GPP)

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

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

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 12 hourly predicted cyclone tracks are then determined from the respective mean sea level pressure fields using a cyclone tracking software. Multiple linear regression technique is used to generate weights (regression coefficients) for each model for each forecast hour (12hr, 24hr, 36 hr, 48hr, 60hr, 72hr, 84hr, 96hr, 108hr and 120 hrs) based on the past data. These coefficients are then used as weights for the ensemble forecasts. 12-hourly forecast latitude (LATf) and longitude (LONf) positions are defined by multiple linear regression technique. 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 of ECMWF 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 be provided 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 be increases from 0% to 100% when the total number of indices satisfied increases from zero to eight. The forecasts are made available in real time from 2013.

1.5.3.5. Decay of Intensity after the landfall

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

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

As part of WMO Program to provide a guidance of tropical cyclone (TC) forecasts in near real-time for the ESCAP/WMO 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 ESCAP/WMO committee Members. The forecast products are made available in real time.

1.5.5. Models run at NCMRWF

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. Apart from the observations that are used in the earlier system, the new observations assimilated at NCMRWF include (i) Precipitation rates from SSM/I and TRMM (ii) GPSRO occultation (iii) AIRS and AMSRE radiances (iv) MODIS winds. Additionally ASCAT ocean surface winds and INSAT-3D AMVs are also assimilated. NCUM (N768/L70) model features a horizontal resolution of 17km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. NCUM is a grid point model which has a Non-hydrostatic dynamics with a deep atmosphere suitable for all scales. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. It features mass-flux for shallow convection with convective momentum transport, non-local mixing and entrainment for boundary layer. NCMRWF Ensemble Prediction System (NEPS) is a global medium range probabilistic forecasting system adapted from UK MET Office. The configuration consists of four cycles of assimilation corresponding to 00Z, 06Z, 12Z & 18Z and 10-day forecasts are made using the 00Z initial condition. The N400L70 forecast model consists of 800x600 grid points on the horizontal surface and has 70 vertical levels. Horizontal resolution of the model is approximately 33 km in the mid-latitudes. The 10 day control forecast run starts with N768L70 analysis of the deterministic assimilation forecast system and 44 ensemble members start from different perturbed initial conditions consistent with the uncertainty in initial conditions. The initial perturbations are generated using Ensemble Transform Kalman Filter (ETKF) method (Bishop et al., 2001). An important component common to both the deterministic and ensemble model is that they do not use any TC relocation in the analysis.

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 an ADvanced CIRCulation (ADCIRC) 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, 115, 130, 145, 160, 175 and 190 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. 1.7

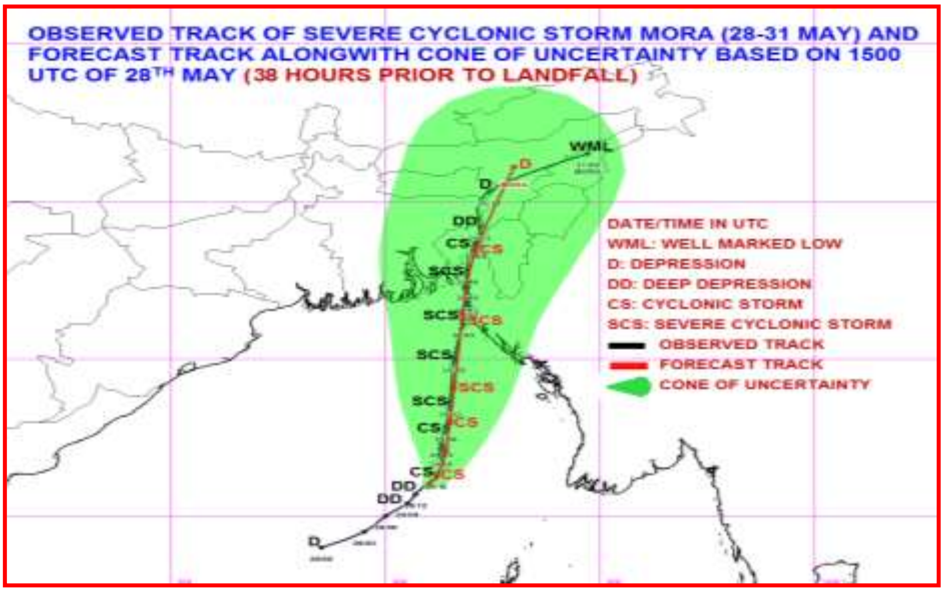


Fig.1.7. A typical example of observed and forecast track along with cone of uncertainty of SCS Mora

1.6.9 Wind forecast for different quadrants

The forecast of the radius of maximum sustained wind in four quadrants of a cyclone commenced with effect from the 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.1.8. This quadrant wind forecast is issued as a bulletin from the deep depression stage onwards to various users through a global telecommunication system. It is also uploaded on RSM, New Delhi website in both textual and graphics form.

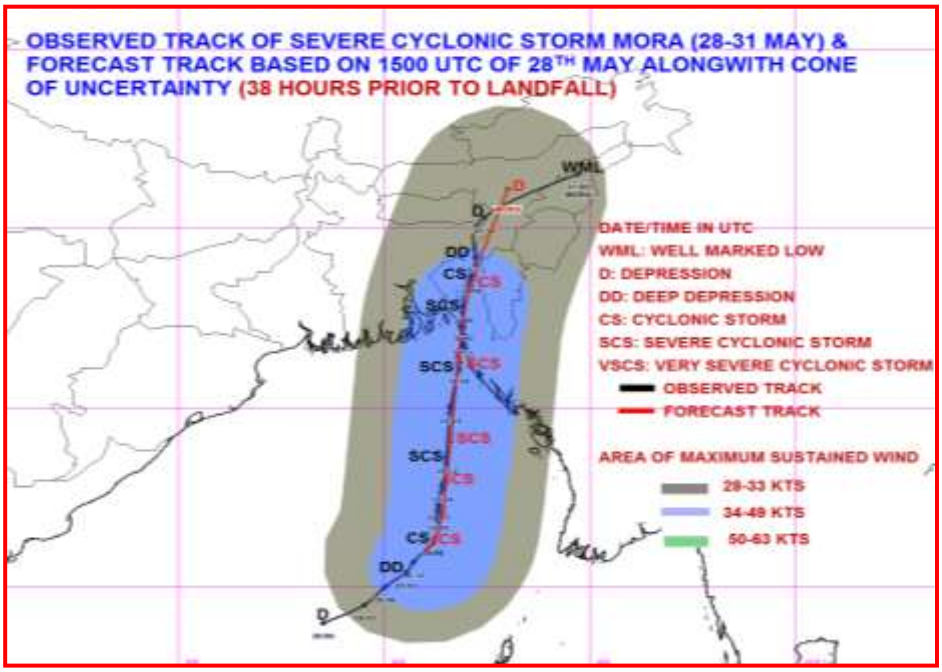


Fig.1.8. A typical graphical presentation of cyclone wind forecast during SCS Mora

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, the 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.

1.7 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 on 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 the 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 the 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 a wide range of users. The

SMS based cyclone alert to the registered 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 the coastal region along east as well as the west coast of India for the operation of lightships and fishermen from 30th March 2016. 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 the 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 2016, 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 farmers 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 a tropical cyclone.

The project is operated during 15 October to 30 November every year. But during the year 2016, due to development of cyclonic disturbances in the month of December, the FDP campaign was extended upto 20 December 2016. Like previous years (2008-2015), several national institutions participated for joint observational, communicational & NWP activities. There was an improved observational campaign with the observation from Buoys, Scatterometer based satellite and microwave imageries products. There was intense observation period for 12 days during the field phase 2016 in association with the systems over the Bay of Bengal and the 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-2016 will be available in RSMC, New Delhi website (www.rsmcnewdelhi.gov.in).

CHAPTER-II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2017

There were 10 cyclonic disturbances (CDs) i.e. depressions and cyclones over the north Indian Ocean (NIO) & adjoining land regions during 2017 against the long period average (LPA) of 11.5 disturbances per year based on data of 1961-2016. Out of 10 CDs, 3 intensified into tropical cyclones against the normal frequency of 4.5 cyclones per year over north Indian Ocean (NIO) based on LPA. It included including 1 cyclonic storm (CS). 1 severe cyclonic storm and 1 very severe cyclonic storm (VSCS). These cyclones are:

- ***Cyclonic storm, Maarutha over Bay of Bengal (15-17 April)***
- ***Severe Cyclonic storm, Mora over Bay of Bengal (28-31 May)***
- ***Very Severe Cyclonic storm, Ockhi over the Bay of Bengal (29 November-05 December)***

- Thus, there was no cyclone over the Arabian Sea and all the three cyclones developed over the Bay of Bengal
- The cyclonic activity over the NIO was below normal during 2017. The activity during post-monsoon was below normal with the formation of 1cyclone during this season.
- There was one severe cyclonic storm or higher intensity storm (Maximum sustained wind speed (MSW) ≥ 48 kts & above) over NIO in 2017 against the average of 2-3 such storms.
- Two cyclones (Mora and Ockhi) during 2017 had recurving tracks. While cyclone Maarutha had straight track.
- The **Cyclonic Storm** (CS) ***Maarutha*** developed from depression (D) developed over southeast Bay of Bengal in the morning of 15th April. Moving northeastwards, it intensified into a deep depression over eastcentral BOB in the afternoon of 15th and into a cyclonic storm "MAARUTHA" over eastcentral BOB in the midnight of 15$^{th.}$ Further moving northeastwards, it reached its peak intensity in the early hours of 16$^{th.}$ The system maintained its peak intensity till evening of 16$^{th.}$ Moving nearly northeastwards, it crossed Myanmar coast near Sandoway (Thandwe) in the midnight. After landfall, the system weakened into a DD in early hours of 17th, into a D in the morning and well marked low pressure area over central Myanmar and neighbourhood in the forenoon of 17th.. The peak maximum sustained surface wind speed (MSW) of the cyclone was 70-80 kmph gusting to 90 kmph (40 knots) and the system crossed Myanmar coast with this peak MSW between 1800-1900 UTC of 16th April. The lowest estimated central pressure was 996 hPa. The system caused heavy rainfall over Andaman & Nicobar Islands.
- The **Severe Cyclonic Storm** (SCS) **Mora** developed from A low pressure area formed over southeast Bay of Bengal & adjoining areas of central Bay of Bengal in the morning of 25th May, 2017. It persisted over the same region on 26th and seen as a well marked low pressure area in the morning of 27th over eastcentral and adjoining westcentral & southeast Bay of Bengal. It moved northeastwards and intensified into a depression over eastcentral Bay of Bengal in the early morning of 28th May. Continuing its northeastwards movement, it further intensified into a deep depression in the afternoon and into a cyclonic storm "MORA" over eastcentral BoB in the late evening of 28th. Thereafter, it moved north-northeastwards and further intensified into a severe cyclonic storm in the evening of 29th. The system reached its peak intensity in the early hours

of 30th. It continued to move nearly north-northeastwards and crossed Bangladesh coast close to south of Chittagong in the forenoon (between 0400 and 0500 UTC) of 30th. After landfall, the system weakened into a cyclonic storm in the afternoon of 30^{th}, into a deep depression in the evening and depression in the same night. It further weakened into a well marked low pressure area over Nagaland & neighbourhood in the early morning of 31^{st}, into a low pressure area in the forenoon and became less marked in the same afternoon. The severe cyclonic storm, MORA developed in the onset phase of southwest monsoon. Its intensification and movement towards north-northeastwards helped in advance of monsoon over the BOB and some parts of northeastern states. The peak maximum sustained surface wind speed of the cyclone was 110- 120 kmph gusting to 130 kmph (60 knots) and the system crossed Bangladesh coast with this peak MSW between 0400-0500 UTC of 30th May. The lowest estimated central pressure was 978 hPa. The system caused heavy rainfall at isolated places over Arunachal Pradesh, Manipur, Nagaland, Mizoram & Tripura and a few places over Assam & Meghalaya..

- The **Very Severe Cyclonic Storm** (VSCS) **Ockhi** developed from a low pressure area over southwest Bay of Bengal and adjoining areas of south Sri Lanka & equatorial Indian Ocean in the forenoon of 28th November. It became a well marked low pressure area in the early morning of 29th over the same region. It further concentrated into a Depression over southwest Bay of Bengal off southeast Sri Lanka coast in the forenoon of 29th Nov. Moving westwards, it crossed Sri Lanka coast after some time. Continuing it's westward movement, it emerged into Comorin area in the evening of 29th and intensified into a Deep Depression in the early hours of 30th. It further moved northwestwards and intensified into a Cyclonic Storm in the forenoon of 30th Nov. over the Comorin area. While moving west-northwestwards, it further intensified into a Severe Cyclonic Storm over Lakshadweep area in the early morning of 01st Dec. and Very Severe Cyclonic Storm over southeast Arabian Sea to the west of Lakshadweep in the afternoon of 01st Dec. It then moved northwestwards and reached its peak intensity of 150-160 kmph gusting to 180 kmph in the afternoon of 2nd Dec with lowest central pressure of 976 hPa. It moved north-northwestwards for some time and then north-northeastwards and maintained its intensity till early morning of 03rd Dec. It then continued to move north-northeastwards and weakened gradually. It crossed south coast of Gujarat between Surat and Dahanu as a well marked low around early morning of 6th Dec. It was a rare cyclone with rapid intensification in genesis stage. It intensified from deep depression into a cyclonic storm over Comorin area within six hours. It caused isolated heavy rainfall over south Tamil Nadu on 28th and 29th and scattered heavy to very heavy rainfall and isolated extremely heavy rainfall over south Tamil Nadu on 30th Nov. and 1st & 2nd Dec. It caused isolated heavy rainfall over south Kerala on 29th Nov. and 1st Dec. and heavy to very heavy rainfall on 30th Nov. It caused heavy to very heavy rainfall over Lakshadweep on 01st and 2nd Dec. There was heavy rainfall over north coastal Maharashtra and adjoining south coastal Gujarat on 5th Dec. Thiruvananthapuram recorded 62 kmph in gustiness at 1300 IST of 30th Nov. The threshold wind speed of 45 kmph was recorded over Thiruvananthapuram from 1230 IST of 30th Nov. onwards.
- Out of three cyclones developing over north Indian Ocean during 2017, Maarutha crossed Myanmar, Mora crossed Bangladesh and Ockhi moved across Lakshadweep and weakened over eastcentral and adjoining northeast Arabian Sea.

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

Table 2.1 Brief statistics of cyclonic disturbances over NIO and adjoining land areas during 2017:

1.	Cyclonic Storm, **MAARUTHA**, over Bay of Bengal (15-17 April, 2017)
2.	Severe Cyclonic Storm,**MORA** over Bay of Bengal (28-31 May, 2017)
3.	Deep Depression over Bay of Bengal (11-13 June, 2017)
4.	Depression over Bay of Bengal(18 -19 July, 2017)
5.	Land Depression over Jharkhand and neighbourhood (26 - 27 July, 2017)
6.	Land Depression over Gangetic West Bengal and adjoining north Bay of Bengal (09 – 10 Oct 2017)
7.	Depression over Bay of Bengal (19-22 Oct, 2017)
8.	Depression over Bay of Bengal (15-17 Nov, 2017)
9.	Very Severe Cyclonic Storm, **OCKHI**, over Bay of Bengal (29 Nov – 06 Dec, 2017)
10.	Deep Depression over Bay of Bengal (06-09 Dec, 2017)

Table 2.2 Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2017

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) **MAARUTHA** over the Bay of Bengal (15-17 April, 2017)	15th April 2017, 0000 UTC over southeast BoB near (12.0/88.0)	Crossed Myanmar coast near Sandoway (Thandwe) during 1800-1900 UTC on 16/04/2017	996 hPa at 2100 UTC 15th April 2017 near (15.5/91.2)	40 knots at 2100 UTC on 15th April 2017 near (15.5/91.2)	T 2.5
2	Severe Cyclonic Storm, **MORA** over Bay of Bengal (28-31 May, 2017)	28th May 2017, 0000 UTC over southeast & adjoining central BoB near (14.0/88.5)	Crossed Bangladesh coast close to south of Chittagong near 22.00N/91.90 E during 0400-0500 UTC on 30/05/2017	980 hPa at 1500 UTC 29th Jun 2017 near (18.8/91.5)	55knots at 1500 UTC of 29th Jun 2017	T 3.5
3	Deep Depression	11th June 2017, 1200	Weakened into a well	996 hPa at 0300 UTC	30 knots at 0000	T 2.0

	over Bay of Bengal (11-13 June, 2017)	UTC over north Bay of Bengal (20.5/89.5)	marked low pressure area over Nagaland & Neighbourhood at 0000 UTC of 13/06/2017.	06th Jul 2016 near (24.8/81.5)	UTC of 12th June 2017.	
4	Depression over Bay of Bengal(18 - 19 July, 2017)	18th July 2017,0000 UTC northwest and adjoining westcentral BoB & coastal areas of Odisha centered near (19.0°N/86.0°)	Weakened into a Well marked low pressure area over interior Odisha and neighbourhood at 0300 UTC of 19/07/2017	992 hPa at 0000 UTC 18th July, 2017 near (19.0/86.0)	25 knots at 0000 UTC 18th July, 2017	T1.5
5	Land Depression over Jharkhand and neighbourhood (26 - 27 July, 2017)	26th July, 2017, 0000 UTC over Jharkhand & neighbourhood (24.0/85.0)	Depression weakened into a well marked low pressure area over northeast Madhya Pradesh & neighbourhood at 0300 UTC of 27th July 2017.	993 hPa at 0000 UTC 26thJuly 2017 near (24.0/85.0)	25 knots at 0000 UTC 26thJuly 2017	----
6	Land Depression over Gangetic West Bengal and adjoining north Bay of Bengal (09 – 10 Oct 2017)	09th Oct 2017, 0000 UTC over over Gangetic West Bengal and adjoining north BoB near (22.4/88.4)	Depression weakened into a low pressure area over the Jharkhand & adjoining West Bengal at 1200 UTC of 10th October 2017	996 hPa at 0000 UTC on 09th Oct 2017 near (22.4/88.4)	30 knots at 0300 UTC on 09th Oct 2017	T 1.5
7	Depression over Bay of Bengal (19-	19th Nov 2017 at 0000 UTC over centered	Weakened into a well marked low	997 hPa at 0000 UTC on 21th Oct	25 knots at 0000 UTC on	T1.5

	22 Oct, 2017)	over westcentral BoB near (16.5/86.5)	pressure area over northeast Bangladesh and adjoining Meghalaya & south Assam at 0000 UTC of 22nd Oct 2017.	2017. (23.0/88.0)	19th Oct 2017.	
8	Depression over Bay of Bengal (15-17 Nov, 2017)	15th Nov 2017, 0300 UTC over westcentral BoB off Andhra Pradesh coast (6.5/87.5)	Weakened into a well marked low pressure area over northwest Bay of Bengal off north Odisha, West Bengal coasts at 0600 UTC of 17th Dec 2017	1001 hPa at 1200 UTC 15th Nov, 2017 near (16.2/83.3)	25 knots at 0300 UTC 15th Nov, 2017	T 1.5
9	Very Severe Cyclonic Storm, **OCKHI**, over Bay of Bengal (29 Nov – 06 Dec, 2017)	06th Dec 2016, 0900 UTC over southeast Bay of Bengal (8.5/91.0)	Weakened into a Well marked low pressure area over northeast Arabian Sea and adjoining eastcentral Arabian Sea, south coastal Gujarat & north coastal Maharashtra at 2100 UTC of 5th Dec 2017	976 hPa at 0600 UTC 02th Dec 2017 near (9.8/71.0)	34 knots at 0600 UTC 02th Dec 2017	T 4.5
10	Depression over Bay of Bengal (06-09 Dec, 2017)	6th December 2017,0300 UTC Over southeast BoB & neighbourhoo	Weakened into a well marked low pressure area over northwest	1002 hPa at 0000 UTC 08th Dec 2017.near (14.3/87.0)	30 knots at 0000 UTC 08th Dec 2017.	T 2.0

		d	Bay of Bengal at 12 UTC of 9th Dec 2017.			

Table 2.3 Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2017

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

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

↔ Peak intensity of the system, LD: Land Depression

B) Life time of cyclonic disturbances during 2017 at different stages of intensity

S.No.	Type	Life Time in (Days)
1	D	13 days
2.	DD	04 days 09 hours
3.	CS	03 days 03 hours
4.	SCS	01 day 15 hours
5.	VSCS	03 days 9 hours
	Total Life Time in(Days)	25 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	10	4	3	3	2	1	-	-	-	-

D) Basin-wise distribution of cyclonic distribution

Basin	Number of cyclonic disturbances
Bay of Bengal	8
Arabian Sea	0
Land depression	2

Table 2.4. Cyclonic disturbances formed over the north Indian Ocean and land areas of India during 1997-2017

Year	Basin	D	DD	CS	SCS	VSCS	ESCS	SuCS	Total
1997	BOB	1	4	1	1	1	0	0	8
	ARB	1	0	0	0	0	0	0	1
	Land	0	0	0	0	0	0	0	0
	Total								**9**
1998	BOB	0	3	0	1	2	0	0	6
	ARB	0	1	1	1	1	0	0	4
	Land	1	0	0	0	0	0	0	1
	Total								**11**
1999	BOB	2	2	1	0	1	0	1	7
	ARB	0	0	0	0	1	0	0	1
	Land	1	0	0	0	0	0	0	1
	Total								**9**
2000	BOB	1	1	2	--	2	0	0	6
	ARB	0	0	0	0	0	0	0	0
	Land	1	0	0	0	0	0	0	1
	Total								**7**
2001	BOB	2	0	1	0	0	0	0	3
	ARB	0	0	2	0	1	0	0	3
	Land	0	0	0	0	0	0	0	0
	Total								**6**
2002	BOB	1	1	2	1	0	0	0	5
	ARB	0	0	0	0	0	0	0	1
	Land	0	0	0	0	0	0	0	0
	Total								**6**
2003	BOB	2	2	0	1	1	0	0	6
	ARB	0	0	0	1	0	0	0	1
	Land	0	0	0	0	0	0	0	0
	Total								**7**
2004	BOB	2	0	0	0	1	0	0	3
	ARB	0	2	0	3	0	0	0	5
	Land	2	0	0	0	0	0	0	2
	Total								**10**
2005	BOB	2	3	4	0	0	0	0	9
	ARB	2	0	0	0	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								**12**
2006	BOB	5	2	1	0	1	0	0	9
	ARB	0	1	0	1	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								**12**
2007	BOB	3	4	1	0	1	0	0	9
	ARB	0	1	1	0	0	0	1	3
	Land	0	0	0	0	0	0	0	0
	Total								**12**

2008	BOB	1	2	3	0	1	0	0	7
	ARB	1	1	0	0	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								**10**
2009	BOB	0	2	2	1	0	0	0	5
	ARB	2	0	1	0	0	0	0	3
	Land	0	0	0	0	0	0	0	0
	Total								**8**
2010	BOB	2	1	0	2	1	0	0	6
	ARB	0	0-	1	0	1	0	0	2
	Land	0	0	0	0	0	0	0	0
	Total								**8**
2011	BOB	2	2	0	0	1	0	0	5
	ARB	1	2	1		0	0	0	4
	Land	1	0	0	0	0	0	0	1
	Total								**10**
2012	BOB	0	2	1	0	0	0	0	3
	ARB	0	1	1	0	0	0	0	2
	LAND	0	0	0	0	0	0	0	0
	Total								**5**
2013	BOB	3	0	1	1	3	0	0	8
	ARB	0	1	0	0	0	0	0	1
	Land	1	0	0	0	0	0	0	1
	Total								**10**
2014	BOB	2	2	0	0	1	0	0	5
	ARB	0	0	1	0	1	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								0
2015	BOB	1	1	1	0	0	0	0	3
	ARB		2	1	0	0	2	0	5
	Land	2	2		0	0	0	0	4
	Total								**12**
2016	BOB	1	2	3	0	1	0	0	7
	ARB	2	0	0	0	0	0	0	2
	Land	1	0	0	0	0	0	0	1
	Total								**10**
2017	BOB	4	1	1	1	1	0	0	**8**
	ARB	0	0	0	0	0	0	0	**0**
	Land	2	0	0	0	0	0	0	**2**
	Total								**10**

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

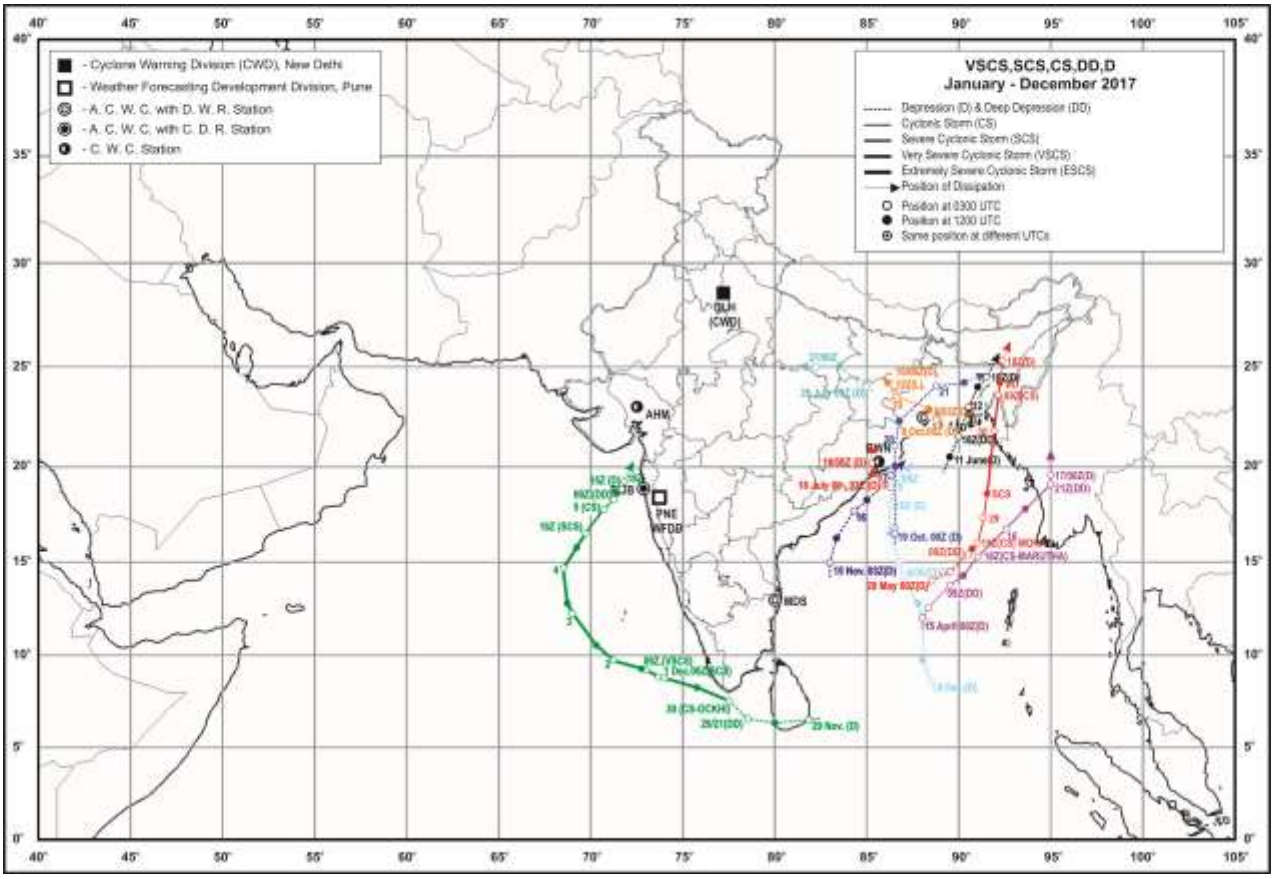


Fig. 2.1.: Tracks of cyclonic disturbances over north Indian Ocean and adjoining land region during 2017

Table 2.5 Average translational speed of Tropical cyclones over the NIO during 2017

TC Name	Basin	Period	Average Translational Speed		
			6 Hr	12 Hr	24 Hr
Maarutha	BOB	15-17 April	24.35	23.63	23.41
Mora	BOB	28-31 May	21.1	20.5	19.6
Ockhi	BOB	29 Nov–5 Dec	15.5	15.0	14.5

Table 2.6 Velocity Flux of Tropical cyclones over the NIO during 2017

TC Name	**Velocity Flux (kt)**	**Accumulated Cyclone Energy (kt^2)**	**Power Dissipation Index (kt^3)**
Maarutha	1900	117950	7825750
Mora	345	17425	898875
Ockhi	1360	92900	6628000
TOTAL	3605	228275	15352625

2.1 Cyclonic Storm "Maarutha" over the Bay of Bengal (15-17 April 2017)

2.1.1 Introduction

A depression (D) developed over southeast Bay of Bengal (BOB) in the morning (0000 UTC) of 15th April. Moving northeastwards, it intensified into a deep depression (DD) over eastcentral BOB in the afternoon of 15th and into a cyclonic storm (CS) "MAARUTHA" over eastcentral BOB in the midnight of 15th. Further moving northeastwards, it reached its peak intensity in the early hours of 16th. The system maintained its peak intensity till evening of 16th. Moving nearly northeastwards, it crossed Myanmar coast near Sandoway (Thandwe) in the midnight. After landfall, the system weakened into a DD in early hours of 17th, into a D in the morning and well marked low pressure area over central Myanmar and neighbourhood in the forenoon of 17th. The salient features of the system were as follows:

i. Climatologically, in the satellite era (1961 onwards), there had been three cyclones developing over north Indian Ocean (NIO) during 1-15th April, including 1 over Arabian Sea (AS) and 2 over BOB. Both the cyclones over BOB had recurving tracks. The cyclone in 2009 crossed Bangladesh coast as DD near Chittagong and the other (in 1972) weakened over eastcentral BOB. The cyclone over AS also had recurving track and weakened over sea. CS Maarutha was the first ever landfalling cyclone over Myanmar developing during the period 1-15 April in satellite era.

ii. The peak maximum sustained surface wind speed (MSW) of the cyclone was 70-80 kmph gusting to 90 kmph (40 knots) and the system crossed Myanmar coast with this peak MSW between 1800-1900 UTC of 16th April. The lowest estimated central pressure was 996 hPa (from 0000 UTC of 16th to 1800 UTC of 16th).

iii. The life period of cyclone was 51 hours (2.13 days).

iv. The track length of the cyclone was about 1170 km.

v. The system moved very fast under the influence of mid-latitude trough in westerlies lying over India in the middle and upper tropospheric levels. In addition an anticyclonic circulation lay to the southeast of system centre which further accentuated the northeasterly winds over the cyclone field. Also the upper tropospheric ridge ran along 10-11^{0}N throughout the life period of the system. As a result, since the genesis stage itself, the system lay to the north of ridge. Under this scenario, Maarutha moved northeastwards very fast with a 12 hrly average speed of 22.8 kmph.

vi. The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 1.95X10^{2} knots, 0.76 X 10^{4} knots^{2} and 0.299 X10^{6} knots^{3} respectively.

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.

2.1.2. Monitoring and Prediction of CS, Maarutha

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) since its inception over southeast BOB on 15th April. At the genesis stage, the system was monitored mainly with satellite observations from INSAT 3D, 3DR and Kalpana along with available ships & buoy observations. On 16th Department of Meteorology and Hydrology, Myanmar provided hourly coastal observations till landfall. Various national and international NWP models and dynamical-statistical models were utilized to predict the genesis, track and intensity of the cyclone. Tropical Cyclone Module, the digitized forecasting system of IMD were utilized for analysis and comparison of various models guidance, decision making process and warning product generation. IMD issued regular bulletins to WMO/ESCAP Panel member countries including Bangladesh, Myanmar and Thailand, National & State Disaster Management Agencies, general public and media since inception of the system over BOB.

2.1.3. Brief life history

2.1.3.1. Genesis

An upper air cyclonic circulation developed over south Andaman Sea & neighbourhood extending upto 3.1 km above mean sea level on 11th. Moving nearly northeastwards, it concentrated into a trough of low over Andaman & Nicobar Islands and neighbourhood on 12th. It lay as a low pressure area over southeast BOB and neighbourhood with upper air cyclonic circulation extending upto 5.8 km above mean sea level in the evening of 13th. It became a well marked low pressure area in the early hours of 14th over the same region. It concentrated into a depression in the early hours of 15th over southeast BOB. At 0000 UTC of 15th the sea surface temperature (SST) around the region of depression was 30-32^{0}C. The ocean thermal energy was about 100 KJ/cm^{2}. The vertical wind shear was about 10-20 knots (moderate) around the system centre. The low level relative vorticity and convergence were about 150 x 10^{-6} s^{-1} and 30 x 10^{-5} s^{-1} respectively. There was favourable poleward outflow in association with the anti-cyclonic circulation lying to the souheast of the system centre. The upper level divergence was about 40 x 10^{-5} s^{-1}. The upper tropospheric ridge at 200 hpa level ran along 10^{0}N. Madden Julain Oscillation (MJO) was in Phase 7 with amplitude less than 1. Hence the environmental conditions were favourable for genesis, except MJO.

The best track parameters are presented in Table 2.1.1 and Fig. 2.1

Table 2.1.1: Best track positions and other parameters of Cyclonic Storm, 'Maarutha' over the Bay of Bengal during 15-17 April, 2017

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
15/04/2017	0000	12.0/88.0	1.5	1001	25	3	**D**
	0300	12.5/88.3	1.5	1001	25	3	D
	0600	13.2/89.0	1.5	1000	25	4	D
	0900	13.7/89.5	2.0	999	30	5	**DD**
	1200	14.3/90.1	2.0	999	30	5	DD
	1800	15.3/91.0	2.5	998	35	6	**CS**
	2100	15.5/91.2	2.5	996	40	8	CS
16/04/2017	0000	16.2/92.0	2.5	996	40	8	CS
	0300	16.7/92.5	2.5	996	40	8	CS
	0600	17.0/92.9	2.5	996	40	8	CS

	0900	17.5/93.2	2.5	996	40	8	CS
	1200	17.8/93.6	2.5	996	40	8	CS
	1500	18.1/93.9	2.5	996	40	8	CS
	1800	18.4/94.3	2.5	996	40	8	CS
	Crossed Myanmar coast near Sandoway (Thandwe) during 1800-1900 UTC						
	2100	19.0/95.0	-	1000	30	5	**DD**
17/04/2017	0000	19.5/95.5	-	1002	20	3	**D**
	0300	**Well Marked Low Pressure Area over central Myanmar and neighbourhood**					

2.1.3.2 Intensification

Moving northeastwards, it intensified into a deep depression (DD) over eastcentral Bay of Bengal in the afternoon of 15th and into a cyclonic storm (CS) “MAARUTHA” over eastcentral in the Bay of Bengal midnight of 15th. On 15th, similar thermodynamical features continued. Under the favourable lower level convergence & vorticity, upper level divergence enhanced by poleward outflow due to an anticyclonic circulation in the southeast of system centre and a trough in mid latitude westerlies around 80^0E and incursion of warm moist air from southeast towards the system centre, the system gradually intenisfied into a CS. However, strong vertical wind shear and unfavourable MJO inhibited rapid intensification or further intensification of the system. Moving northeastwards, it reached its peak intensity in the early hours of 16th. The system maintained its peak intensity till landfall near Sandoway (Thandwe) in the midnight. After landfall, the system weakened into a Deep Depression in early hours of 17th, into a Depression in the morning and well marked low pressure area over central Myanmar and neighbourhood in the forenoon of 17th.

The lowest estimated central pressure and the maximum sustained wind speed are presented in Fig.2.1.1.

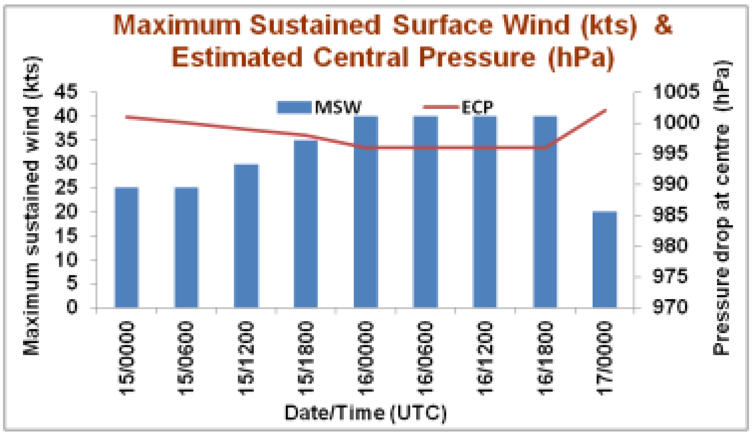


Fig.2.1.1: Lowest estimated central pressure and the maximum sustained wind speed

The lowest estimated central pressure had been 996 hPa. The estimated maximum sustained surface wind speed (MSW) was 40 knots during 2100 UTC of 15th to 1800 UTC of 16th April. At the time of landfall, the ECP was 996 hPa and MSW was 40 knots (cyclonic storm). The ECP and Vmax graph also indicates that the system intensified gradually till 0000 UTC of 16th April and maintained its intensity till landfall at 1800 UTC of 16th April and then weakened rapidly into a well marked low pressure area at 0300 UTC of 17th April. There was no rapid intensification and rapid weakening of the system throughout its life cycle.

The total precipitable water imageries (TPW) during 15h to 17nd April are presented in Fig.2.1.2.

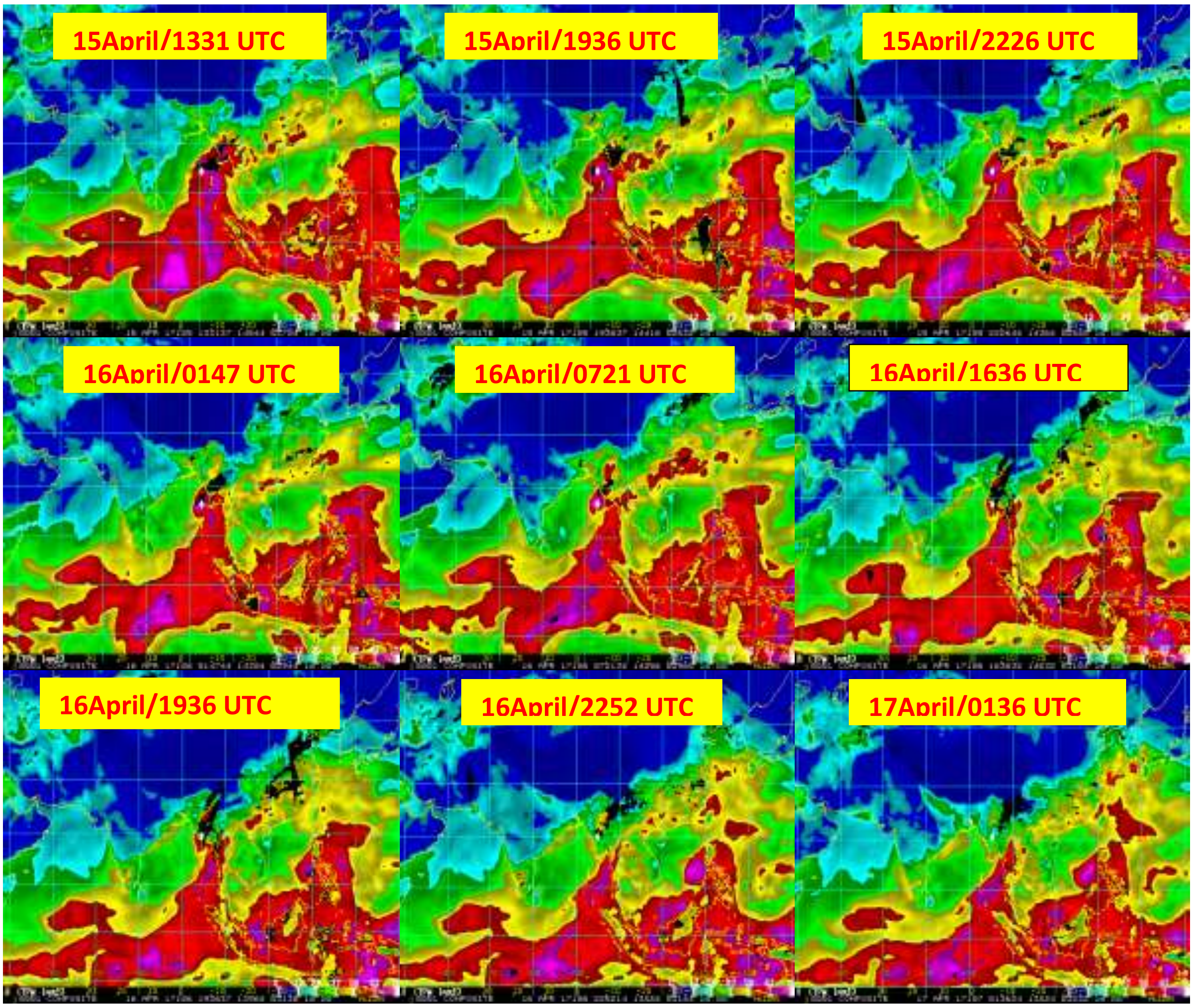


Fig.2.1.2 : Total precipitable water imageries during 15th to 17th April 2017

It indicates that due to cross equatorial flow, warm and moist air continued to converge around the system centre till 0600 UTC of 16th. It resulted in intensification of depression into cyclonic stotrm on 15th night. Futher, it maintained its intensity till landfall on 16th midnight. There was poleward outflow throughout the life period of the system in association with an anticyclonic circulation lying to the southeast of the system centre and an upper tropospheric trough lying over India roughly along 85^0E as seen from. It helped in increasing the upper level divergence and hence favouring the intensification. The SST was high 30-32^0C over central Bay of Bengal and adjoining areas. Also the Ocean thermal energy was high over this region. The vertical wind shear of horizontal wind was high (> 20 knots) during most part of the life period, which was not favourable for intensification. The high vertical wind shear was due to the upper tropospheric trough lying to the west of the system. The favourable upper level divergence coupled with lower level relative vorticity was being countered by the unfavourable vertical wind shear. As a result, the system maintained its intensity as a cyclonic storm only. The large scale feature like Madden Julian Oscillation was not favourable for intensification, as MJO index lay over phase-7 with amplitude greater than 1. The system moved very fast with a 12 hrly average speed of 25 kmph, which was not favourable for intensification, as it limited its life period and stay over the sea.

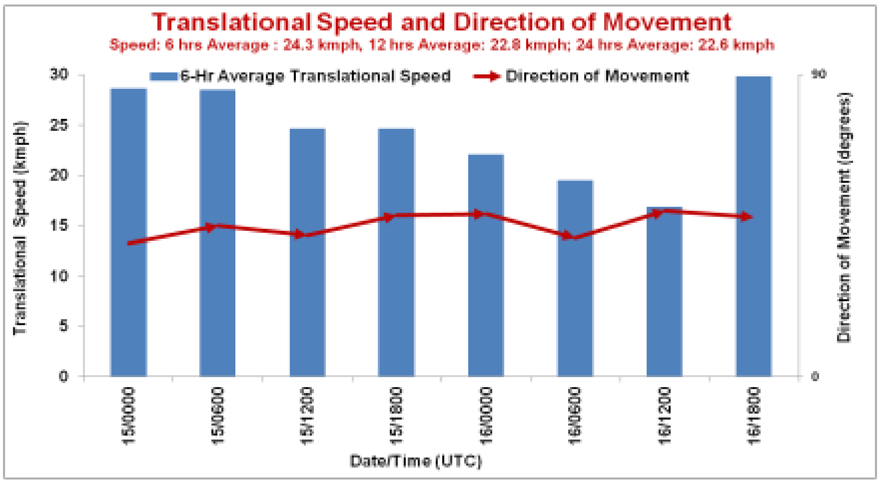


Fig.2.1.3 Six hourly average translational speed (kmph) and direction of movement in association with CS Maarutha

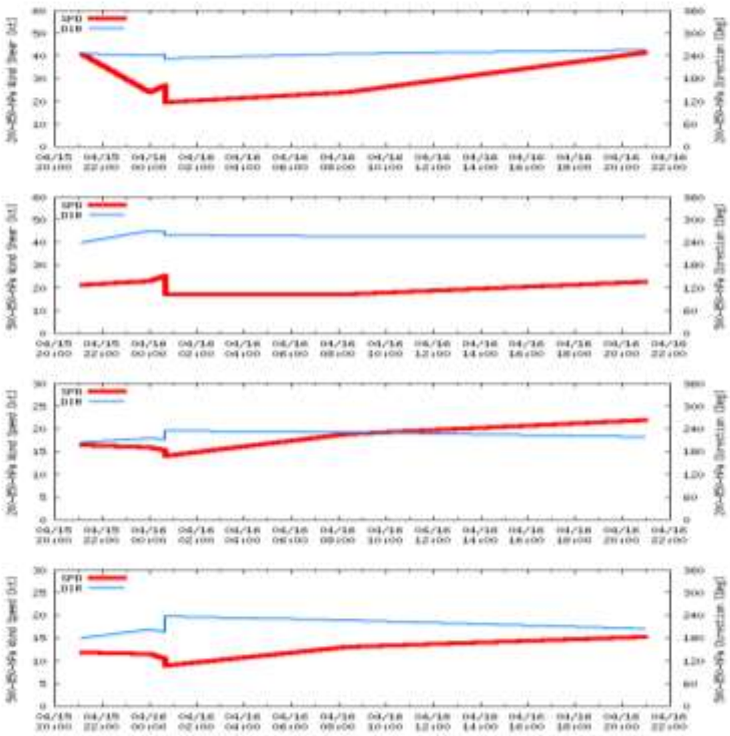


Fig.2.1.4.Wind shear and wind speed in the middle and deep layer around the system during 15th to 16th April 2017.

2.1.3.3. Movement

CS Maarutha moved nearly northeastwards throughout its life period, under the influence of anticyclonic circulation located to the southeast of the system centre. There was a trough in middle and upper tropospheric levels lying to the west of system centre roughly along 85^{0}E which further helped in northeastwards movement of the system and higher translational speed. At the genesis stage the translational speed was maximum and was about 27 kmph. It then gradually decreased to minimum of about 16 kmph prior to landfall. After the landfall it increased sharply to about 30 kmph over Myanmar. The six hourly average translational speed of CS Maarutha is presented in Fig.2.1.3.

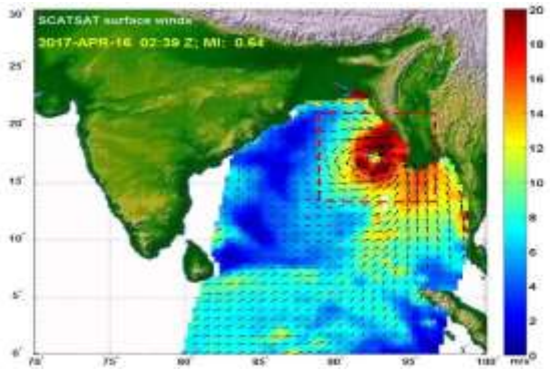


Fig.2.1.5a: Typical SCAT SAT surface wind imagery based on 0239 UTC of 16th April

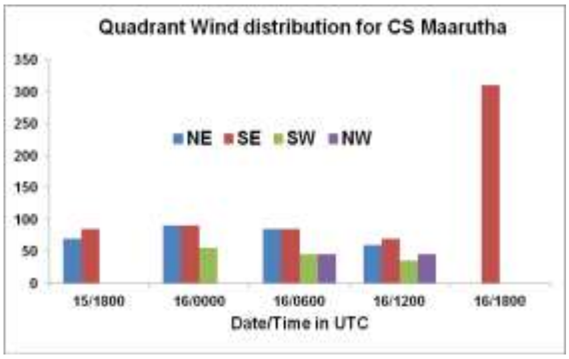


Fig.2.1.5b:Quadrant wind distribution during life cycle of CS Maarutha from CIRA

The wind speed in middle and deep layer around the system centre is presented in Fig.2.1.4. It indicates that the mean wind speed in deep and middle layer decreased slightly from 2000 UTC of 15th to 0000 UTC of 16th and then increased gradually from 0000 UTC of 16th to 2000 UTC of 16th. The mean wind direction in deep and middle layer also indicates northeast/ north-northeastward movement. The southerly shear prevailed over the centre and to the left of the cyclone.

2.1.3.4. Structure

SCATSAT surface winds from SAC, ISRO (Fig.2.1.5a) indicated that the winds were observed around system centre with maxima in northeast and southeast sector. It also agrees with best track estimates of CS Maarutha. The multisat imageries from CIRA (Fig.2.1.5b) also indicated similar distribution of winds. The average size of 34 kts winds was 59 nm.

2.1.3.5. Landfall Point and Time:

The plot of hourly synoptic observations during 0600-1800 UTC of 16th April is presented in Fig. 2.1.6.

2.1.4. Climatological aspects

Considering the area of genesis (+/- 2^0 around the genesis point), the cliamtological tracks of the TCs during 1961-2015 are presented in Fig.2.1.7.

Occurrence of cyclone in the month of April is very rare. Climatologically, in the satellite era (1961 onwards), there had been three cyclones developing over north Indian Ocean (NIO) during 1-15th April, including 1 over Arabian Sea (AS) and 2 over BOB. Both the cyclones over BOB had recurving tracks. The cyclone in 2009 crossed Bangladesh coast as DD near

Chittagong and the other (in 1972) weakened over eastcentral BOB. The cyclone over AS also had recurving track and weakened over sea. The CS Maarutha was the first ever landfalling cyclone over Myanmar developing during the period 1-15 April during satellite era.

Observation Time ➡ Stations ⬇	0600	0700	0800	0900	1000	1100
48062 (Sittwe)	064 -3.7	061 -2.1	058 -1.9	047 -1.9	037 -3.0	029 -3.0
48071 (Kyaykpyu)	078 -2.1	061 3.3	053 -4.0	041 -3.2	023 -5.3	023 -4.8
48080 (Sandoway)	039 -5.7	030 -6.3	013 -6.3	003 -3.2	992 -9.5	984 -8.9
48085 (Gwa)	036 -6.2	030 -7.2	018 -5.8	011 -7.2	992 -7.7	005 -6.4
48094 (Pathein)	039 -5.6	029 -6.2	026 -5.0	023 -4.2	020 -3.7	024 -3.1

Observation Time ➡ Stations ⬇	1200	1300	1400	1500	1600	1700	1800
48062 (Sittwe)	025 -3.2	024 -3.8	030 -3.4	044 -3.5	050 -3.6	054 - 3.5	054 -3.1
48071 (Kyaykpyu)	018 -5.8	023 -5.5	033 -4.0	041 -5.2	045 -5.3	060 -4.0	060 -3.0
48080 (Sandoway)	984 -8.7	991 - 7.9	997 -7.7	010 -9.0	016 -8.4	020 -7.3	021 -5.3
48085 (Gwa)	016 -4.9	027 -4.3	032 -4.8	043 -4.5	053 -3.3	056 -2.5	058 -1.9

Fig.2.1.6: The plot of hourly synoptic observations during 0600-1800 UTC of 16th April

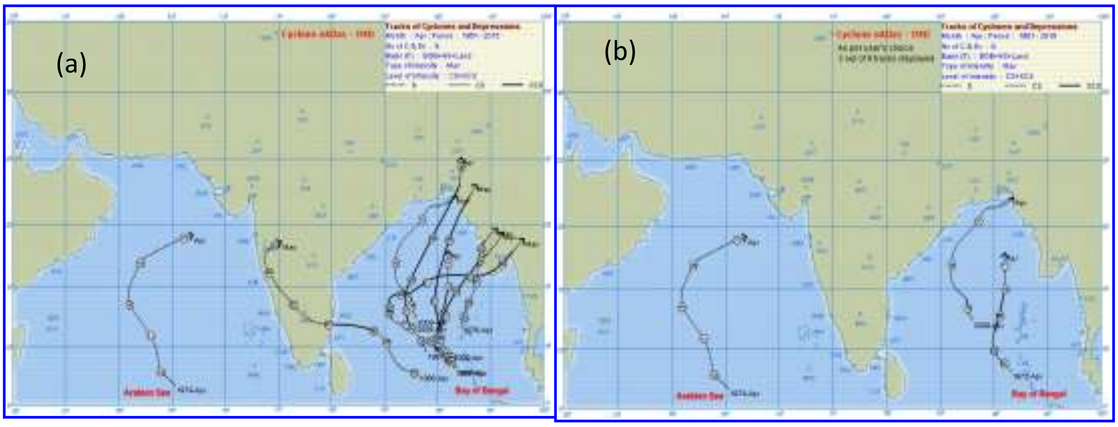


Fig 2.1.7: Climatological tracks of TCs forming over north Indian Ocean region during 1961-2015 in the (a) month of April and (b) during 1-15 April.

2.1.5. Features observed through satellite and Radar

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 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered.

2.1.5.1 INSAT-3D features

Typical INSAT-3D enhanced coloured imageries, cloud top brightness temperature, visible and IR imageries are presented in Fig.2.1.8.

According to available satellite imageries, the system attained intensity of T 1.5 at 0000 UTC of 15th April. The convection showed curved band pattern with well defined wrapping from eastern sector. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 6.5^0 N to 16.0^{0}N and longitude 83.0^0 E to 93.0^0 E. The lowest cloud top temperature was minus 70^{0}Celcius. At 0900 UTC of 15th the system intensified into a DD and attained intensity of T 2.0. The convection showed curved band pattern with well defined wrapping from eastern sector. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 10.5^0 N to 17.0^0 N and longitude 87.5^0 E to 95.5^0 E. The lowest cloud top temperature was minus 85^0 celcius. At 1800 UTC of 15th, the system attained the intensity of T 2.5. The convection showed curved band pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 13.5^0 N to 18.5^0 N and longitude 88.8^0 E to 93.0^0 E. The lowest cloud top temperature was minus 90^0 celcius. Majority of the convective cloud mass lay to the east of the system centre. The curved band was wrapping towards the centre from the southeast.

At 0000 UTC of 16th, the intensity was T 2.5. The convection showed curved band pattern, however it also showed signs of weakening with tendency of disorganisation. Associated broken low and medium clouds with embedded intense to very intense convection lay over south and adjoining eastcentral BOB between latitude 13.5^0 N to 17.5^0 N and longitude 89.0^0 E to 93.5^0 E. The lowest cloud top temperature was minus 85^0 celcius. At 1200 UTC of 16th, intensity of the system was T 2.5. The convection showed curved band pattern. Associated broken low and medium clouds with embedded intense to very intense convection lay over eastcentral BOB between latitude 14.0^0 N to 20.0^0 N and east of longitude 91.0^0 & Arakan coast, Gulf of Martaban adjoining south Myanmar. The lowest cloud top temperature was minus 90^0 celcius.

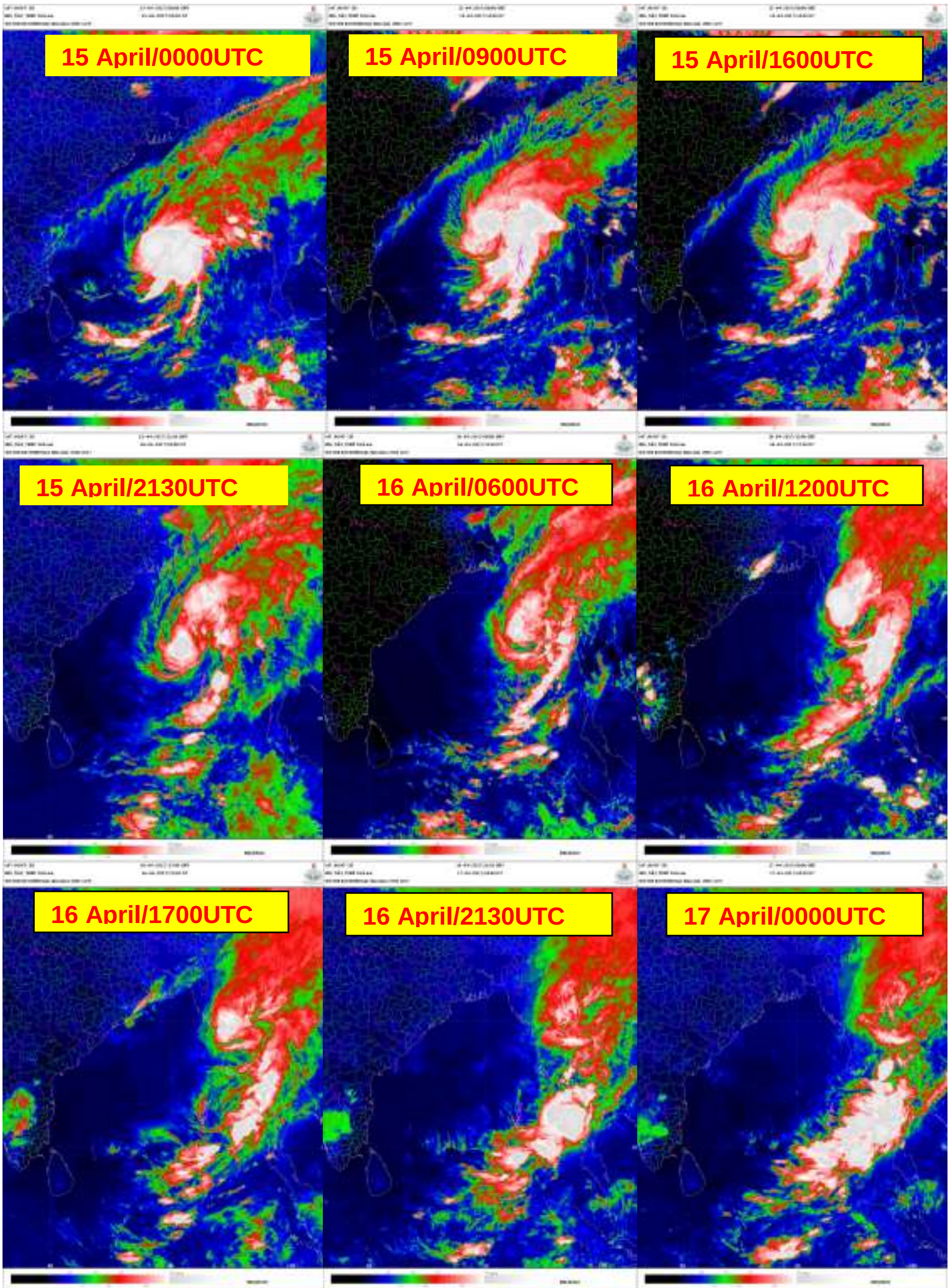


Fig.2.1.8(a) INSAT-3D enhanced colored imageries during 15-17 April 2017

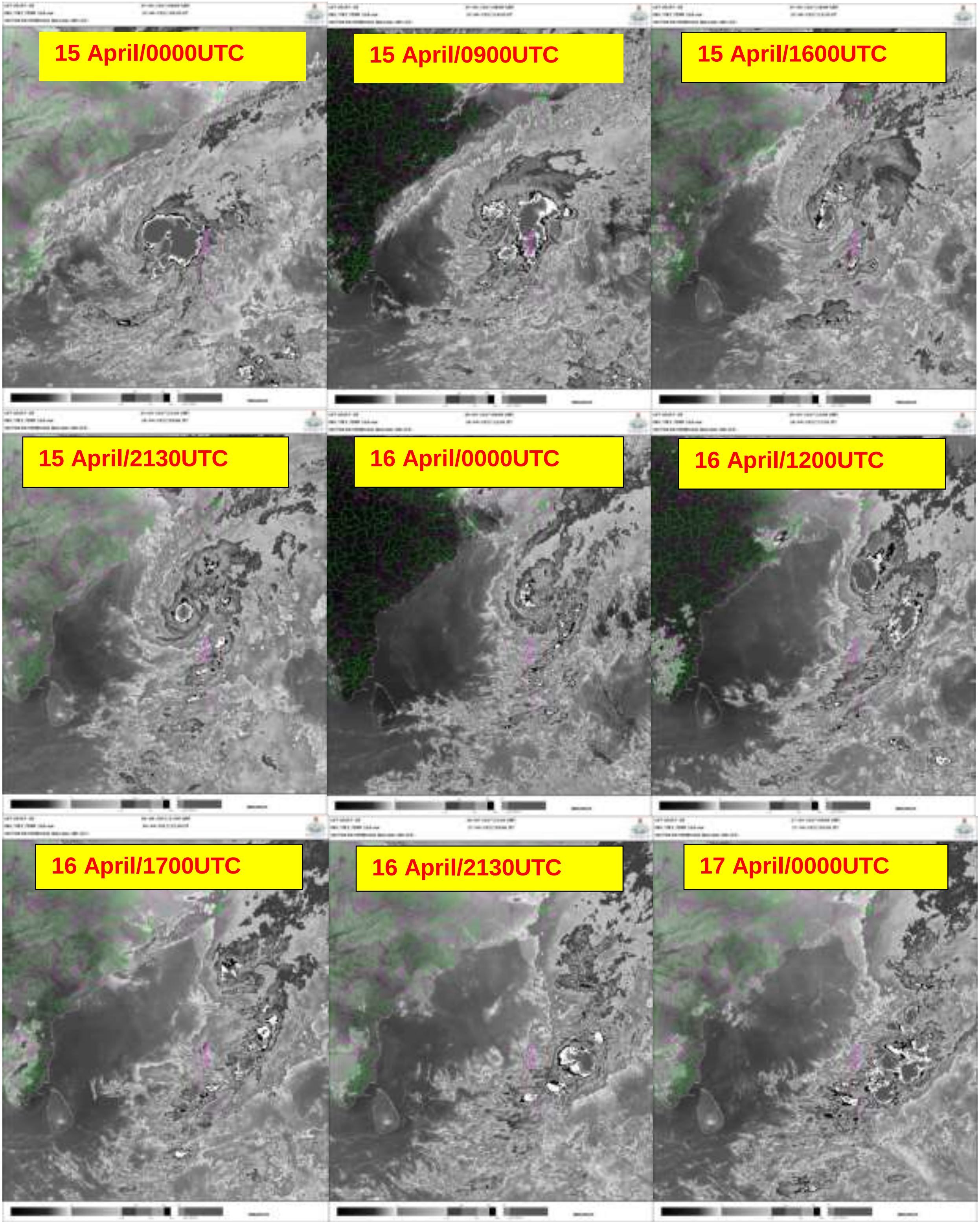


Fig.2.1.8(b) INSAT-3D enhanced colored imageries during 15-17 April 2017

At 1800 UTC of 16th, the intensity was T2.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over Arakan coast and south Myanmar. The system showed interactions with land surface, major parts of the convection were lying over the land and showed sign of disorganisation.

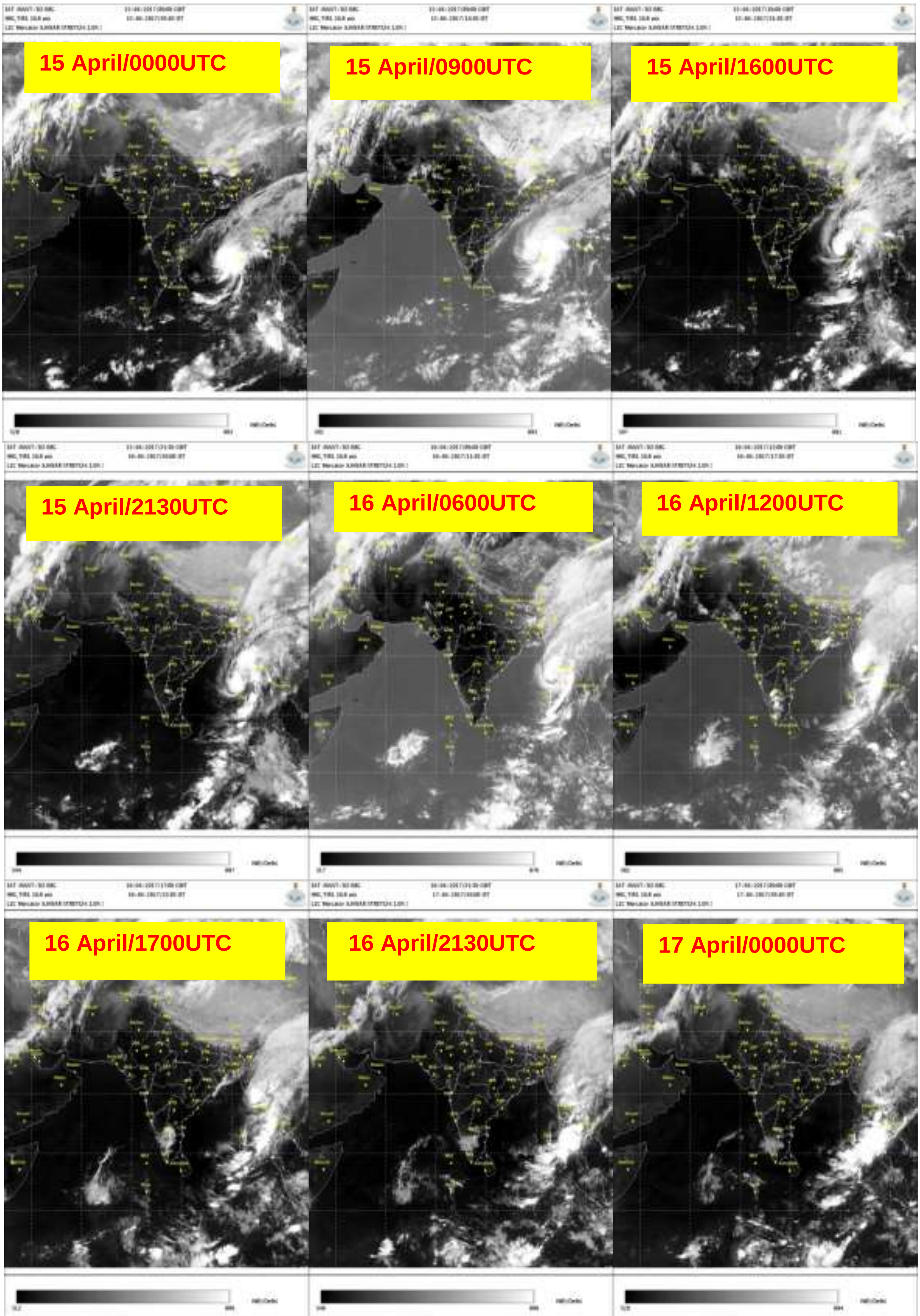


Fig. 2.1.8(c): INSAT-3D IR imageries during 15-17 April 2017

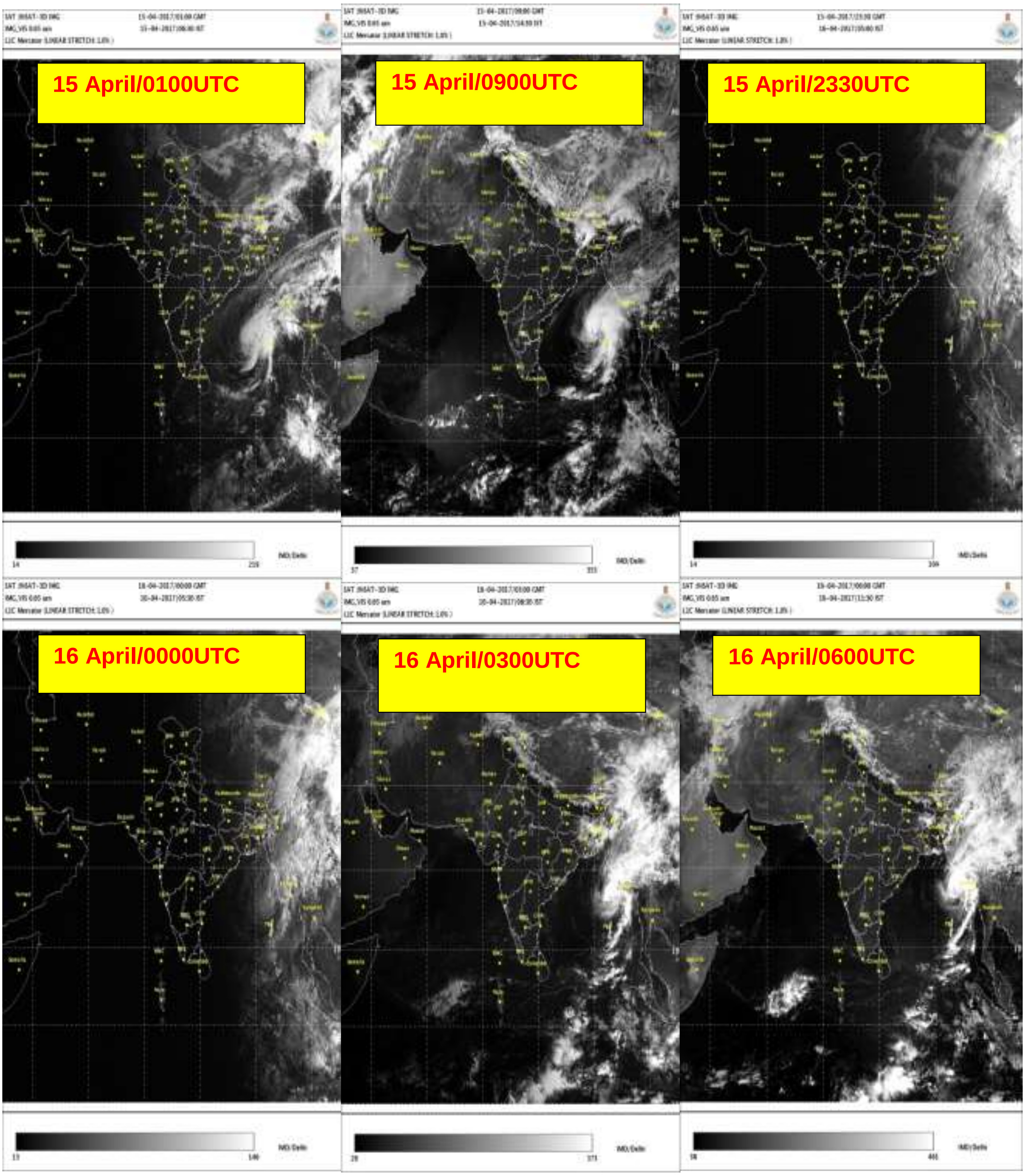


Fig. 2.1.8(d): INSAT-3D Visible imageries during 15-17 April 2017

2.1.5.2 Microwave features

F-15, F-16, F-17 microwave imageries of the CS Maarutha covering its life period from 15th to 17th April 2017 are presented in Fig.2.1.9. These imageries helped in understanding the internal structure of the system and better estimation of location of the system. It could indicate the region of intense convection and hence the rainfall. On 15th, the major region of intense convection lay over northeast sector of system with feeding from southeast. However, there was also intense convection in the western sector close to the system centre. On 16th, however the convection area lay entirely in the northeast.

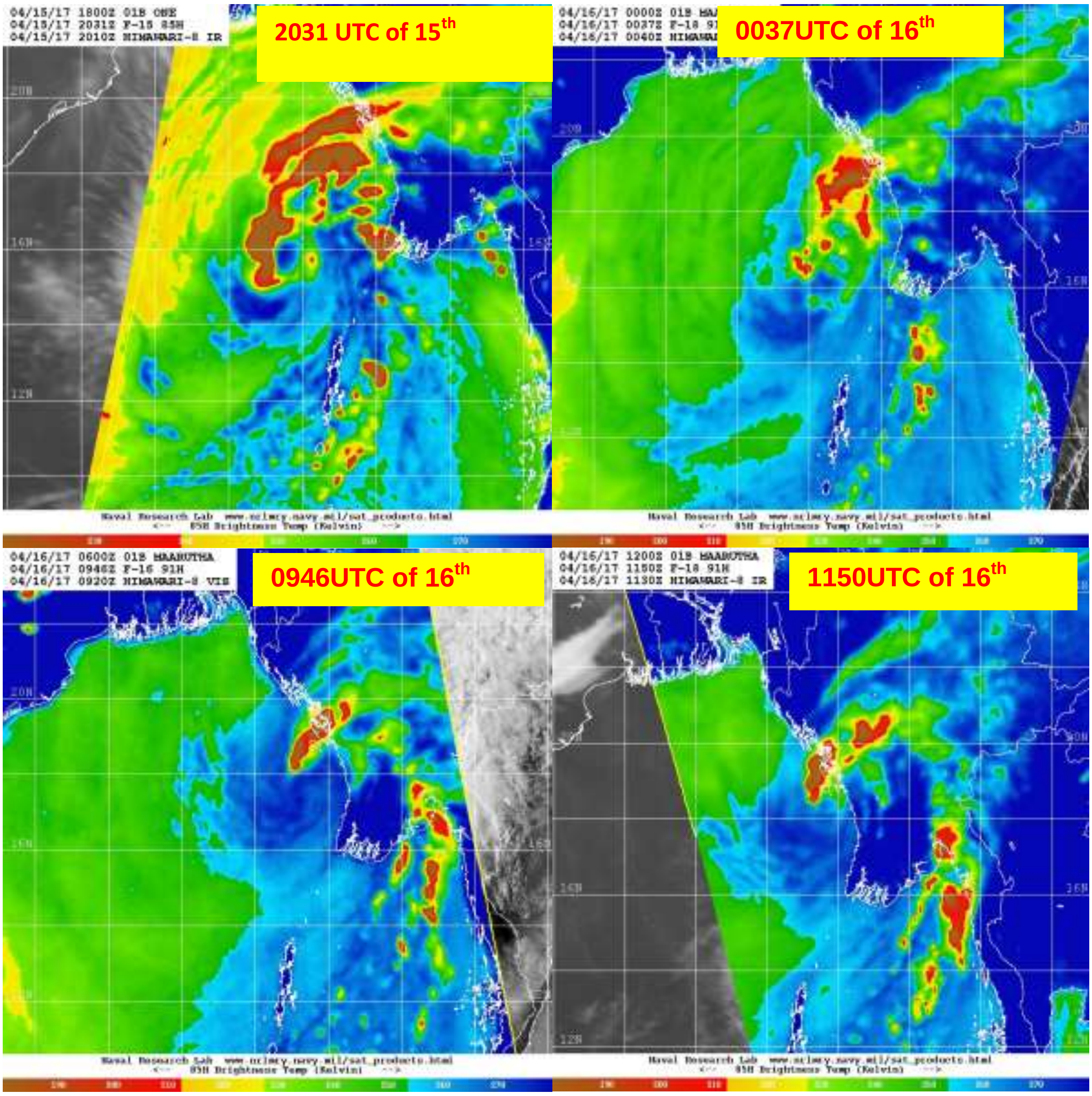


Fig.2.1.9: Typical microwave imageries during 15-17 April 2017

2.1.5. Dynamical features

IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels are presented in Fig.2.1.10. GFS (T574) could simulate the genesis of the system and the associated circulation features during the life period of Maarutha. However, the deep trough in westerlies over India was seen as a feeble trough.

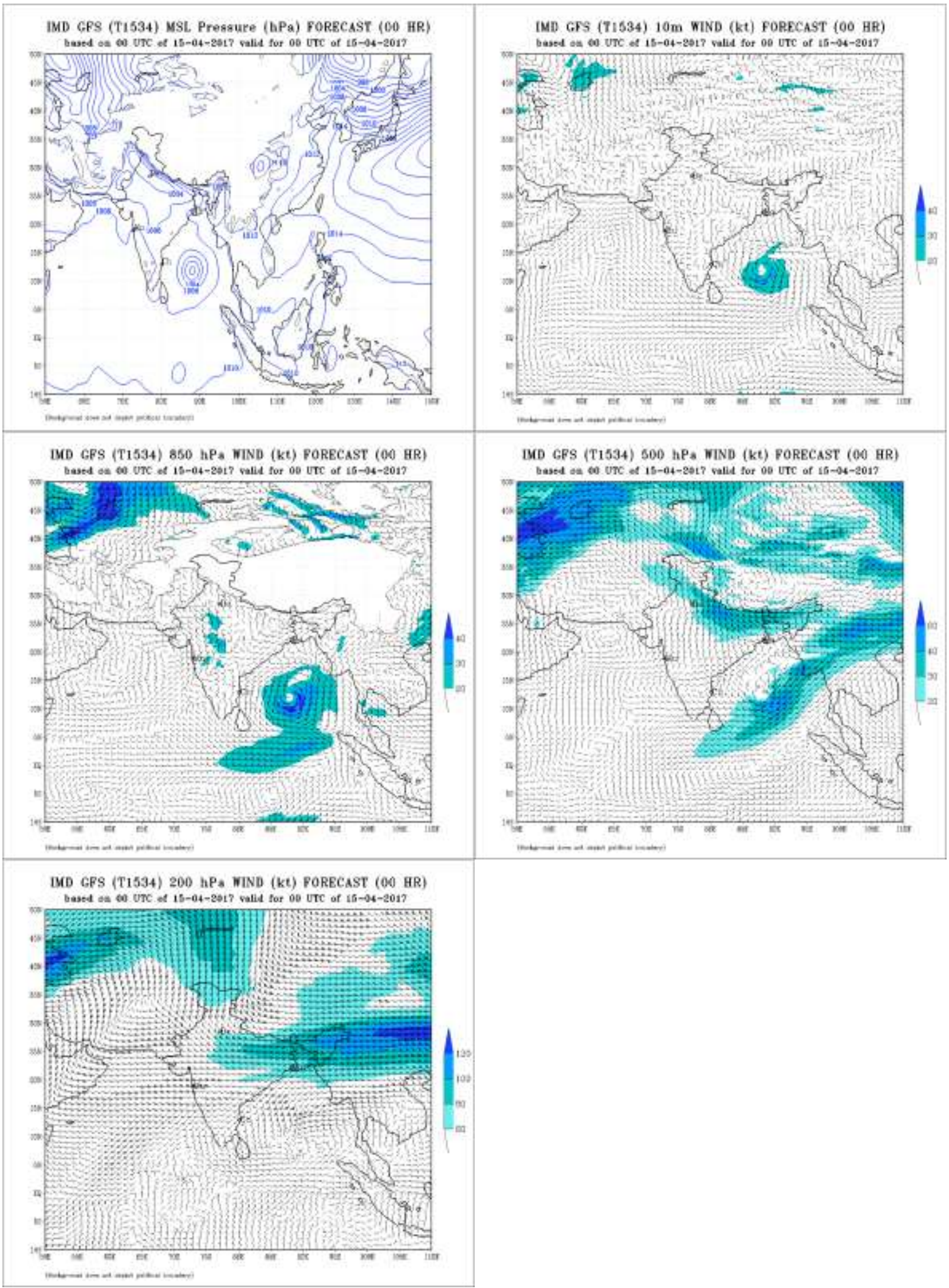


Fig. 2.1.10 (a): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 15th April 2017.

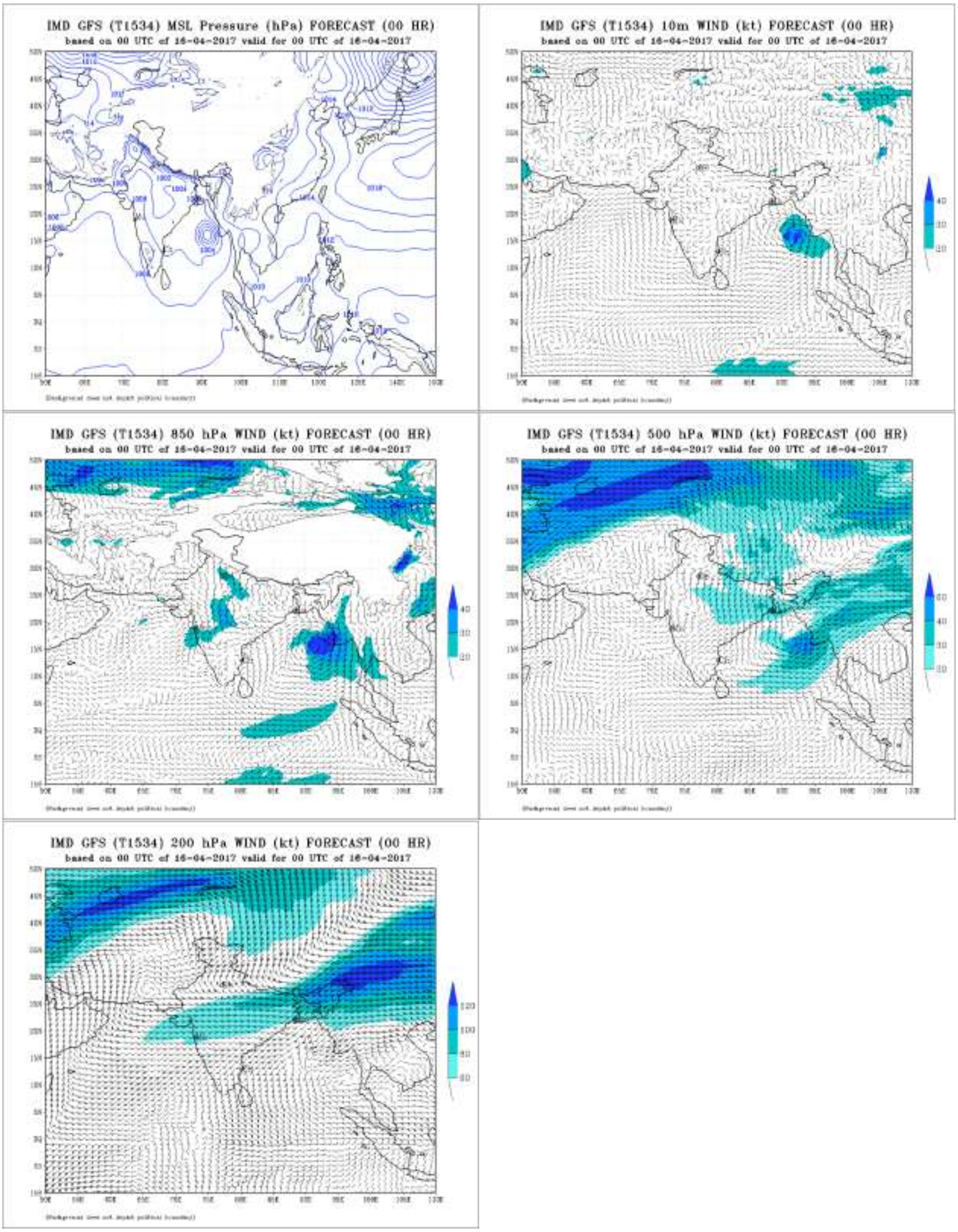


Fig. 2.1.10 (b): IMD GFS analysis of MSLP, 10 m wind, winds at 850, 500 and 250 hPa based on 0000 UTC of 15th April 2017.

2.1.7. Realized Weather:

IMD-NCMRWF GPM merged gauge rainfall data is presented in Fig 2.1.11. It indicates that the system caused heavy to very heavy rainfall in southeast and adjoining eastcentral BOB on 15th and heavy to very heavy rainfall over eastcentral BOB on16th. The rainfall was higher in eastern sector, especially northeast sector. The rainfall decreased significantly at the time of landfall and thereafter.

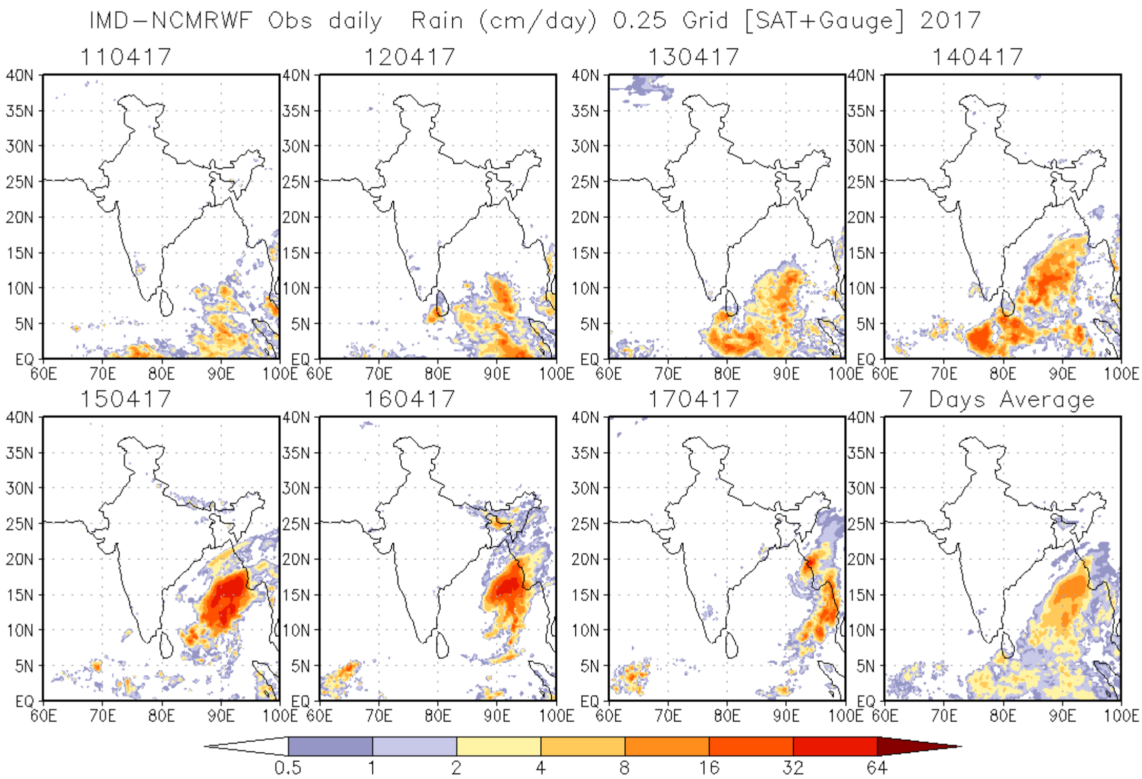


Fig.2.1.11: Realised rainfall during 15-17 April, 2017

2.1.8. Damage due to CS Maarutha over Myanmar

Three people were killed in Irrawaddy Division. A total of 81 houses were damaged by the storm. Some damage photographs from Myanmar are presented in Fig. 2.1.12.

Fig.2.1.12: Damage photographs from Myanmar

2.2. Severe Cyclonic Storm 'Mora' over the Bay of Bengal (28-31 May 2017)

2.2.1. Introduction

A low pressure area formed over southeast Bay of Bengal & adjoining areas of central Bay of Bengal in the morning (0300 UTC) of 25th May, 2017. It persisted over the same region on 26th and seen as a well marked low pressure area in the morning (0300 UTC) of 27th over eastcentral and adjoining westcentral & southeast Bay of Bengal. It moved northeastwards and intensified into a depression (D) over eastcentral Bay of Bengal (BoB) in the early morning (0000 UTC) of 28th May. Continuing its northeastwards movement, it further intensified into a deep depression (DD) in the afternoon (0900 UTC) and into a cyclonic storm (CS) "**MORA**" over eastcentral BoB in the late evening (1800 UTC) of 28th. Thereafter, it moved north-northeastwards and further intensified into a severe cyclonic storm (SCS) in the evening (1200 UTC) of 29th. The system reached its peak intensity in the early hours of 30th (2100 UTC of 29th). It continued to move nearly north-northeastwards and crossed Bangladesh coast close to south of Chittagong in the forenoon (between 0400 and 0500 UTC) of 30th. After landfall, the system weakened into a CS in the afternoon (0900 UTC) of 30th, into a DD in the evening (1200 UTC) and D in the same night (1800 UTC). It further weakened into a well marked low pressure area over Nagaland & neighbourhood in the early morning (0000 UTC) of 31st, into a low pressure area in the forenoon (0300 UTC) and became less marked in the same afternoon (0900 UTC).

The observed track of the SCS Mora is shown in **Fig. 2.2.1**. The salient features of the system are as follows.

(i) It was the first severe cyclonic storm of the year 2017.

(ii) The severe cyclonic storm, **MORA** developed in the onset phase of southwest monsoon. Its intensification and movement towards north-northeastwards helped in advance of monsoon over the BOB and some parts of northeastern states.

(iii) Like previous cyclone **MAARUTHA** in the pre-monsoon season, it also maintained its peak intensity till landfall.

(iv) The severe cyclonic storm, **MORA** had a north-northeastwards moving track. Considering the area of genesis (± 2^0 around the genesis point), it is seen that about 63% of the cyclones moved north-northeatwards and crossed Bangladesh coast, whereas another 25% moved northeastwards and crossed Myanmar coast and 12% moved westwards towards Andhra Pradesh coast (**Fig. 2.2.7**). Hence, the direction of the movement of the cyclone was climatological in nature.

(v) The peak maximum sustained surface wind speed (MSW) of the cyclone was 110-120 kmph gusting to 130 kmph (60 knots) and the system crossed Bangladesh coast with this peak MSW between 0400-0500 UTC (0930-1030 hrs IST) of 30th May. The lowest estimated central pressure was 978 hPa (from 2100 UTC of 29th to till landfall around 0430 UTC of 30th).

(vi) The cyclone life period was about 72 hours (3 days).

(vii) The track length of the cyclone was 1086 km.

(viii) The 12 hour average translational speed of the cyclone was about 20.4 kmph and hence was fast moving in nature. The system moved fast under the influence of mid-latitude trough in westerlies lying over India in the middle & upper tropospheric levels and the anti-cyclonic cyclonic circulation lying to the northeast of the system. This trough created strong north-northeasterly steering winds over the cyclone field in middle & upper tropospheric levels, which was further accentuated by the north-northeasterly winds from anticyclonic circulation.

(ix) The Velocity Flux was $3.45X10^2$ knots.

(x) Lowest estimated central pressure (ECP) was 978.0 hPa with a pressure drop of 18 hPa.

(xi) The Accumulated Cyclone Energy (ACE) which is a measure of damage potential was about 1.74×10^4 knot^2.

(xii) The Power Dissipation Index which is a measure of loss due to a cyclone was 0.899×10^6 knot^3.

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.

2.2.2. Monitoring of SCS, 'MORA'

The cyclone was monitored & predicted continuously since its inception by India Meteorological Department (IMD). The observed track of the cyclone over BoB during 28-31 May is shown in **Fig. 2.1**. The best track parameters of the systems are presented in **Table 2.2.1.**

The cyclone was monitored & predicted continuously by IMD since its inception over southeast BoB and adjoining areas of central BoB on 25th May. At the genesis stage, the system was monitored mainly with satellite observations and buoy observations. From 30th May morning, the system was continuously monitored by Doppler Weather Radar at Khepupara. Various national and international NWP models and dynamical-statistical models 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. IMD issued regular bulletins to WMO/ESCAP Panel member countries, National & State Disaster Management Agencies, general public and media since inception of the system over BOB.

2.2.3. Brief life history

2.2.3.1. Genesis

Under the influence of an upper air cyclonic circulation over southeast BoB, a low pressure area formed over southeast BoB & adjoining central BoB with associated upper air cyclonic circulation extending upto 5.8 km above mean sea level at 0300 UTC of 25th May. Moving northeastwards, it was seen as a well marked low pressure area in the morning of 27th over eastcentral and adjoining westcentral & southeast Bay of Bengal. At 0300 UTC of 27th, the sea surface temperature (SST) was around 29-30˚C. The low level convergence was about $20x10^{-5}$ second^{-1}, the upper level divergence was around $30x10^{-5}$ second^{-1} and the low level relative vorticity was about $50\text{-}100x10^{-6}$ second^{-1} around the system centre. The vertical wind shear of horizontal wind was moderate (10 knots). The Madden Julian Oscillation (MJO) index was in phase 2 with amplitude >1. The upper tropospheric ridge at 200 hPa level was along 17^0N in association with anticyclonic circulation to the northeast of the system centre. Under these favourable environmental conditions, the well marked low pressure area over eastcentral and adjoining westcentral & southeast Bay of Bengal moved northeastwards and concentrated into a depression (D) at 0000 UTC of 28th over southeast & adjoining central BoB near latitude 14.0ºN and longitude 88.5ºE.

2.2.3.2. Intensification

At 0900 UTC of 28th, SST was around 29-30˚C. The low level convergence was about 20x10^{-5} second^{-1}, the upper level divergence was around 40x10^{-5} second^{-1} and the low level relative vorticity was about 150x10^{-6} second^{-1}. The vertical wind shear of horizontal wind was moderate (10 knots). The MJO index was in phase 2 with amplitude near 1. The upper tropospheric ridge at 200 hPa level lay along 18^{0}N in association with anticyclonic circulation to the northeast of the system centre. A trough in upper and middle tropospheric levels was lying over eastern India near longitude 85.0^{0}E. Under these favourable environmental conditions, the system moved nearly east-northeastwards and concentrated into a deep depression **(DD)** at 0900 UTC of 28th over eastcentral BoB near latitude 15.4ºN and longitude 90.5ºE. At 1500 UTC of 28th, similar environmental conditions prevailed; SST was around 30-31˚C and ocean thermal energy was around 100 KJ/cm^{2}. Moving northeastwards, the system intensified into a cyclonic storm **(CS)** over eastcentral BoB near latitude 16.0ºN and longitude 91.0ºE.

At 1200 UTC of 29th, thermal conditions remained the same. The low level convergence was about 40x10^{-5} second^{-1}, the upper level divergence was around 30-40x10^{-5} second^{-1} around the system centre and the low level relative vorticity increased to about 200x10^{-5} second^{-1}. The vertical wind shear of horizontal wind was high (15-20 knots) around the system centre. The MJO index was in phase 3 with amplitude >1. The upper tropospheric ridge at 200 hPa level laid along 18^{0}N in association with anticyclonic circulation to the northeast of the system centre. The system laid in the western periphery of anticyclonic circulation. Under these environmental parameters, the system moved nearly north-northeastwards, intensified gradually into severe cyclonic storm **(SCS)** and lay centered over northeast and adjoining eastcentral BoB near latitude 18.6ºN and longitude 91.5.4ºE. The advection of warm moist air from southeast sector continued and under similar thermo-environmental conditions the system attained its peak intensity of 60 kts at 2100 UTC of 29th. Moving north-northeastwards, the system crossed Chittagong between 0400 and 0500 UTC of 30th. Due to the interaction of the system with orographically dominated land surface, the system weakened into a **CS** and laid centered over Bangladesh and adjoining Mizoram & Tripura near latitude 23.6ºN and longitude 92.1ºE at 0900 UTC of 30th. Moving further north-northeastwards, the system weakened into **DD** at 1200 UTC over Tripura & neighbourhood and into a **D** at 1800 UTC of 30th over south Meghalaya & neighbourhood. While moving northeastwards, the system weakened into a well marked low pressure area over Nagaland & neighbourhood at 0000 UTC of 31st May.

The total precipitable water imageries (TPW) during 27-31 May are presented in **Fig.2.2.1**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system. From 30th morning, the system started interacting with land surfaces and moisture supply also reduced from southeast sector.

Table 2.2.1: Best track positions and other parameters of the Severe Cyclonic Storm, 'Mora' over the Bay of Bengal during 28-31 May, 2017

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
28/05/2017	0000	14.0/88.5	1.5	998	25	3	**D**
	0300	14.5/89.5	1.5	998	25	3	D
	0600	15.0/90.0	1.5	997	25	3	D
	0900	15.4/90.5	2.0	996	30	4	**DD**
	1200	15.7/90.7	2.0	995	30	5	DD
	1500	16.0/91.0	2.5	994	35	6	**CS**
	1800	16.3/91.2	2.5	994	35	6	CS
	2100	16.6/91.3	2.5	992	40	8	CS
29/05/2017	0000	17.0/91.3	3.0	990	45	10	CS
	0300	17.3/91.3	3.0	990	45	10	CS
	0600	17.8/91.4	3.0	988	45	10	CS
	0900	18.3/91.5	3.0	986	45	11	CS
	1200	18.6/91.5	3.0	984	50	12	**SCS**
	1500	18.8/91.5	3.5	980	55	16	SCS
	1800	20.0/91.6	3.5	980	55	16	SCS
	2100	20.3/91.6	3.5	978	60	18	SCS
30/05/2017	0000	21.1/91.8	3.5	978	60	18	SCS
	0300	21.8/91.9	3.5	978	60	18	SCS
	Crossed Bangladesh coast close to south of Chittagong near 22. 0^{0}N/91.9^{0}E during 0400-0500 UTC						
	0600	22.8/91.9	-	982	55	16	**SCS**
	0900	23.6/92.1	-	988	40	10	**CS**
	1200	24.2/92.2	-	990	30	6	**DD**
	1800	25.3/92.4	-	994	20	4	**D**
31/05/2017	0000	**Weakened into a well marked low pressure area over Nagaland & neighbourhood**					

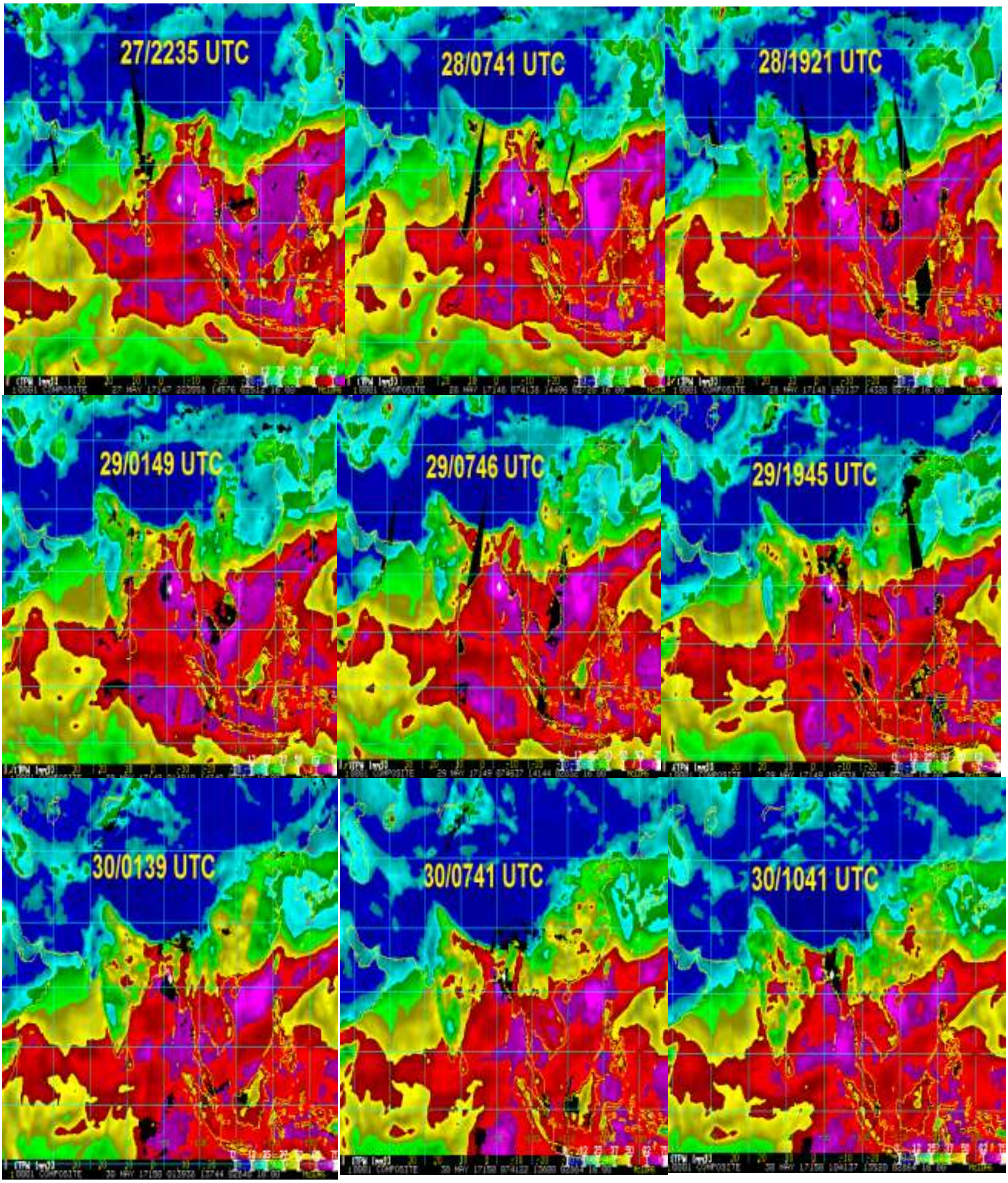


Fig. 2.2.1.: Total Precipitable Water Imageries during 27-30 May, 2017

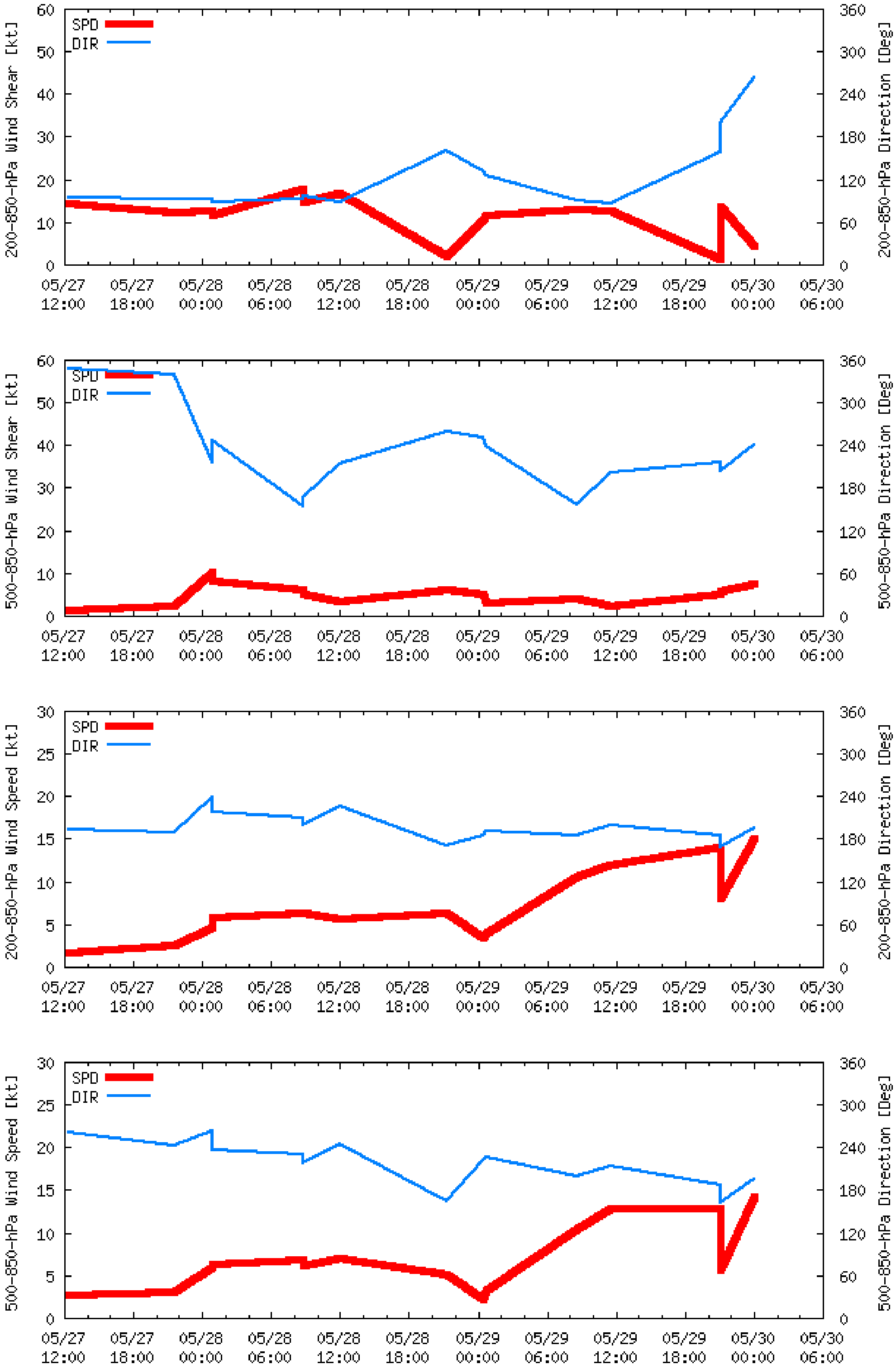


Fig. 2.2.2 Wind shear and wind speed in the middle and deep layer around the system during 28th to 31st May 2017.

The wind speed in middle and deep layer around the system centre is presented in **Fig. 2.2.2**. The wind shear around the system between 200 & 850 hPa levels remained steady till 1200 UTC of 28th May. It decreased rapidly from 28th night to 29th morning becoming steady till evening of 29th. Thereafter, it decreased gradually till morning of 30th.

The wind shear was 10 knots or less on 29th and 30th, helping the intensification of the system. Further, the anticyclonic wind shear over the region also helped in intensification of the system

As the wind shear was east-southeasterly from 28th evening to night, the convective cloud mass was sheared towards west-northwestwards of the system centre till 28th night. Thereafter, it gradually became northeasterly by 29th night, shearing the cloud mass cloud mass to southwest sector of system. By 30th morning, it gradually became southeasterly, shearing cloud mass to northwest of system centre.

2.2.3.3 Movement

From **Fig. 2.2.2**, it indicates that from 29th onwards, the mean deep layer winds between 200-850 hPa levels steered the near north-northeast movement of the system. The northeasterly movement after the landfall was in association with trough in westerly over eastern India. The initial northeasterly movement of the system was in association with the upper tropospheric ridge lying to the north of the system centre. The SCS, Mora moved initially northeastwards till late evening (1500 UTC) of 28th May. It then moved north-northeastwards till night (1800 UTC) of 30th. Thereafter, it moved east-northeastwards till 0600 UTC of 29th and nearly northwards thereafter. The twelve hourly movement of SCS Mora is presented in **Fig. 2.2.3**. The 12 hour average translational speed of the cyclone was about 20.4 kmph and hence was fast moving in nature. The system moved fast under the influence of mid-latitude trough in westerlies and the anti-cyclonic cyclonic circulation lying to the northeast of the system. This trough created strong north-northeasterly steering winds over the cyclone field in middle and upper tropospheric levels, which was further accentuated by the north-northeasterly winds from anticyclonic circulation. The system had a track length of about 1086 km during its life period.

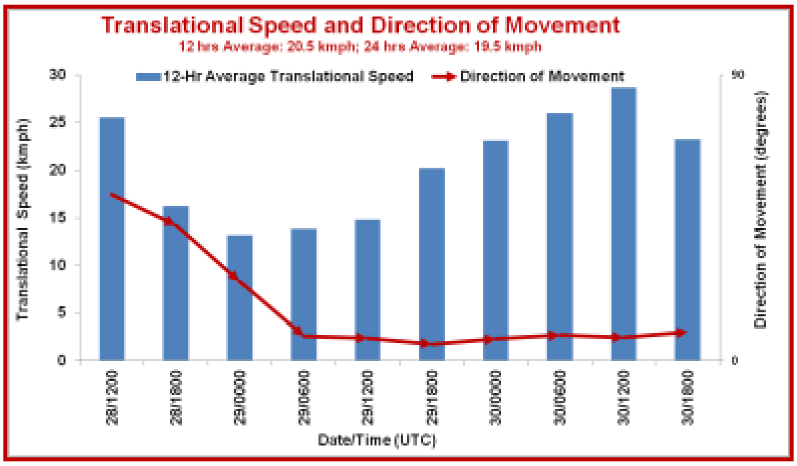


Fig. 2.2.3 Twelve hourly average translational speed (kmph) and direction of movement in association with SCS Mora

2.2.3.4. Landfall point and time:

The observed track during 0300-0600 UTC of 30th May is presented in **Fig. 2.2.4**. It indicates that system crossed Bangladesh coast close to south of Chittagong around 0400-0500 UTC of 30th May.

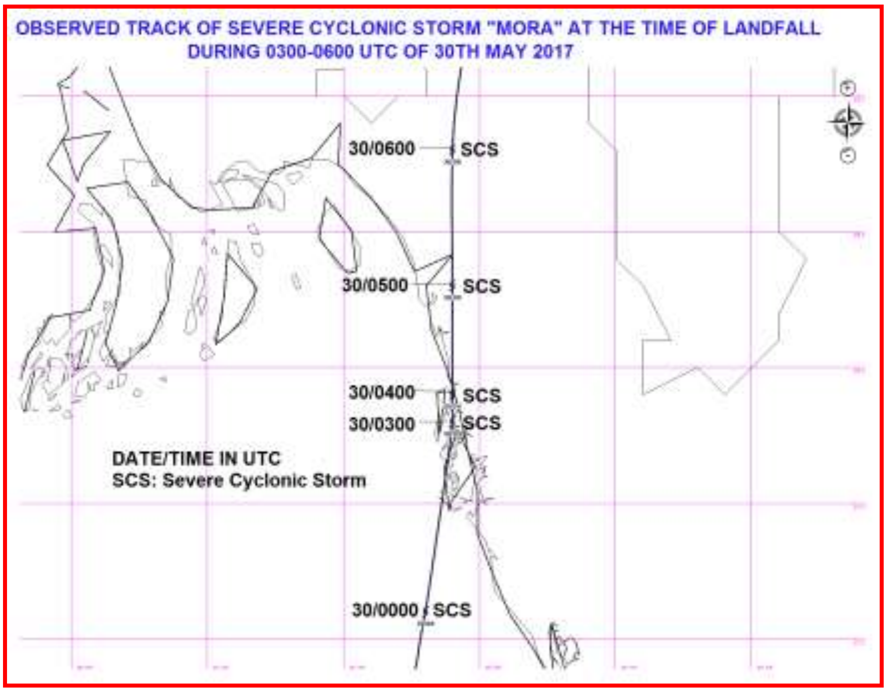


Fig. 2.2.4: Observed track of SCS Mora during 0300 -0600 UTC of 30th May, 2017

2.2.3.5. Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig. 2.2.5**. The lowest estimated central pressure had been 978 hPa during 2100 UTC of 29th to 0300 UTC of 30th. The estimated maximum sustained surface wind speed (MSW) was 60 knots during the same period. At the time of landfall, the ECP was 978 hPa and MSW was 60 knots (severe cyclonic storm). The ECP and Vmax graph indicate that the system intensified gradually till 2100 UTC of 29th, maintained its intensity till 0300 UTC of 30th and started weakening gradually after landfall.

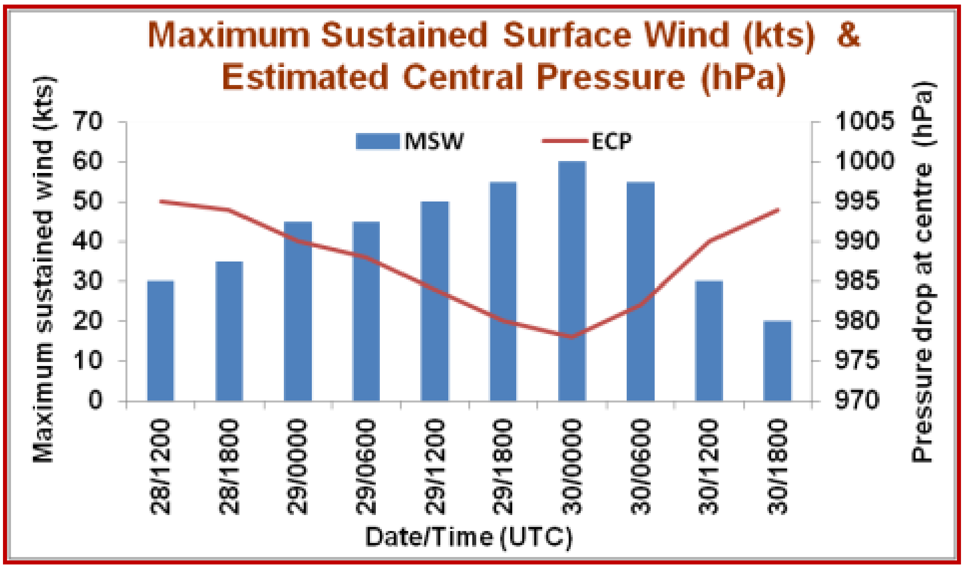


Fig. 2.2.5 Lowest estimated central pressure and the maximum sustained wind speed

2.2.4. Climatological aspects

The severe cyclonic storm, **MORA** had a north-northeastwards moving track. Considering the area of genesis (+/- 2^0 around the genesis point), it is seen that about 63% of the cyclones moved north-northeatwards and crossed Bangladesh coast, whereas another 25% moved northeastwards and crossed Myanmar coast and 12% moved westwards towards Andhra Pradesh coast (Fig. 2.2.6). Hence, the direction of the movement of the cyclone was climatological in nature.

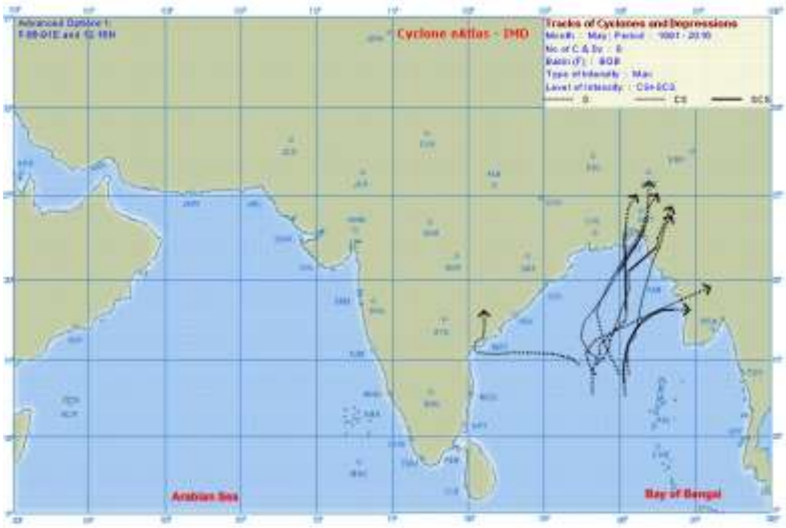


Fig 2.2.6. Climatological tracks of TCs (SCS and above) forming within +/- 2^0 around the genesis point during 1891-2016

2.2.5. Features observed through satellite and Radar

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 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered.

2.2.5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.2.7**. Intensity estimation using Dvorak's technique suggested that the system attained the intensity of T 1.5 at 0000 UTC of 28th. The cloud pattern was curved band type with well defined wrapping into the centre from eastern sector. Associated broken low and medium clouds with embedded intense to very intense convection laid over BoB between latitude 11.0^0N & 18.0^0N and longitude 85.0^0E & 91.0^0E. At 0900 UTC of 28th, well defined banding features were seen. Banding wrapped 0.35 on 10 degree log spiral. The system attained the intensity of T2.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 10.0^0N & 20.0^0N and longitude 85.0^0E & 93.0^0E. At 1500 UTC of 28th, the system intensified to T2.5. Convection showed curved band pattern with wrap 0.50 in 10 degree log spiral. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 12.0^0N & 20.0^0N and longitude 85.0^0E & 92.0^0E. At 0000 UTC of 29th, the system attained the intensity of T 3.0. Convection showed curve band pattern with wrap 0.85 in 10 degree log spiral. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 12.0^{0}N & 20.0^{0}N and longitude 85.0^{0}E & 92.5^{0}E. Thereafter the system crossed Bangladesh coast to the south of Chittagong between 0400 to 0500 UTC.

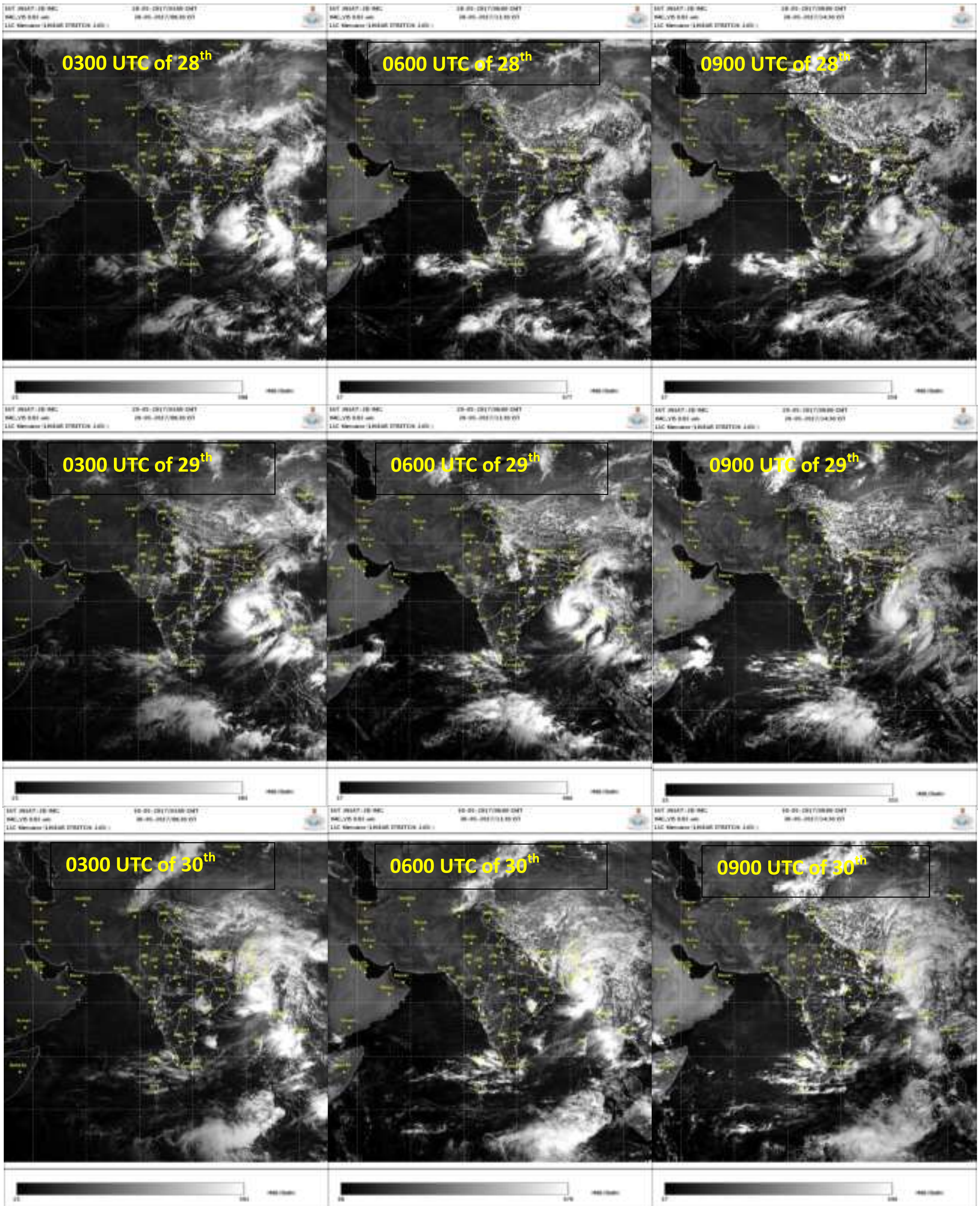


Fig. 2.2.7a: INSAT-3D visible imageries during life cycle of SCS Mora (28-31 May, 2017)

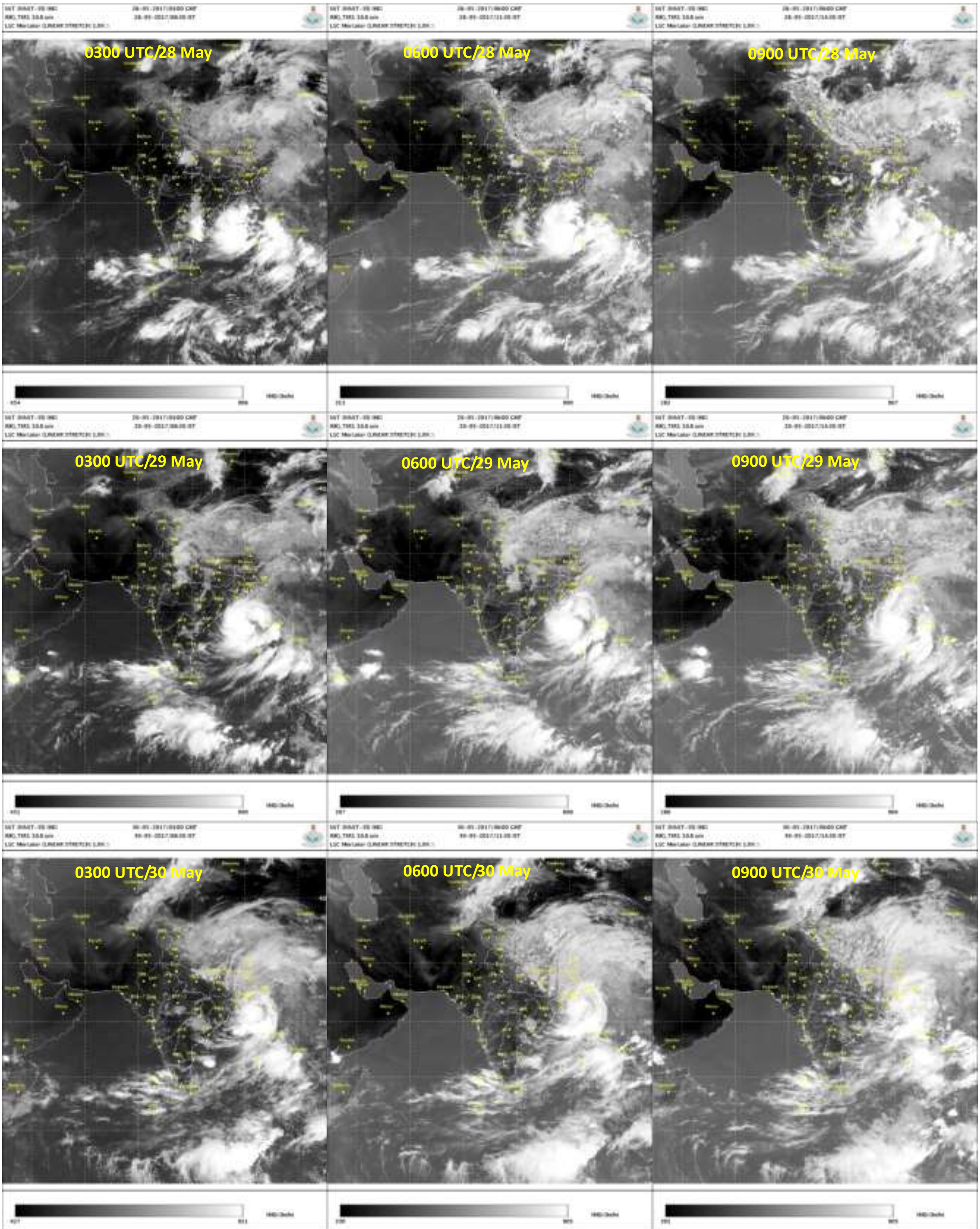


Fig. 2.2.7b: INSAT-3D IR imageries during life cycle of SCS Mora (28-31 May, 2017)

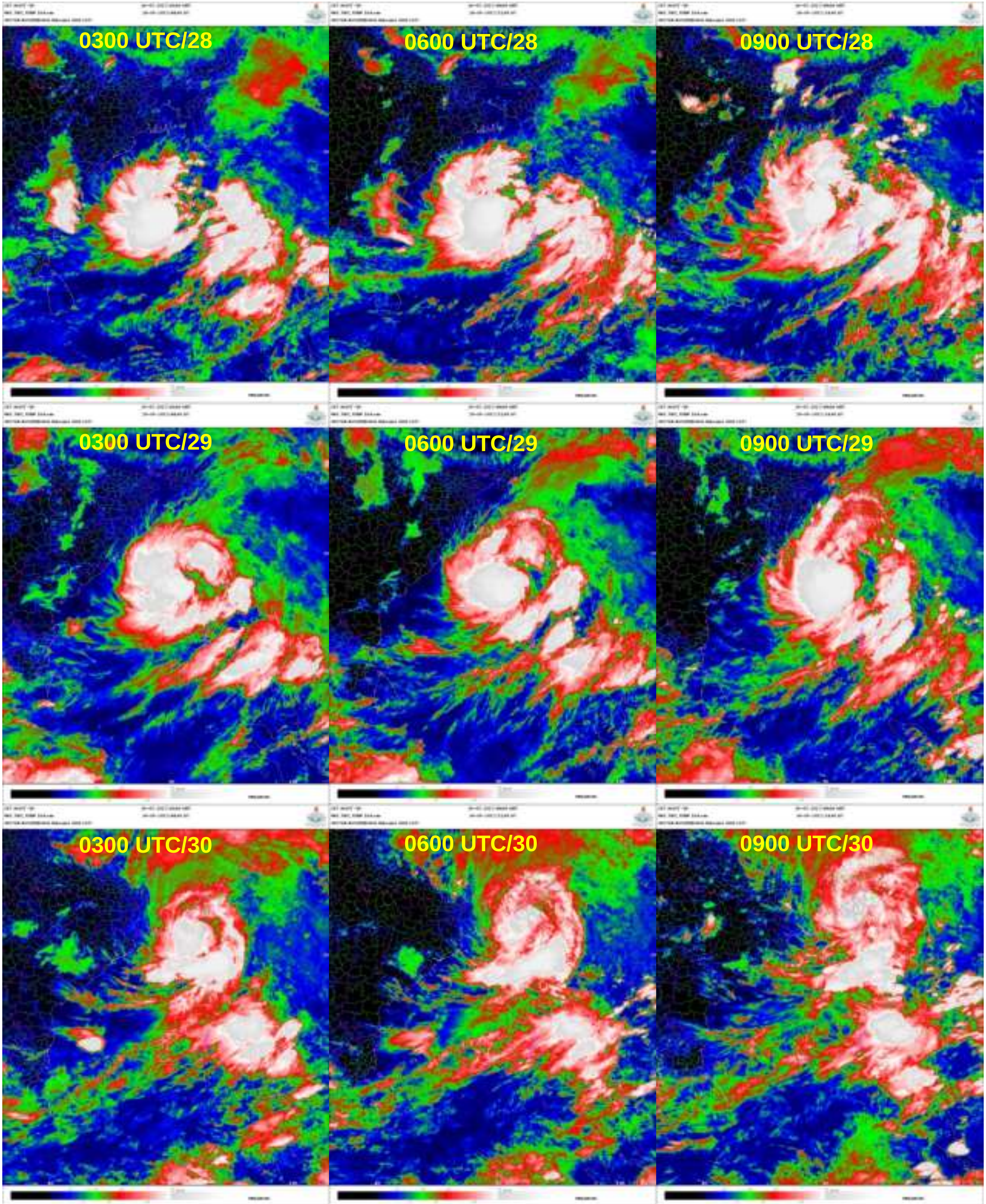


Fig. 2.2.7c: INSAT-3D enhanced colored imageries during life cycle of SCS Mora (28-31 May 2017)

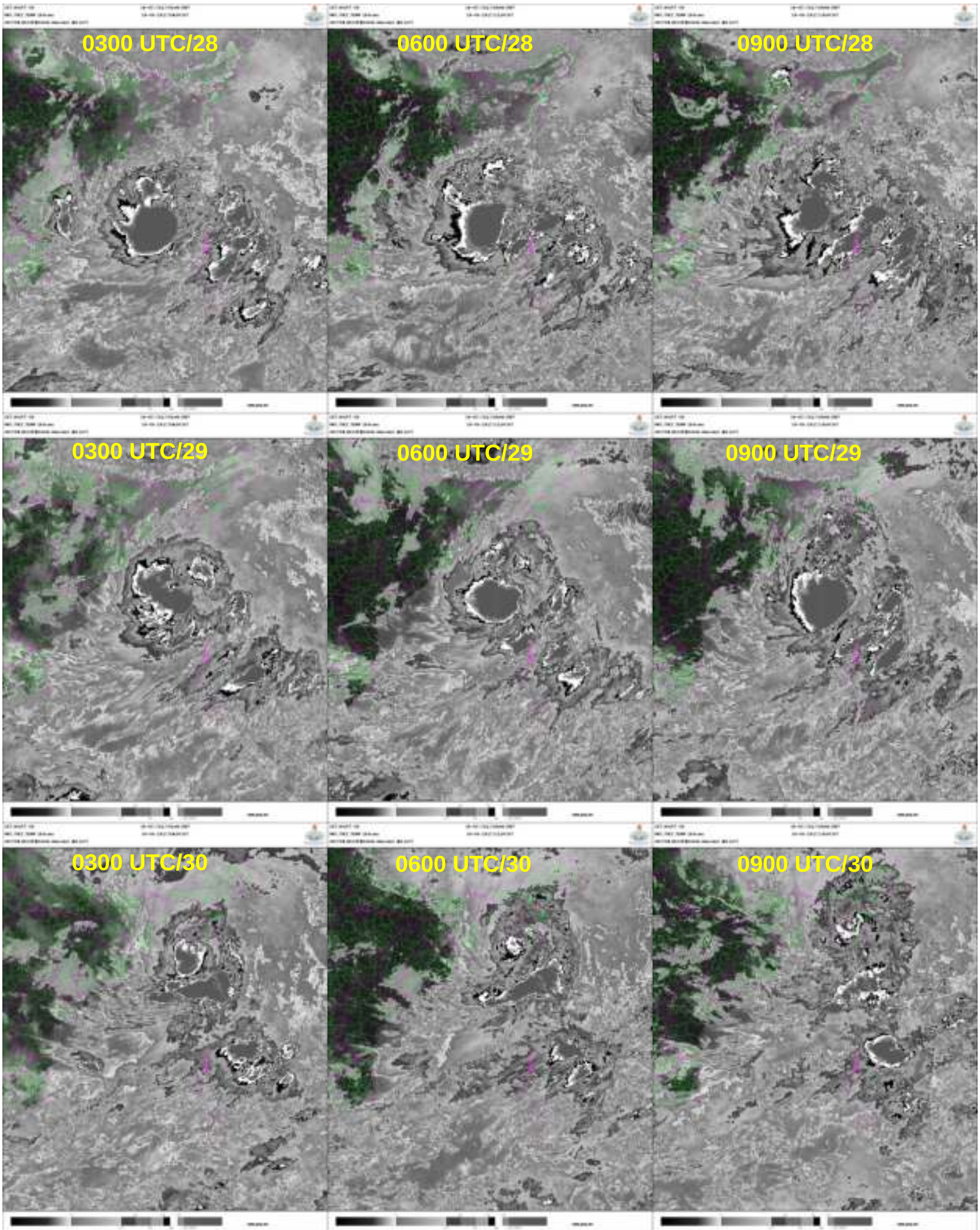


Fig. 2.2.7d: INSAT-3D cloud top brightness temperature imageries during life cycle of SCS Mora (28-31 May, 2017)

2.2.5.2 Microwave features

F-15, F-16, F-17, GPM and GCOM-W1 microwave imageries of the SCS Mora covering its life period from 27th to 31st May 2017 are presented in **Fig. 2.2.8(a).** These imageries helped in understanding the internal structure of the system and better estimation of location of the system. It could indicate the region of intense convection and hence the rainfall. Area of intense convection was seen in the southwest sector in the night of 28th gradually extending to northwest and then northeast sector by early hours of 29th. From 29th night to early hours of 30th morning, intense convection was observed in southern sector. From afternoon of 30th, region of intense convection shifted to northeast sector.

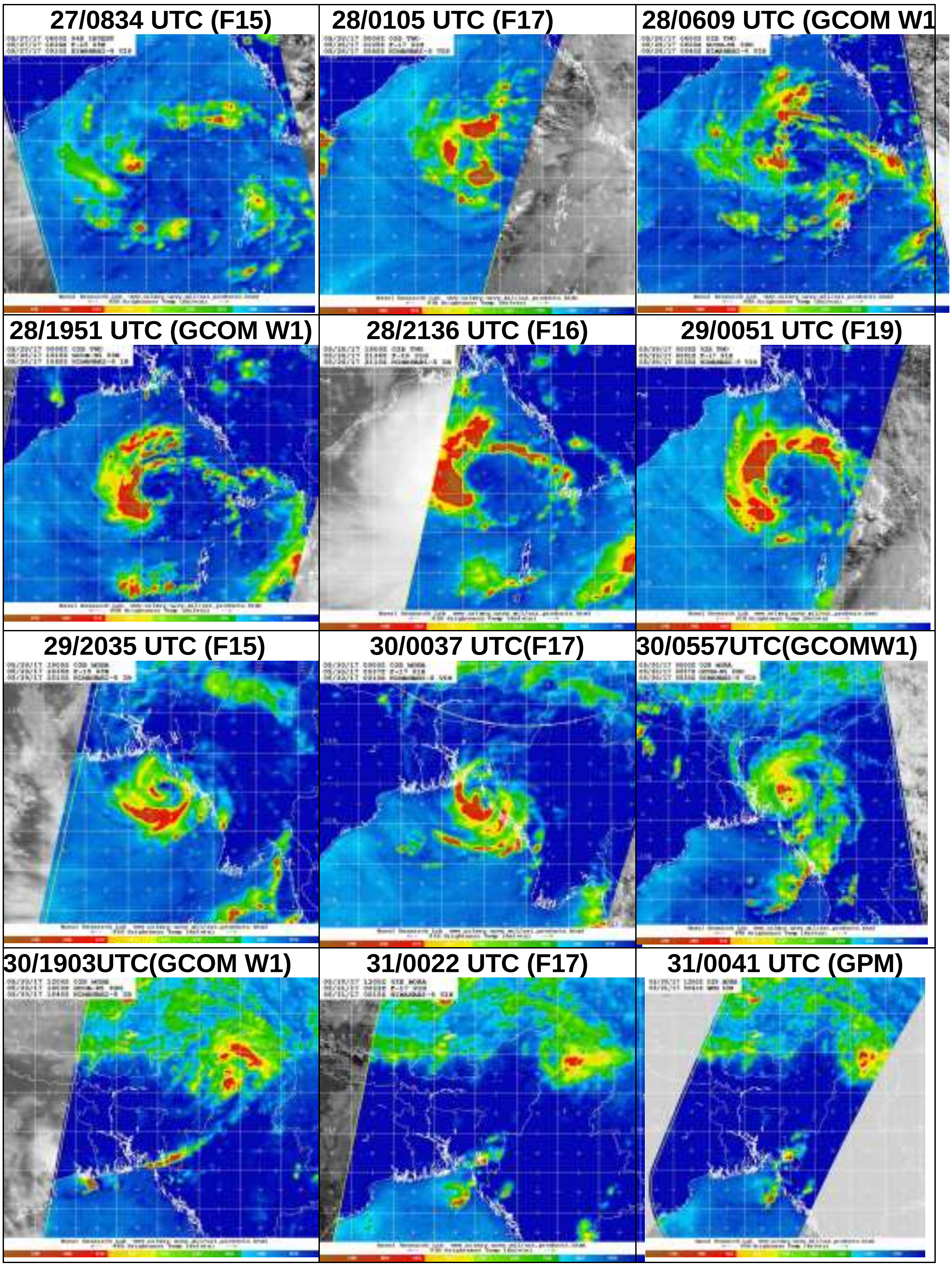


Fig. 2.2.8(a): Microwave imageries during life cycle of SCS Mora

2.2.5.3: Features observed through SCATSAT imageries

Typical imageries from polar satellite, SCATSAT are presented in **Fig. 2.2.8(b).** SCATSAT passes are available twice a day at 0400 UTC and 1700 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 1449 UTC of 27th indicated cyclonic circulation over southeast and adjoining eastcentral BoB. Stronger winds were seen in southwest sector. The imagery indicated large scale cross equatorial flow, inflow of warm and moist air into the system centre from southeast. At 0310 UTC, the area of strong winds extended to entire southern sector. At 1400 UTC of 28th, winds became uniform near the core. At 0221 UTC of 29th, the radial extent of 34kts winds was more in the northeast sector followed by southeast sector due to warm and moist air advection in the southeast and northeast sector. The estimated intensity by SCATSAT matched best track estimates. The maximum size in the northeast sector is also due to higher southeasterly wind shear in the region.

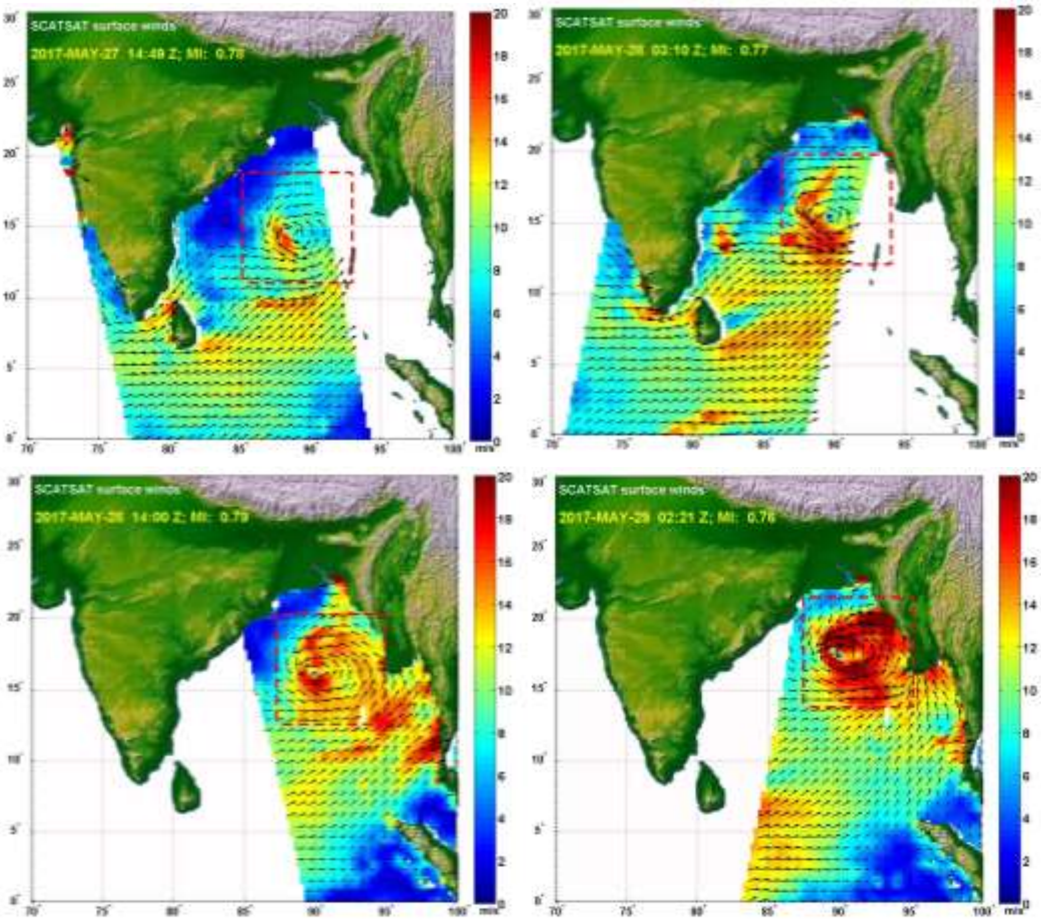


Fig. 2.2.8(b): Imageries from SCATSAT during 27th to 29th May 2017.

2.2.5.4. Features observed through Radar

As the system was moving towards Bangladesh coast, it was tracked by DWR Khepupara, Cox's Bazar and Molvibazar. Typical Radar imageries from these Radars as received from Bangladesh Meteorological Department on 30th May are presented in **Fig. 2.2.9.** These imageries could detect the location of the system correctly. It also helped in estimating the past precipitation and predicting the precipitation in short range.

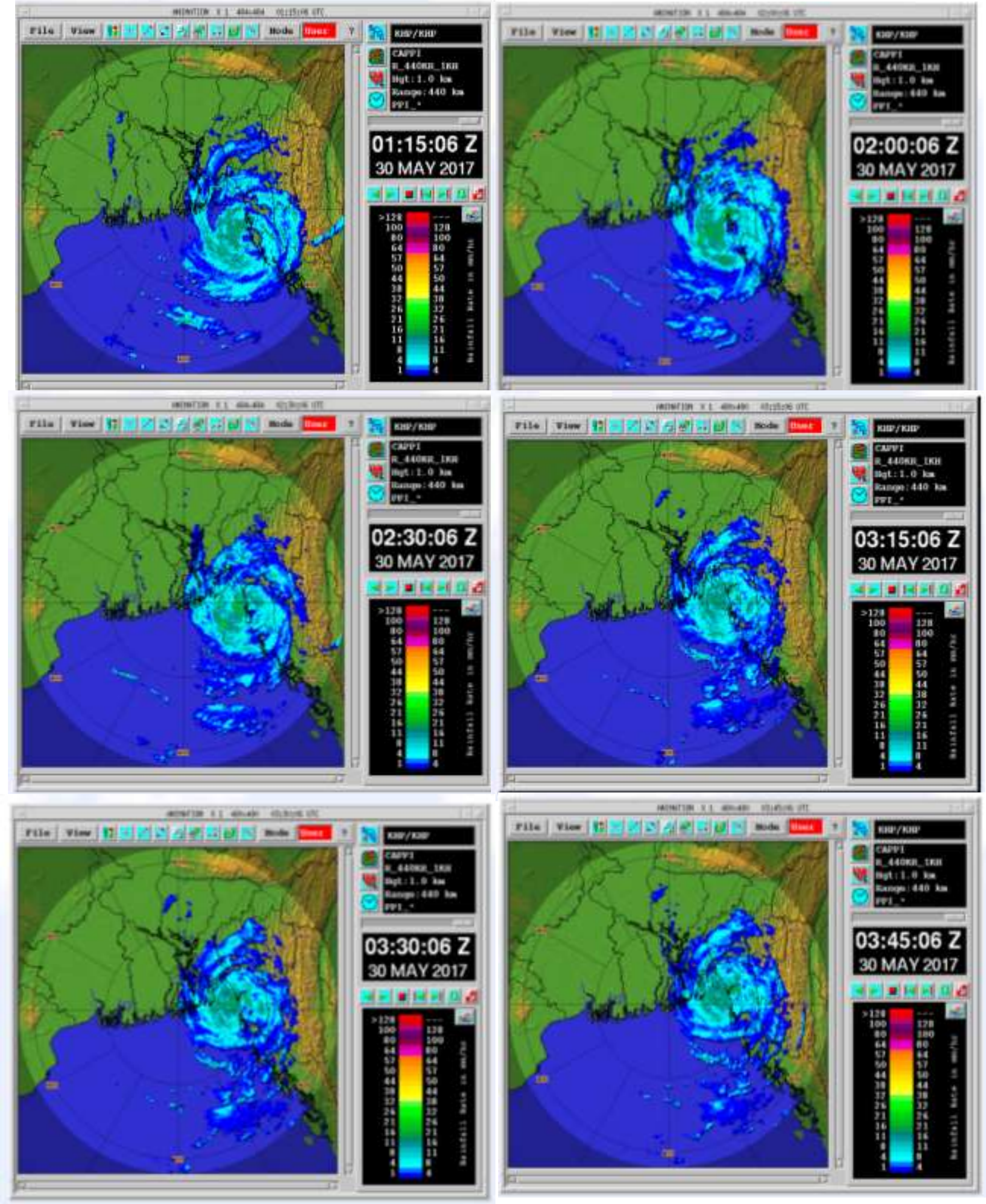


Fig. 2.2.9: Imageries from Doppler Weather Radar Khepupara, Bangladesh during 0100 UTC to 0345 UTC of 30th May.

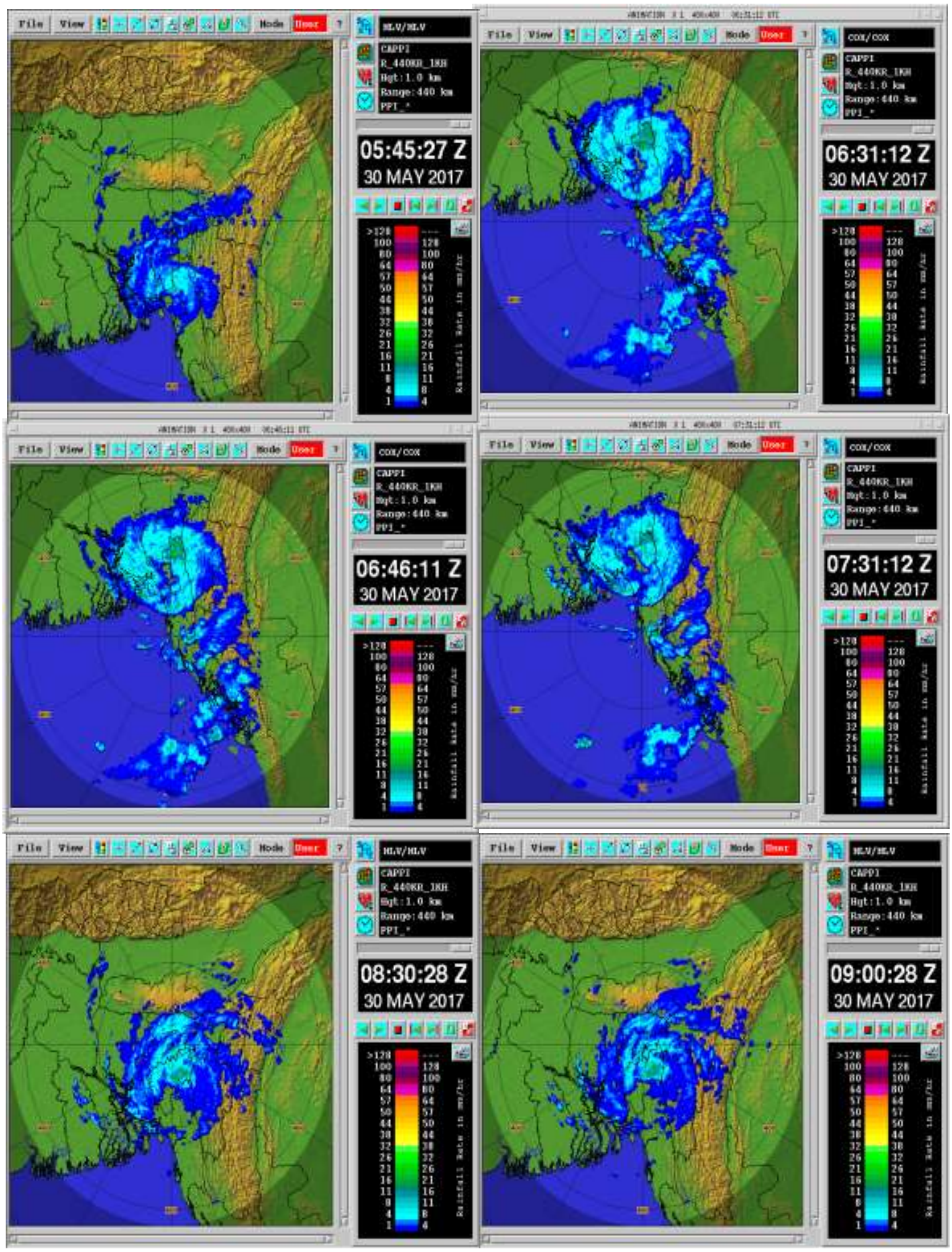


Fig. 2.2.9 (contd.): Imageries from Doppler Weather Radar Cox's Bazar and Molvibazar, Bangladesh during 0545 UTC to 0900 UTC of 30th May

2.2.6 Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 28th-31st May are presented in Fig. 2.2.10. GFS (T1534). Based on 0000 UTC observations of 28th, the model predicted formation of depression over southeast and adjoining eastcentral BoB extending upto 500 hPa level. At 200 hPa level, it could predict presence of ridge around 18^0N in association with anticyclonic circulation over eastcentral BoB off Myanmar coast and a trough in westerlies over western India around 78^0E.

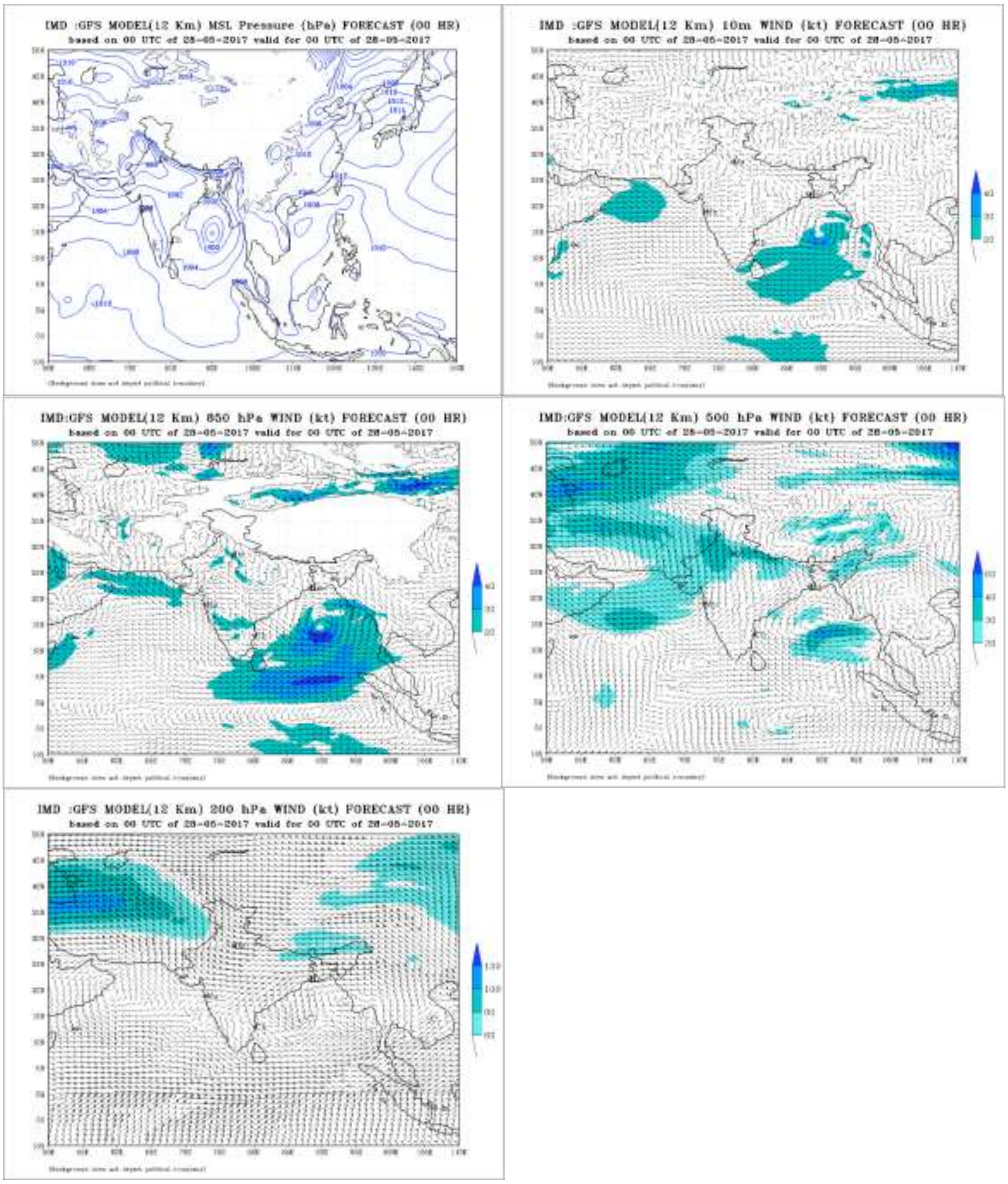


Fig. 2.2.10(a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 28th May

Analysis based on 0000 UTC of 29th May, predicted intensification of system into a cyclonic storm. Vertically the system extended upto 500 hPa levels. At 200 hPa level, it could capture the trough over western India and an anticyclonic circulation to the northeast of system centre.

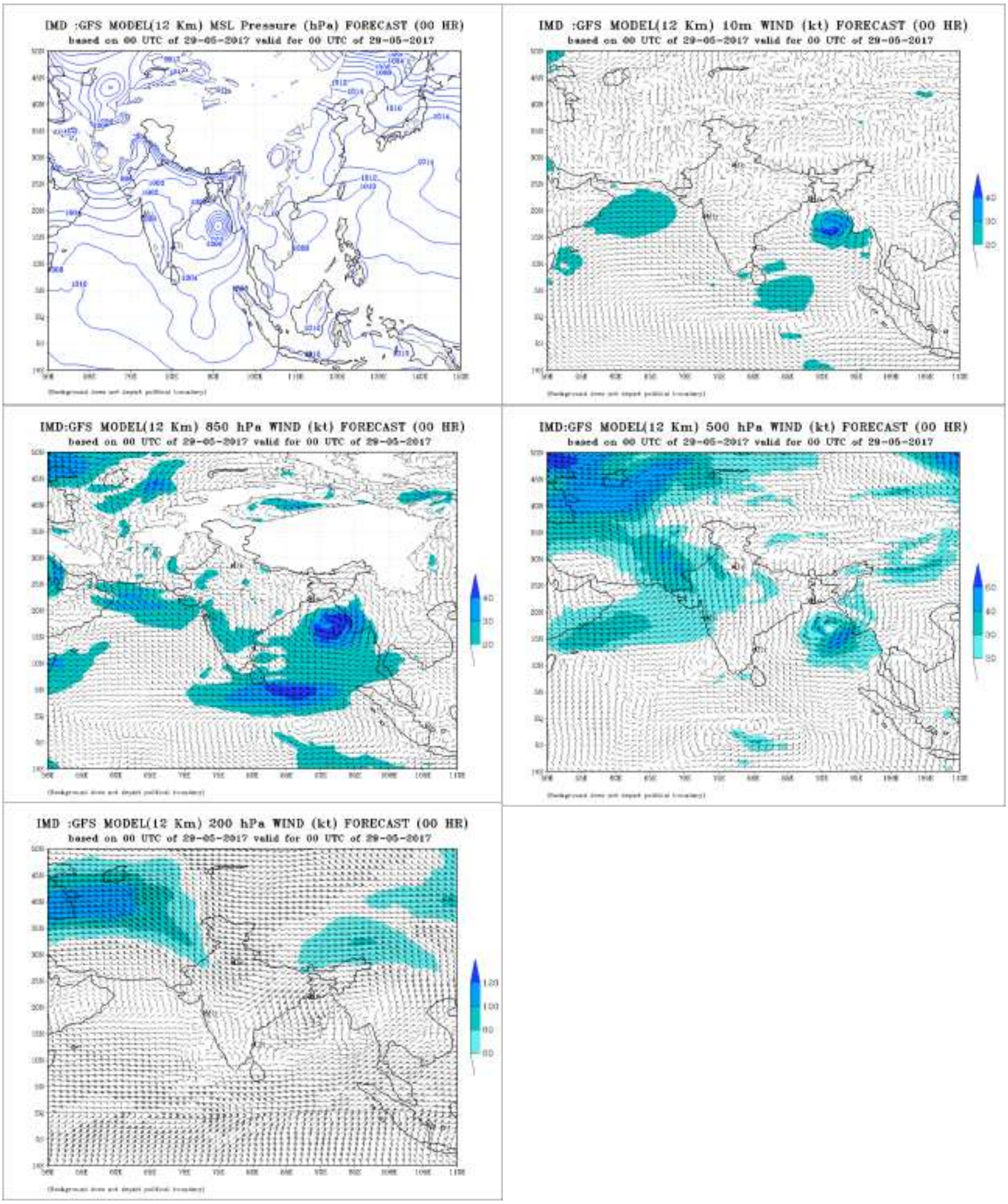


Fig. 2.2.10(b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 29th May

Analysis based on 0000 UTC of 30th May predicted landfall over Bangladesh near $21.5^0N/92.0^0E$ with severe cyclone intensity.

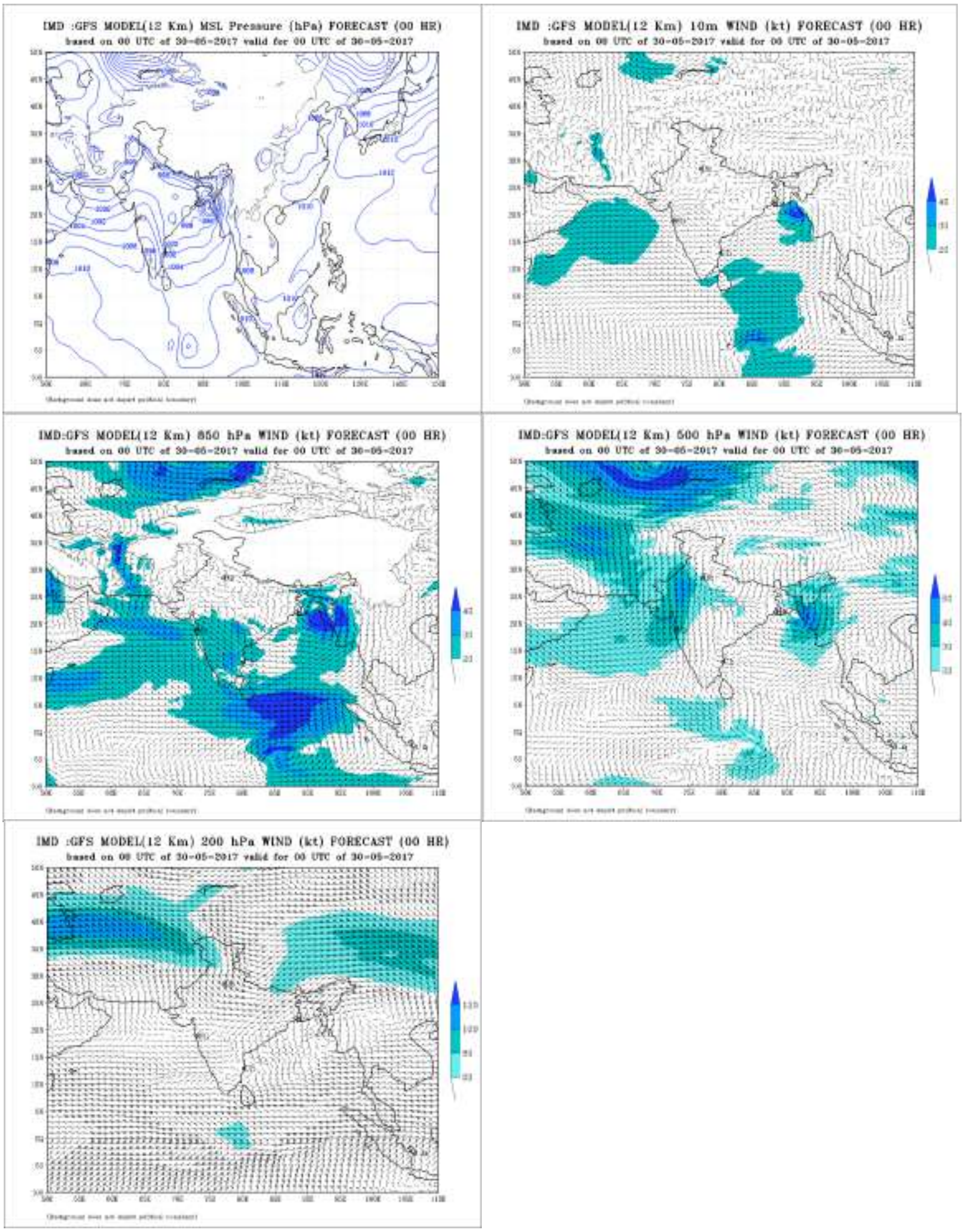


Fig. 2.2.10(c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30th May

Analysis based on 0000 UTC of 31st May indicated weakening of system and movement towards Tripura.

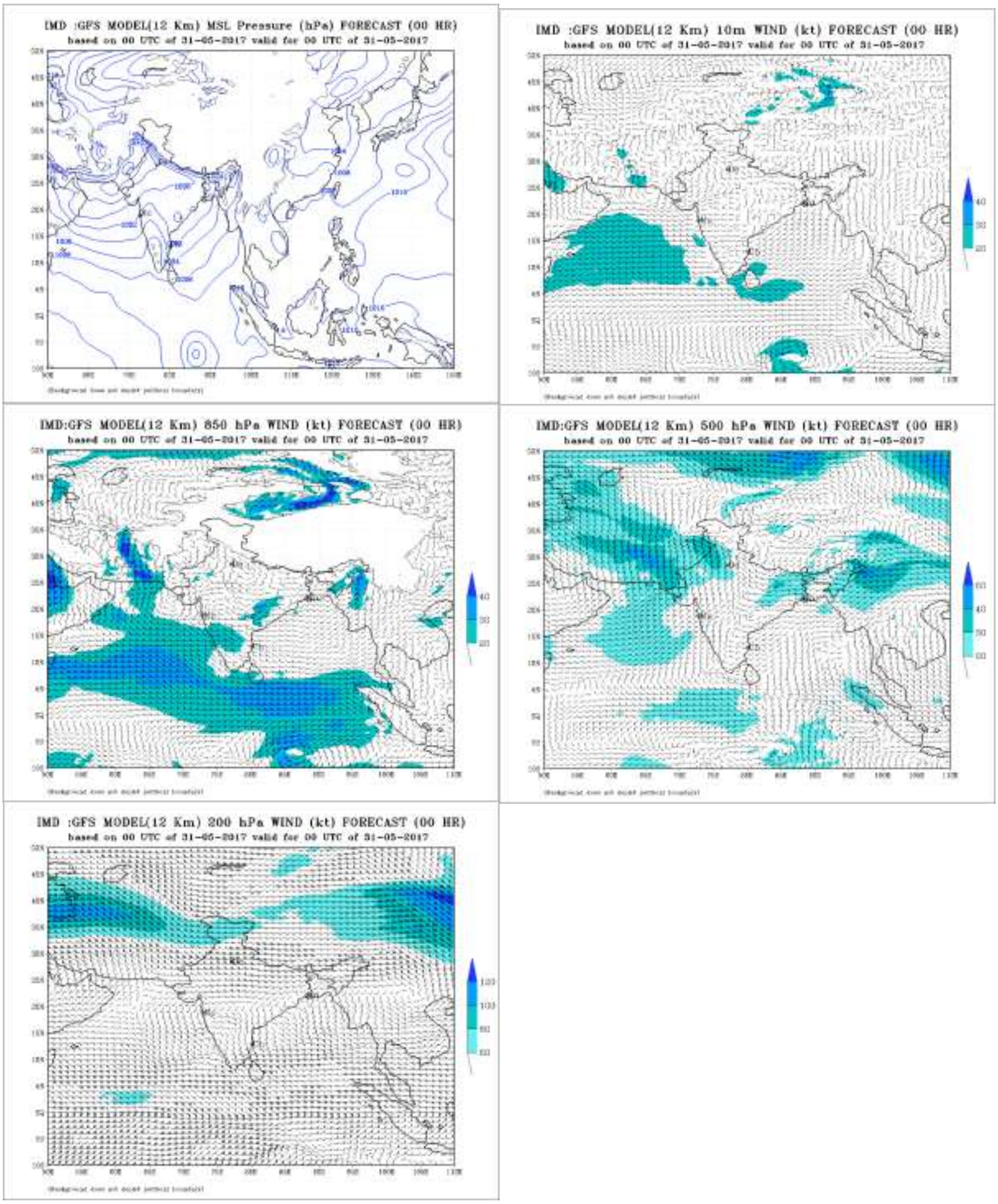


Fig. 2.2.10(d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 31st May

Hence to conclude, to a large extent IMD GFS could simulate the genesis of the system and the associated circulation features during the life period of the system.

2.2.7. Realized Weather:

2.2.7.1 Rainfall:

(a) Indian States:

Rainfall associated with SCS Mora based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 2.2.11**.

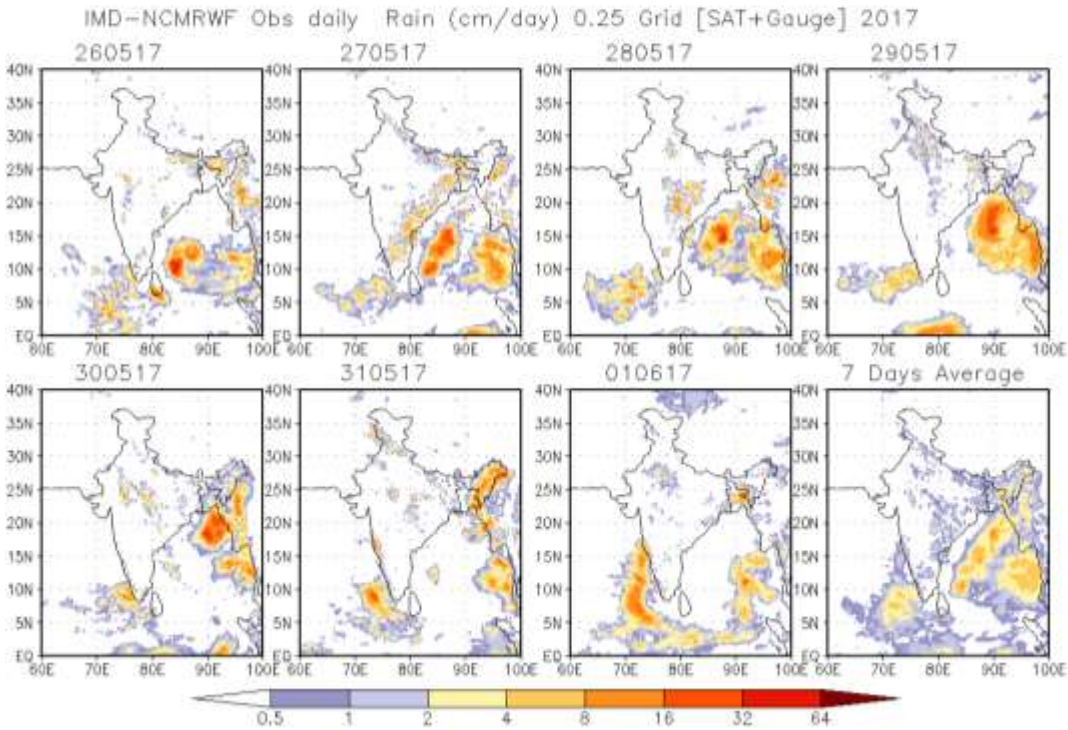


Fig. 2.2.11: IMD-NCMRWF GPM merged gauge rainfall during 26th May– 1st June and 7 days average rainfall (cm/day)

Realized 24 hrs accumulated rainfall **(≥7cm)** ending at 0830 hrs IST of date due to the cyclone is presented below:

(a) Indian States

31.05.2017

Arunachal Pradesh: Pasighat AERO and Basar-8 each

Assam & Meghalaya: Halflong and B P Ghat-11 each, Lumding-10, Shillong C.S.O.-9, Lakhipur-8 and Karimganj, Chauldhowaghat, Matijuri, Barpathar, Jia Bharali N T Xing and N.Lakhimpur/Lilabari-7 each

Nagaland, Manipur, Mizoram & Tripura: Lunglei and Serchip (Hydro)-10 each and Kohima-7.

(b) Bangladesh

On 30th May, rainfall of 17.7 cm over Chittagong, 17.3 cm over Sandwip, 13.8 cm over Sitakunda, 8.7 cm over Rangamati, 8.3 cm over Hatiya and 11.5 cm over Kutubdia was reported. On 31st May, rainfall of 9.6 cm over Netrokona and 13.9 cm over Hatiya was reported.

(Heavy rain : 64.5 – 115.5 mm, Very heavy rain: 115.6 – 200.4 mm, Extremely heavy rain: 200.5 mm or more).

2.2.8. Damage due to SCS Mora

(a) **Damage over India:**

No casualties were reported from any Indian state due to SCS Mora. However, rains triggered landslides at many places in Mizoram. It is reported that about 20 houses were damaged in Khawbung village of Champhai district. About 10 houses including a church have been also been damaged in Serchhip district **(Fig 2.2.12)**.

Fig 2.2.12 (a): Flooded streets in Imphal The Indian Express, 31st May

Fig. 2.2.12 (b): Uprooted trees in Mizoram The Hindustan Times, 31st May

(b) **Damage over Bangladesh:**

As per preliminary report released by Department Disaster Management, Government of the People's Republic of Bangladesh 7 people lost their lives and 61 got injured due to 'Cyclone Mora'. The damage photographs from Bangladesh Meteorological Department are presented in **Fig. 2.2.13**.

Fig. 2.2.13 (a): Heavy rains at Cox's Bazar (b) Rains damaged Rohingya camp in Bangladesh

Fig. 2.2.13 (c-d): Damaged shelters and uprooted trees in Cox's Bazar, Bangladesh

Fig. 2.2.13 (e): Damaged homes in Cox's ravaging Bazar

Fig. 2.2.13(f): Strong winds Dhaka city

Fig. 2.2.13(g): Mora making landfall

Fig. 2.2.13 (h): Tidal effects of Mora

Fig.2.2.13 (i): People moving to cyclone shelters

Fig. 2.2.13(j): Inundation at Teknaf

2.3. Deep Depression over Bay of Bengal (11-13 June 2017)

2.3.1. Introduction

A depression formed over north Bay of Bengal (BoB) in the evening of 11^{th} June 2017 in association with advance of southwest monsoon over the region. It moved north-northeastwards, intensified into a **deep depression** and crossed Bangladesh coast near Khepupara between 0430 & 0530 hrs IST of 12th June 2017. It lay as a deep depression over coastal Bangladesh, close to Northeast of Khepupara at 0530 hrs IST of 12^{th} June 2017. It then moved northeastwards across Bangladesh and weakened gradually. It weakened into a depression around mid night of 12th June 2017 and further into a well marked low pressure area over east Bangladesh and neighbourhood in the early morning of 13^{th} June 2017. It caused heavy rainfall activity over northeastern states and Bangladesh.

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.

2.3.2. Monitoring and Prediction of system

The deep depression was monitored & predicted continuously by India Meteorological Department (IMD) since its inception over north BOB in the evening of 11^{th} June. At the genesis stage, the system was monitored mainly with satellite observations from INSAT 3D, 3DR and Kalpana along with available ships & buoy observations. On 11^{th}, Bangladesh Meteorological Department provided imageries from Doppler Weather Radar (DWR), Cox's Bazar. Various national and international NWP models and dynamical-statistical models were utilized to predict the genesis, track and intensity of the system. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation. IMD issued regular bulletins to WMO/ESCAP Panel member countries including Bangladesh, National & State Disaster Management Agencies, general public and media since inception of the system over BOB.

2.3.2.1. Genesis

A low pressure area formed over westcentral & adjoining north BoB off north Andhra Pradesh - south Odisha coast in the morning of 10^{th} June. It concentrated into a well marked low pressure area over northern parts of central BoB & adjoining north BoB on 11^{th} morning and into a depression over north BoB in the evening of 11^{th}. At 1200 UTC of 11^{th}, the sea surface temperature around the region of depression was 29-30^0C. The ocean thermal energy was less than 50 KJ/cm^2. The vertical wind shear was moderate to high (15-25 knots) around the system centre. The low level relative vorticity and convergence were about $150 \times 10^{-6}\ s^{-1}$ and $20 \times 10^{-5}\ s^{-1}$. An anti-cyclonic circulation lay to the southeast of the system centre leading to poleward outflow favouring genesis of the system. The upper level divergence was about $30 \times 10^{-5}\ s^{-1}$. The upper tropospheric ridge at 200 hpa level ran along 23.5^0N.

2.2.3.2. Intensification and movement

Moving nearly north-northeastwards, it intensified into a deep depression over north BoB in the night of 11^{th} (1800 UTC). Moving north-northeastwards, it crossed Bangladesh coast near Khepupara between 2300 UTC of 11^{th} and 0000 UTC of 12^{th} June. It lay centered near latitude 22.5ºN and longitude 90.5ºE over south Bangladesh & neighbourhood at 0000

UTC of today, the 12th. At 0000 UTC of 12^{th}, the vertical wind shear around the system centre was moderate to high (15-20 knots). The low level relative vorticity and convergence were about $200 \times 10^{-6}\ s^{-1}$ and $30 \times 10^{-5}\ s^{-1}$. There was favourable poleward outflow in association with the anti-cyclonic circulation lying to the souheast of the system centre. The upper level divergence was about $30 \times 10^{-5}\ s^{-1}$. The upper tropospheric ridge at 200 hpa level ran along 22.0^0N. As the system moved over land, it weakened gradually into a depression over east Bangladesh & neighbourhood due to land surface interaction and lay centered near latitude 24.5°N & longitude 91.5°E at 1800 UTC . The system moved north-northeastwards under the influence of anticyclonic circulation lying to southeast of system centre.

The best track of the system is presented in Fig. **2.**1 and the best track parameters are shown in Table **2.3.**1.

Table 2.3.1: Best track positions and other parameters of the deep depression (11-13 June, 2017)

<table>
<tr><th>Date</th><th>Time (UTC)</th><th>Centre lat.^{0} N/ long. ^{0} E</th><th>C.I. NO.</th><th>Estimated Central Pressure (hPa)</th><th>Estimated Maximum Sustained Surface Wind (kt)</th><th>Estimated Pressure drop at the Centre (hPa)</th><th>Grade</th></tr>
<tr><td rowspan="3">11/06/2017</td><td>1200</td><td>20.5/89.5</td><td>1.5</td><td>990</td><td>25</td><td>4</td><td>D</td></tr>
<tr><td>1800</td><td>21.5/90.0</td><td>2.0</td><td>988</td><td>25</td><td>6</td><td>DD</td></tr>
<tr><td colspan="7">Crossed Bangladesh coast near Khepupara between 2300 UTC of 11^{th} and 0000 UTC of 12^{th}</td></tr>
<tr><td rowspan="5">12/06/2017</td><td>0000</td><td>22.5/90.5</td><td>-</td><td>988</td><td>30</td><td>6</td><td>DD</td></tr>
<tr><td>0300</td><td>23.0/90.5</td><td>-</td><td>990</td><td>30</td><td>5</td><td>DD</td></tr>
<tr><td>0600</td><td>23.5/90.7</td><td>-</td><td>990</td><td>30</td><td>5</td><td>DD</td></tr>
<tr><td>1200</td><td>24.0/91.0</td><td>-</td><td>990</td><td>30</td><td>5</td><td>DD</td></tr>
<tr><td>1800</td><td>24.5/91.5</td><td>-</td><td>995</td><td>25</td><td>3</td><td>D</td></tr>
<tr><td>13/06/2017</td><td>0000</td><td colspan="6">Weakened into a well marked low pressure area over Nagaland & neighbourhood</td></tr>
</table>

2.3.4. Features observed through satellite and Radar

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 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered for monitoring the system.

2.3.4.1 INSAT-3D features

Typical INSAT-3D visible and IR imageries are presented in Fig.2.3.1. According to satellite imageries at 1200 UTC of 11^{th}, intensity was C.I. 1.5. The convection showed shear pattern. Maximum convection lay over southwest sector of the depression. Associated broken low and medium clouds with embedded intense to very intense convection lay over north and adjoining westcentral BoB, coastal Odisha and coastal areas of West Bengal and Bangladesh.

At 0000 UTC of 12th, intensity was C.I. 2.0. The convection further got organised. Associated broken low and medium clouds with embedded intense to very intense convection lay over northwest and adjoining northeast BoB. At 1800 UTC of 12th, broken low and medium clouds with embedded intense to very intense convection lay over south Bangladesh, northeast & adjoining northwest BoB and south gangetic West Bengal. At 0000 UTC of 13th, broken low and medium clouds with embedded intense to very intense convection lay over south Bangladesh, northeast & adjoining northwest BoB and south Gangetic West Bengal.

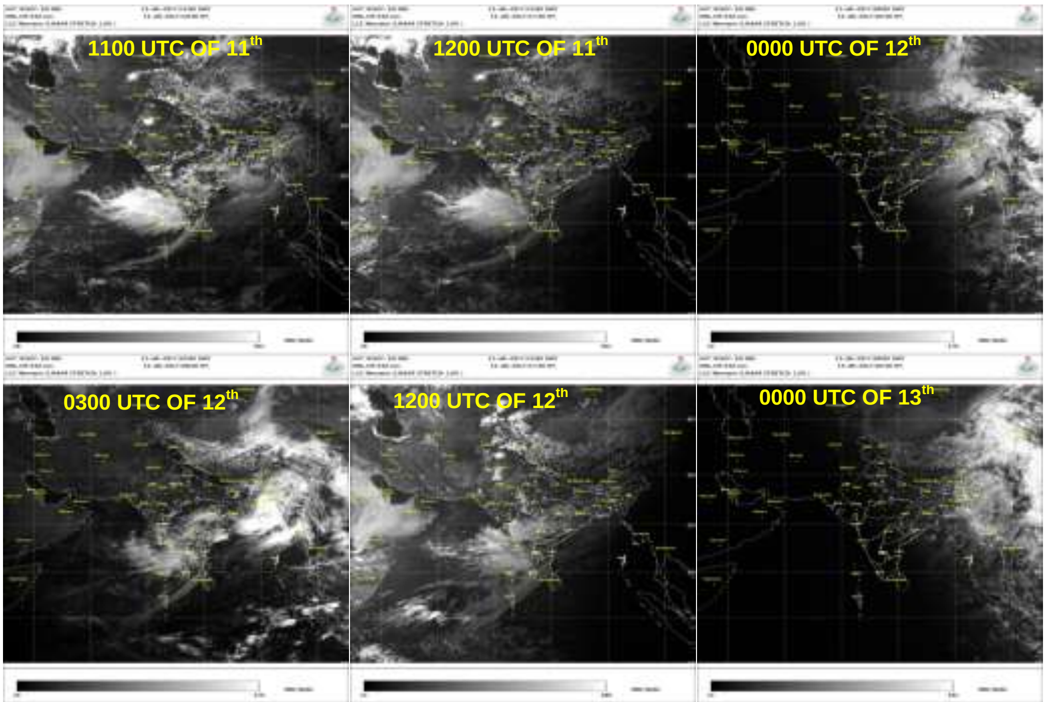


Fig.2.3.1 (i) INSAT 3D based visible imagery of deep depression during 11-13 June, 2017

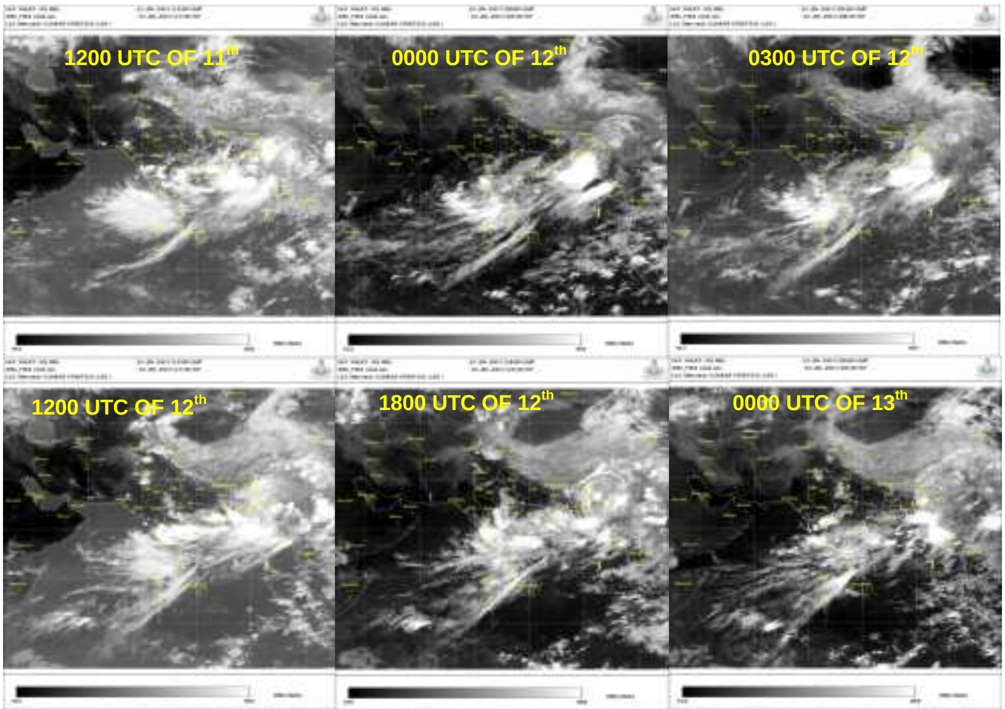


Fig.2.3.1(ii). INSAT 3D based IR imagery of deep depression during 11-13 June, 2017

2.3.4.2 Radar features

As the system was moving north-northeastwards, it was tracked by DWR Cox's Bazar on 11th June. Typical Radar imageries are presented in Fig. 2.3.2. DWR Cox's Bazar could capture the location and associated rainfall correctly. It could also show curved bands entering towards the centre from the southeast.

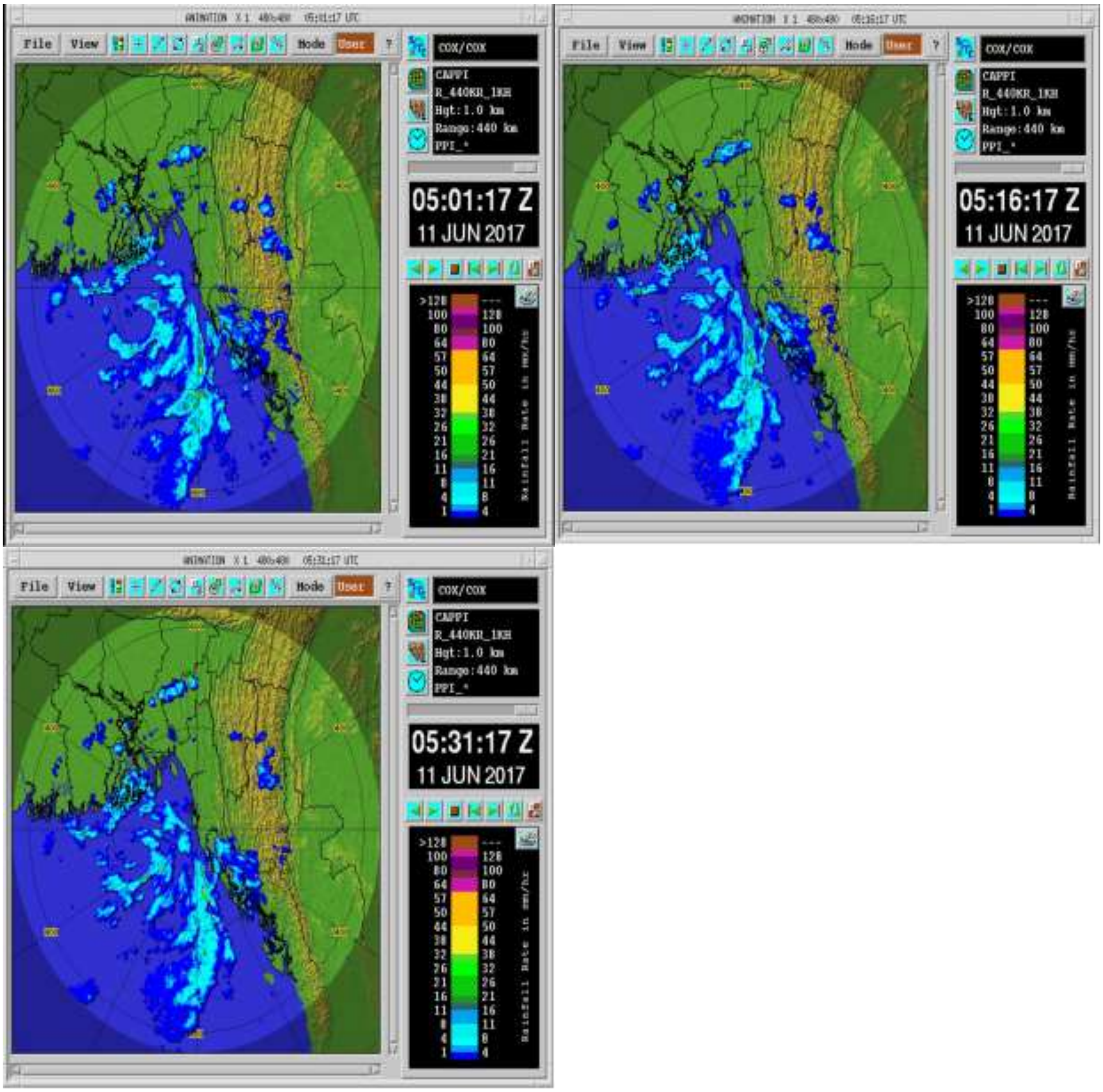


Fig.2.3.2. Typical Radar imageries of deep depression on 11th June, 2017

2.3.5. Dynamical features

IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels are presented in Fig. 2.3.3. GFS (T574) could simulate the genesis of the system and the associated circulation features during it’s life period. Anticyclonic circulation lying to the northeast of system centre was well captured by the system.

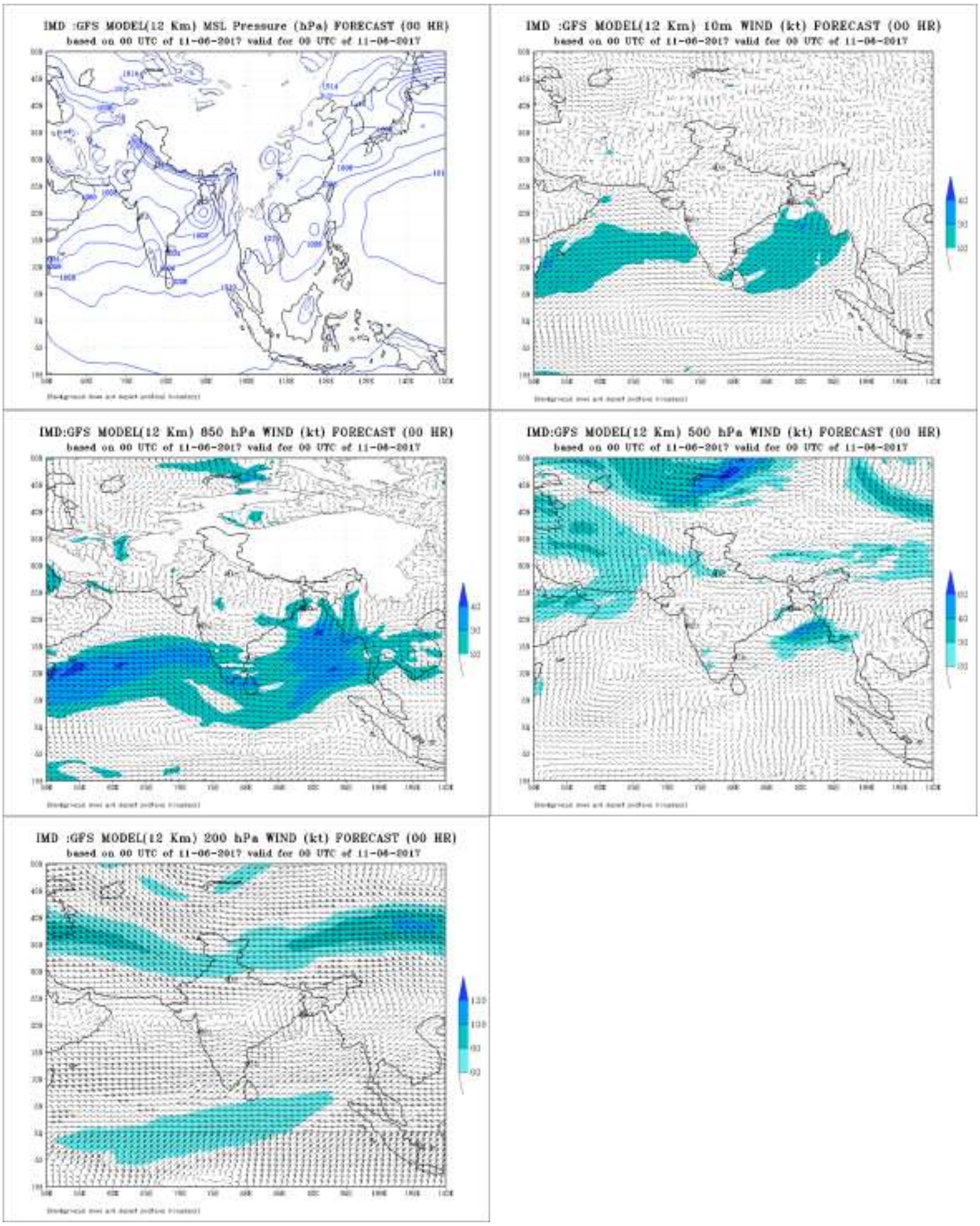


Fig. 2.3.3 (i) IMD GFS Model analyses of mean sea level pressure (MSLP), 10m wind and winds at 850, 500 & 200 hPa levels of 0000 UTC of 11th June

At 0000 UTC of 12th, it could capture that the system has crossed Bangladesh coast as a DD.

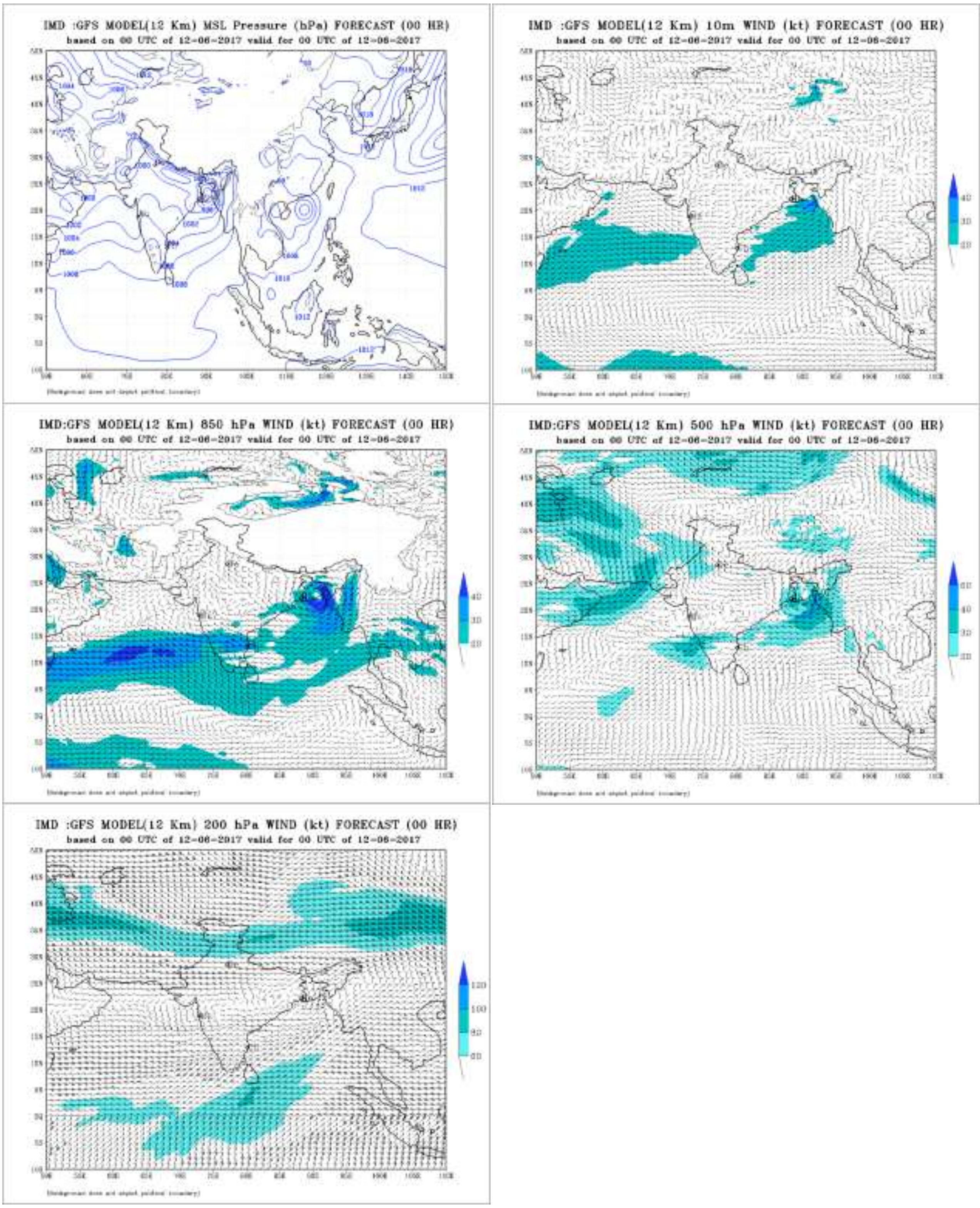


Fig. 2.3.3 (ii) IMD GFS Model analyses of mean sea level pressure (MSLP), 10m wind and winds at 850, 500 & 200 hPa levels of 0000 UTC of 12th June

At 0000 UTC of 13th, it could capture weakening of the system over southeast Bangladesh.

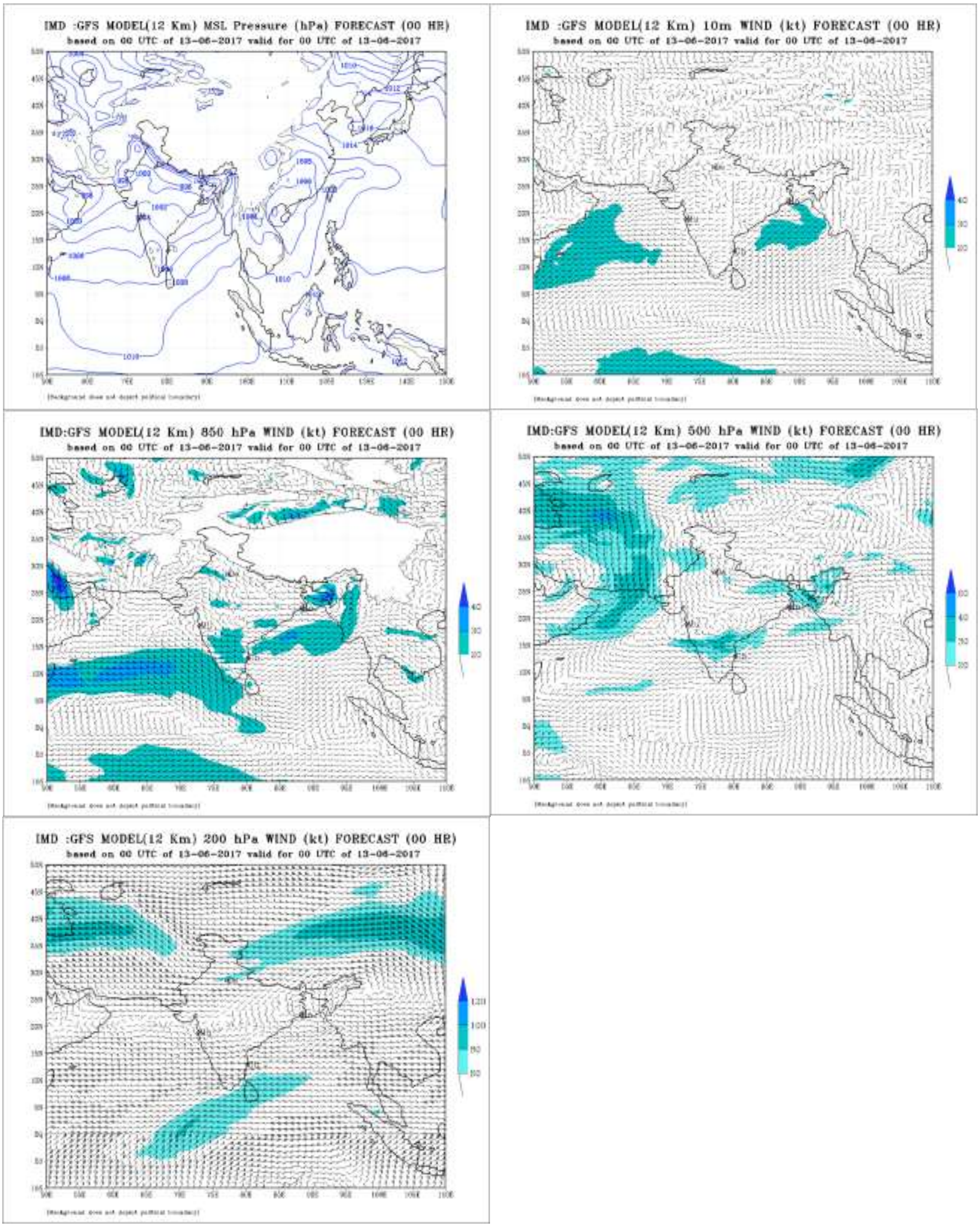


Fig. 2.3.3 (iii) IMD GFS Model analyses of mean sea level pressure (MSLP), 10m wind and winds at 850, 500 & 200 hPa levels of 0000 UTC of 13th June

2.3.6. Realised weather:

The deep depression caused heavy rainfall over northeastern states and Bangladesh. The chief amounts of 24 hr cumulative rainfall ending at 0830 hrs IST of data are given below:

12 June 2017:

Assam & Meghalaya: N.Lakhimpur/Lilabari and Kampur : 7 each

Nagaland, Manipur, Mizoram & Tripura: Bishalgarh: 9 and Arundhutinagar: 7.

13 June 2017:

Assam & Meghalaya: Cherrapunji : 32, Mawsynram: 19, Shillong: 11, Williamnagar: 10, Karimganj, Panbari : 10 each, Goalpara, Barpeta: 8 each, Beky Railway.Bridge: 7, **Nagaland, Manipur, Mizoram &Amp; Tripura:** Serchip: 24, Aizwal: 18, Bishalgarh: 10, Agartala : 9, Khowai: 8 and Arundhutinagar & Kailashahar : 7 each.

14 June 2017:

Arunachal Pradesh: Itanagar, Naharlagun : 7 each **Assam & Meghalaya:** Jia Bharali N T Xing, Puthimari & Guwahati Airport: 11 each; Tezpur, Majbat & Karimganj : 9 each; Goibargaon, Dhekiajuli, Badatighat: 8 each and Nalbari & Pagladia: 7 each.

2.4. Depression over the Bay of Bengal (18-19 July 2017)

2.4.1. Introduction

In association with active monsoon conditions, an upper air cyclonic circulation developed over eastern parts of Gangetic West Bengal & neighbourhood in the morning of 12^{th} July. Under its influence, a low pressure area formed over northwest Bay of Bengal (BoB) off north Odisha & Gangetic West Bengal coast on 15^{th} morning. It lay as a well marked low pressure area over northwest & adjoining westcentral BoB and coastal areas of Odisha & north Andhra Pradesh in the morning of 17^{th}. It concentrated into a depression over northwest and adjoining westcentral BoB & coastal areas of Odisha in the morning of 18^{th}. Thereafter, it moved west-northwestwards and crossed Odisha coast near Puri around 2030 hours IST on the same day. It weakened into a well marked low pressure area in the morning of 19^{th} over interior Odisha & neighbourhood and into a low pressure area over interior Odisha & adjoining Chhattisgarh in the evening of 19^{th} July, 2017. It continued to move west northwestwards and weakened gradually.

2.4.2. Brief life history

2.4.2.1. Genesis and intensification

An upper air cyclonic circulation lay over northwest BoB extending upto 7.6 Km above mean sea level tilting southwestwards with height on 12^{th}, over North Bay of Bengal & neighbourhood on 13^{th}; over northwest BoB & neighborhood on 14^{th} July. Under its influence, a low pressure area formed over northwest BoB off north Odisha & West Bengal coast on 15^{th} with the associated upper air cyclonic circulation extending upto 7.6 km above mean sea level. It persisted over the same region on 16^{th} July. It lay as a well marked low pressure area over northwest BoB and adjoining westcentral BoB and coastal areas of Odisha & north Andhra Pradesh with associated upper air cyclonic circulation extending up to 7.6 Km above mean sea level tilting southwestwards with height on 17^{th} July. It concentrated into a depression over northwest and adjoining westcentral BoB & coastal areas of Odisha centered near Lat.19.0°N and Long.86.0°E, about 120 km east-southeast of Gopalpur (Odisha) and about 80 km south-southeast of Puri at 0830 hours IST on 18^{th} July. It moved west-northwestwards and crossed Odisha coast near Puri around 2030 hours IST on the same day and lay over interior Odisha & neighbourhood as a well marked low pressure with associated upper air cyclonic circulation extending up to 7.6 Km above mean sea level tilting southwestwards with height in the morning on 19^{th}; It weakened further and lay over interior Odisha and adjoining Chhattisgarh as a low pressure area in the evening of 19^{th} July 2017.

According to satellite imageries, the intensity of the system was CI.1.5 at the time of formation of depression. The estimated central pressure was 992 hPa. The maximum sustained wind speed was 25 knots gusting 35 knots. Sea condition was rough to very rough around system centre. Associated broken low and medium clouds with embedded moderate to intense to very intense convection lay over Bay of Bengal between latitude 16.0^0N and 19.0^0N & west of longitude 89.0^0E, south coastal Odisha, north coastal Andhra Pradesh and adjoining areas.

The sea surface temperature (SST) was around 28-29˚C. The ocean heat content was < 50 kJ/cm^2 near Odisha coast. The low level convergence was about $20x10^{-5}$ second^{-1} to the southwest of system centre, the upper level divergence was around $10x\ 10^{-5}$ second^{-1}

to the southwest of system centre and the low level relative vorticity was around 100×10^{-6} $second^{-1}$. The vertical wind shear of horizontal wind was moderate (15 knots) around the system centre and was increasing towards northwest. The Madden Julian Oscillation (MJO) index lay in phase 4 with amplitude <1. The upper tropospheric ridge ran along 30^0N. All the above favourable environmental parameters led to intensification of the system into depression. However, the proximity towards the land surface, unfavourable amplitude of the MJO index and higher wind shear towards northwest (direction of motion of depression) did not favour further intensification. Rather, it led to gradual weakening of the system.

The best track parameters are shown in Table 2.4.1. The track of the depression is shown in Fig. 2.1. The typical satellite imageries are shown in Fig. 2.4.1.

Table 2.4.1: Best track positions and other parameters of the Depression over the west central Bay of Bengal and coastal areas of Odisha & north Andhra Pradesh during 18-19 July, 2017

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
18/07/2017	0000	19.0/86.0	1.5	992	25	4	D
	0300	19.0/86.0	1.5	992	25	4	D
	0600	19.5/85.5	1.5	992	25	4	D
	1200	19.9/85.3	1.5	992	25	4	D
	Crossed South Odisha coast close to south of Puri around 1500 UTC of 18.07.2017						
	1800	19.9/85.3	-	994	25	3	D
19/07/2017	0000	20.1/85.2	-	994	25	3	D
	0300	Weakened into a Well-marked low pressure area over interior Odisha and neighbourhood					

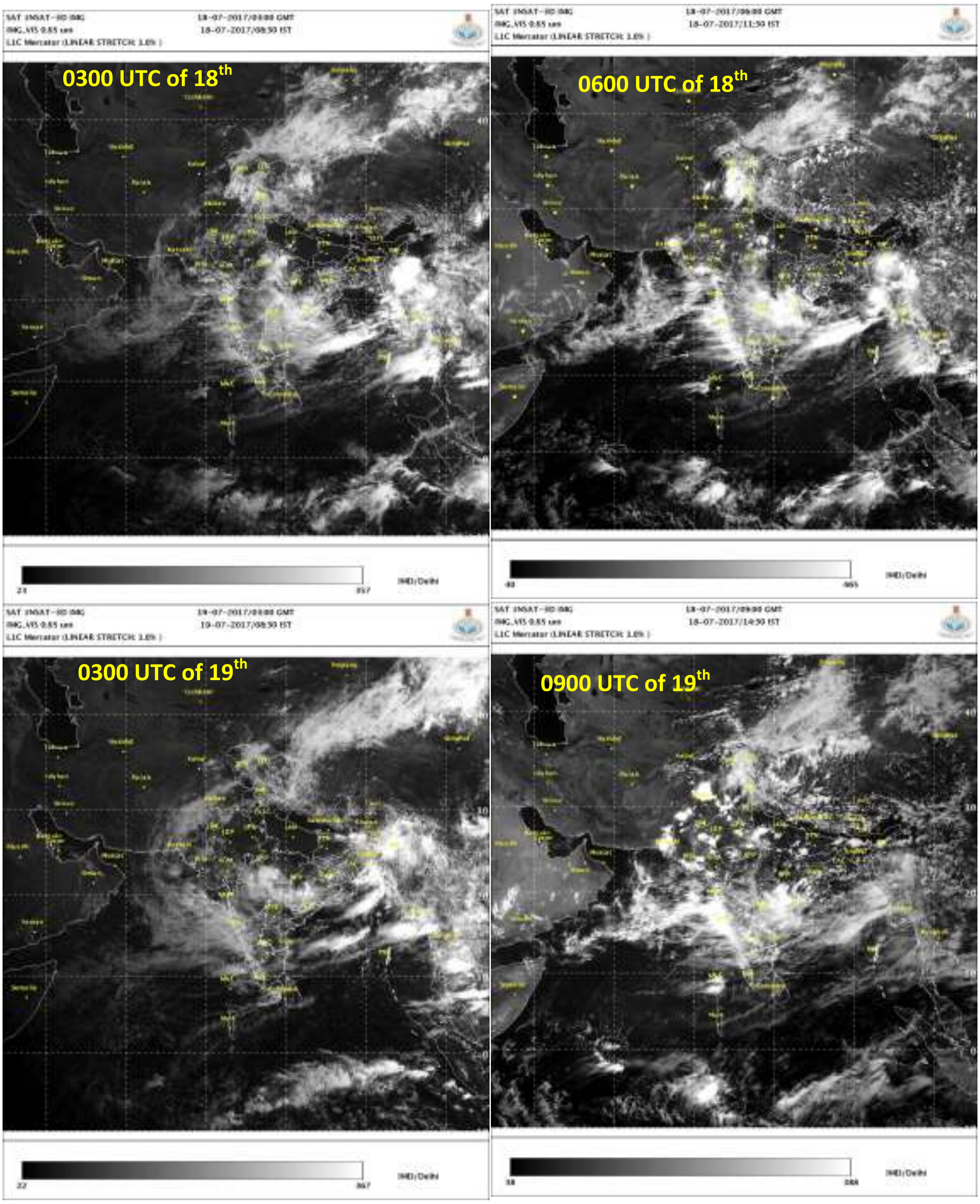


Fig. 2.4.2(i): INSAT-3D visible imageries during Depression (18-19 July, 2017)

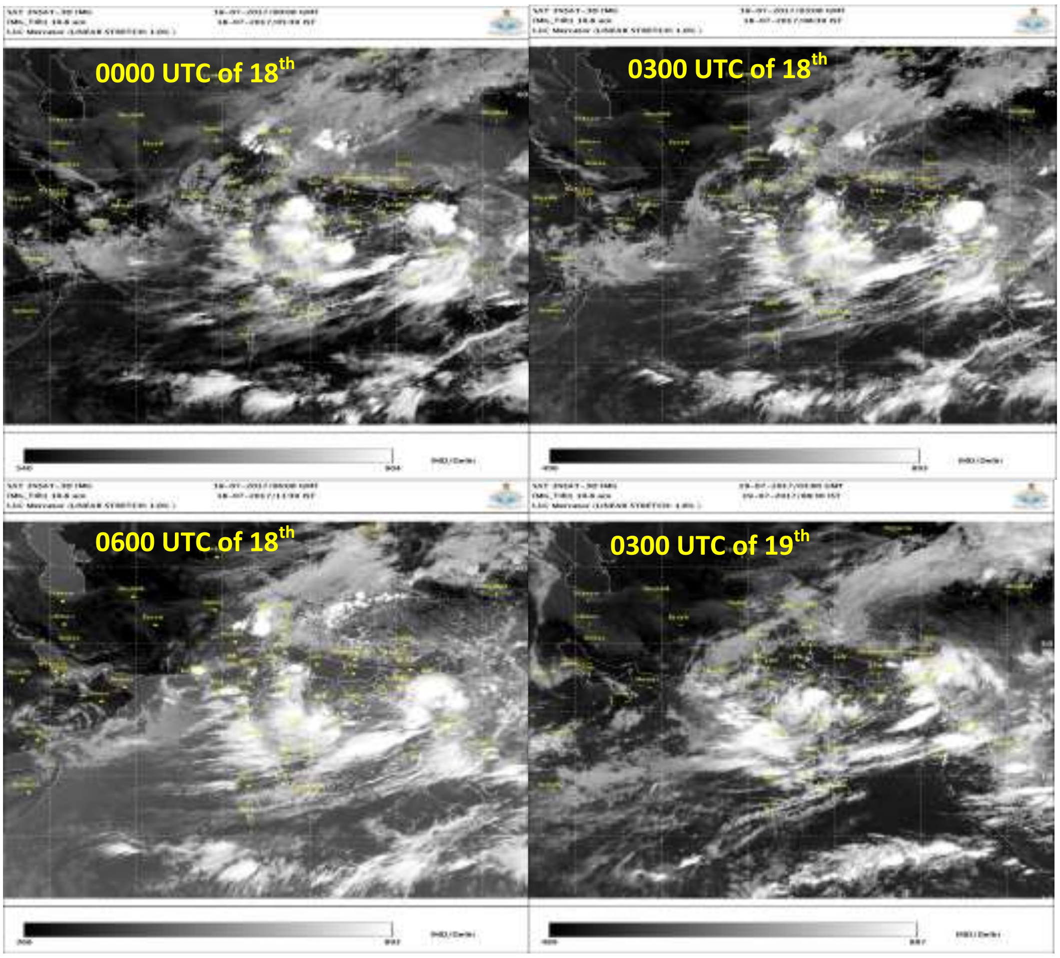


Fig. 2.4.2(ii): INSAT-3D IR imageries during Depression (18-19 July, 2017)

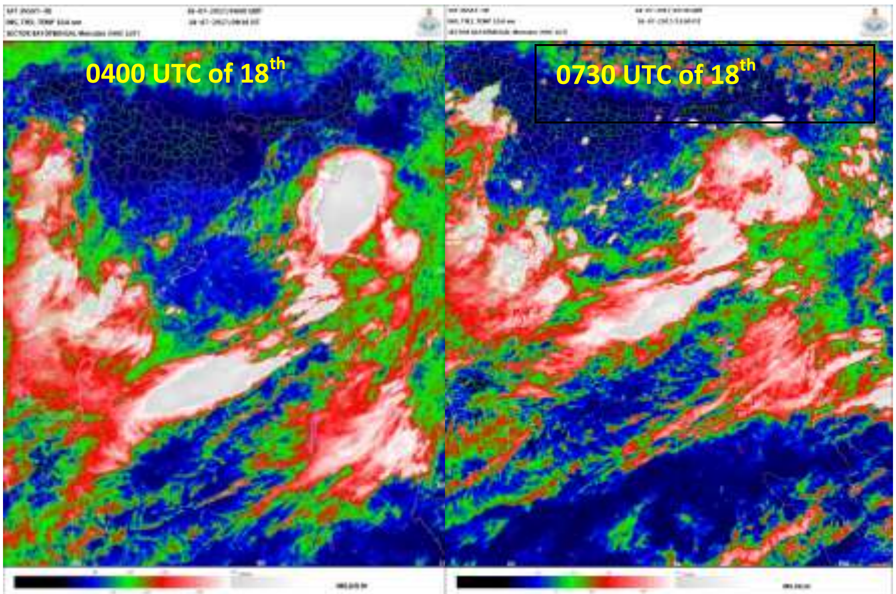


Fig. 2.4.2(iii): INSAT-3D enhanced coloured imageries during Depression (18-19 July, 2017)

2.4.3. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.4.3. GFS (T1534) could simulate the genesis of the system and the associated circulation features during the life period of Depression.

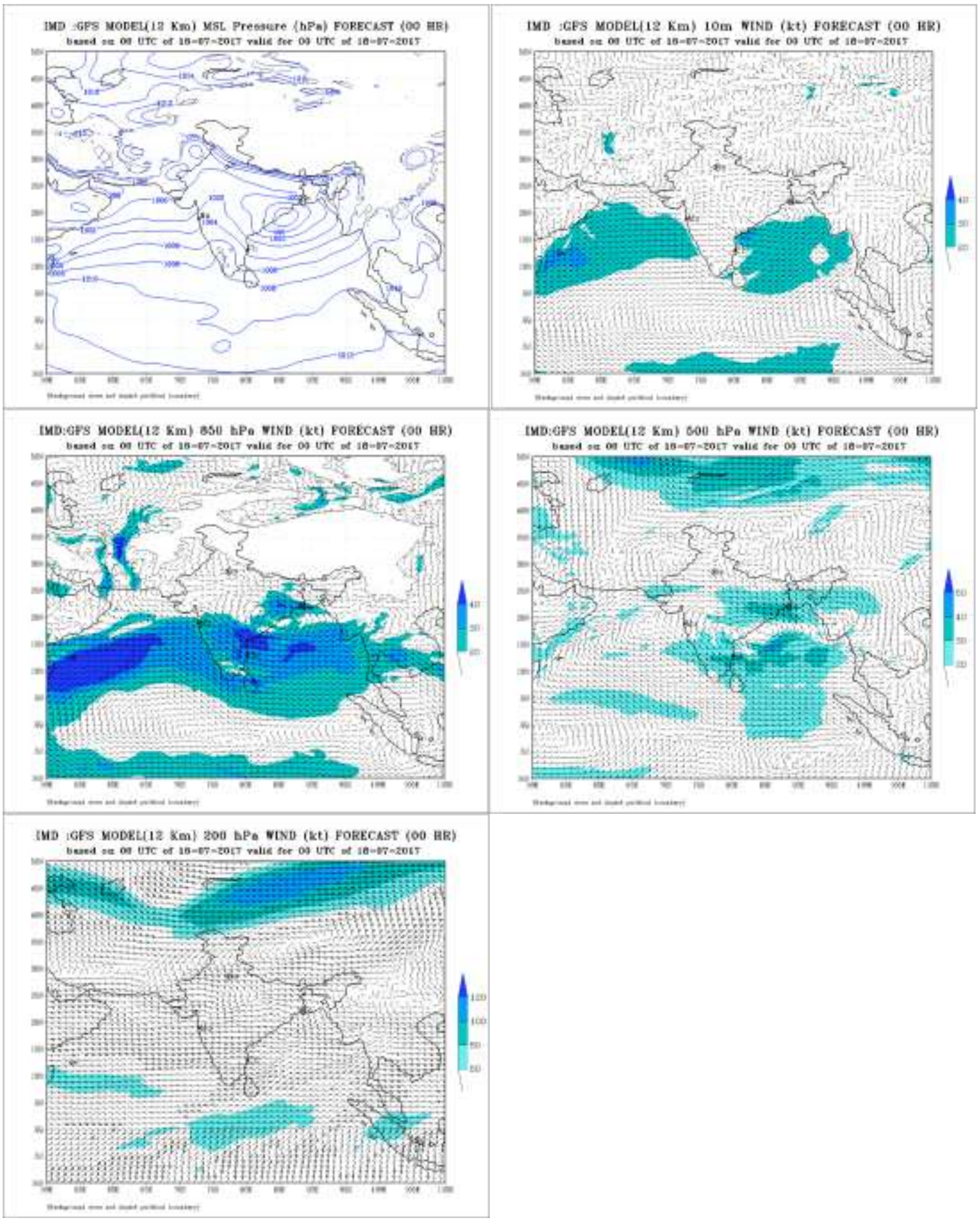


Fig. 2.4.3 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th July

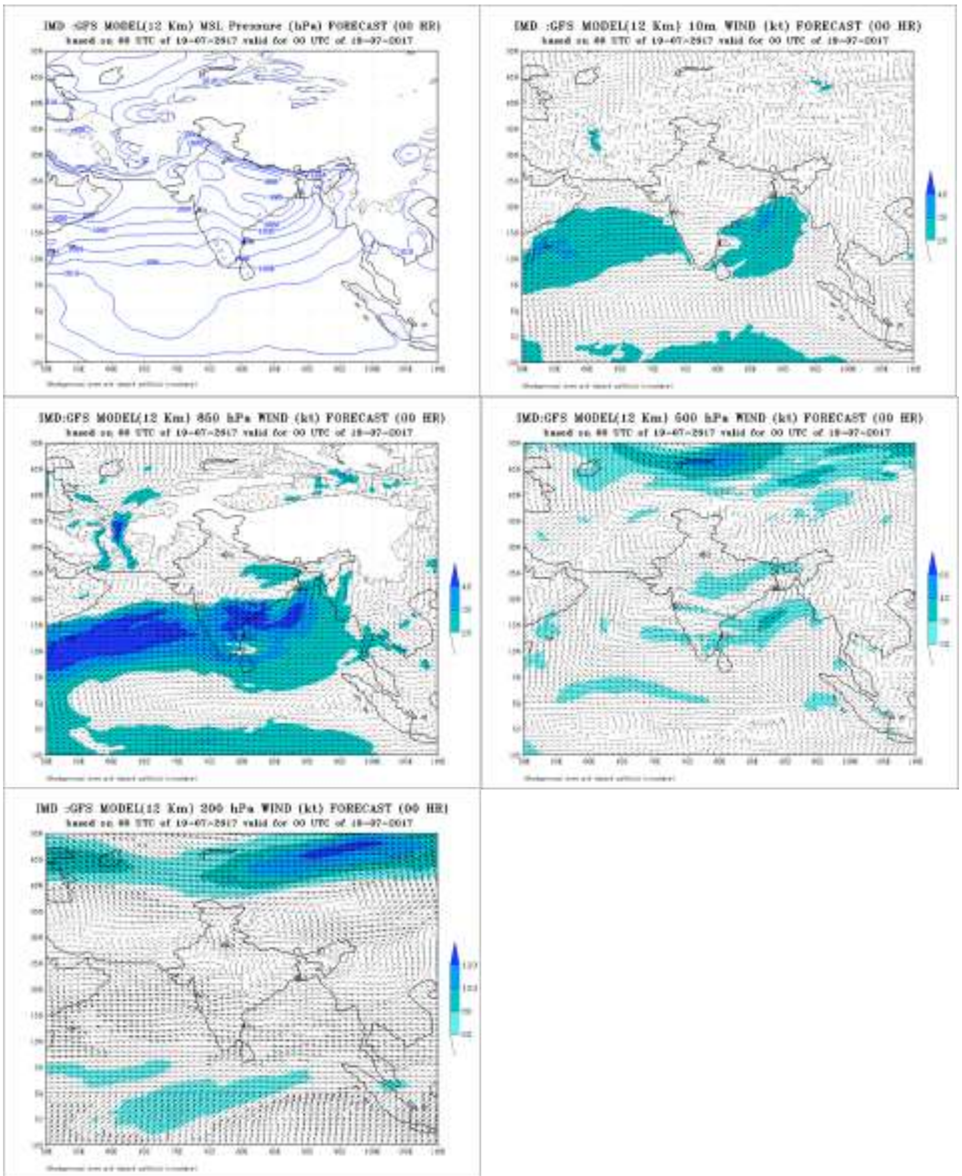


Fig. 2.4.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th July

2.4.4. Realized Weather:

2.4.4.1 Rainfall:

Under the influence of the Depression, rainfall at most places with heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall occurred over Chhattisgarh on 17th and Vidarbha on 18th July. Rainfall at most places with heavy to very heavy rainfall at isolated places occurred over Odisha, Vidarbha, coastal Andhra Pradesh, Telangana on 17th, over Odisha, West Madhya Pradesh, Chhattisgarh and coastal Andhra Pradesh on 18th, over Vidarbha & Chhattisgarh on 190th and over West Madhya Pradesh, East Madhya Pradesh and Chhattisgarh on 20th July. The realised rainfall as per the gridded rainfall data of IMD/NCMRWF based satellite estimation over sea area and point rainfall over land region during 18-20 July 2017 is shown in Fig.2.4.4.

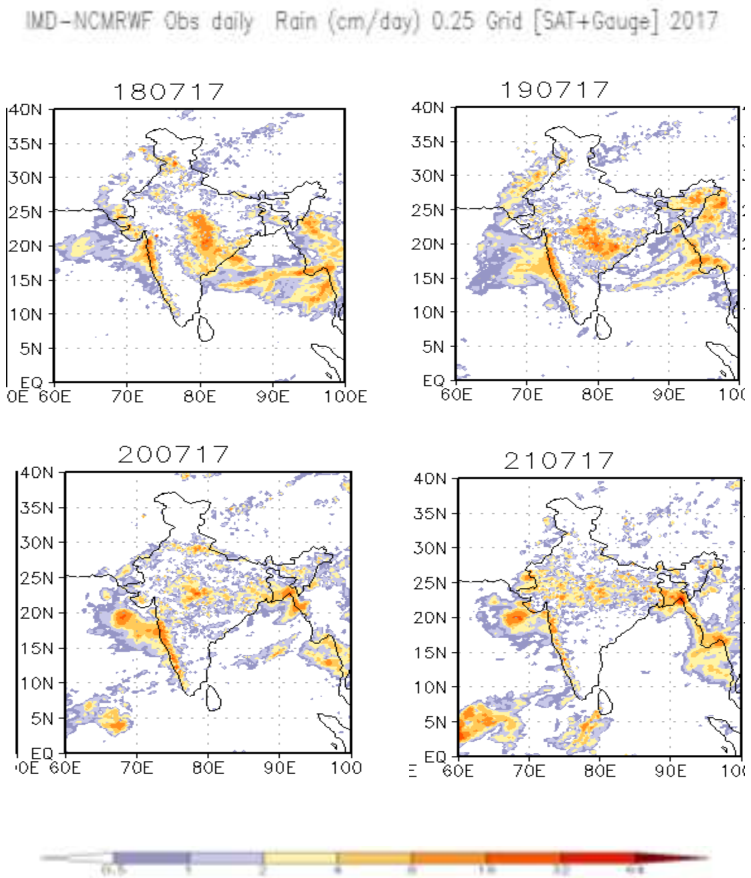


Fig. 2.4.4: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 18-21 July 2017.

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date during the life cycle of the system are presented below:

<u>18 July 2017</u>

Odisha: Kosagumda-17, Tentulikhunti ARG-14, Dabugan, Banki Arg-13 each, Jeypore-12, Koraput, Binjharpur, Mundali-11 each, Dharmagarh, Jhorigam, Similiguda, Jaipatna-9 each, Junagarh, Umarkote, Raighar, Kaptipada-8 each, Bhawanipatna, Bari, Hindol, Pottangi-7 each.

Chhattisgarh: Dondilohara-27, Kanker-16, Balod-14, Ambagarh Chowki, Jagdalpur-12 each, Dhamtari-10, Bhanupratappur-9, Kondagaon, Simga, Konta-8 each, Dongargarh, Gandai, Katghora, Deobhog, Gariabund-7 each,

Vidarbha: Nagpur Aerodrome-13, Kamptee-12, Amgaon, Korchi-11 each, Armori, Mauda-10 each, Salekasa-9, Kurkheda-8, Bhamragad, Pauni, Gondia-7 each.

Coastal Andhra Pradesh: Kalingapatnam, Gudivada-9 each, Chintur, Bondapalle, Paleru Bridge-8 each, Gajapathinagaram, Vijayawada A.P.-7 each.

Telangana: Madhira-9, Bonakal-8, Hayathnagar, Koida, Chinthakam-7 each.

19 July 2017

Odisha: Dabugan-20, Jhorigam-19, Chandahandi-16, Kosagumda, Jaipatna-15 each, Dharmagarh-14, Raighar, Tentulikhunti-13 each, Umarkote, Junagarh-11 each, Gudari, Mohana, Jeypore, Nawarangpur-10 each, Bhawanipatna, Kashipur-0 each, Koraput, Malkangiri-8 each, Narla, Nawana, Belpada, Odagaon-7 each.

West Madhya Pradesh: Pachmarhi-12, Khandwa-Aws-9, Bhainsdehi-7, East Madhya Pradesh: Chindwara-AWS, Seoni-AWS-7 each

Vidarbha: Bhamragad-34, Chamorshi-26, Bramhapuri-21, Sindewahi-19, Mul-17, Etapalli, Pauni, Pombhurna, Ahiri-13 each, Gadchiroli, Mulchera, Warora-12 each, Hinganghat-11, Bhadravati, Samudrapur, Saoli, Chandrapur-10 each, Gondpipri, Lakhandur, Armori, Ballarpur, Ramtek-9 each , Dhanora, Chandur Rlwy, Bhiwapur8, Nagbhir, Rajura-8 each, Wani, Warud, Deoli, Mauda, Arjuni Morgaon, Narkheda, Saoner, Wardha, Pandherikawara, Babulgaon-7 each

Chhattisgarh: Jagdalpur-19, Dantewara-14, Deobhog-13, Kanker, Dondilohara-9 each, Narayanpur-8, Kondagaon-7

Coastal Andhra Pradesh: Gudivada-9, Vijayawada A.P, Vararamachandrapur-7 each.

20 July 2017

Vidarbha: Risod-15, Gondia Ap-11, Ramtek-10, Mohadi-9, Chhattisgarh: Katghora-9, Korba, Janjgir7, Champa-7 each.

21 July 2017

West Madhya Pradesh: Khategaon-11, Nusrulgunj-Arg-10, Thandla, Bhopal-AWS-9 each, Petlawad, Ashta, Pichhore, Ichhawar-8 each, Sehore-AWS, Depalpur-7 each.

East Madhya Pradesh: Jabalpur-New--Aws-12, Lakhnadon-10, Dindori-AWS-8, Katni-AWS, Ghansore, Malanjkhand, Umaria-AWS-7 each, Chhattisgarh: Pathalgaon-8

2.5. Depression Northwest Jharkhand and neighbourhood (26-27 July 2017)

2.5.1. Introduction

In association with active monsoon condition, a low pressure area formed over Gangetic West Bengal and adjoining Jharkhand in the evening of 23rd July 2017. It concentrated into a depression over northwest Jharkhand & neighbourhood in the morning of 26th. It moved northwestwards and maintained the intensity of depression till early morning of 27th It then weakened into a well marked low pressure area over northeast Madhya Pradesh and neighbourhood in the morning of 27th July. The remnant low pressure area moved upto south Rajasthan and neighbourhood. As a result there was active monsoon condition across central part of the country and there was intense rainfall activity over this region.

2.5.2. Brief life history

In association with active monsoon condition, an upper air cyclonic circulation developed over south Bangladesh and Gangetic West Bengal and adjoining north Bay of Bengal in the morning of 22nd July. Under its influence, a low pressure area formed over Gangetic West Bengal and adjoining Jharkhand in the evening of 23rd. It lay as a well marked low pressure area over Gangetic West Bengal and adjoining Jharkhand in the morning of 24th. It intensified into a depression over Jharkhand & neighbourhood and lay centered at 0000 UTC of 26th July 2017 near Lat. 24.0ºN and Long.85.0ºE, close to Hazaribagh. It moved northwestwards initially till 1200 UTC of 26th July 2017 and then nearly westwards upto northeast Madhya Pradesh. Due to lack of moisture supply and high vertical wind shear, the depression did not intensify further. Rather, it weakened into a well marked low pressure area over northeast Madhya Pradesh at 0300 UTC of 27th July 2017. It continued to move westwards and weakened gradually.

The best track parameters are shown in Table 2.5.1. The track of the depression is shown in Fig. 2.1. The typical satellite imageries are shown in Fig. 2.5.1.

Table 2.5.1: Best track positions and other parameters of the Depression over the west central Bay of Bengal and coastal areas of Odisha & north Andhra Pradesh during 26-27 July, 2017

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
26/07/2017	0000	24.0ºN/85.0º E	-	993	25	3	D
	0300	24.2ºN/84.7º E	-	994	25	3	D
	0600	24.5ºN/84.5º E	-	994	25	3	D
	1200	25.0ºN/83.5º E	-	994	20	3	D

	1800	25.0ºN/82.5º E	-	995	20	3	D
27/07/2017	0000	25.0ºN/82.0º E	-	995	20	3	D
	0300	Depression weakened into a well marked low pressure area over northeast Madhya Pradesh & neighbourhood at 0300 UTC of 27th July					

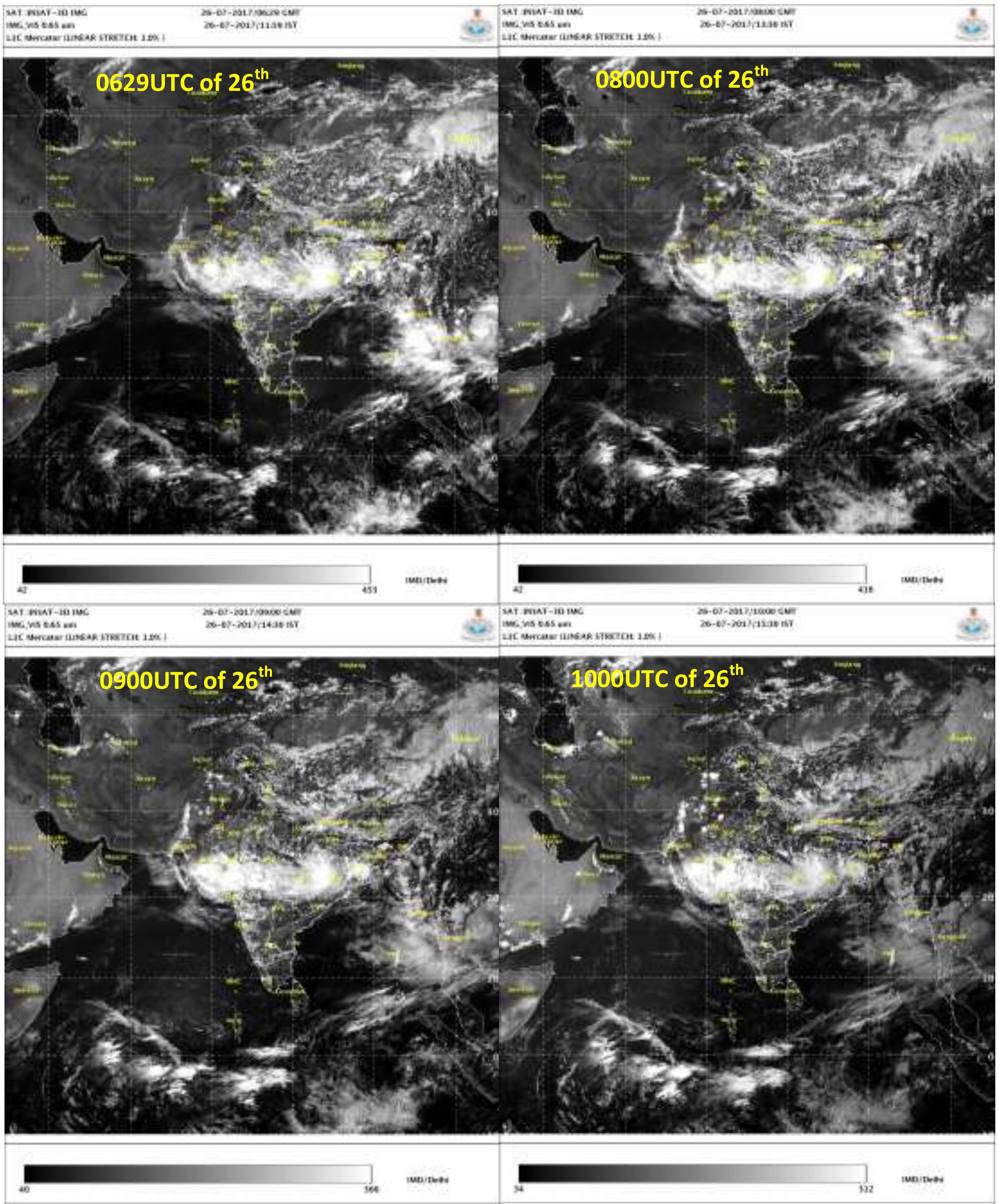


Fig. 2.5.1(i): INSAT-3D visible imageries during Depression (26-27 July, 2017)

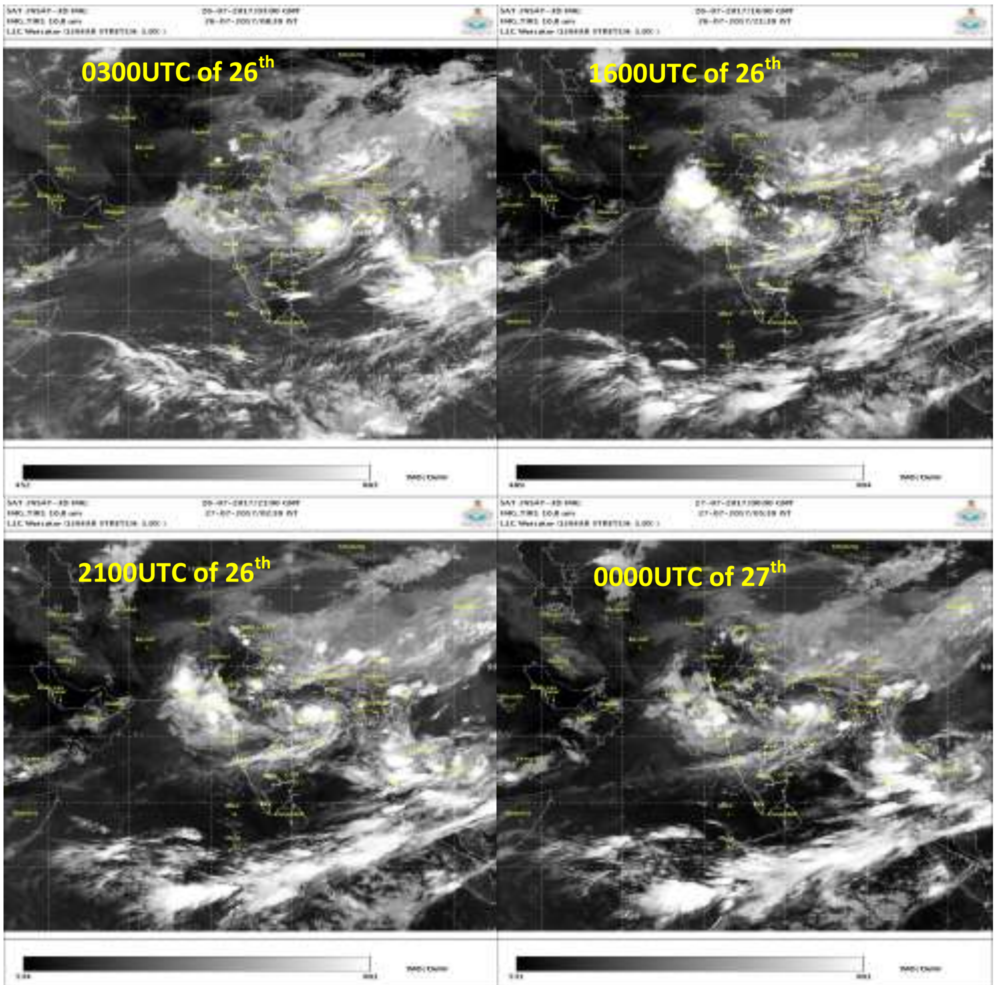


Fig. 2.5.1(ii): INSAT-3D IR imageries during Depression (26-27 July, 2017)

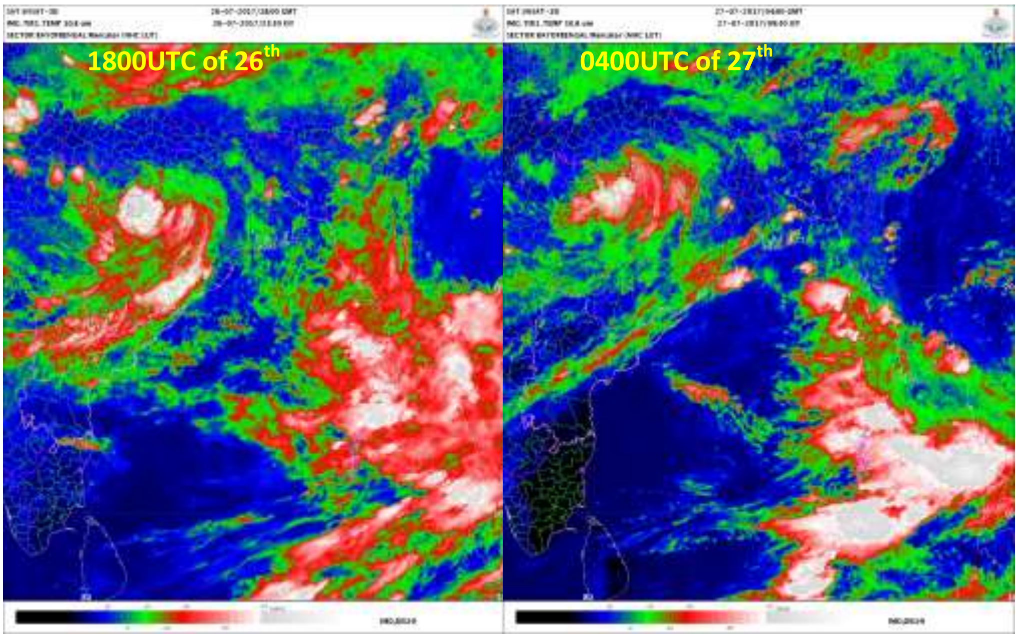


Fig. 2.5.1(iii): INSAT-3D enhanced coloured imageries during Depression (26-27 July, 2017)

2.5.3. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.5.2. GFS (T1534) could simulate the genesis of the system and the associated circulation features during the life period of Depression.

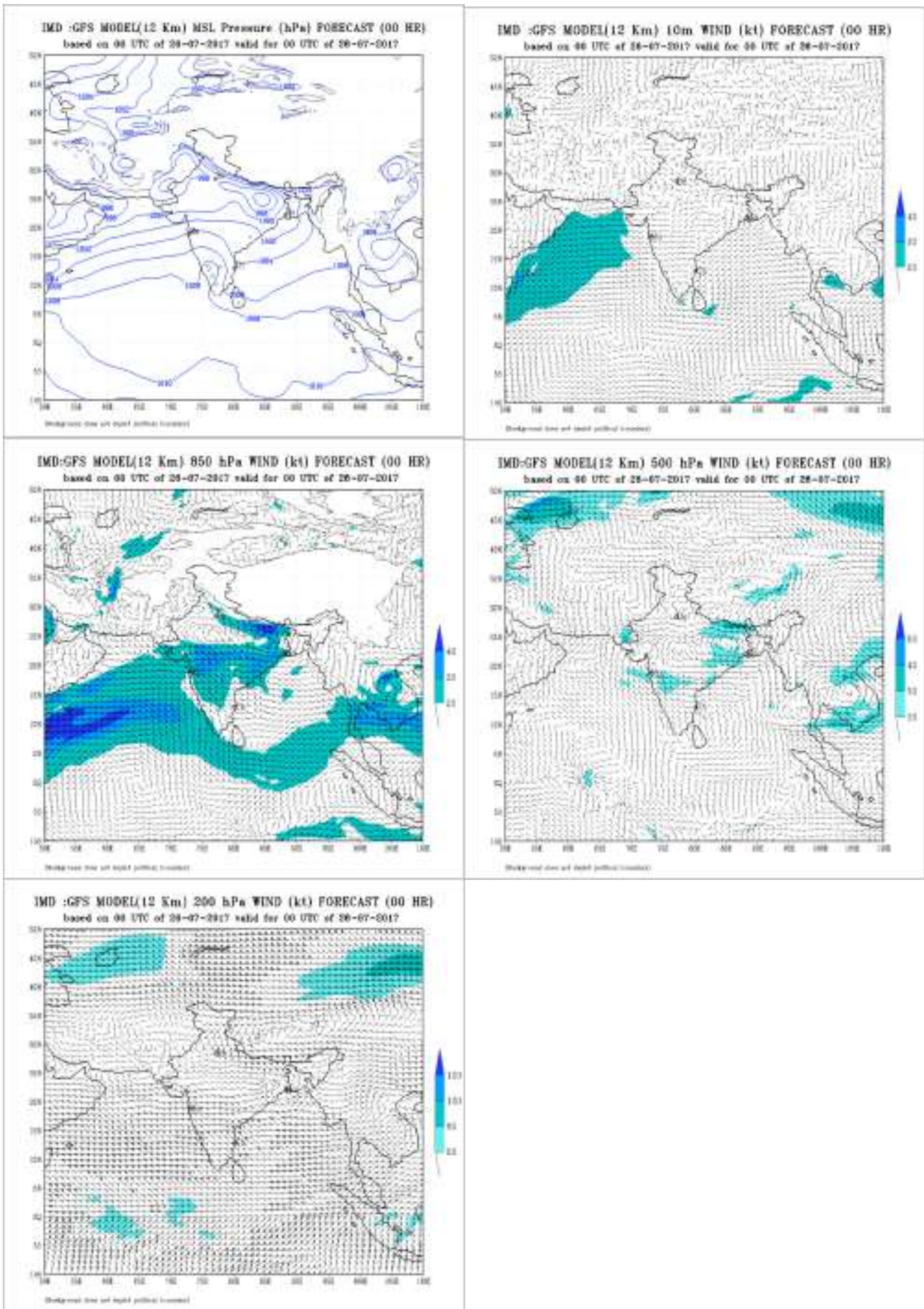


Fig. 2.5.2 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th July

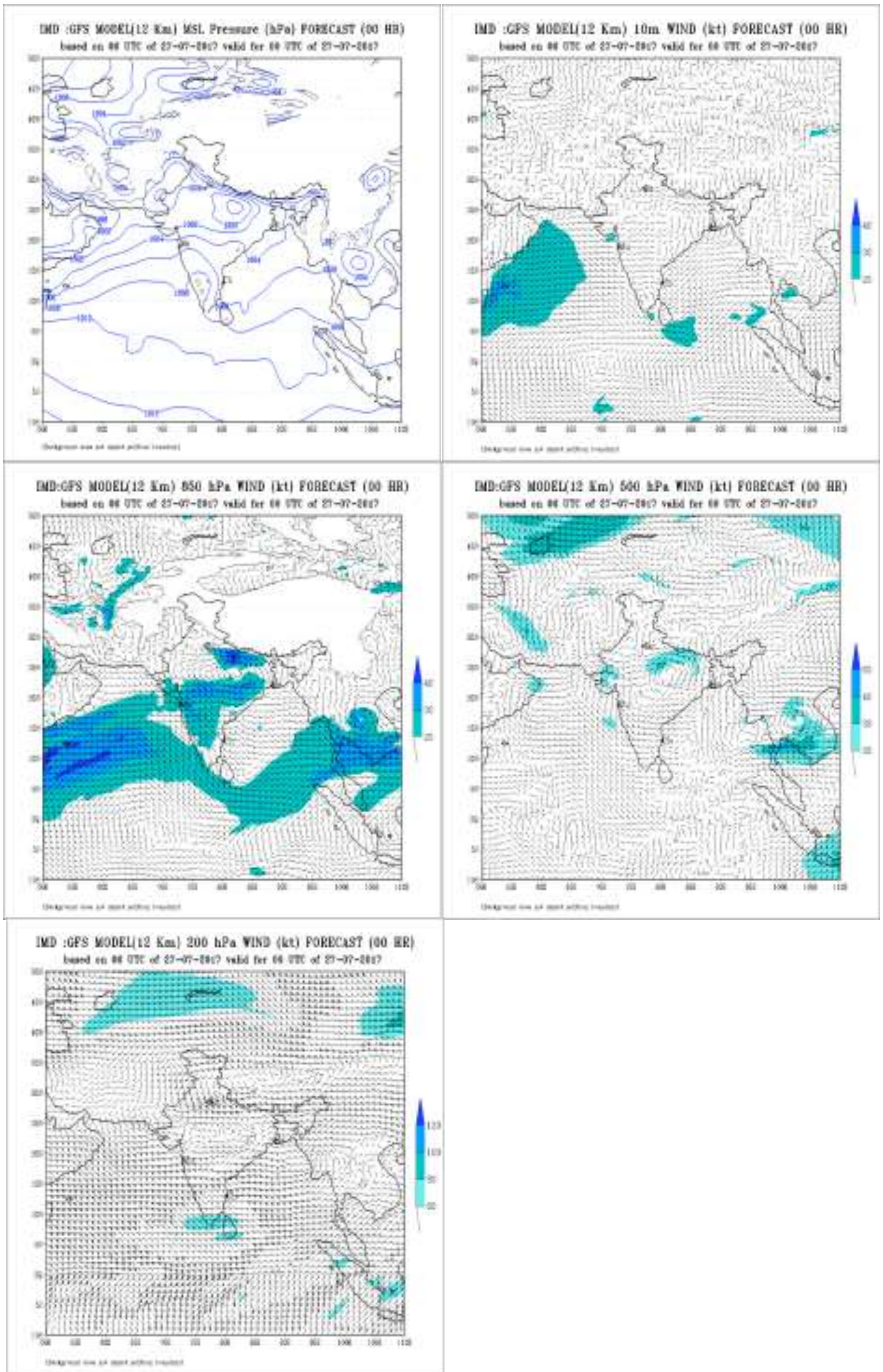


Fig. 2.5.2 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 27th July

2.5.4. Realized Weather:

2.5.4.1 Rainfall:

Realised weather:

Under the influence of this depression, rainfall at most places with heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall occurred over Jharkhand on 25th and over west Madhya Pradesh on 27th. Rainfall at most paces with isolated heavy to very heavy rainfall occurred over Chhattisgarh and east Uttar Pradesh on 25th, Chhattisgarh, east and west Uttar Pradesh, east and west Madhya Pradesh on 26th, and over west Uttar Pradesh, east and west Madhya Pradesh on 27th. The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig. 2.5.3.

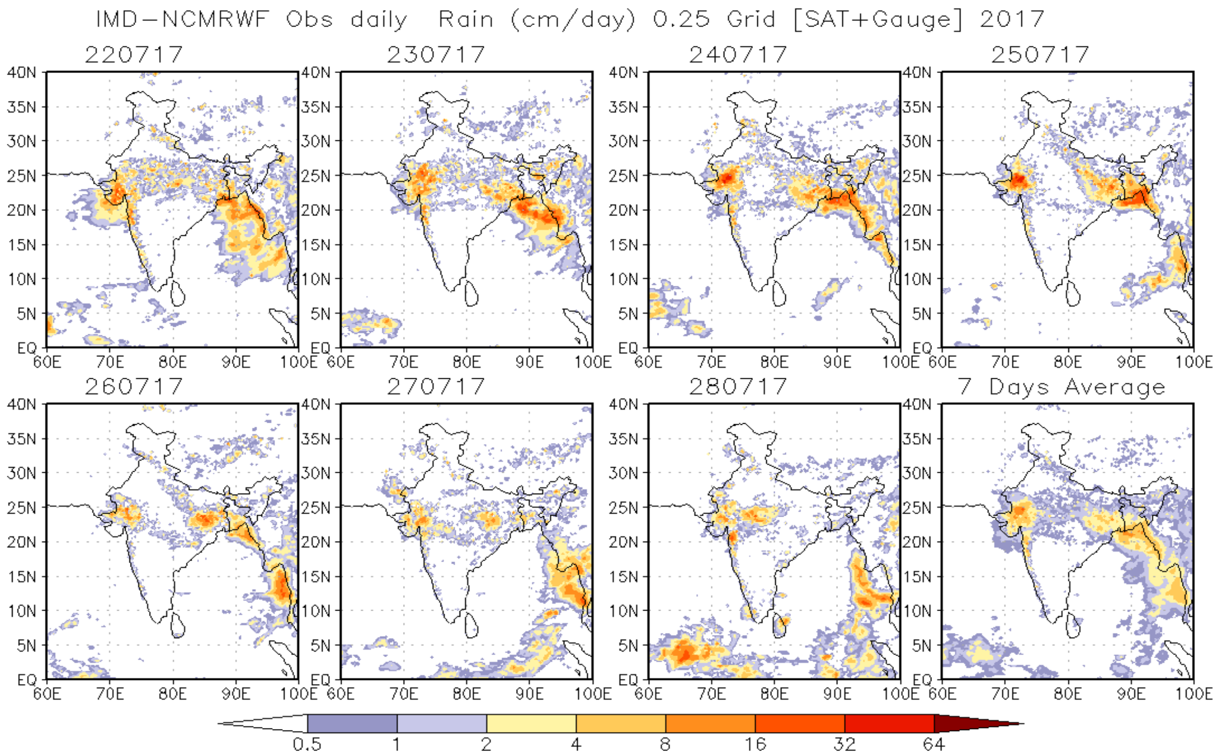


Fig. 2.5.3: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 22-28 July 2017.

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date during the life cycle of the system are presented below:

<u>26th July:</u>

Jharkhand: Latehar-27, Mandar-25, Hindgir, Ranchi-21 each, Kuru-19, Lohardaga-17, Gomia, Maheshpur-14 each, Ramgarh, Daltonganj-13 each, Jamshedpur-12, Pupunki, Dhanbad, Koner-10 each, Putki-9, Panchet, Tenughat, Maithon, Topchanchi, Jaridih, Palkot-8 each, Raidih, Nandadih, Giridih, Dumri, Bokaro, Torpa, Barhi, Barkisuraiya, Gumla-7 each,

Chhattisgarh: Ramanujganj-9

East Uttar Pradesh: Ghorawal-9

27th July

Jharkhand: Daltonganj-10, Lohardaga, Kurdeg, Ramgarh-9 each

Chhattisgarh: Ambikapur-13, Pathalgaon-11, Surajpur, Jashpurnagar-9 each

East Uttar Pradesh: Dudhi-10

West Uttar Pradesh: Deoband-7

West Madhya Pradesh: Khandwa-AWS-9

East Madhya Pradesh: Singrauli-AWS-8,

28th July

West Uttar Pradesh: Lalitpur-9

East Madhya Pradesh: Panna-AWS-8, Tendukheda-7.

West Madhya Pradesh: Narsingarh-23, Raisen-AWS-21, Bareli & Agar-12 each, Suvasara-11, Guna-AWS-10, Khilchipur & Ashoknagar-AWS- 9 each, Biaora, Chanderi & Isagarh-8 each, Manasa, Vidisha-AWS, Sarangpur & Udaipura-7 each

29th July:

West Madhya Pradesh: Agar & Neemuch-AWS-11 each, Jawad-10, Mandsaur-AWS-9, Bhanpura-7.

East Rajasthan: Pratapgarh-24, Rashmi SR-16, Nimbahera & Bakani SR-15 each, Chhotisadri, Dug, Kapasan SR, Chittorgarh, Pachpahar SR, Asnawar SR-13 each, Jhalarapatan SR, Pindwara, Mangliawas SR-12 each, Dungla SR, Badesar SR, Kotda SR, Bari-Sadri, Chambal/R.B.Dam-11 each, Banera SR, Mount Abu, Mounntabu Tehsil, Khanpur, Arnod SR-10, Bhainsroadgarh, Bhopalsagar SR, Begu Sr, Nasirabad & Sheoganj-9 each, Gangdhar SR & Ramganjmandi SR-8 each, Sirohi, Mandal SR, Nayanagar/Beawar, Aklera, Gangrar, Salumber & Bhilwara Tehsil SR-7 each.

2.6. Deep Depression over Gangetic West Bengal and adjoining north Bay of Bengal (09-10 October 2017)

2.6.1. Introduction

A **low pressure area** formed over North Bay of Bengal (BoB) and adjoining south Bangladesh on 8th October 2017 morning. It lay as a well marked low pressure area (WML) over north BoB and adjoining coastal areas of Bangladesh & West Bengal in the same evening. It concentrated into a depression in the early morning of 9th October over Gangetic West Bengal (GWB) and adjoining north BoB. Moving northwestwards, it intensified into a deep depression (DD) over GWB in the morning of 9th. It moved nearly north-northwestwards and weakened into a depression around noon of 10th October and into a well marked low pressure area over northeast Jharkhand and adjoining West Bengal in the evening of the same day. It became less marked on 11th. The observed track of the system is presented in Fig. 2.1.

The salient features of the system were as follows:

(i) The total life period of the system was 33 hours against the average life period of deep depression of 90 hours in post monsoon season over the BoB.

(ii) The system caused heavy to very heavy rainfall at isolated places over GWB and heavy rainfall at isolated places over Bihar on 10th October and heavy rainfall at isolated places over GWB, Jharkhand & Bihar on 11th October 2017.

IMD mobilised all its resources to track the system and regular warnings w.r.t. track, intensity, landfall and associated adverse weather were issued to concerned central and state disaster management agencies, print & electronic media and general public. Regular advisories were also issued to WMO/ESCAP Panel member countries including Bangladesh.

The brief life history, associated weather and forecast performance of IMD/RSMC, New Delhi are presented below.

2.6.2. Brief life history

2.6.2.1. Genesis, Intensification and Movement

Under the influence of a cyclonic circulation over North BoB & neighbourhood extending upto 4.5 km above mean sea level, a low pressure area formed over north BoB and adjoining south Bangladesh at 0300 UTC of 8th October. It lay as a well marked low pressure area (WML) over northwest BoB and adjoining coastal areas of Bangladesh & West Bengal at 1200 UTC of same day. It concentrated into a depression at 0000 UTC of 9th October over Gangetic West Bengal and adjoining north BoB with centre near latitude 22.4º N and longitude 88.4 ºE.

Considering the environmental conditions, at 0000 UTC of 9th October, the vertical wind shear was low (about 10 knots) around the system centre. The low level relative vorticity was about 100 x 10^{-6} s^{-1}. The lower level convergence was about 20 x 10^{-5} s^{-1}. The upper level divergence was about 30 x 10^{-5} s^{-1}. All these conditions favoured the development of depression over Gangetic West Bengal and adjoining north BoB in the early hours of 9th October. The Madden Julian Oscillation Index lay over phase 4 with amplitude 1. All these conditions helped in maintaining the intensity of the system and associated convection.

At 0000 UTC of 9th October, the upper tropospheric ridge at 200 hPa level ran along 22^0N and along 24^0N in the middle level. An anticyclonic circulation lay over central India in the middle & upper tropospheric levels. In addition, a trough in mid-latitude westerlies run along longitude 72˚ E to the north of latitude 32˚ N. These conditions caused the system to move west-northwestwards slowly and restricted it’s movement towards west.

At 0300 UTC of 10^{th}, the vertical wind shear was moderate (about 10-20 knots) around the system centre. The low level relative vorticity was about 100 x 10^{-6} s^{-1}. The lower level convergence decreased and was about 5 x 10^{-5} s^{-1} to the southeast of the system centre. The upper level divergence also decreased and was about 10 x 10^{-5} s^{-1} around the system centre. The upper tropospheric ridge at 200 hpa level ran along 23^0N. All these conditions led to weakening of system into a depression and lay centred over Gangetic West Bengal and adjoining Jharkhand near latitude 23.8º N and longitude 86.6 ºE, at 0600 UTC of 10th Oct. 2017. Under these conditions the system weakened further and into a well marked low pressure area over northeast Jharkhand and adjoining West Bengal at 1200 UTC of same day. It became less marked on 11^{th}. The best track parameters are shown in Table 2.6.1. The typical satellite imageries are shown in Fig. 2.6.1.

Table 2.6.1: Best track positions and other parameters of the Deep depression over Gangetic West Bengal and adjoining north Bay of Bengal (09-10 October, 2017)

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
09/10/2107	0000	22.4/88.4	1.5	996	25	4	D
	0300	22.5/88.4	-	996	30	5	DD
	0600	22.6/88.3	-	996	30	5	DD
	1200	22.9/88.1	-	997	30	5	DD
	1800	23.1/87.8	-	997	30	5	DD
10/10/2017	0000	23.2/87.1	-	998	30	5	DD
	0300	23.5/86.7	-	1000	30	5	DD
	0600	23.8/86.6	-	1000	25	3	D
	1200	Depression weakened into a low pressure area over the Jharkhand & adjoining West Bengal at 1200 UTC of 10^{th} October					

2.6.3. Features observed through satellite and Radar

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries from SCATSAT and international geostationary and polar orbiting satellites were also considered for monitoring the system.

2.6.3.1 INSAT-3D features

Typical INSAT-3D visible, IR and enhanced colored imageries are presented in Fig. 2.6.2. At 0000 UTC of 9^{th} October, the intensity of the system was C.I. 1.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over south Bangladesh, Gangetic West Bengal and north BoB. At 0300 UTC of 9^{th}, associated broken low and medium clouds with embedded intense to very intense convection lay over southeast Gangetic West Bengal. At 0300 UTC of 10^{th}, associated broken low and medium clouds with embedded moderate to intense convection lay over east Jharkhand and Gangetic West Bengal. Scattered low and medium clouds with embedded weak to moderate convection lay over south Chattisgarh, Odisha, east Bihar, sub Himalayan West Bengal and adjoining Assam, Sikkim and Bhutan.

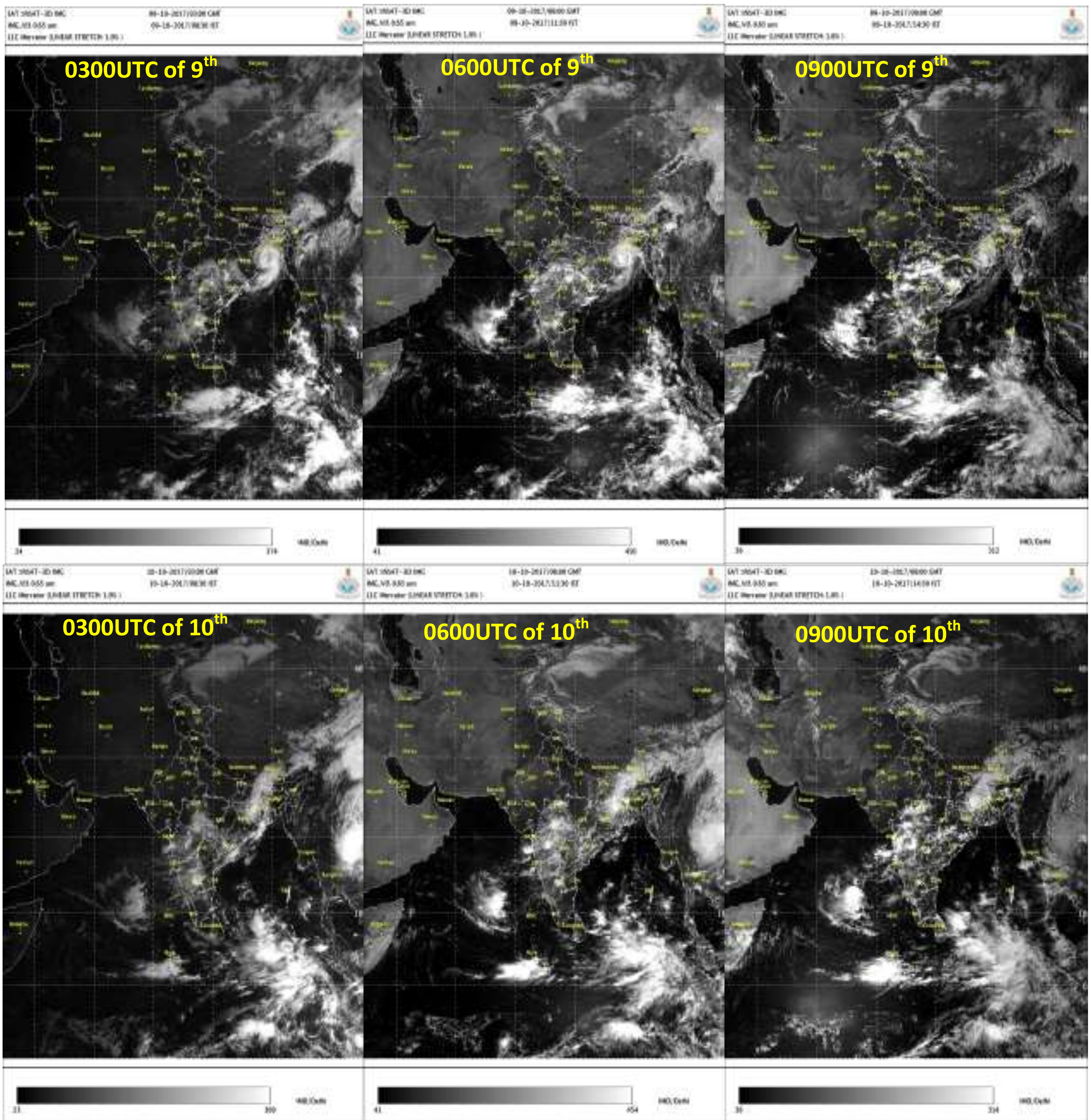


Fig. 2.6.1(i): INSAT-3D visible imageries of Depression (09-10 October, 2017)

Satellite imageries indicated that at the time of genesis, there was warm and moist air advection from the sea reaching upto northeast sector of depression. The convection was well organised with distinct spiral banding till 0000 UTC of 10th. The structure started disorganising from 0300 UTC onwards, with shearing of convection far away from the system centre over south Chattisgarh, Odisha, east Bihar, sub Himalayan West Bengal and adjoining Assam, Sikkim and Bhutan. Gradually, the depression weakened into a well marked low pressure area at 1200 UTC of 10th October.

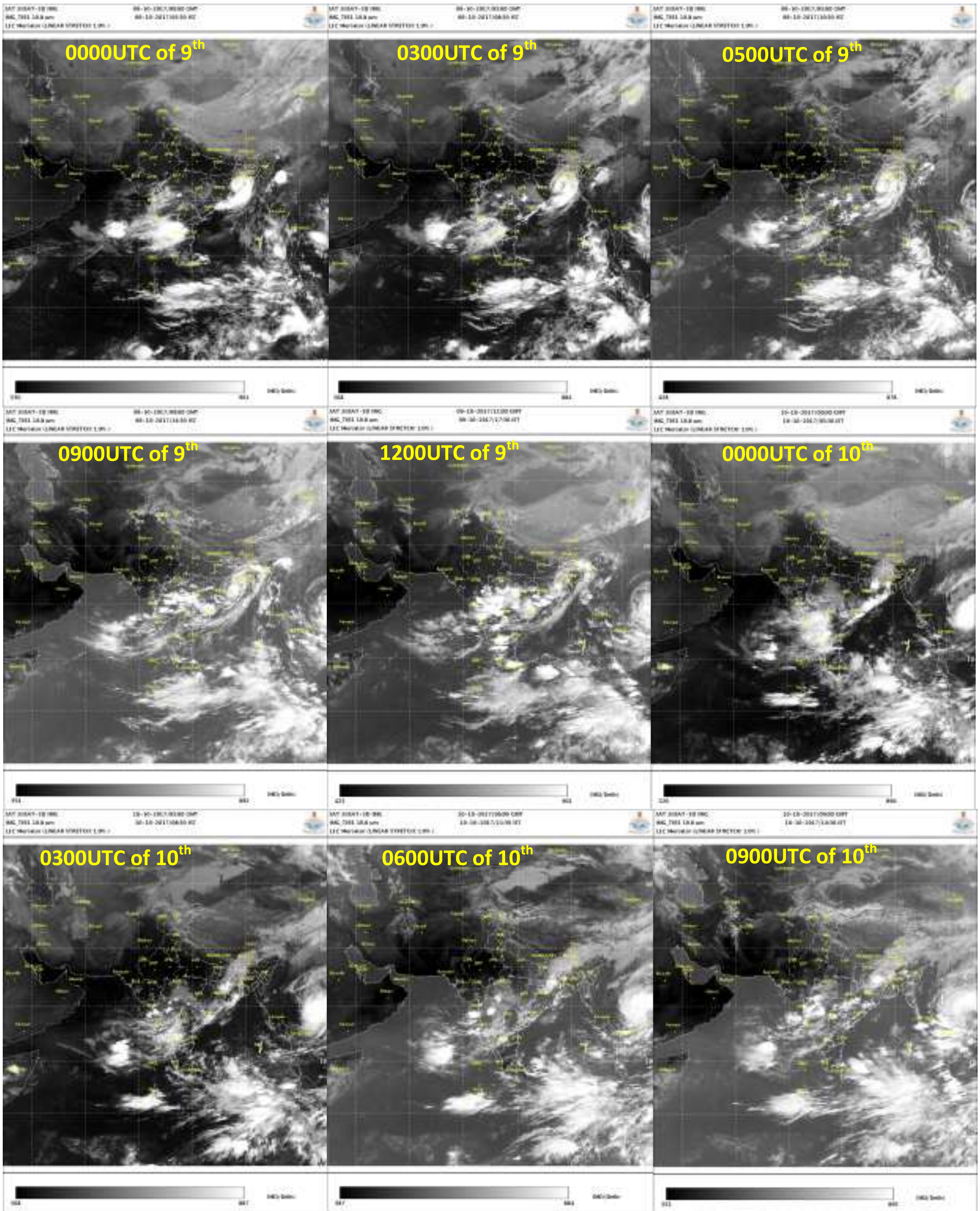


Fig. 2.6.1(ii): INSAT-3D IR imageries of Depression (09-10 October, 2017)

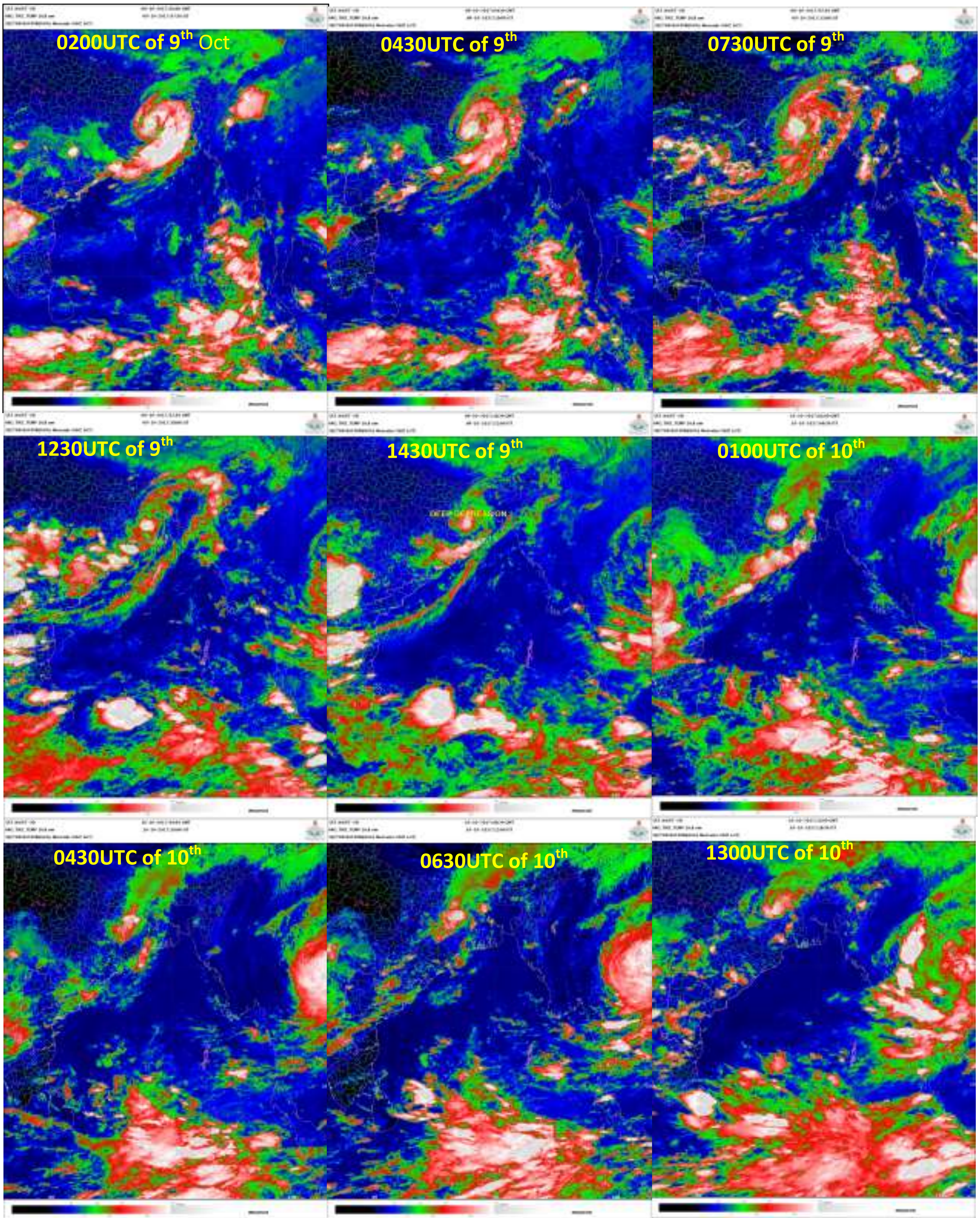


Fig. 2.6.1(iii): INSAT-3D enhanced coloured imageries of Depression (09-10 October, 2017)

2.6.4. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.6.2. IMD GFS (T1534) could not simulate the genesis and intensification of the system. However, it picked up the associated cyclonic circulation extending upto mid- tropospheric level. It also predicted presence of anticyclone over central India in middle and upper tropospheric levels and trough in mid-latitude westerlies based on initial conditions of 0000 UTC of 9th October 2017.

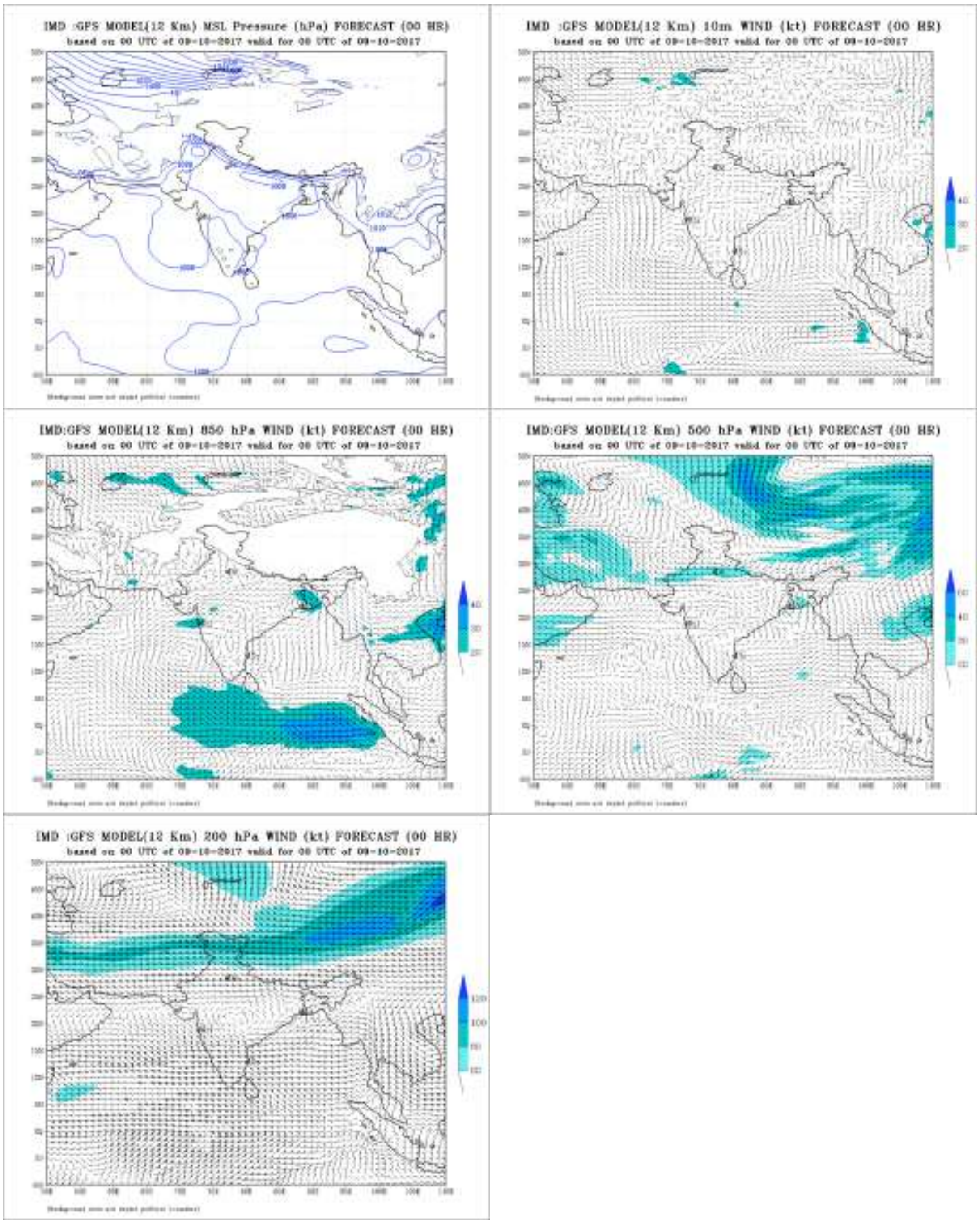


Fig. 2.6.2 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 09th October 2017

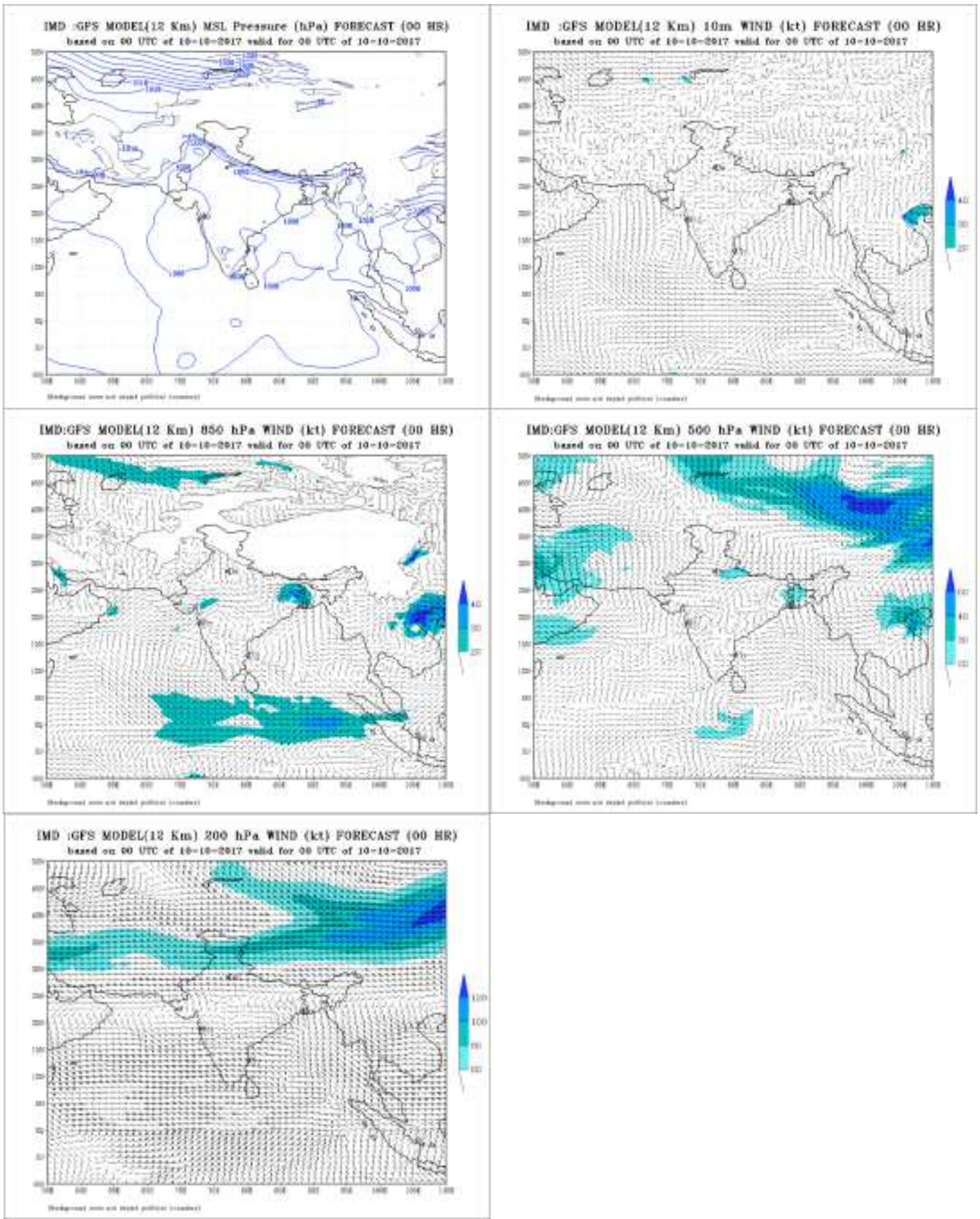


Fig. 2.6.2 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th October 2017

2.6.5. Realized Weather:

2.6.5.1 Rainfall:

The system caused heavy to very heavy rainfall at isolated places over Gangetic West Bengal and heavy rainfall at isolated places over Bihar on 10th October and heavy rainfall at isolated places over Gangetic West Bengal, Jharkhand and Bihar on 11th October 2017. The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig. 2.6.3. It depicts that the system caused heavy to very heavy rainfall over north BoB and adjoining Gangetic West Bengal on 7th and 8th. On 9th, it caused heavy to very heavy rainfall at isolated places over Gangetic West Bengal. On 10th, it caused heavy to very heavy falls at isolated places over Gangetic West Bengal and Bihar.

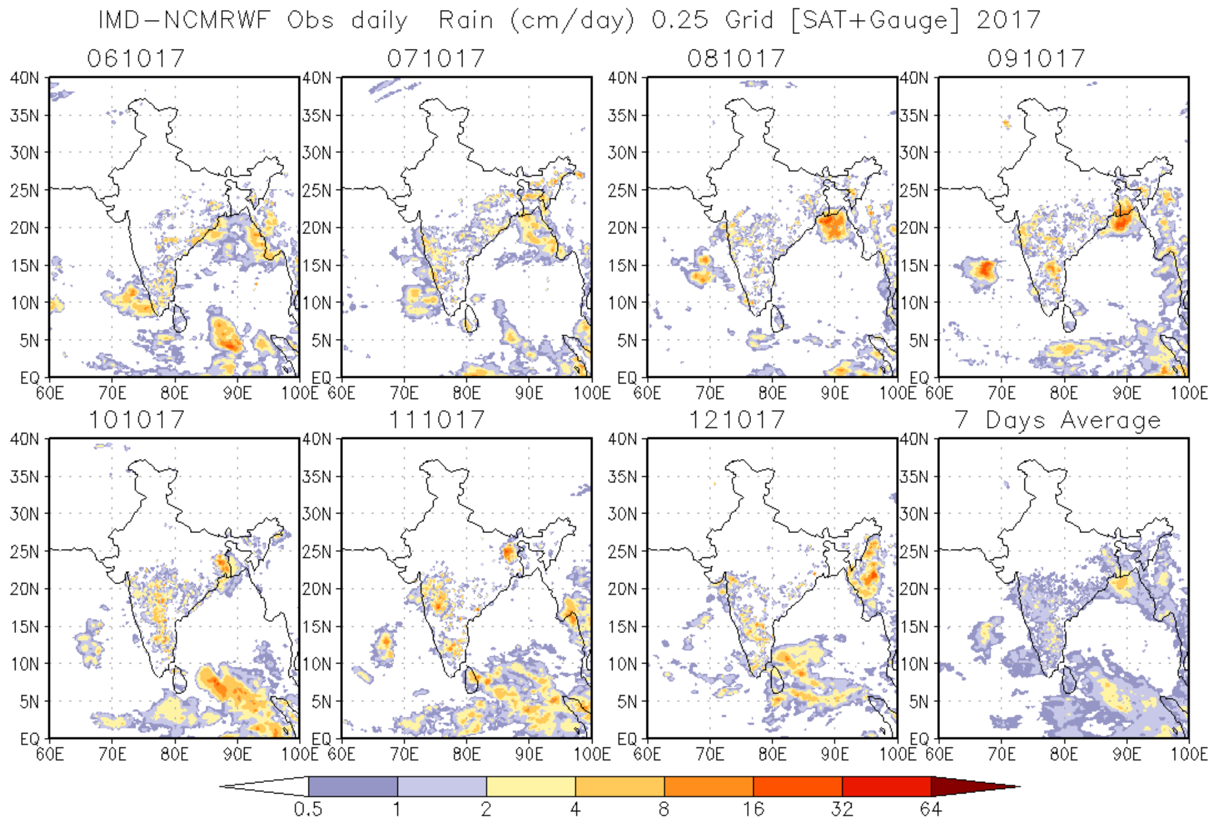


Fig. 2.6.3: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 09-10 October 2017 ending at 0300 UTC of day.

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date during the life cycle of the system are presented below:

9TH OCTOBER:

GANGETIC WEST BENGAL: Canning-14, Baruipur & Manmothnagar-12 each, Diamond Harbour-7

Odisha: Talcher-9.

10 OCTOBER 2017:

GANGETIC WEST BENGAL: Durgapur-19, Burdawan (STATE)-17, Panagarh & Asansol-16 each, Asansol-15, Gheropara-14, Bolpur & Burdwan-13 each, Sri Niketan-12, Narayanpur & Kanksa-11 each, Barrackpur-10, Uluberia-9, Bagati, Chinsura Mangalkote & Bongaon-8 each, Hetampur, Uluberia, Dum Dum, Alipore, Amta & Bankura-7 each

ODISHA: Niali-7

JHARKHAND: Dumka-11, Maithon-11, Gobindpur-8, Mohanpur-7

CHHATTISGARH: Sukma-8, Rajim-7

11 OCTOBER 2017:

GANGETIC WEST BENGAL: Asansol-9, Narayanpur-7

ODISHA: Bhograi-7,

JHARKHAND: Jamtara-14, Giridih-10, Pathargama & Moharo- 9 each, Madhupur & Dumka-8 each,

BIHAR: Jamui-19, Sono-18, Suryagadha-17, Bhagalpur-15, Jhajha-14, Parbatta-13, LakhisaraI, Banka & Bihpur-11 each, Monghyr & Sabour-10 each, Cheria B.Puri & Katoria-8 each, Gogri-7

2.7. Depression over westcentral Bay of Bengal (19-22 October 2017)

2.7.1. Introduction

A low pressure area (LPA) formed over central Bay of Bengal (BoB) in the morning of 15th October. It lay as a well marked low pressure area (WML) over central and adjoining south BoB in the morning of 17th. It further concentrated into a depression in the early hours of 19th over westcentral BoB. Moving nearly northwards, it crossed Odisha coast close to Paradip in the late evening of 19th. The system started recurving and moved nearly eastwards for sometime from the night of 20th. It then moved northeastwards across Gangetic West Bengal and Bangladesh. It weakened into a well marked low pressure area over northeast Bangladesh and adjoining Meghalaya & South Assam in the early morning of 22nd October. The observed track of the system is presented in Fig. 2.1.

The salient features of the system were as follows:

(iii) The system had a clockwise recurving track after landfall. It moved nearly northward before landfall

(iv) The total life period of the system was 96 hours (4 days) against the average life period of depression of 65 hours (2 and 1/2 days) in post monsoon season over the BoB.

(v) The system caused heavy to very heavy rainfall over Odisha, Gangetic West Bengal, Assam, Meghalaya, Nagaland, Manipur & Mizoram during 19th to 21st October.

IMD mobilised all its resources to track the system and regular warnings w.r.t. track, intensity, landfall and associated adverse weather were issued to concerned central and state disaster management agencies, print & electronic media and general public. Regular advisories were also issued to WMO/ESCAP Panel member countries including Bangladesh.

The brief life history, associated weather and forecast performance of IMD/RSMC, New Delhi are presented below.

2.7.2. Brief life history

2.7.2.1. Genesis

Under the influence of an upper air cyclonic circulation over southwest BoB & neighbourhood and the east-west shear zone along latitude 12.0°N, a low pressure area (LPA) formed over central BoB in the morning of 15th October. The associated cyclonic circulation extended upto 5.8 km above mean sea level tilting southwestwards with height. It lay as a well marked low pressure area (WML) over central and adjoining south BoB in the morning of 17th with associated cyclonic circulation extending upto 5.8 km above mean sea level. It concentrated into a depression and lay centered over westcentral BoB at 0000 UTC of 19th near latitude 16.5º N and longitude 86.5 ºE, about 470 km south of Chandbali and 370 km south-southeast of Puri.

Considering the environmental conditions, at 0000 UTC of 19th, the sea surface temperature over the region was 30-32^{0}C. The ocean thermal energy was about 80-100 KJ/cm^2 over the area with increasing magnitude (more than 100 KJ/cm^2) near north Andhra Pradesh-south Odisha coast. The vertical wind shear between upper and lower levels was moderate (15-25 knots) around the system centre. It was decreasing towards north and was around 10 knots near Odisha coast and increasing towards south. The vertical wind shear between middle and lower levels was low (5-10 knots). The low level relative vorticity was around 50-100 x 10^{-6} s^{-1} to the south of system centre. Low level convergence was about 20 x 10^{-5} s^{-1} to the north and 10 x 10^{-5} s^{-1} to the south of system centre. The upper level divergence was around 20 x 10^{-5} s^{-1} to the southwest of system centre. The upper tropospheric ridge at 200 hpa level ran along 20.0^0N. The upper level winds were mainly westerly over the area. The analysis of the mean layer winds suggested that the system was being steered by the lower and middle tropospheric mean winds towards north-northwest with a speed of about 06 knots. The Madden Julian Oscillation (MJO) index lay in phase 5 with amplitude > 1. The lower vertical wind shear between middle and lower levels and movement of the system towards the region of low vertical wind shear, increased low level relative vorticity and favourable MJO Phase favoured the genesis of depression over westcentral Bay of Bengal at 0000 UTC of 19th.

2.7.2.2. Intensification and Movement:

Similar environmental conditions prevailed and the system maintained it's intensity. The lower vertical wind shear between middle and lower levels helped in maintaining the intensity of the system. The system lay close to the upper and middle tropospheric ridge. As a result it moved nearly northward and made landfall over Odisha coast close to Paradip during 1400 to 1500 UTC of 19th.

It continued it's northward movement for some time and then north-northeastwards movement till night of 20th. It then moved nearly north-eastwards and lay centered at 0300 UTC of 21st over Bangladesh and adjoining West Bengal near Latitude 24.0º N and longitude 88.7º E, about 35 km west-northwest of Ishurdi (Bangladesh) and 45 km east- southeast of Berhampore (West Bengal). It then moved nearly eastwards and weakened into a well marked low pressure area over northeast Bangladesh and adjoining Meghalaya & South Assam at 0000 UTC of 22nd October.

Under the influence of the trough in westerly to the west of the system and the anticyclonic circulation to the east, the depression recurved initially northeastwards and then eastwards towards Bangladesh.

The best track parameters of the system are presented in Table 2.7.1.

Table 2.7.1: Best track positions and other parameters of the Depression over the westcentral Bay of Bengal during 19-22 October, 2017

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
19/10/2017	0000	16.5/86.5	1.5	999	25	3	D
	0300	16.8/86.5	1.5	998	25	4	D
	0600	17.3/86.3	1.5	998	25	4	D
	1200	20.0/86.5	1.5	998	25	4	D
	Crossed Odisha coast close to Paradip around 1400-1500 UTC of 19th October						
	1800	20.3/86.5	-	998	25	4	D

20/10/2017	0000	20.8/86.5	-	998	25	4	D
	0300	21.0/86.5	-	998	25	4	D
	0600	21.5/86.5	-	998	25	4	D
	1200	22.2/86.7	-	998	25	4	D
	1800	22.8/87.0	-	998	25	4	D
21/10/2017	0000	23.0/88.0	-	997	25	4	D
	0300	24.0/88.7	-	997	25	4	D
	0600	24.2/89.3	-	997	25	4	D
	1200	24.2/90.2	-	997	20	4	D
	1800	24.3/91.0	-	998	20	3	D
22/10/2017	Weakened into a well marked low pressure area over northeast Bangladesh and adjoining Meghalaya & south Assam at 0000 UTC of 22nd October						

The total precipitable water imageries (TPW) during 16-19 October are presented in Fig.2.7.1.

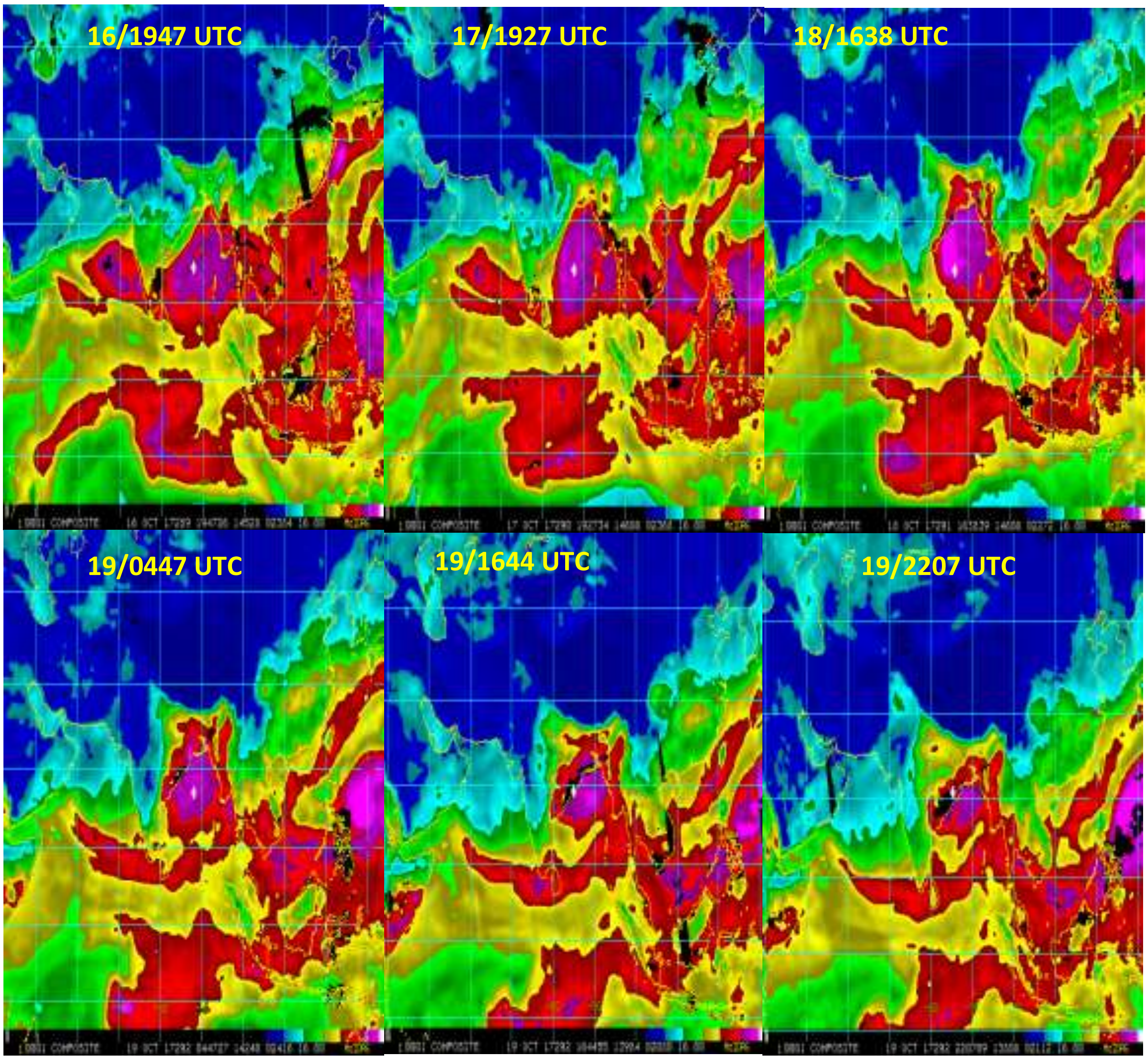


Fig. 2.7.1: The total precipitable water imageries (TPW) imageries during 16-19 October

These imageries indicate continuous warm and moist air advection from the southeast sector into the system. The intensity of the system as depression was maintained for about two days over the land due to (i) continuous warm and moist air advection into the core of the system from the southeast sector and (ii) due to saturated soil moisture over the region in association with normal to excess rainfall monsoon in previous days of October 2017.

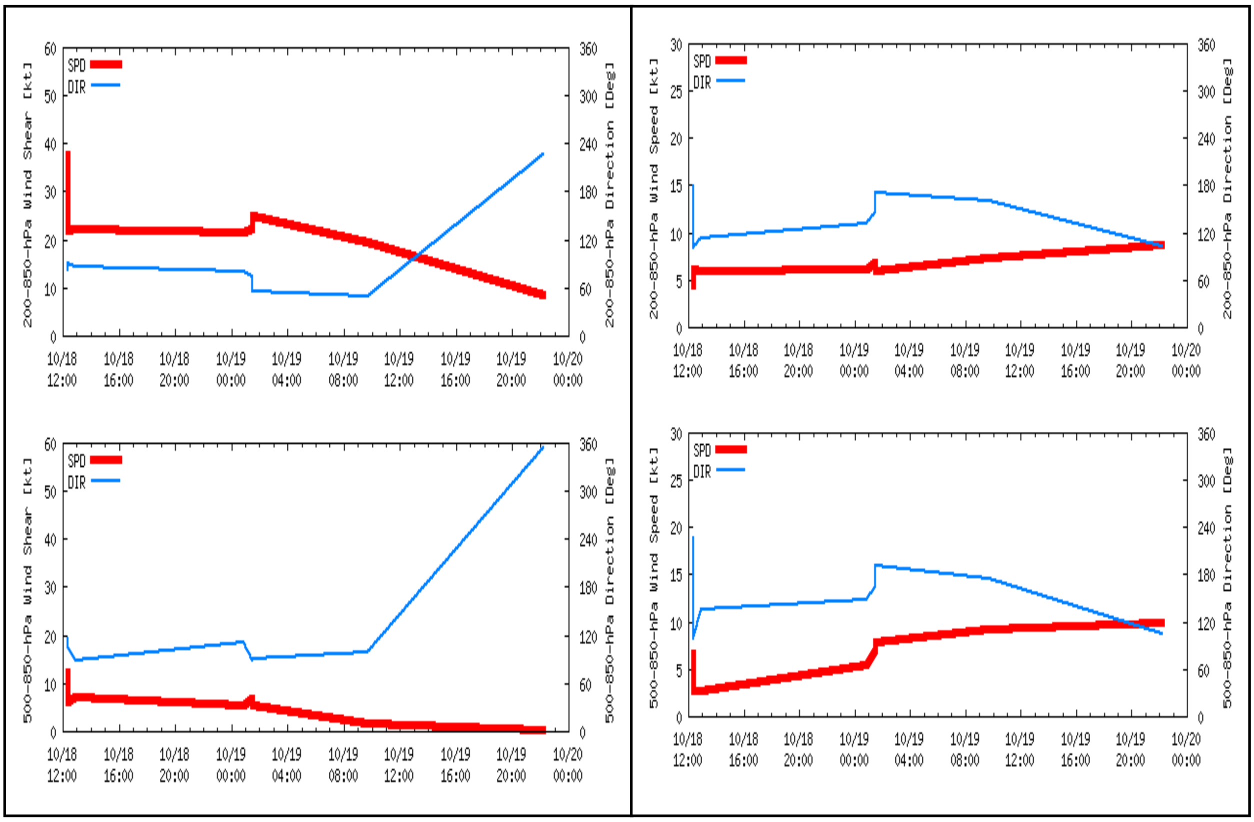


Fig. 2.7.2 Wind shear and wind speed in the middle and deep layer around the system during 28th to 31st May 2017.

The wind speed in middle and deep layer around the system centre is presented in Fig. 2.7.2. The wind shear around the system between 200 & 850 hPa levels was about 20 KTs prior to genesis. After genesis, it decreased gradually becoming low to moderate (10-15 KTs). The wind shear around the system between 500 & 850 hPa levels was about 10 KTs prior to genesis and less than 5 KTs at the time of genesis. All these helped the system to maintain it's intensity.

The mean wind speed between lower to upper levels was about 5 KTs till genesis. It gradually increased becoming about 9 KTs on 20th morning. The mean wind speed between lower and middle tropospheric levels was also less than 10 KTs at the time of genesis and it gradually increased becoming about 10 KTs on 20th morning. The average direction of the wind was 140^0 at the time and prior to genesis. It was 180^0 during 19/00 to 19/12 UTC, 140^0 during 19/12 to 19/18 UTC and 100^0 at 20/00 UTC.

The twelve hourly movement of the system is presented in Fig. 2.7.3. The 12 hour average translational speed of the cyclone decreased gradually on 19th during landfall and then abruptly in the early morning of 20th. It then increased gradually till noon of 21st and decreased thereafter.

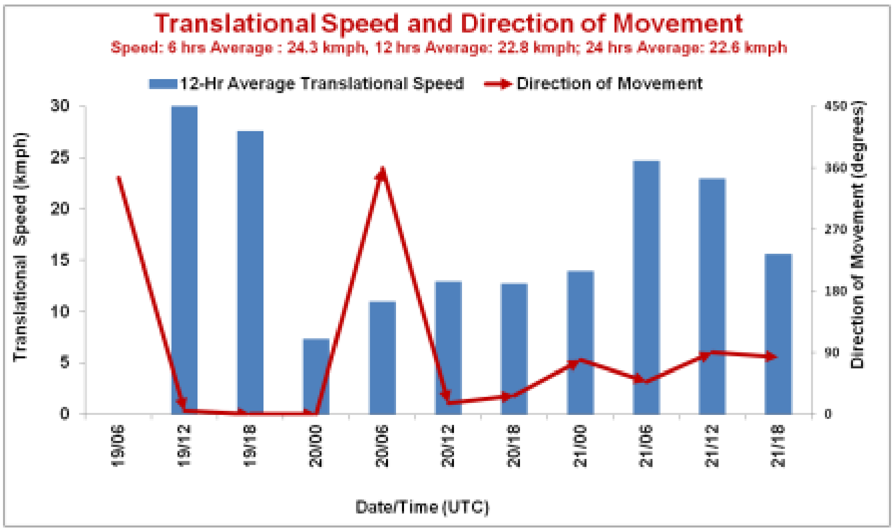


Fig. 2.7.3: 12 hour average translational speed during 19th to 21st October

2.7.3. Features observed through satellite and Radar

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and INSAT-3D imageries. Satellite imageries from SCAT SAT and international geostationary satellites Meteosat-7 & MTSAT, microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered for monitoring the system.

2.7.3.1 INSAT-3D features

Typical INSAT-3D visible, IR and enhanced colored imageries are presented in Fig. 2.7.4. At 0000 UTC of 19th, the intensity of the system was T 1.5. Associated broken low/medium clouds with embedded intense to very intense convection lay over central and adjoining northwest BoB between lattitude 13.0N & 20.0N and west of longitude 90.0E, Odisha and adjoining West Bengal and north Andhra Pradesh. Minimum cloud top temperature (CTT) was -93.0^{0}C. During genesis, maximum convection was sheared to west-northwestward direction.

At 1200 UTC of 19th, intensity of the system was T 1.5. Associated broken low/medium clouds with embedded intense to very intense convection lay over central and adjoining northwest BoB between lattitude 14.5N & 21.0N and west of longitude 91.0E. Minimum CTT was minus 93.0^{0}C. Gradually as the system moved northwards, the convection shifted towards northwest sector. At the time of landfall, the maximum convection lay over the northern sector. Thereafter, with the northeastward movement of the system, the convection also shifted to the northeast sector of the depression. The convection was well organised with distinct spiral banding as can be seen from satellite and radar imageries. The spiral bands clearly depicted warm and moist air advection from the sea reaching upto northeast sector of depression even after landfall. The structure got disorganised gradually on 21st with shearing of convection far away from the system centre over Bangladesh on 21st October. As a result, the depression weakened into a well marked low on 22nd morning and dissipated rapidly on 23rd as the system moved away from the coast and interacted with the rugged terrain of northeast India and Bangladesh. Typical satellite and radar imageries are presented in Fig. 2.7.4 and Fig. 2.7.5 respectively.

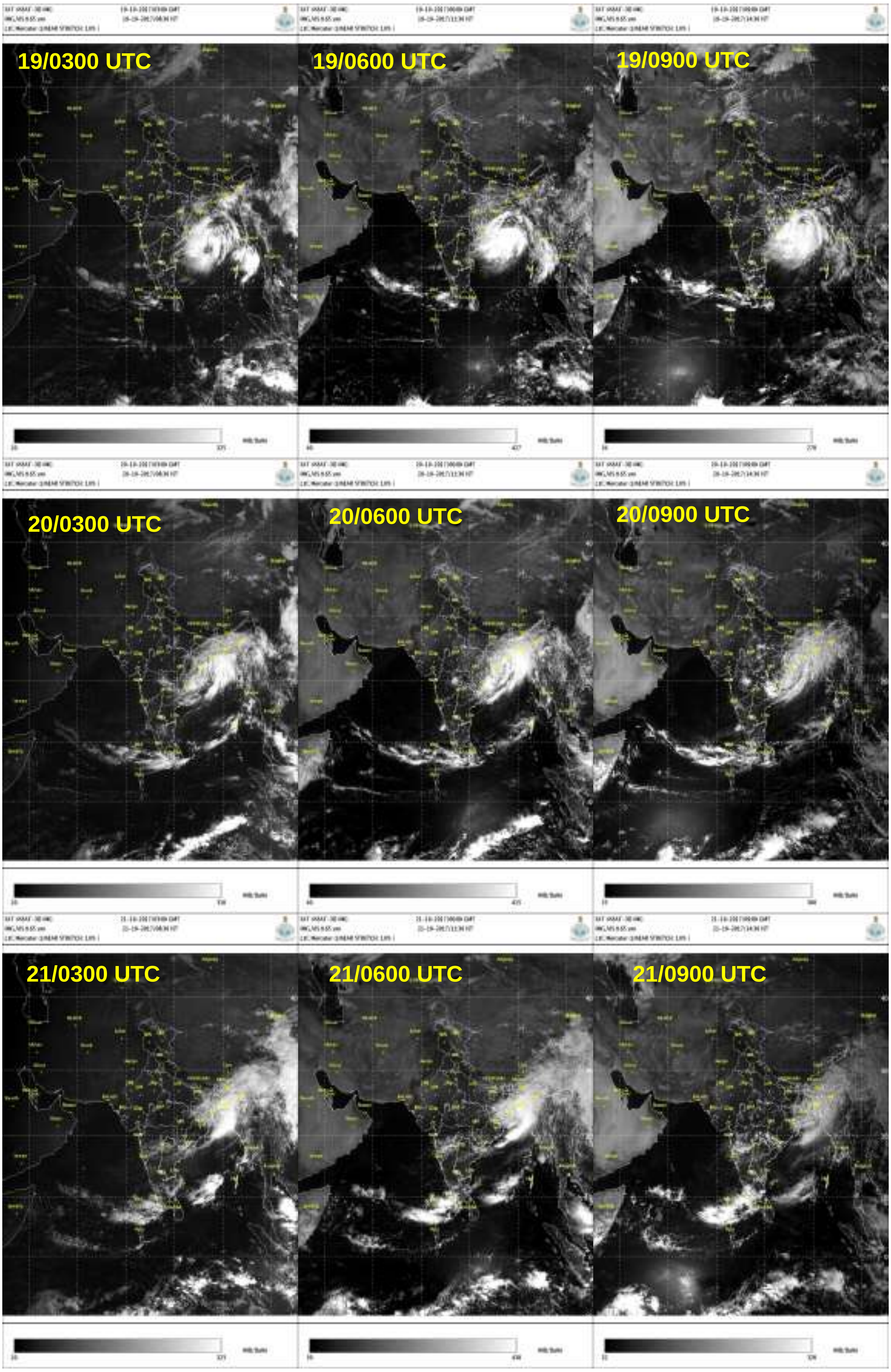


Fig. 2.7.4 (i): INSAT-3D visible imageries during Depression (19-22 October, 2017)

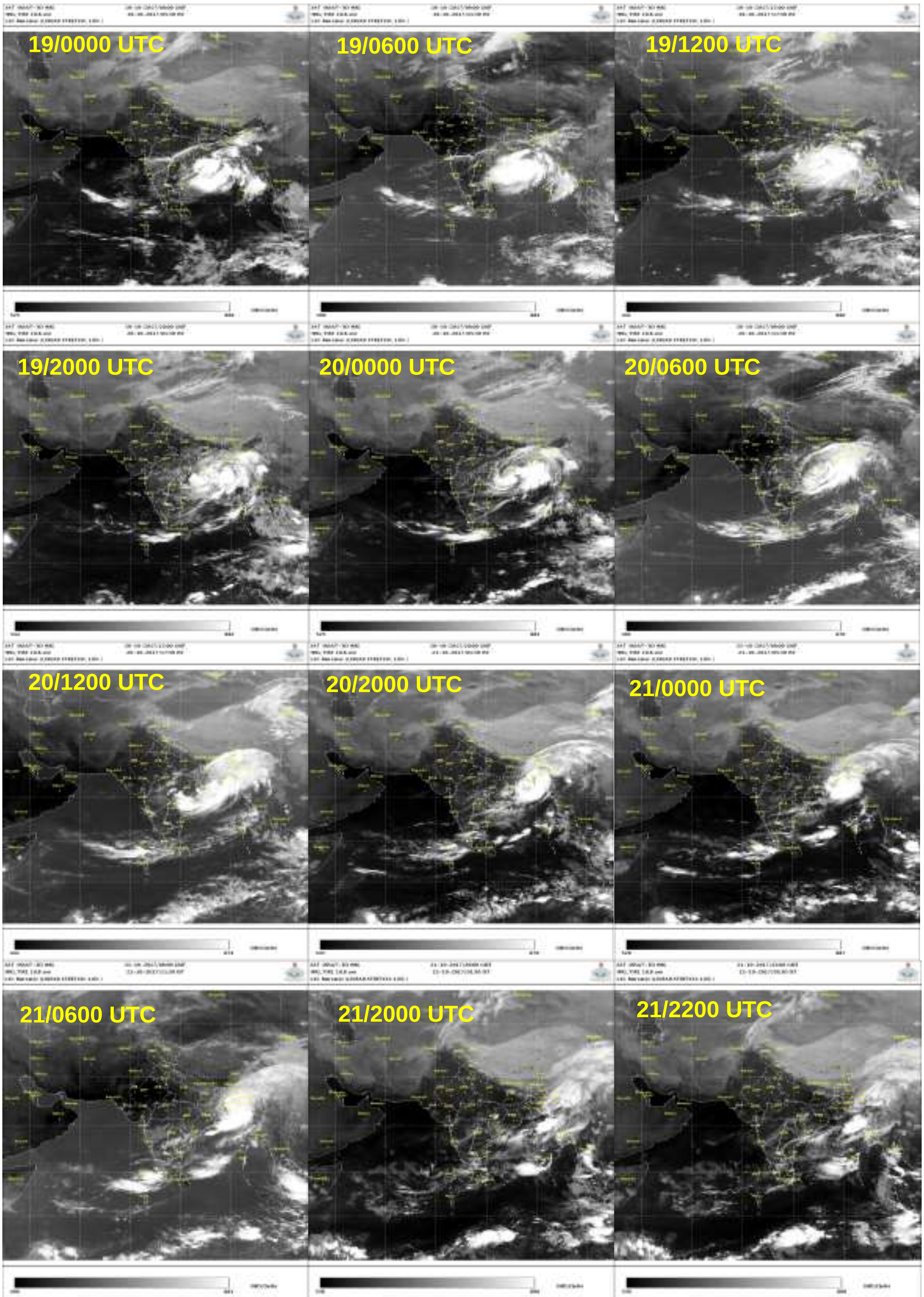


Fig. 2.7.4(ii): INSAT-3D IR imageries during Depression (19-22 October, 2017)

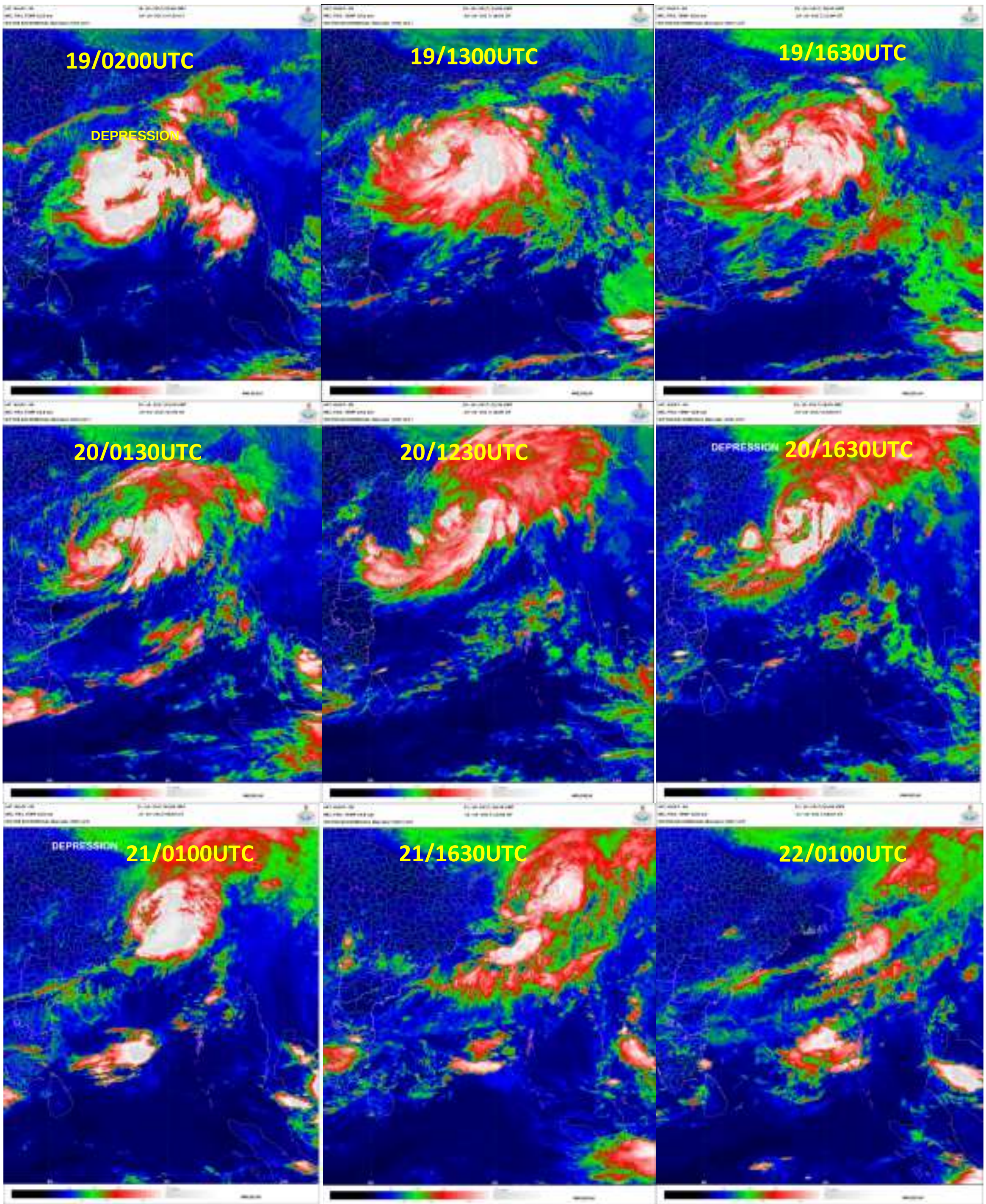


Fig. 2.7.4(iii): INSAT-3D enhanced coloured imageries during Depression (19-22 October, 2017)

2.7.3.2: Features observed through SCATSAT imageries

Typical imageries from polar satellite, SCATSAT are presented in **Fig. 2.7.4 (iv).** SCATSAT passes are available twice a day at 0400 UTC and 1700 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 1349 UTC of 18th indicated cyclonic circulation over westcentral BoB. Stronger winds were seen in eastern sector. Winds of the order of 31 kts were seen in the eastern sector. SCAT SAT gives 1 minute averaged wind. The equivalent 3 minute averaged intensity is about 25 KTs. Thus, the estimated intensity by SCATSAT matched best track estimates.

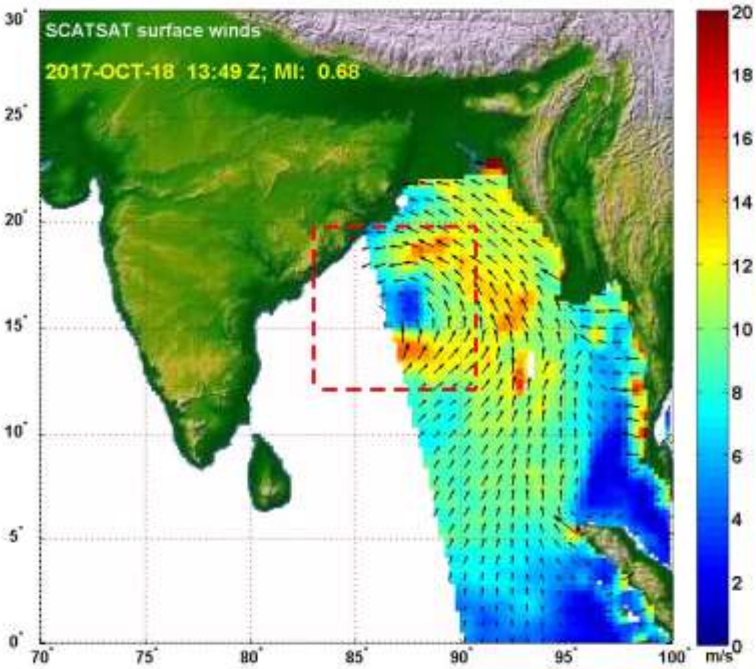


Fig. 2.7.4 (iv): SCAT SAT imagery based on 1349 UTC of 18th October

The matching index developed by SAC-ISRO for prediction of TC genesis based on the scatterometer observation of 1349 UTC of 18th October was above the threshold (>0.6), indicating intensification of system into a cyclonic storm. However, the depression did not intensify into a cyclonic storm.

2.7.3.3 Features observed through Microwave imageries:

F-15, F-17, F-18 and GCOM-W1 microwave imageries of the system during 19th to 20th October 2017 are presented in **Fig. 2.7.4 (v).** These imageries helped in understanding the internal structure of the system and better estimation of location of the system. It could indicate the region of intense convection and hence the rainfall. Area of intense convection was seen in the northeast sector around noon of 19th with a well defined spiral band extending from southwest sector to northeast sector. Around 1200 UTC an intense convection patch was seen over Odisha with spiral bands extending in northeast sector upto eastcentral BoB. On 00 UTC of 20th, well defined convective clouds were seen over Gangetic West Bengal, Bangladesh and northeast India.

2.7.3.4. Features observed through Radar:

Since genesis, the system was tracked by DWR Paradip. Hourly images from DWR Paradip were utilized for determining the location and movement of system since its genesis. Typical DWR imageries are presented in Fig.2.7.5.

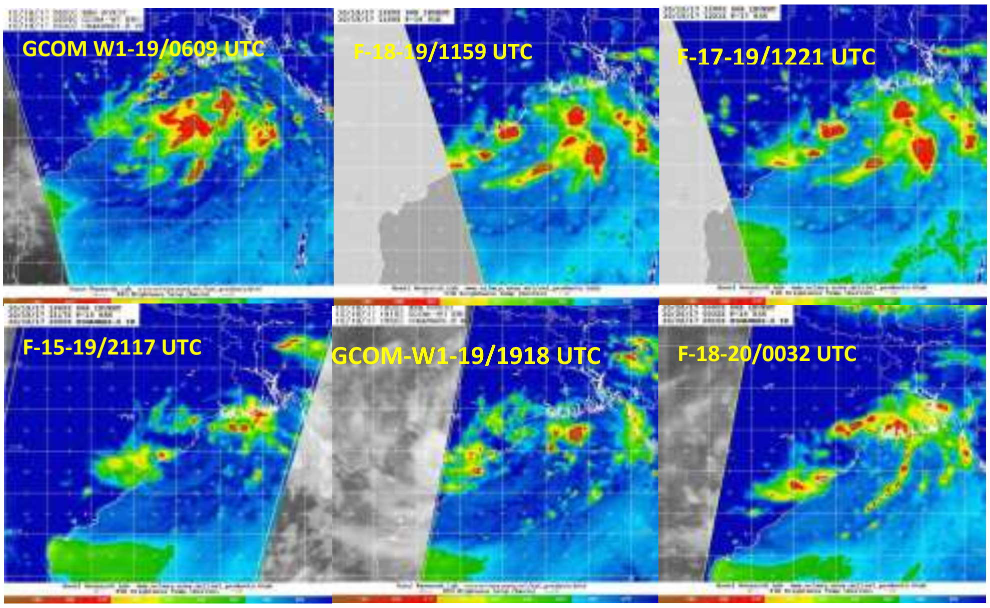


Fig. 2.7.5 (v): Microwave imageries during life cycle of depression over BoB

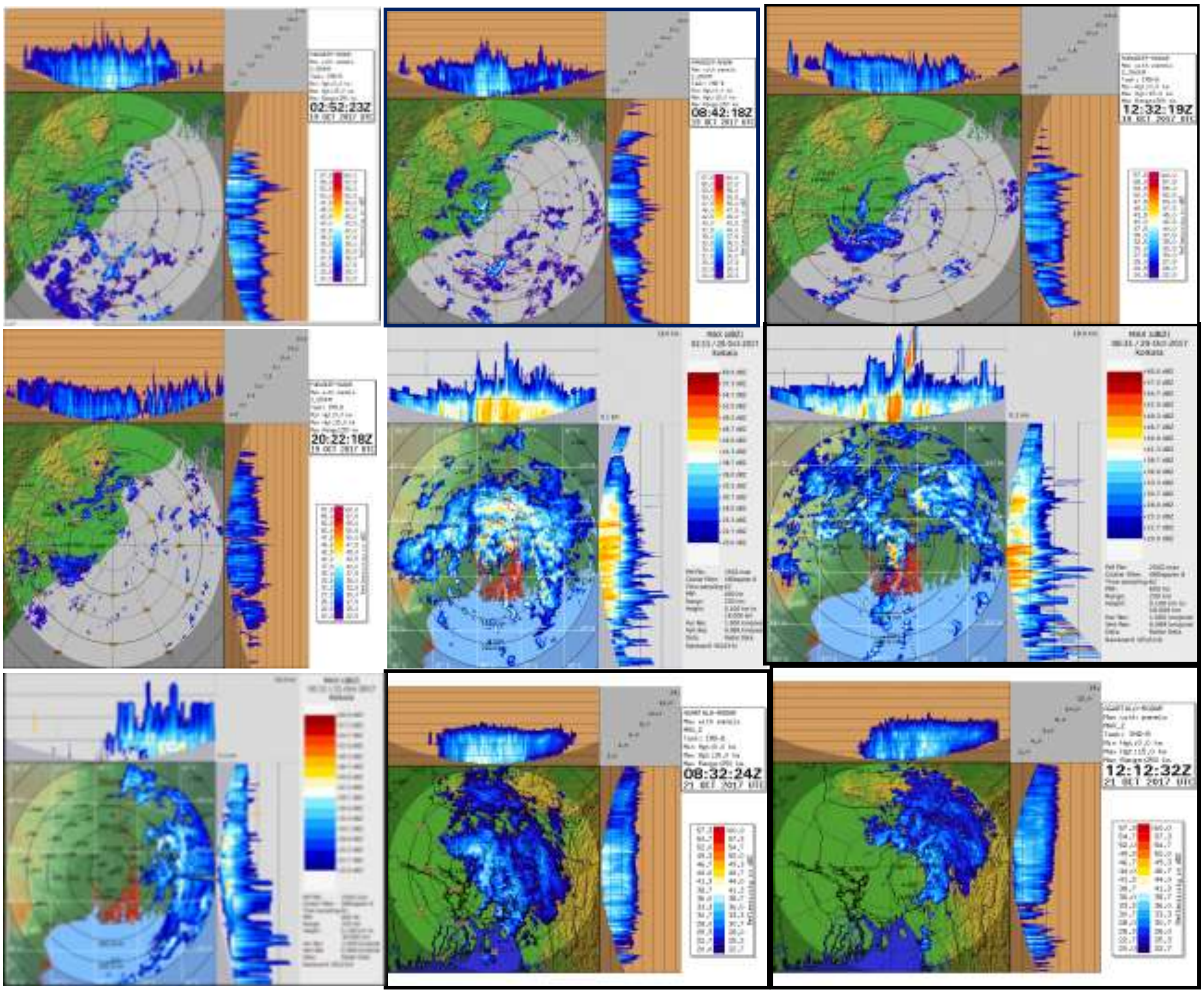


Fig. 2.7.5: DWR Paradip Radar imageries during Depression (19-22 October, 2017)

2.7.4. Dynamical features

IMD GFS (T1534) analysis and forecast of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig.2.7.6. IMD GFS (T1534) could simulate the genesis of the system on 19th October. However, it predicted intensification of system on 20th & 21st.

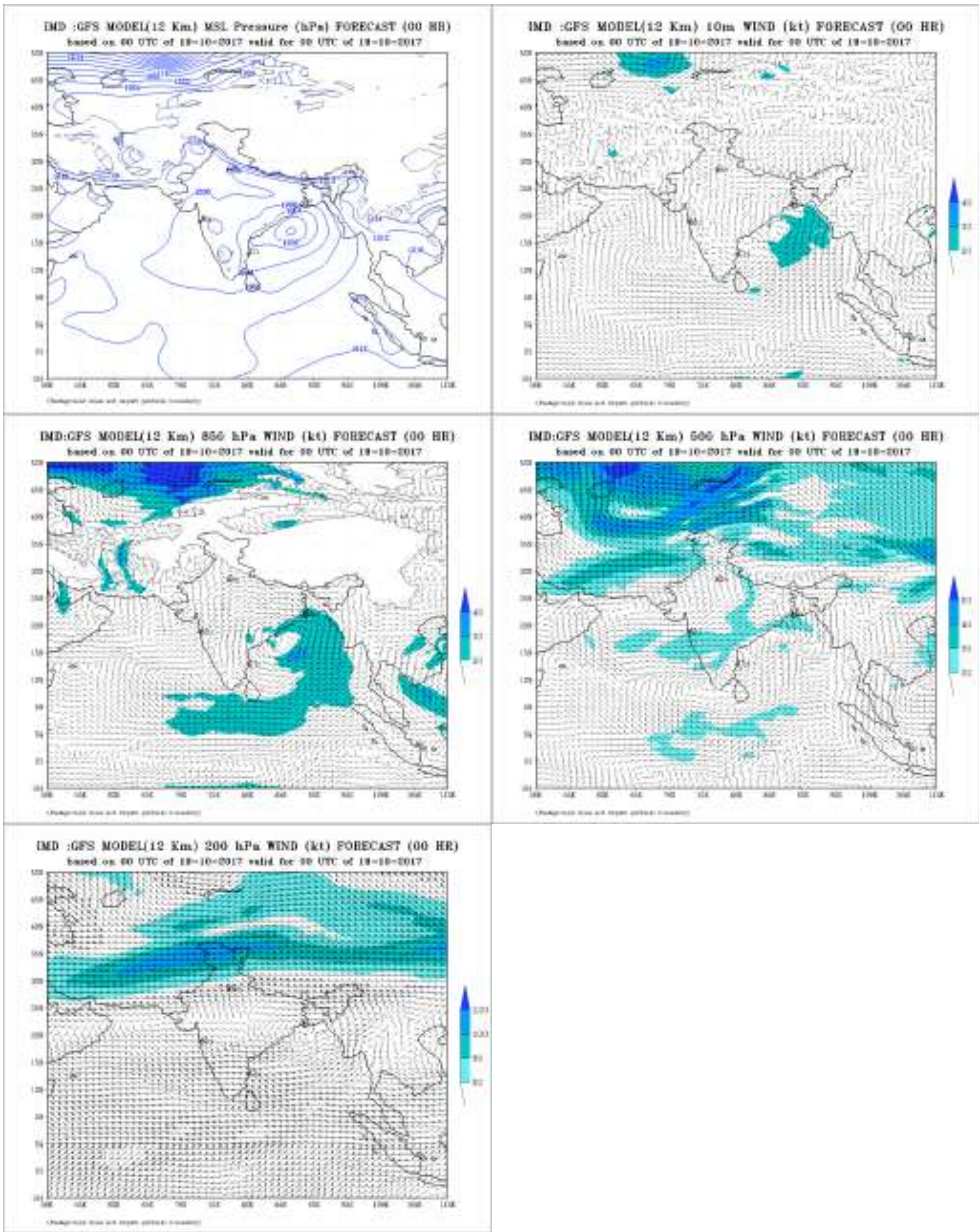


Fig. 2.7.6 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th October

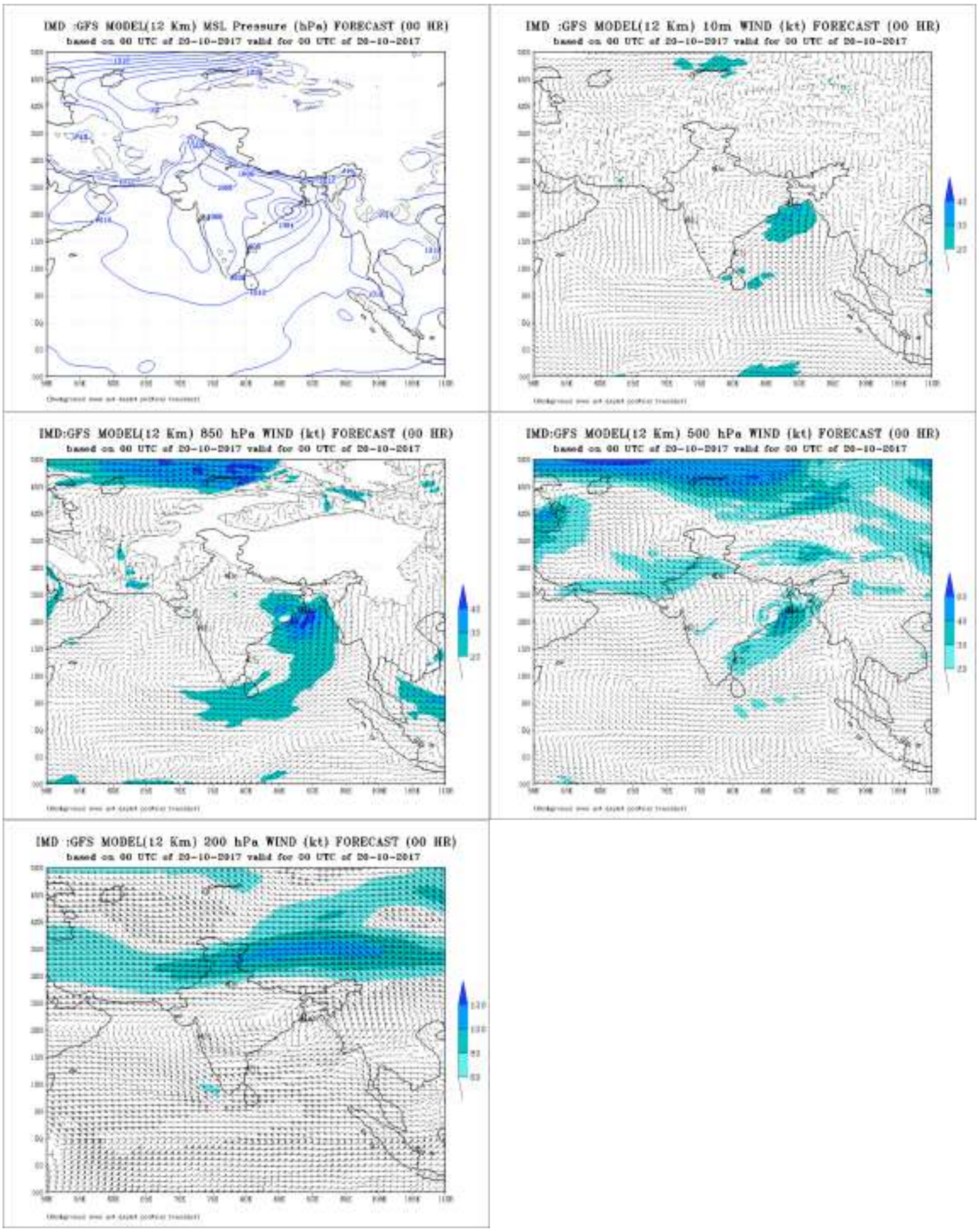


Fig. 2.7.6 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th October

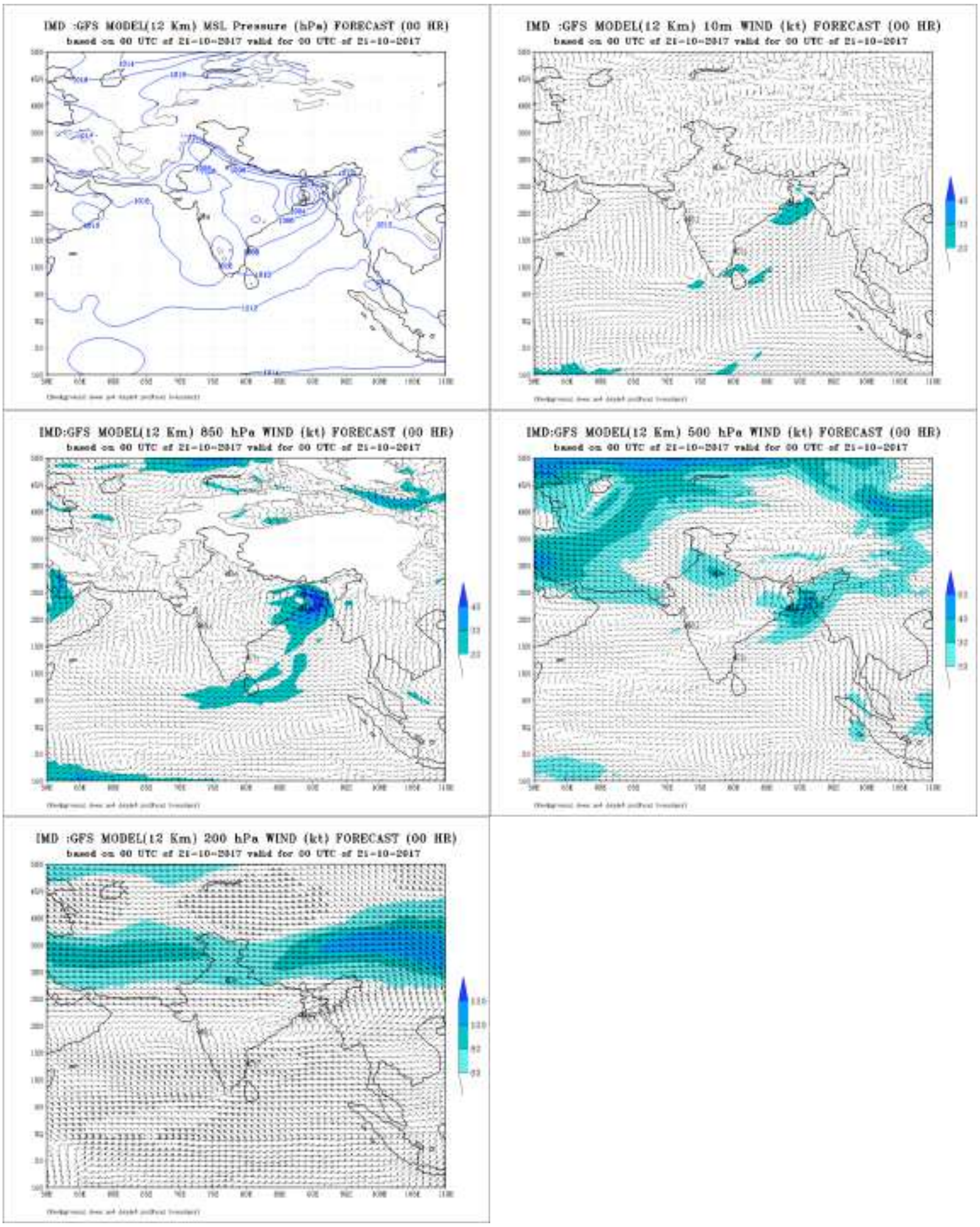


Fig. 2.7.6 (iii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st October

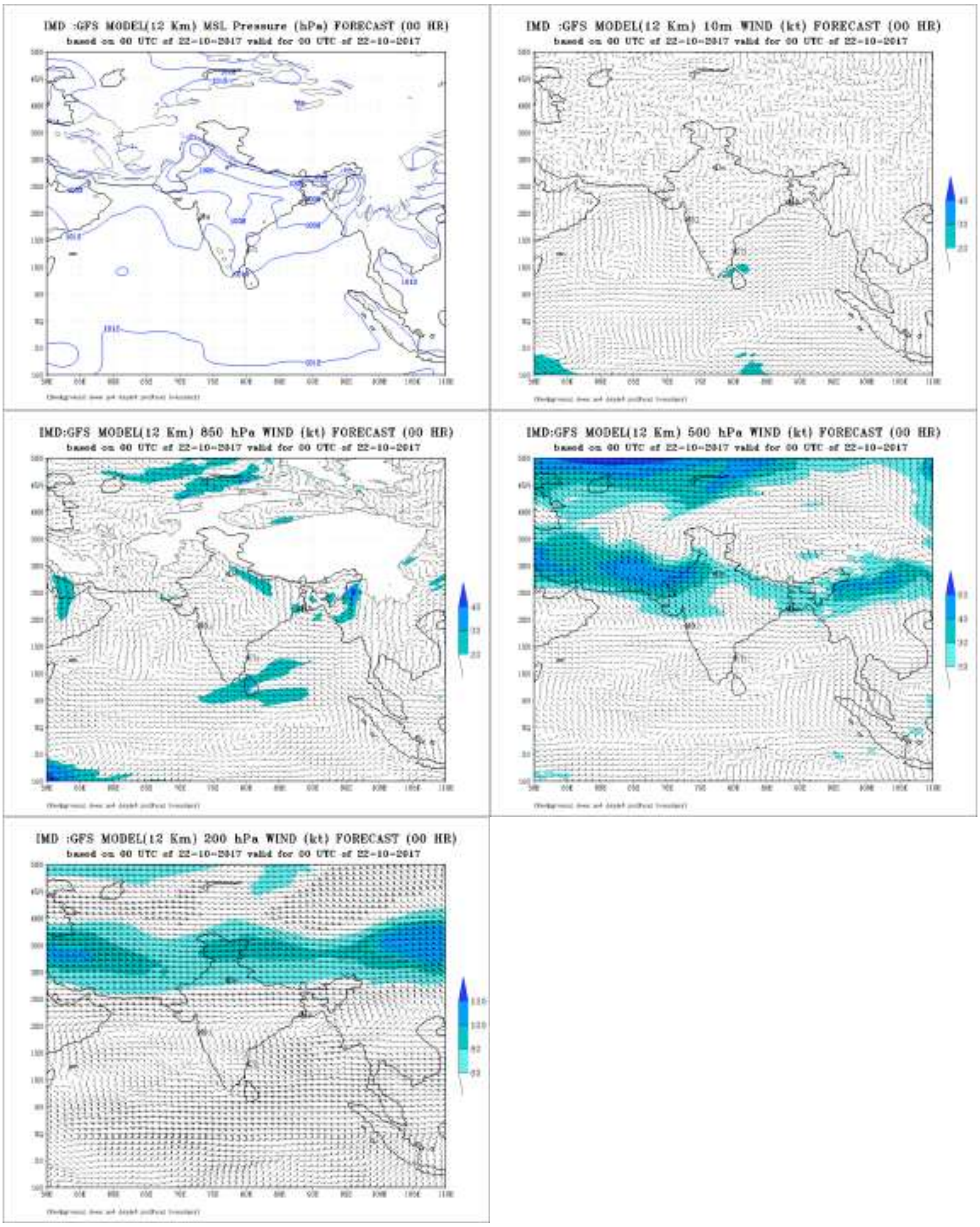


Fig. 2.7.6 (iv): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd October

2.7.5. Realized Weather:

2.7.5.1 Rainfall:

Realised weather:

Under its influence, isolated heavy rainfall occurred over Odisha on 18th. It caused isolated heavy rainfall over Gangetic West Bengal and scattered heavy with isolated very heavy rainfall over Odisha on 19th. On 20th, Assam & Meghalaya experienced isolated heavy to very heavy rainfall, Gangetic West Bengal experienced scattered heavy and isolated very heavy to extremely heavy rainfall. The system caused, isolated heavy to very heavy rainfall with extremely heavy falls at one or two places over Assam & Meghalaya and widespread heavy to very heavy rainfall over Nagaland, Manipur, Mizoram & Tripura on 21st October.

The rainfall is categorized as: heavy rain: 64.5 – 115.5 mm, very heavy rain: 115.6 – 200.4 mm, extremely heavy rain: 200.5 mm or more.

The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig.2.7.8. It can be seen that the system caused heavy to very heavy rainfall (8-16 cm) mainly over eastcentral and some parts of westcentral BoB on 18th. On 19th, the heavy to very rainfall was seen over coastal Odisha, West Bengal and southwest Bangladesh. On 20th, entire Bangladesh received heavy to very heavy rainfall with rainfall belt extending northeastwards over Nagaland, Manipur, Mizoram and Tripura. On 21st heavy to very heavy rainfall was observed over Eastern parts of Bangladesh, Assam, Nagaland and Manipur.

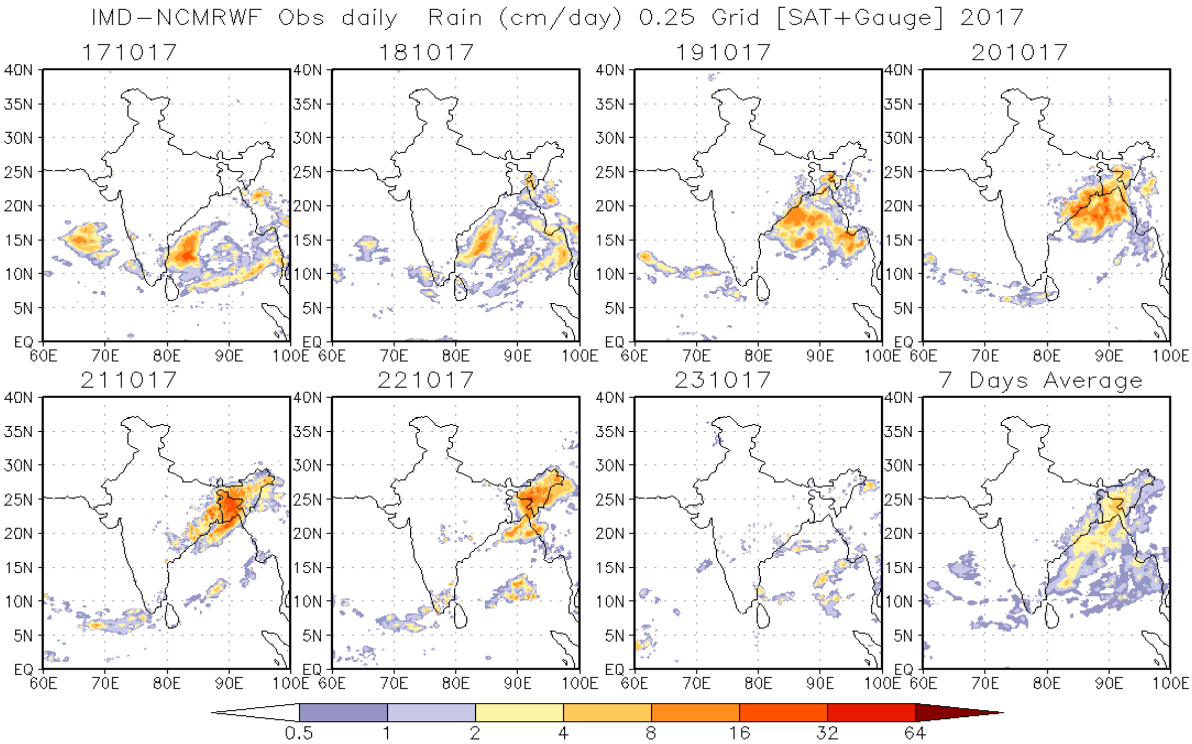


Fig. 2.7.7. Daily rainfall distribution ending at 0300 UTC (0830 IST) of date based on merged grided rainfall data of IMD/NCMRWF during 17-23 October 2017.

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date during the life cycle of the system is presented below:

19th October:

Nagaland, Manipur, Mizoram & Tripura: Kamalpur-7

Odisha: Derabis ARG-8, Balikuda ARG, Pattamundai, Nimpara, Tirtol ARG-7 each

20th October

Nagaland, Manipur, Mizoram & Tripura: Serchip (Hydro)-8

Gangetic West Bengal: Contai-10, Kalaikunda (IAF)-8, Canning-7

Odisha: Balimundali-22, Tikarpara-21, Jaipur-20, Tirtol ARG-20, Gop-19, Tangi-18, Remuna ARG, Pipili, Brahmagiri AWS-17 each, Chandikhol ARG, Puri-16 each, Jajpur, Balasore, Soro-15 each, Banpur, Ranpur, Nilgiri, Kakatpur, Nawana-14 each, Bolagarh ARG, Nimpara-13 each, Krishnaprasad, Alipingal, Satyabadi ARG, Chandbali, Bonth, Chandanpur, Bari ARG-12 each, Nh5 Gobindpur, Daitari, Rajkanika, Binjharpur ARG, Udala, Nuagada ARG, Balikuda ARG, Jagatsinghpur Aws, Kantapada ARG-11 each, Mohana, Hindol-10 each, Kujanga ARG, Betanati ARG, Astaranga ARG, Dhamnagar ARG, Rajghat, Anandpur, Balipatna ARG, Niali ARG, Karanjia, Kaptipada ARG, Phulbani, Chhatrapur, Sukinda, R.Udaigiri, Banki ARG, Bhadrak Aws, Bhograi-9 each, Jenapur, Marsaghai ARG, Bhubaneswar Aero, Mundali, Mahanga ARG, Danagadi ARG, Lanjigarh, Daringibadi, Berhampur, Mahendragarh, Odagaon ARG, Jaleswar, Nayagarh, Kotagarh, Akhuapada, Samakhunta Aws, Baliguda-8 each, Ambadola, Athgarh, Bhuban ARG, Baripada, Garadapur ARG, Harichandanpur ARG, KeonjhARGarh, Purushottampur, Khandapara, Jamsolaghat, Muniguda ARG, Tihidi ARG, Bangiriposi, Gopalpur, Naraj-7 each.

21st October

Arunachal Pradesh: Namsai-18, Miao-11

Assam & Meghalaya: Manash Nh Xing-14, Kokrajhar-13, Aie Nh Xing-9, Williamnagar 8, Panbari 8, Beky Rly.Bridge-7 each

Nagaland, Manipur, Mizoram & Tripura: Sonamura-11

Sub-Himalayan West Bengal & Sikkim: Cooch Behar-7

Gangetic West Bengal: Bankura-28, Bankura(CWC)-21, Kalaikunda (Iaf)-20, Narayanpur-18, Phulberia, Kansabati Dam-12 each, Suri (CWC)-11, Tusuma, Panagarh (Iaf), D.P.Ghat, Sri Niketan-10 each, Gheropara, Tilpara Barrage, Hetampur, Salar-9 each, Midnapore(CWC), Bagati, Amtala, Midnapore-8 each, Debagram, Purulia, Burdwan (Pto)-7 each.

Odisha: Nawana-12, Basudevpur AWS-10, Birmaharajpur ARG-9, Banki ARG, Barmul, Mohana, Rairangpur, Ullunda ARG-7 each

Jharkhand: Ghatsila 7

22nd October:

Assam & Meghalaya: Cherrapunji(Rkm)-31, Cherrapunji-28, Halflong-14, MARGherita-13, Karimganj-13, Williamnagar-11, A P Ghat, Silchar-8 each, B P Ghat, Lakhipur, Bokajan-7 each

Nagaland, Manipur, Mizoram & Tripura: Amarpur-18, Belonia-17, Kamalpur-15, Sabroom, Dharmanagar/ Panisagar-13 each, Chhamonu, Agartala Aero-11 each, Kailashahar Aero, Khowai, Sonamura-10 each, Arundhutinagar, Udaipur-9 each, Imphal T-Aero 8

2.8. Depression over westcentral Bay of Bengal (15-17 November 2017)

2.8.1. Introduction

A low pressure area (LPA) formed over southwest Bay of Bengal (BoB) and neighborhood in the morning of 10th November, 2017. It lay as a well marked low pressure area (WML) over southwest BoB and neighborhood in the morning of 13th. It further concentrated into a depression over westcentral BoB off Andhra Pradesh. Moving nearly north-northeastwards, it weakened into a WML over northwest Bay of Bengal off Odisha Coast. The observed track of the system is presented in Fig.2.1.

The salient features of the system were as follows:

(vi) The system moved nearly north-northeastward and weakened over Sea.
(vii) The total life period of the system was 51 hours against the average life period of depression of 65 hours in post monsoon season over the BoB.
(viii) The system caused heavy to very heavy rainfall at isolated places over Odisha and coastal Andhra Pradesh on 15th and heavy rainfall at isolated places on 17th.

IMD mobilised all its resources to monitor the system and regular warnings w.r.t. track, intensity, landfall and associated adverse weather were issued to concerned central and state disaster management agencies, print & electronic media and general public. Regular advisories were also issued to WMO/ESCAP Panel member countries including Bangladesh.

The brief life history, associated weather and forecast performance of IMD/RSMC, New Delhi are presented below.

2.8.2. Brief life history

2.8.2.1. Genesis

An LPA formed over southwest BoB and neighborhood at 0300 UTC of 10th November, 2017. It lay over southwest BoB and adjoining Sri Lanka coast at 0300 UTC of 12th. It lay as a WML over southwest BoB and neighborhood at 0300 UTC of 13th. It further lay over westcentral and adjoining southwest BoB at 0300 UTC of 14th. It concentrated into a depression over westcentral BoB off Andhra Pradesh coast and lay centred at 0300 UTC of 15th November near latitude 15.0^0 N and longitude 83.0^{0}E about 230 km southeast of Machilipatnam (Andhra Pradesh), 300 km south of Visakhapatnam and 510 km south-southwest of Gopalpur (Odisha) .

Considering the environmental conditions, at 0000 UTC of 15th, the sea surface temperature over the region was 28-29^{0}C. The ocean thermal energy was about 70-80 KJ/cm^2 over the area. The vertical wind shear between upper and lower levels was low to moderate (5-15 kt) around the system centre. It was increasing towards north and south. The vertical wind shear between middle and lower levels was low (5-10 knots). The low level relative vorticity was around 100 x 10^{-6} s^{-1} to the southwest of system centre. Low level convergence was about 20 x 10^{-5} s^{-1} to the north-northeast of system centre. The upper level divergence was around 30 x 10^{-5} s^{-1} near system centre. The upper tropospheric ridge at 200 hpa level ran along 17.0^{0}N over BoB and Andaman Sea. The analysis of the mean layer winds suggested that the system was being steered by the lower to upper tropospheric mean winds towards north with a speed of about 06 knots. The Madden Julian Oscillation (MJO) index lay in phase 5 with amplitude < 1. The increased vertical wind shear towards north & northeast and unfavourable MJO conditions suggested that the system would not intensify further.

2.8.2.2. Intensification and Movement:

At 0000 UTC of 16th, the sea surface temperature over the region was 28-29^{0}C. However, it was about 26-27^{0}C over coastal Odisha. The ocean thermal energy was about 70-80 KJ/cm^2 over the area. It decreased to 50 KJ/cm^2 to the north of 20^{0}N. The vertical wind shear between upper and lower levels was low to moderate (10-15 kt) around the system centre and it was increasing towards north. The low level relative vorticity was around 100 x 10^{-6} s^{-1} to the southeast of system centre. Low level convergence was about 40 x 10^{-5} s^{-1} to the east of system centre. The upper level divergence was around 40 x 10^{-5} s^{-1} to the northeast of system centre. The upper tropospheric ridge at 200 hpa level ran along 17.0^{0}N over BoB and Andaman Sea. The analysis of the mean layer winds suggested that the system was being steered by the lower to upper tropospheric mean winds towards north with a speed of about 06 knots. The analysis of the mean layer winds suggested that the system was being steered by lower to upper level winds. The upper tropospheric ridge ran along 17^{0}N in association with an anticyclonic circulation over central BoB. A trough in westerly ran along 67 ^{0}E to the north of 18 ^{0}N. As a result, strong southerly/ southwesterly winds prevailed near the system. All these features favoured north-northeastward movement of the system. Further, the increased wind shear, lower sea surface temperatures and ocean thermal energy to the north suggested weakening of the system as it would move further northwards. Continuing north-northeastward movement, it weakened into a WML at 0600 UTC of 17th over northwest BoB off north Odisha- West Bengal coasts. The best track parameters of the system are presented in Table 2.8.1.

Table 2.8.1: Best track positions and other parameters of the Depression over the westcentral Bay of Bengal during 19-22 October, 2017

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
15/11/2017	0300	15.0/83.0	1.5	1004	25	4	D
	0600	15.5/83.0	1.5	1004	25	4	D
	1200	16.2/83.3	1.5	1001	25	4	D
	1800	17.0/83.8	1.5	1002	25	4	D
16/11/2017	0000	17.5/84.1	1.5	1004	25	4	D
	0300	17.7/84.3	1.5	1004	25	4	D
	0600	17.7/84.3	1.5	1004	25	4	D
	1200	18.1/85.0	1.5	1004	25	4	D
	1800	18.5/85.5	1.5	1004	25	4	D
17/11/2017	0000	18.8/85.8	1.5	1004	25	4	D
	0300	19.5/86.3	1.5	1006	25	4	D
	Weakened into a well marked low pressure area over northwest Bay of Bengal off north Odisha-West Bengal coasts at 0600 UTC						

2.8.3. Features observed through satellite and Radar

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and INSAT-3D imageries. Satellite imageries from SCATSAT and international geostationary satellites Meteosat-7 & MTSAT, microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered for monitoring the system.

2.8.3.1 INSAT-3D features

Typical INSAT-3D visible, IR and enhanced colored imageries are presented in Fig.2.8.1. At 0300 UTC of 15th, intensity of the system was T 1.5. Broken low & medium clouds with embedded intense to very intense convection lay over westcentral and adjoining northwest BoB. At 1200 UTC of 15th, broken low & medium clouds with embedded intense to very intense convection lay over westcentral & adjoining eastcentral BoB and northwest BoB. As the system moved further north-northeastwards, at 0300 UTC of 16th, broken low & medium clouds with embedded moderate to intense convection lay over westcentral and adjoining eastcentral BoB and over northwest BoB. The cloud mass started disorganizing from the night of 16th and at 0300 UTC of 17th, broken low & medium clouds with embedded moderate to intense convection lay over westcentral and adjoining eastcentral BoB, northwest BoB and coastal Odisha. At 0600 UTC of 17th, the system weakened into a well marked low pressure area with broken low & medium clouds with embedded moderate to intense convection lay over north BoB and coastal Odisha, coastal West Bengal and coastal Bangladesh.

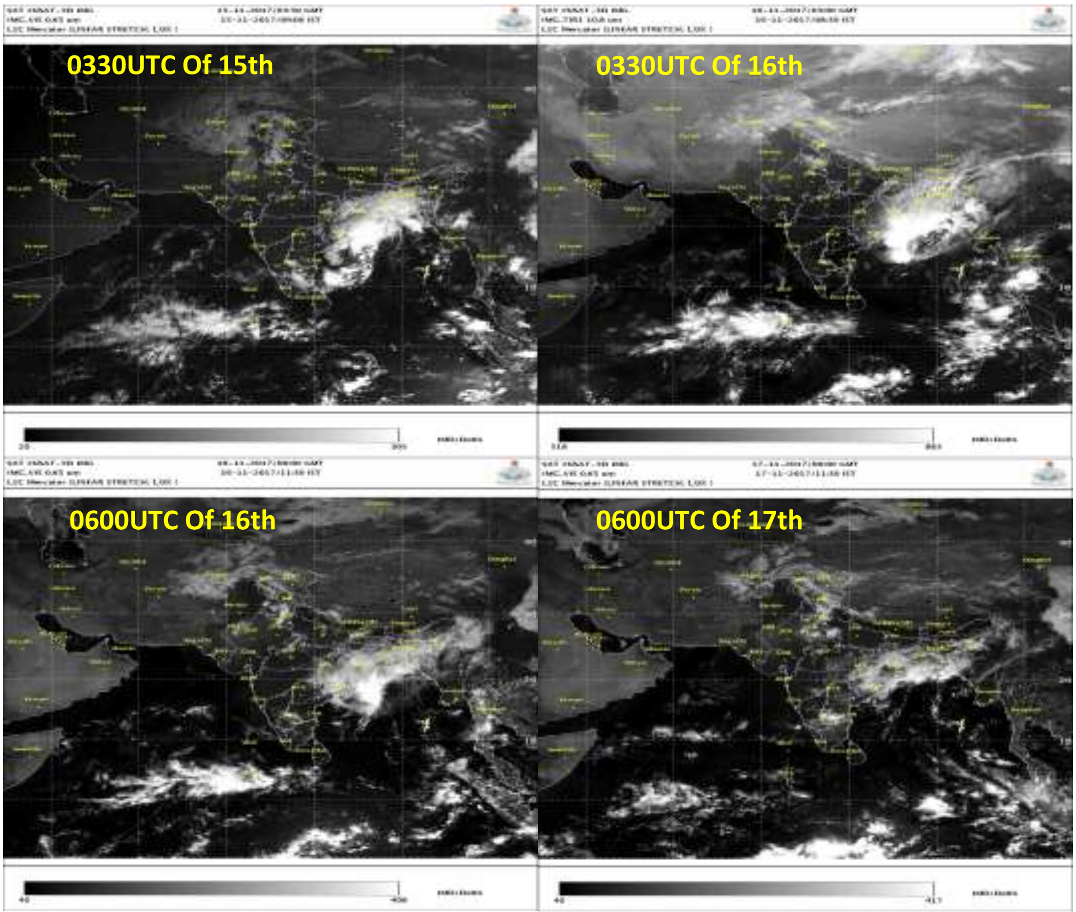


Fig. 2.8.1(i): INSAT-3D Visible imageries of Depression (15-17 November, 2017)

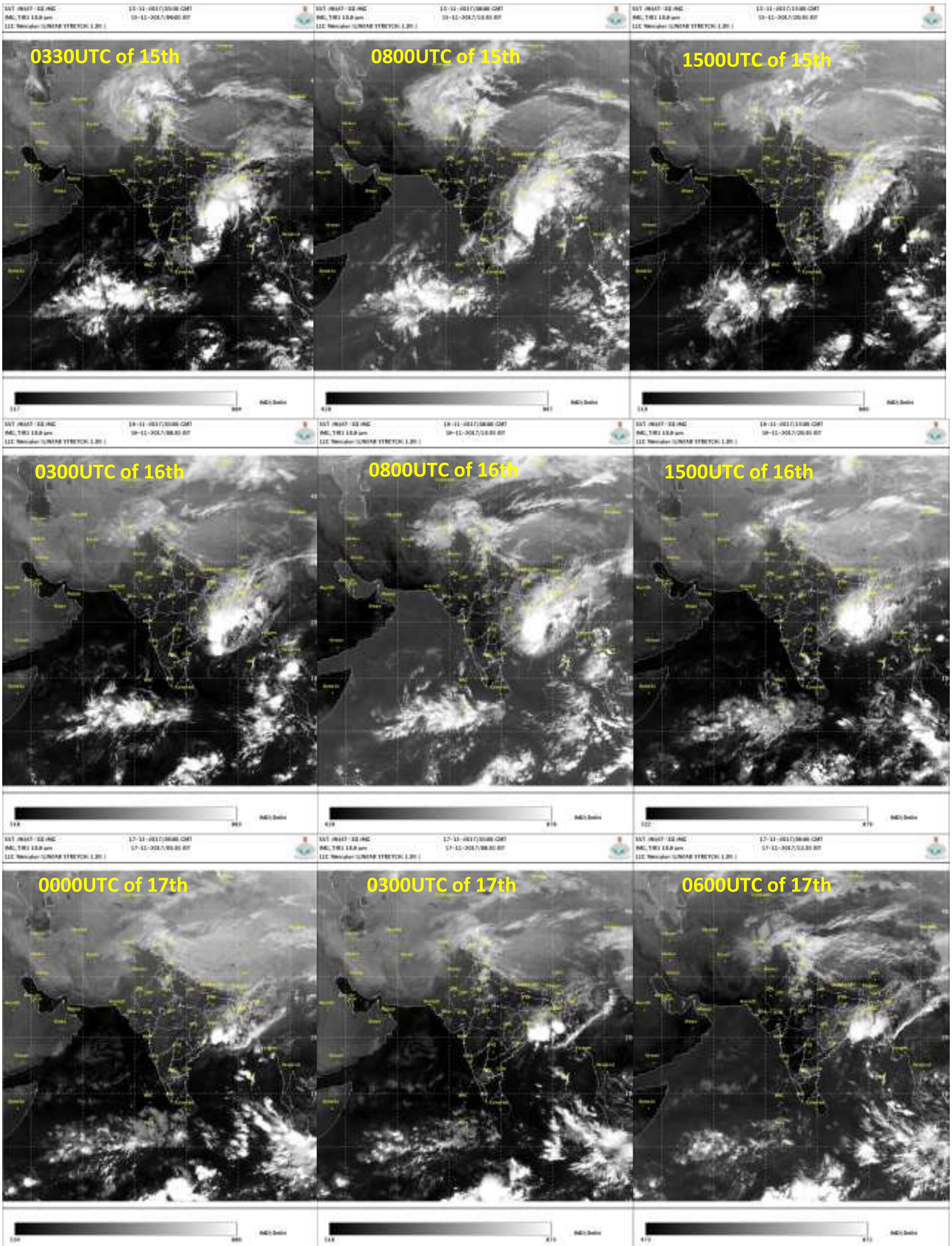


Fig. 2.8.1(ii): INSAT-3D IR imageries of Depression (15-17 November, 2017)

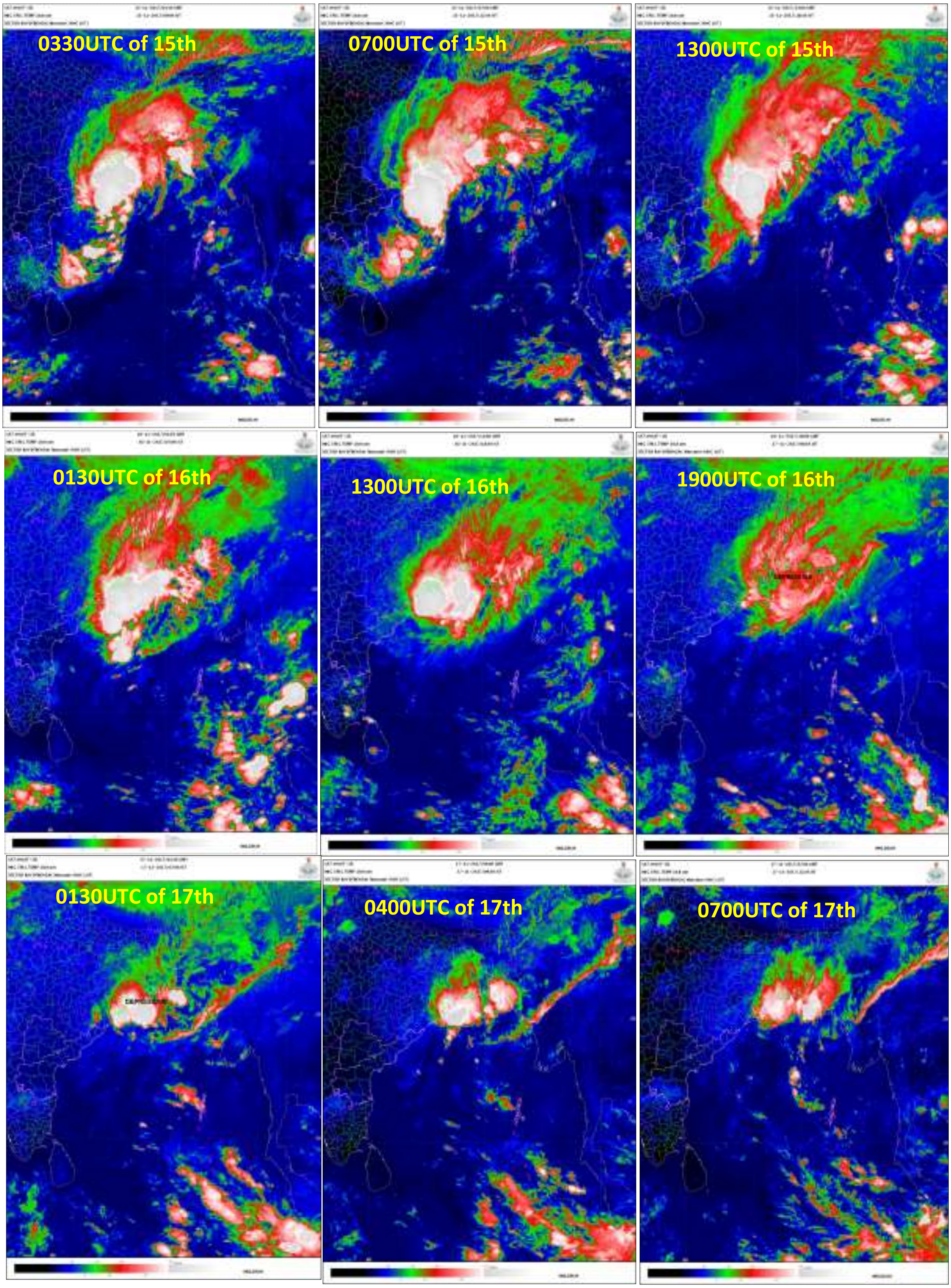


Fig. 2.8.1(iii): INSAT-3D enhanced coloured imageries of Depression (15-17 November, 2017)

2.8.3.3. Features observed through Radar:

Throughout its life cycle, the system was tracked by DWR Paradip, Visakhapatnam and Kolkata. These imageries were utilized for determining the location and movement of system. Typical DWR imageries are presented in Fig.2.8.2.

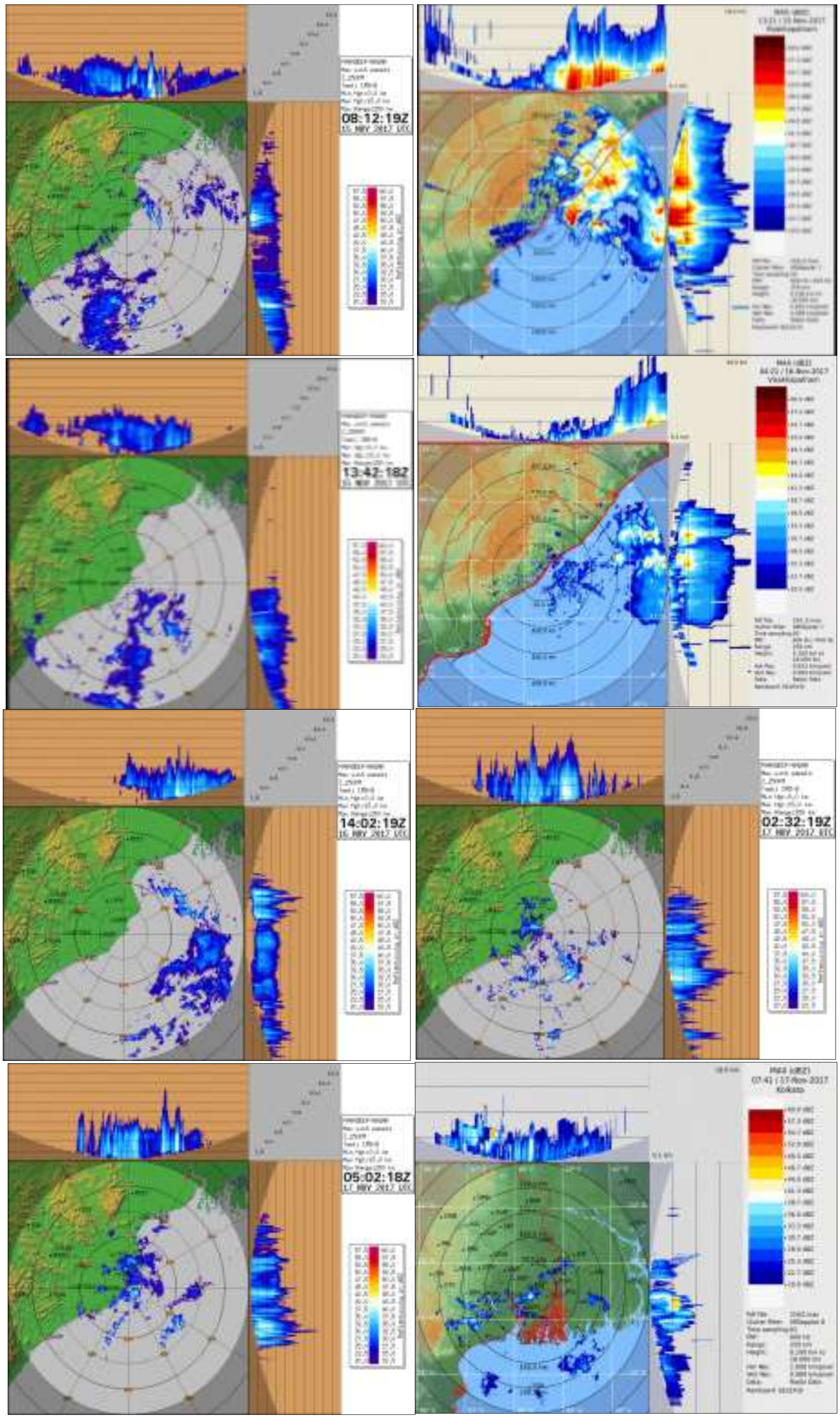


Fig. 2.8.2: Typical DWR imageries during Depression (15-17 November, 2017)

2.8.4. Dynamical features

IMD GFS (T1534) analysis and forecast of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig.2.8.3. IMD GFS (T1534) could well simulate the genesis of the system on 15th November, it's north-northeastward movement and dissipation on 17th. It could also capture broad scale features like trough in westerlies along 62^0E to the north of 20^0N.

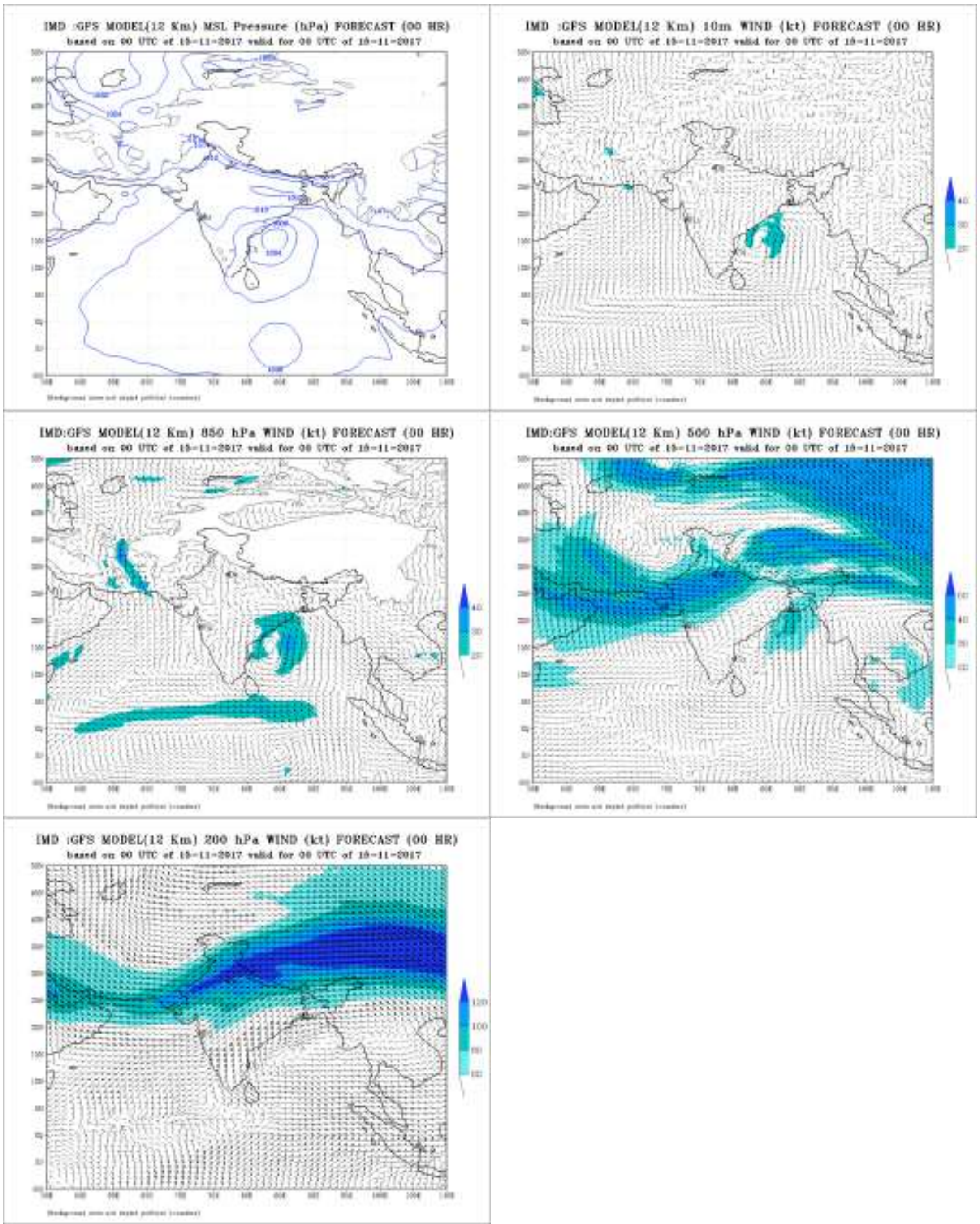


Fig. 2.8.3 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th November 2017

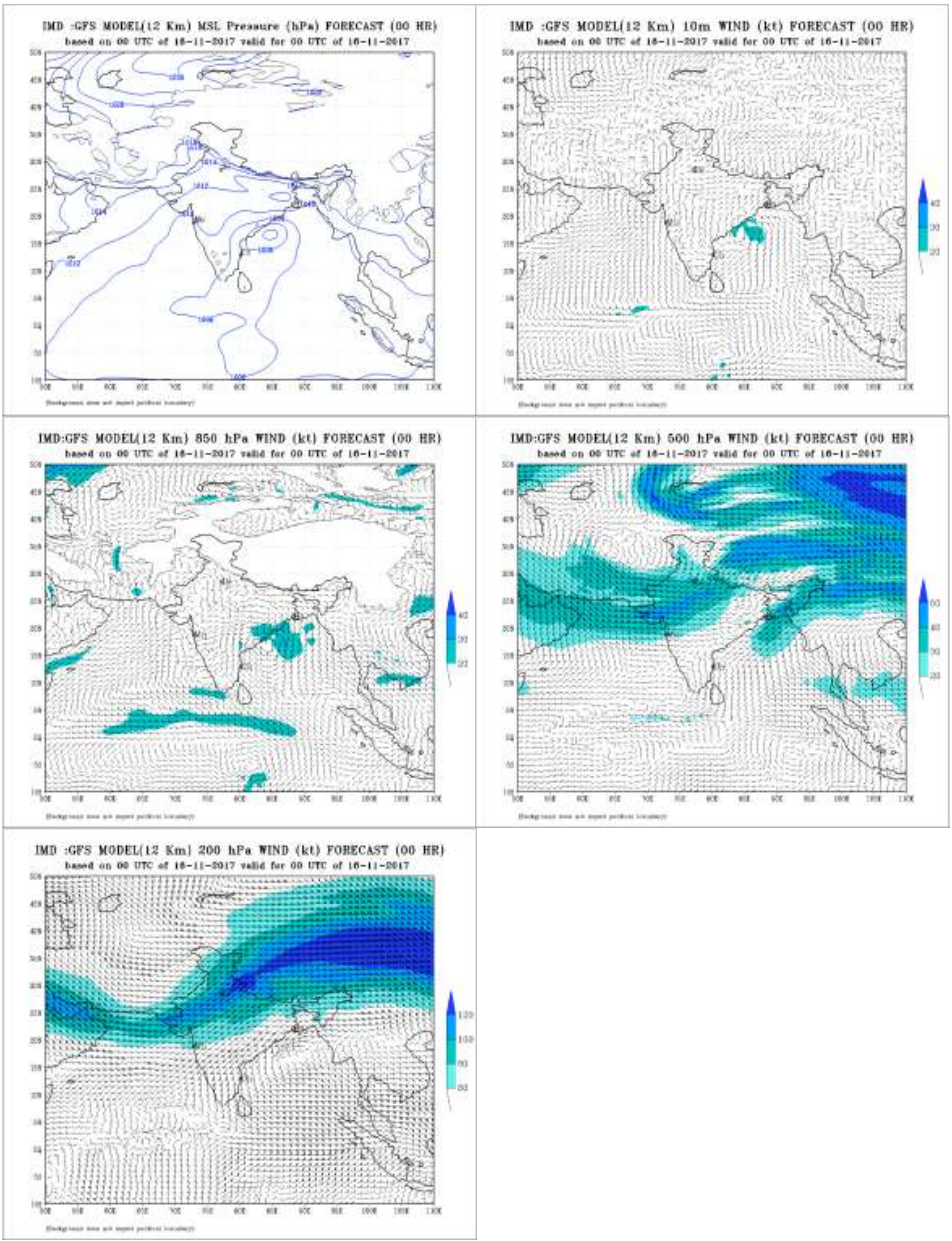


Fig. 2.8.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th November 2017

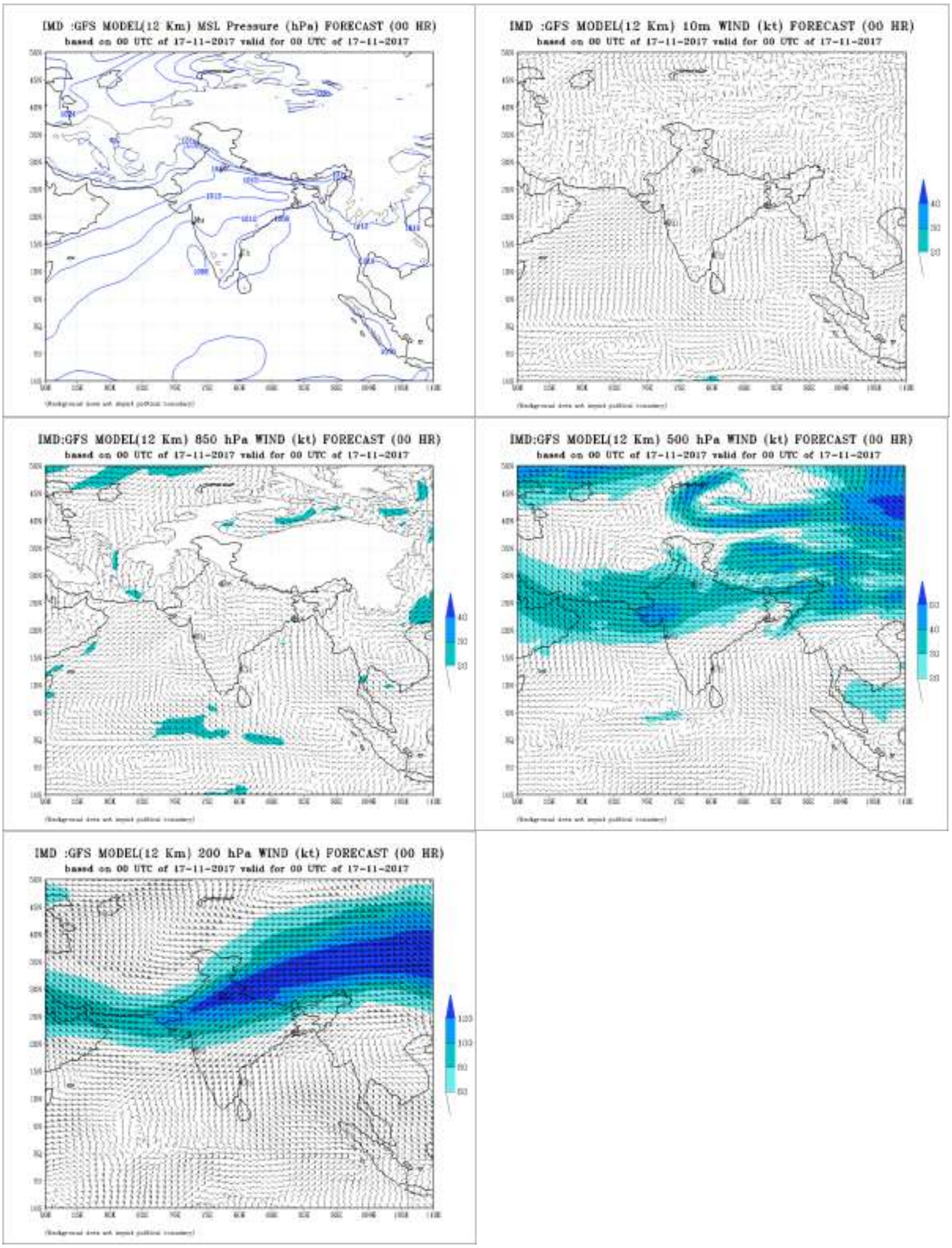


Fig. 2.8.3 (iii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th November 2017

2.8.5. Realized Weather:

2.8.5.1 Rainfall:

Realised weather:

Under its influence, isolated heavy rainfall occurred over Odisha and isolated heavy to very rainfall over Andhra Pradesh occurred on 15th. On 17th, heavy rainfall occurred at isolated places over Odisha and Andhra Pradesh.

The rainfall is categorized as: heavy rain: 64.5 – 115.5 mm, very heavy rain: 115.6 – 200.4 mm, extremely heavy rain: 200.5 mm or more.

The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig. 2.8.4. It can be seen that the system caused heavy to very heavy rainfall (16-32 cm) rainfall over eastcentral BoB and 2-4 cm rainfall over coastal Odisha, Gangetic West Bengal and Bangladesh. On 17th, the heavy to very rainfall was seen over eastcentral BoB.

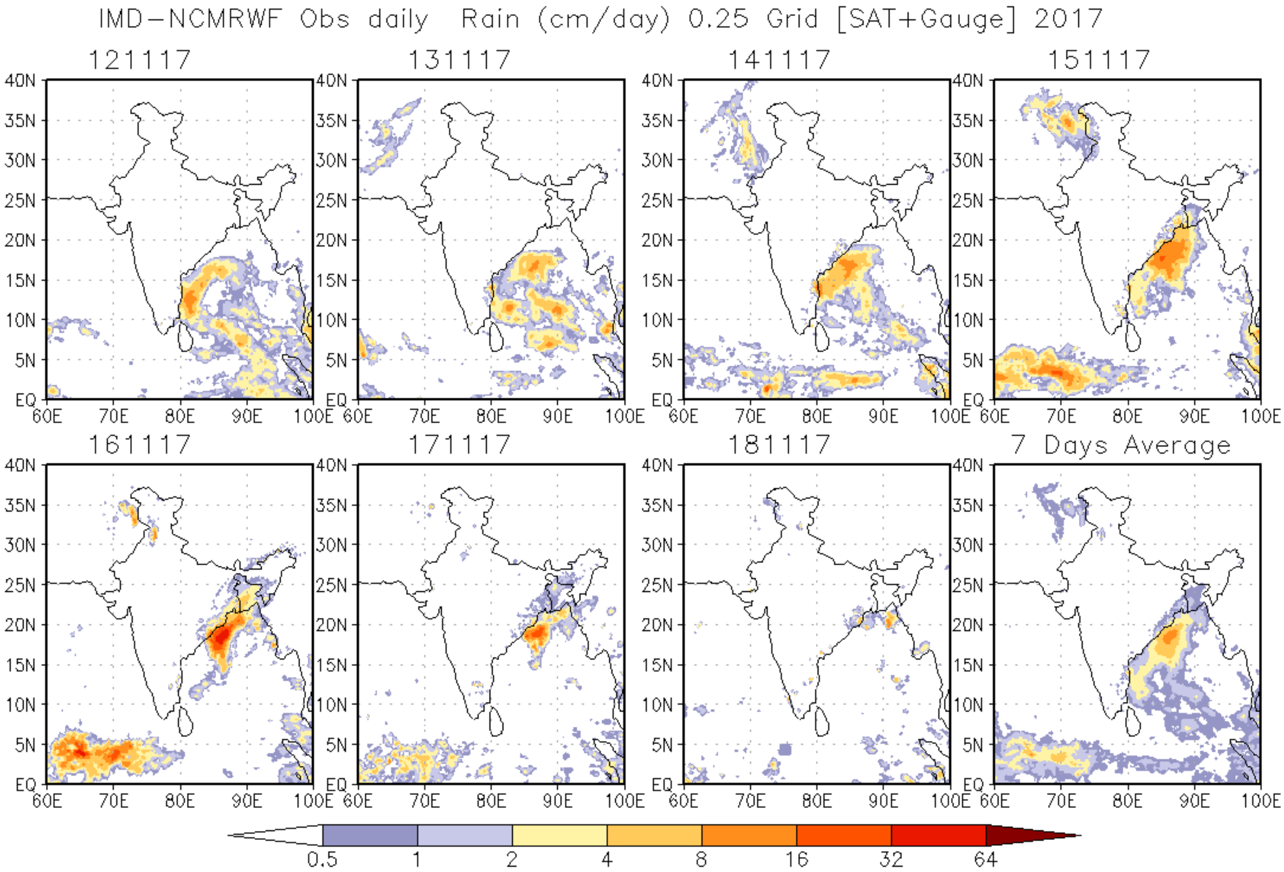


Fig.2.8.4: Daily rainfall distribution ending at 0300 UTC (0830 IST) of date based on merged grided rainfall data of IMD/NCMRWF during 17-23 October 2017.

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date during the life cycle of the system is presented below:

15 November 2017

Puducherry: Thanjavur-7

16 November 2017

Odisha: GOP & Astaranga – 9 each and Puri, Paradeep, Digapahandi, Paralakhemundi, Mahendragarh, Tirtol, Balikuda, Kujanga & Nischintakoili -7 each

Coastal Andhra Pradesh: Sompeta-18, Ichchapuram-17, Mandasa-14, Palasa & Kalingapatnam-11, Tekkali-9 and Pathapatnam-7

18 November 2017

Odisha: Tirtol - 8 and Rajkanika & Binjharpur -7 each

Coastal Andhra Pradesh: Vijayawada A.P.-9

2.9. Very Severe Cyclonic Storm 'Ockhi' over the Bay of Bengal (29 November-05 December 2017)

2.9.1. Introduction

Very Severe Cyclonic Storm (VSCS) Ockhi originated from a low pressure area which formed over southwest Bay of Bengal (BoB) and adjoining areas of south Sri Lanka & equatorial Indian Ocean in the forenoon (0830 IST) of 28th November. It became a well marked low pressure area in the early morning (0530 IST) of 29th over the same region. Under favourable environmental conditions, it concentrated into a Depression (D) over southwest BoB off southeast Sri Lanka coast in the forenoon (0830 IST) of 29th Nov. Moving westwards, it crossed Sri Lanka coast after some time. Continuing it's westward movement, it emerged into Comorin area in the evening (1730 IST) of 29th and intensified into a Deep Depression (DD) in the early hours (0230 IST) of 30th over the Comorin area and neighbourhood. It further moved northwestwards and intensified into a Cyclonic Storm (CS) in the forenoon (0830 IST) of 30th over the Comorin area. There was rapid intensification of Ockhi during its genesis stage, as it intensified into a CS at 0830 IST of 30th, after its genesis as a depression at 0830 IST of 29th (within 24 hrs). It further intensified into a Severe Cyclonic Storm (SCS) over Lakshadweep area in the early morning (0530 IST) of 01st Dec. and Very Severe Cyclonic Storm (VSCS) over southeast (SE) Arabian Sea to the west of Lakshadweep in the afternoon(1430 IST) of 01st Dec. It then moved northwards and reached its peak intensity of 85 knots (150-160 kmph) in the morning (0830 IST) of 4th Dec. It then moved north-northeastwards and weakened gradually into an SCS on 4th midnight (2330 IST), a CS in the morning of 5th (0830 IST), a DD in the afternoon of 5th (1430 IST) and D in the late evening (2030 IST) of same day. It crossed South Gujarat coast between Surat and Dahanu as a well marked low around early morning (0530 IST) of 6th Dec.

The observed track of the VSCS Ockhi is shown in Fig. 2.1. The salient features of the system are as follows.

- **(i)** This was the fourth cyclonic storm developing over Comorin Sea (south of Kerala and Tamil Nadu and west of Sri Lanka). However, cyclone, Ockhi did not cross Tamil Nadu and Kerala coast and moved across Lakshadweep Islands. Previously two cyclones in 1912 and another in 1925 developed over Comorin Area **(Fig. 2.9.1).** All these cyclones affected south Kerala and south Tamil Nadu. However the cyclone during 19-21 Nov. 1912 moved across south Tamil Nadu and Kerala on 19th Nov. and the cyclone during 6-10 Nov. 1925 crossed north Kerala coast on 10th Nov. Other cyclone in 1912 skirted Kerala coast.
- **(ii)** Thus, it was a rare cyclone with rapid intensification in genesis stage (from depression to cyclonic storm within 24 hours).
- **(iii)** Ockhi had a clockwise recurving track. The track length of the cyclone was 2538 km.
- **(iv)** The 12 hourly average translational speed of the cyclone was 15.0 kmph. However, it moved faster in it's genesis stage (29/0830 IST to 30/0830 IST) with 12 hourly average translational speed of 19 kmph.
- **(v)** The life period of cyclone was 6 days & 18 hours against long period average of 4.7 days for very severe cyclonic storm over north Indian Ocean.
- **(vi)** The peak maximum sustained surface wind speed (MSW) of the cyclone was 150-160 kmph gusting to 175 kmph (85 knots) during 0600 UTC of 2nd to 0000 UTC of 3rd December.

(vii) The lowest estimated central pressure was 976 hPa (from 0300 UTC of 2nd to 0000 UTC of 3rd December) with a pressure drop of 34 hPa.

(viii) The Velocity Flux associated with the system was 13.6X10^{2} knots against the normal of 19.76 x10^{2} over north Indian Ocean for post monsoon season based on data of 1990-2013.

(ix) The Accumulated Cyclone Energy (ACE) which is a measure of damage potential was about 9.29 X 10^{4} knot^{2} against the normal of 9.0 x 10^{4} over north Indian Ocean for post monsoon season based on data of 1990-2013.

(x) The Power Dissipation Index which is a measure of loss due to a cyclone was 6.63 X 10^{6} knot^{3} against the normal of 5.3 x 10^{6} over north Indian Ocean for post monsoon season based on data of 1990-2013.

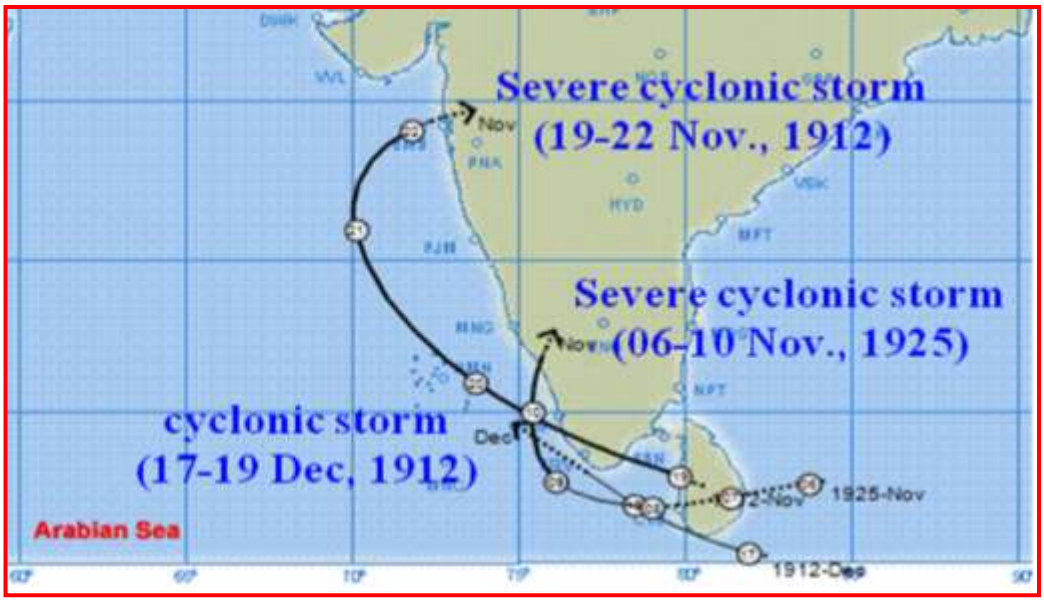


Fig. 2.9.1: Climatological tracks of cyclones affecting Kerala and Kanyakumari during 1891-2016.

2.9.2. Monitoring of VSCS,'Ockhi'

The system was monitored & predicted continuously by India Meteorological Department (IMD) as it maintained round the clock watch and prepared a daily report on the diagnostics and prognostics of possible development of cyclogenesis commencing from 15th October 2017. A trough of low lay over southwest BOB and adjoining equatorial Indian Ocean off Southeast Sri Lanka coast on 27th November. Subsequent formation of low pressure area over southwest BOB and adjoining south Sri Lanka & adjoining equatorial Indian Ocean occurred on 28th November. At the genesis stage, the system was monitored mainly with satellite observations from INSAT 3D, 3DR, SCATSAT and ASCAT alongwith available ships, buoy and coastal observations. The system was also monitored by Doppler Weather Radar Chennai, Thiruvananthapuram, Karaikal, Kochi, Goa and Mumbai.

Various national and international NWP models and dynamical-statistical models were utilized to predict the genesis, track and intensity of the cyclone. IMD operationally runs a regional model, WRF for short-range prediction and one Global model GFS T1534 for medium range prediction (10 days). GFS model has been introduced in 2010, which is extensively used for short to medium range forecast of cyclones over the north Indian Ocean. It's resolution has been improved to 12 km since 2017 to provide forecast upto 7 days. The WRF-VAR model is run at the horizontal resolution of 27 km, 9 km and 3 km with 38 Eta levels in the vertical and the integration is carried up to 72 hours over three domains covering the area between lat. 25^0S to 45^0 N long 40^0 E to 120^0 E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 12 km. The boundary conditions are updated at every six hours interval.

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. Apart from the observations that are used in the earlier system, the new observations assimilated at NCMRWF include (i) Precipitation rates from SSM/I and TRMM (ii) GPSRO occultation (iii) AIRS and AMSRE radiances (iv) MODIS winds. Additionally ASCAT ocean surface winds and INSAT-3D AMVs are also assimilated. NCUM (N768/L70) model features a horizontal resolution of 17km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. NCUM is a grid point model which has a Non-hydrostatic dynamics with a deep atmosphere suitable for all scales. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. It features mass-flux for shallow convection with convective momentum transport, non-local mixing and entrainment for boundary layer. (For additional details refer to http://www.ncmrwf.gov.in/). NCMRWF Ensemble Prediction System (NEPS) is a global medium-range probabilistic forecasting system adapted from UK MET Office. The configuration consists of four cycles of assimilation corresponding to 00Z, 06Z, 12Z 18Z and 10-day forecasts are made using the 00Z initial condition. The N400L70 forecast model consists of 800x600 grid points on the horizontal surface and has 70 vertical levels. Horizontal resolution of the model is approximately 33 km in the midlatitudes. The 10-day control forecast run starts with N768L70 analysis of the deterministic assimilation forecast system and 44 ensemble members start from different perturbed initial conditions consistent with the uncertainty in initial conditions. The initial perturbations are generated using Ensemble Transform Kalman Filter (ETKF) method (Bishop et al., 2001). An important component common to both the deterministic (NCUM) and ensemble model (NEPS) is that they do not use any TC relocation in the analysis. However, the ACCESS-TC model features TC relocation. The Met Office bi-variate approach to tracking TCs is used in the real-time to track the location of the CS 'Vardah'. This method is in contrast to the earlier operational National Centers for Environmental Prediction (NCEP) who use any or all of MSLP, 850 hPa and 700 hPa RV and geopotential height to track tropical cyclones (Marchok, 2002). The bi-variate method identifies TCs by examination of the 850RV field but then fixes the TC center to the nearest local MSLP minimum (Hamming,2016). This is the adopted method in Met Office UK. The key advantage of the method is that it gives a strong signal of the approximate center of the TC even for weak systems and does not depend on the '*tcvitals*' information for tracking.

IMD also makes use of NWP products prepared by some other operational NWP centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency). Hurricane WRF (HWRF) model and Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

In addition to the above NWP models, IMD also run operationally dynamical statistical models. The dynamical statistical models have been developed for (a) Cyclone

Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and I Predicting decay in intensity after the landfall. Genesis potential parameter (GPP) is used for predicting potential of cyclogenesis (T3.0) and forecast for potential cyclogenesis zone. The multi-model ensemble (MME) for predicting the track (at 12h interval up to 120h) of tropical cyclones for the Indian Seas is developed applying multiple linear regression technique using the member models IMD-GFS, IMD-WRF, GFS (NCEP), ECMWF and JMA. The SCIP model is used for 12 hourly intensity predictions up to 72-h and a rapid intensification index (RII) is developed and implemented for the probability forecast of rapid intensification (RI). Decay model is used for prediction of intensity after landfall. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclone Ockhi are presented and discussed.

IMD also runs cyclone specific Hurricane-WRF model for Tropical Cyclone track and intensity forecast over 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 Ocean 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). The Princeton 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. During cyclone Ockhi, the forecast was generated using POM-TC model. The model is run on real time six hourly basis 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-T1534L64 analysis/forecast as first guess. The model is run with a resolution of 18km, 6km, and 2km from post-monsoon season in 2016.

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. IMD issued regular bulletins to WMO/ESCAP Panel member countries including Sri Lanka and Maldives, National & State Disaster Management Agencies, general public and media since inception of the system over BOB till it's weakening.

Brief environmental conditions prior to genesis of system over BoB, life history of VSCS Ockhi, characteristic features and associated weather alongwith performance of various NWP models and operational forecast of IMD are presented and discussed in following sections.

2.9.3. Prevalent conditions over Bay of Bengal prior to genesis of cyclone, Ockhi

Due to active inter-tropical convergence zone (ITCZ) and associated meso-scale convection, the trough in easterly winds or low pressure systems developed over the southern part of BoB and moved westwards causing rainfall activity over the southern peninsular India in regular intervals. In this scenario, a low pressure area formed over Andaman Sea on 22nd Nov., under the influence of a remnant upper air cyclonic circulation

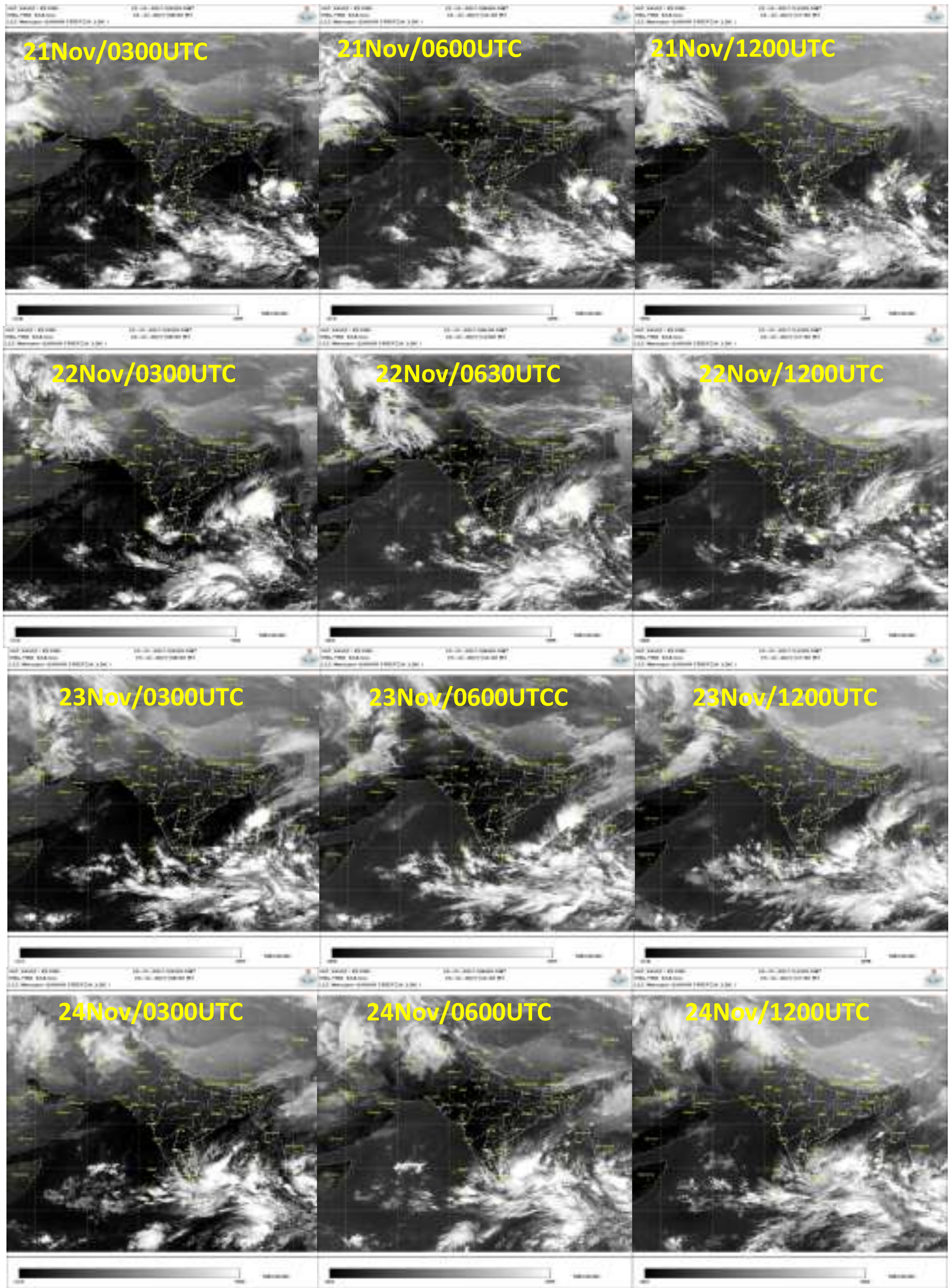


Fig. 2.9.2:. INSAT-3D (IR) imageries during 21st to 30th Nov. 2017

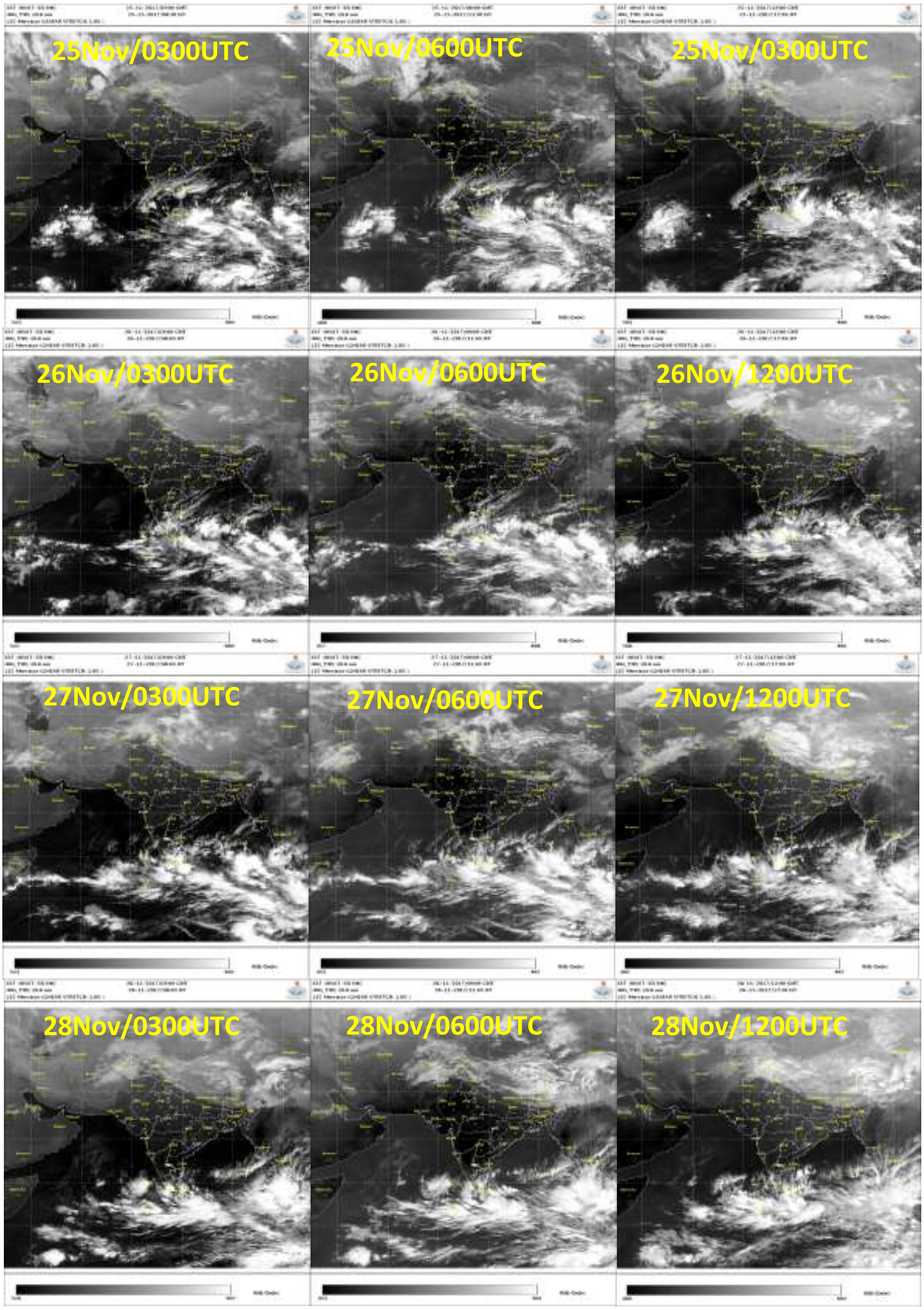


Fig. 2.9.2:.(Cont.) INSAT-3D (IR) imageries during 21st to 28th Nov. 2017

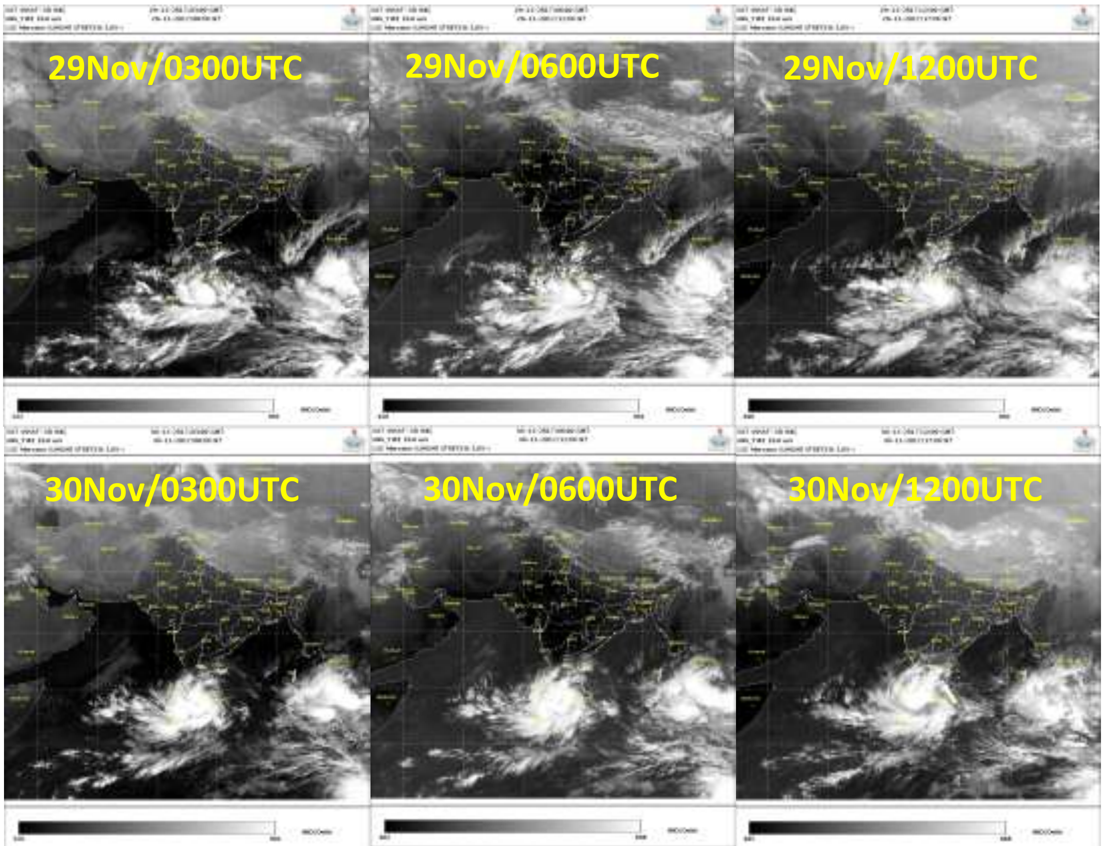


Fig. 2.9.2:.(contd.) INSAT-3D (IR) imageries during 29th to 30th Nov. 2017

from Gulf of Thailand. It lay over southeast and adjoining eastcentral BoB on 23rd, central part of south BoB on 24th, southwest BoB and adjoining equatorial Indian Ocean on 25th, southwest BoB and adjoining southeast Sri Lanka on 26th. It weakened and lay as a trough of low over southeast Arabian Sea and adjoining Maldives on 27th and over southeast Arabian Sea and adjoining Lakshadweep & Maldives on 28th Nov. 2017. It then moved away westwards and became less marked. It caused scattered heavy to very heavy rainfall over Tamil Nadu on 26th Nov and Kerala received isolated heavy rainfall on 26th and 27th.

Hence there was no remnant of any circulation system moving from Gulf of Thailand that intensified near Sri Lanka and later became cyclone, Ockhi over Comorin Sea. To justify the above, the INSAT-3D (IR) imageries during 21st to 30th Nov. 2017 are shown in Fig. 2.9.2. The environmental parameters like low level relative vorticity, lower level convergence, upper level divergence and vertical wind shear, SST and Ocean heat content during the period 27th-30th are shown in Fig. 2.9.3 (a-f) (Source: CIMSS Tropical Cyclones, http://tropic.ssec.wisc.edu/ and http://www.aoml.noaa.gov/phod/cyclone/data/ni.html). The variation of these parameters during 21st November -6th December is presented in Fig. 2.9.**3** g). The MJO index during the life period of Ockhi is presented in Fig. 2.9.**4** (Source: Climate Prediction Centre, NOAA, http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/CLIVAR/clivar_wh.shtml). These figures also indicate in-situ cyclogenesis of Ockhi on 29th over southwest BoB off southeast Sri Lanka coast.

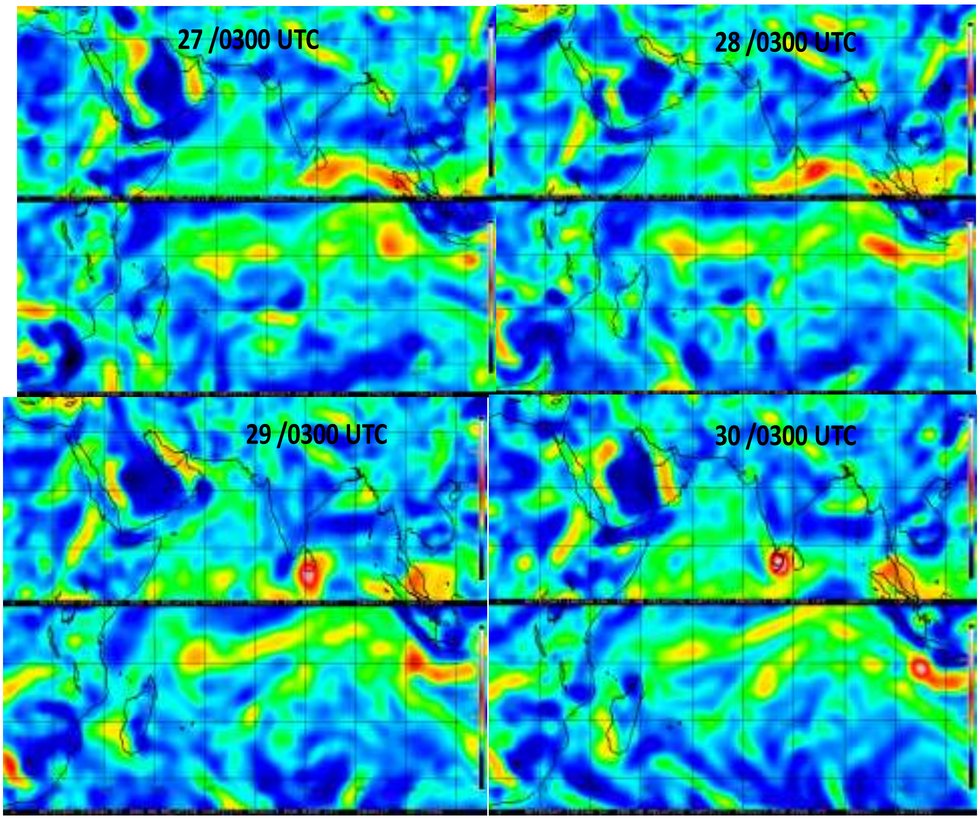


Fig. 2.9.3 (a) Vorticity at 850 hpa level based on 0300 UTC during the period 27th-30th.

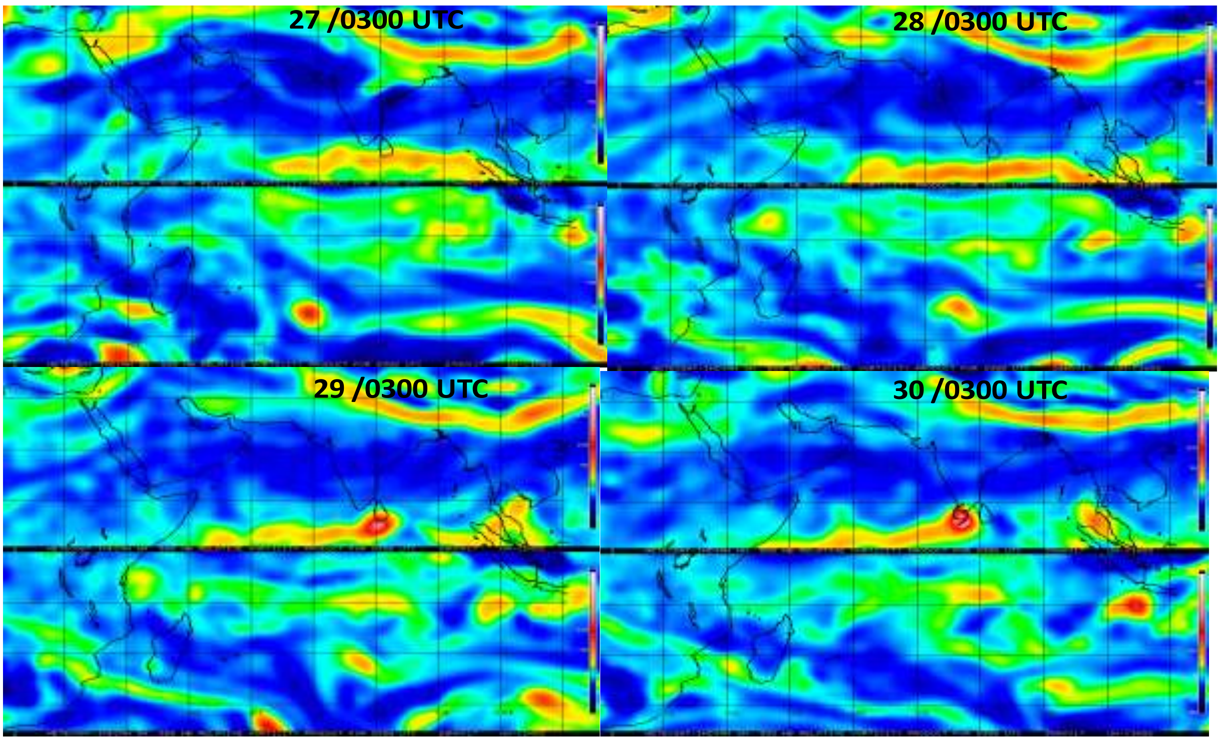


Fig. 2.9.3(a) (contd.) Vorticity at 200 hpa level during the period 27th-30th.

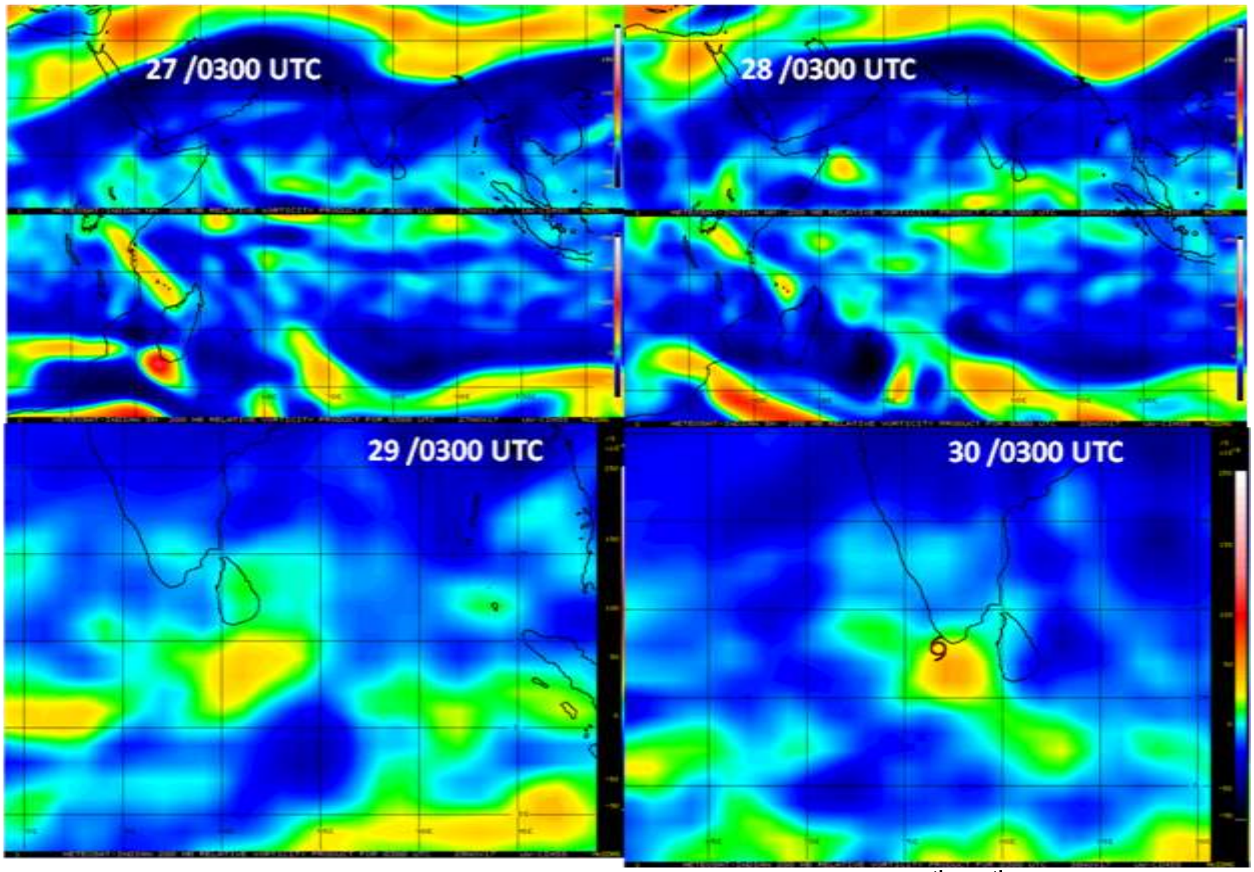


Fig. 2.9.3(a) (contd.) Vorticity at 500 hpa level during the period 27th-30th.

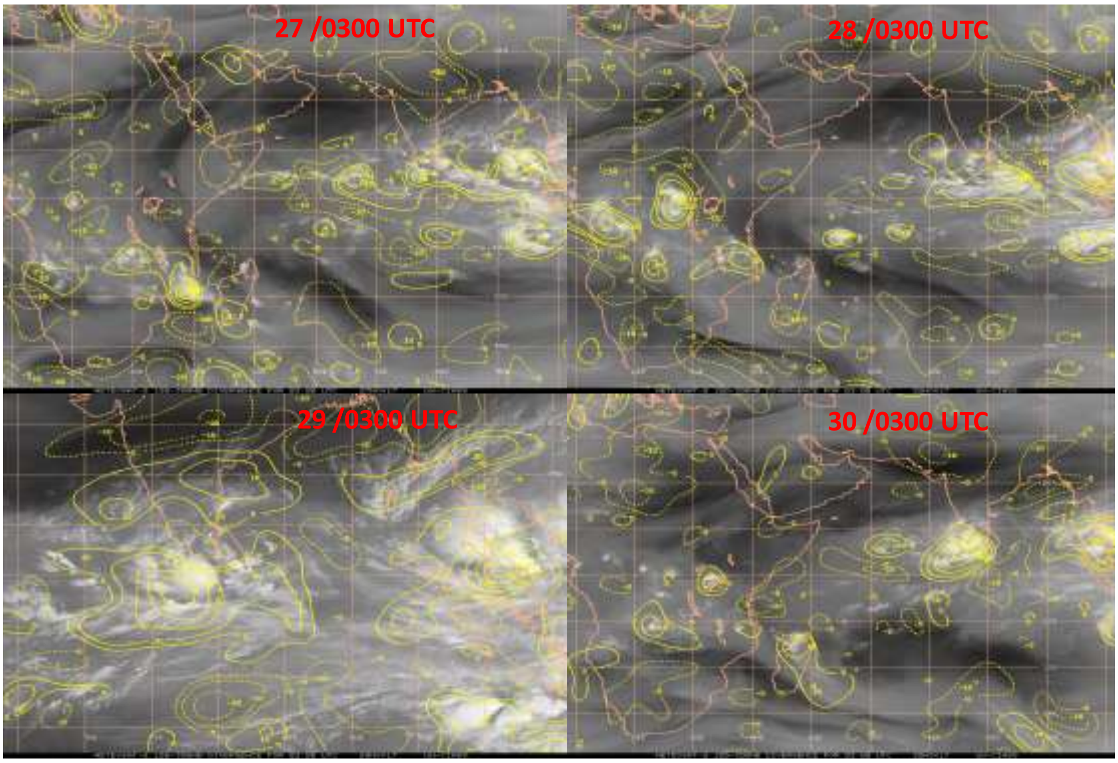


Fig. 2.9.3(b) Lower Level Convergence based on 0300 UTC during the period 27th-30th.

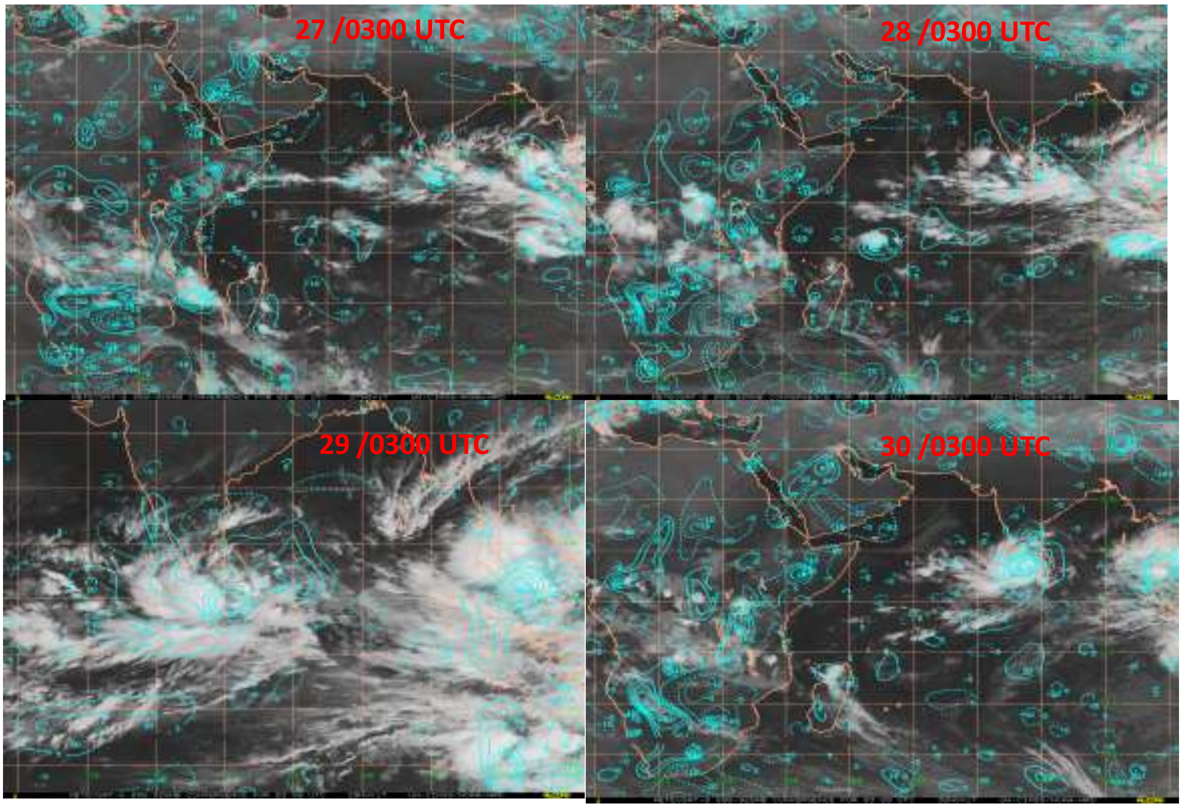


Fig. 2.9.3(c): Upper Level Divergence based on 0300 UTC during the period 27th-30th.

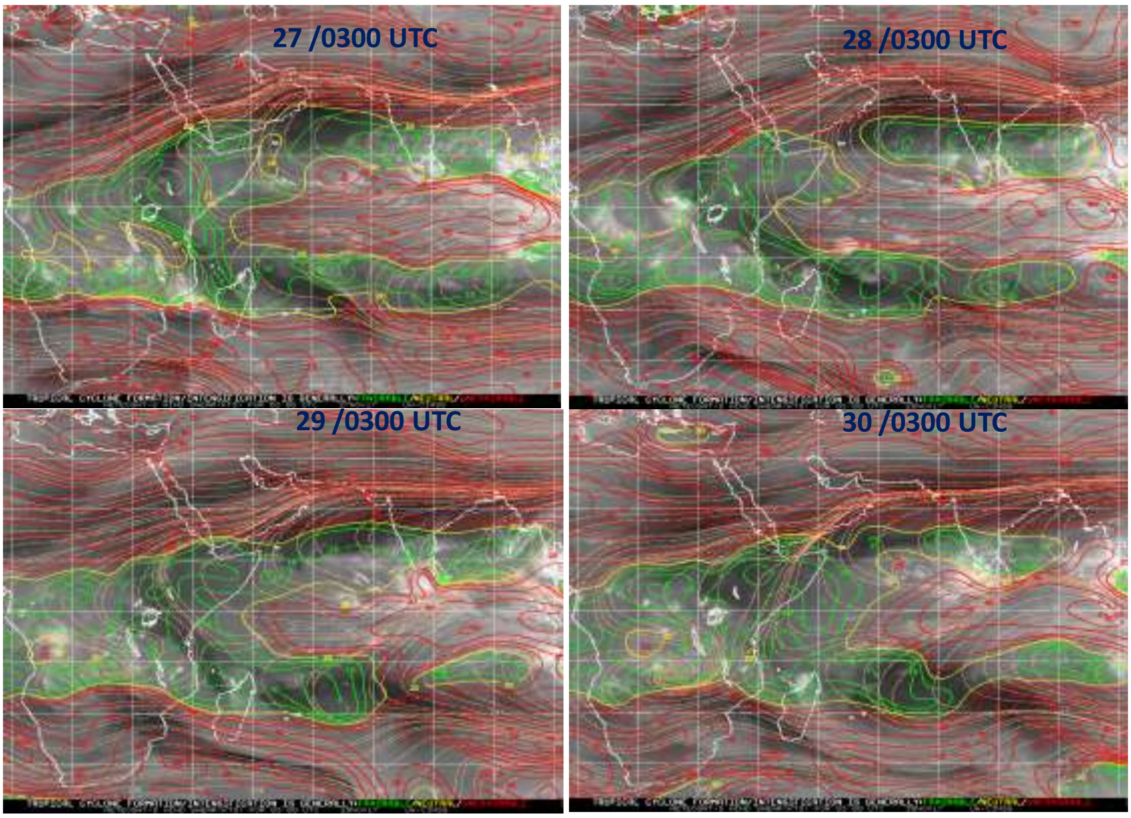


Fig. 2.9.3(d): Vertical wind shear based on 0300 UTC of during the period 27th-30th.

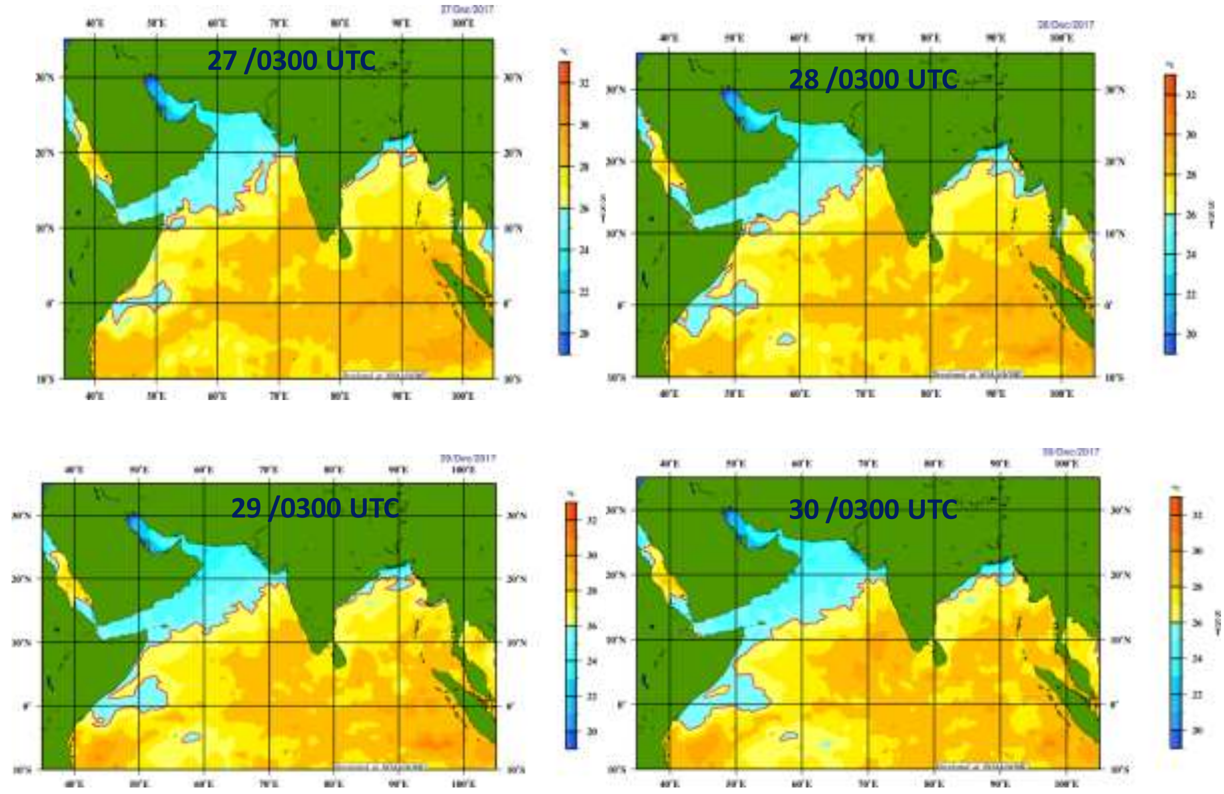


Fig. 2.9.3(e): Sea Surface Temperature (SST) during 27th-30th

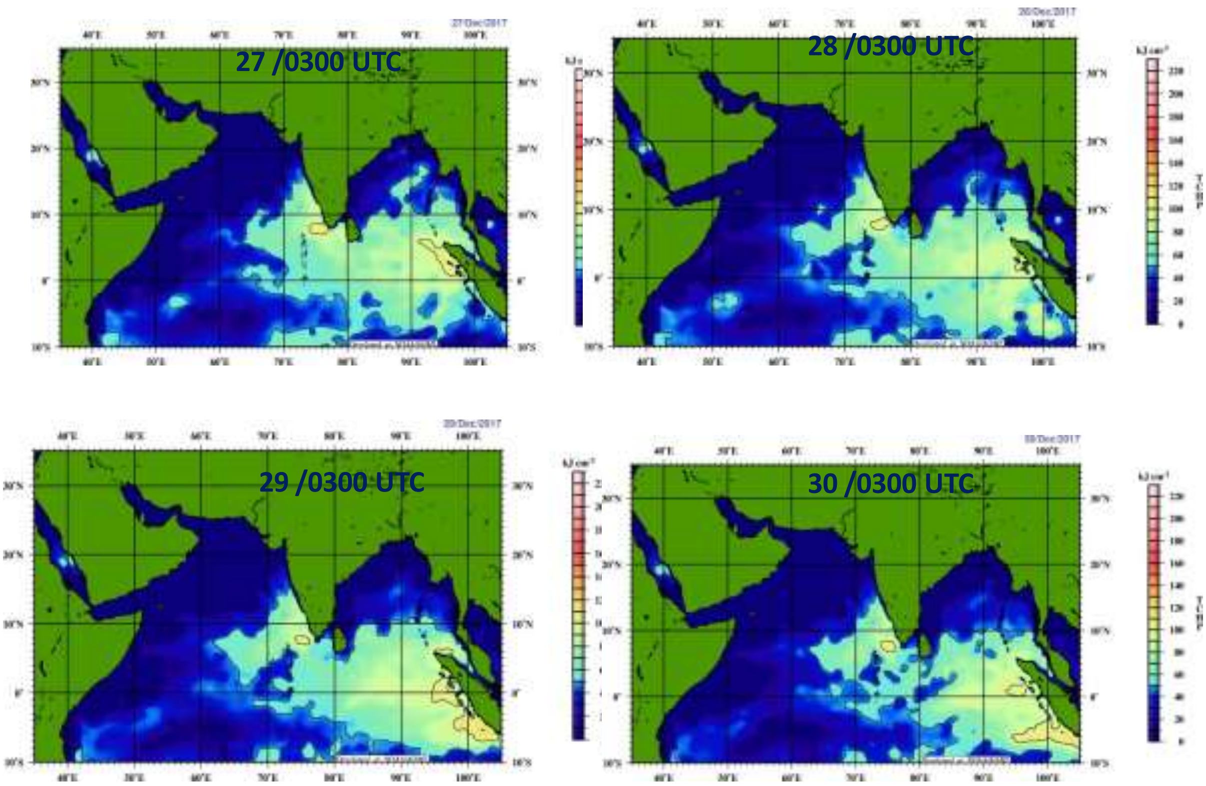


Fig. 2.9.3(f): Ocean Heat Content during the period 27th-30th.

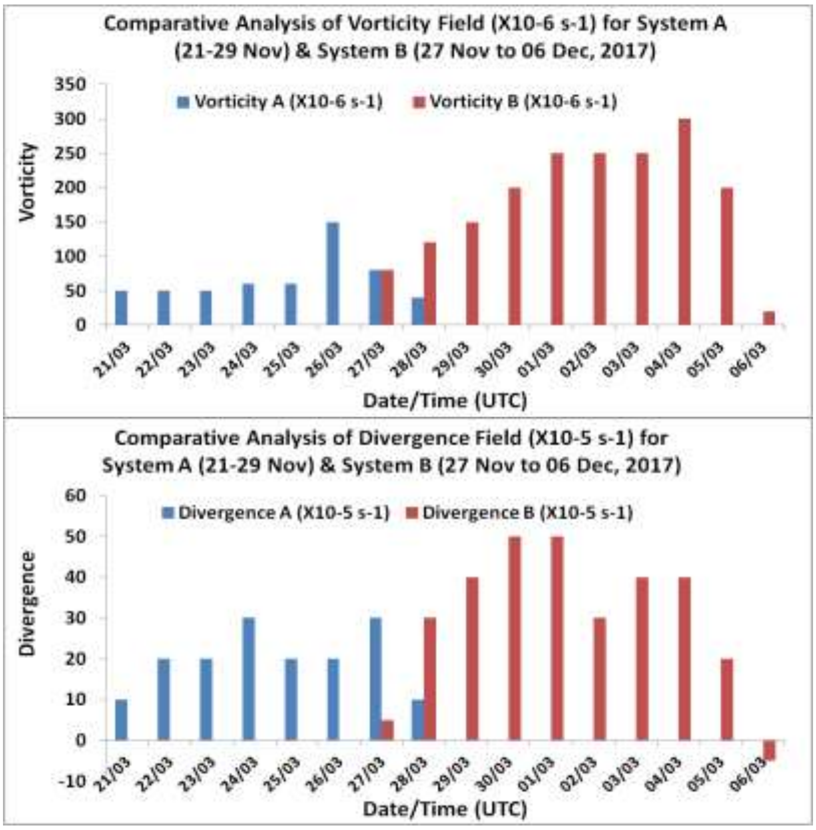


Fig. 2.9.3 (g): Comparative analysis of vorticity and divergence fields during 21-29 Nov and 27-06 Dec for the systems A (prior to genesis of Ockhi) and system B (Ockhi)

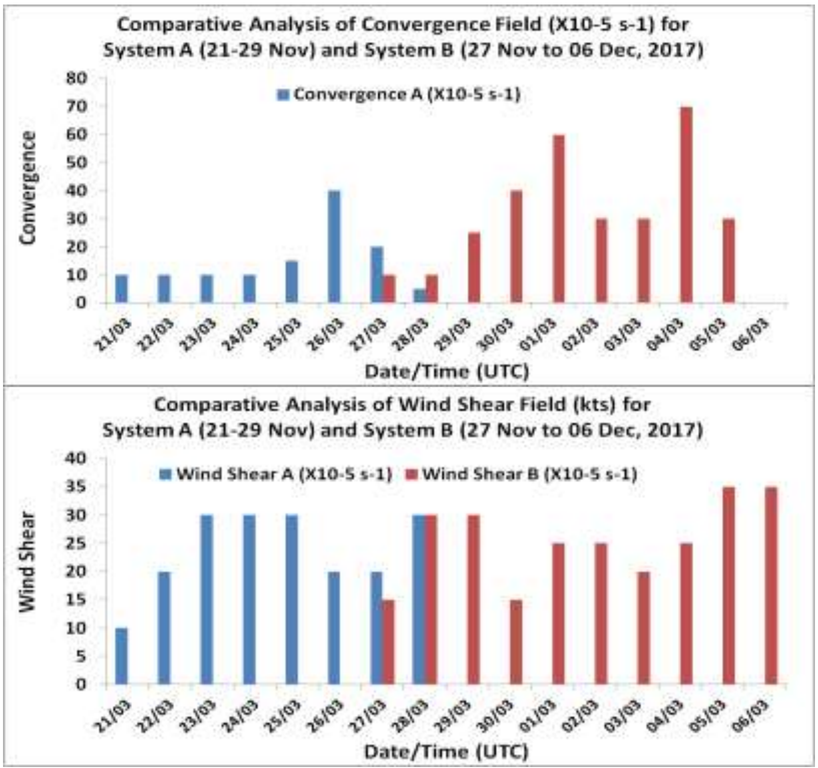


Fig. 2.9.3 (g) (contd.): Comparative analysis of convergence and wind shear fields during 21-29 Nov and 27 Nov-06 Dec for the systems A (prior to genesis of Ockhi) & system B (Ockhi)

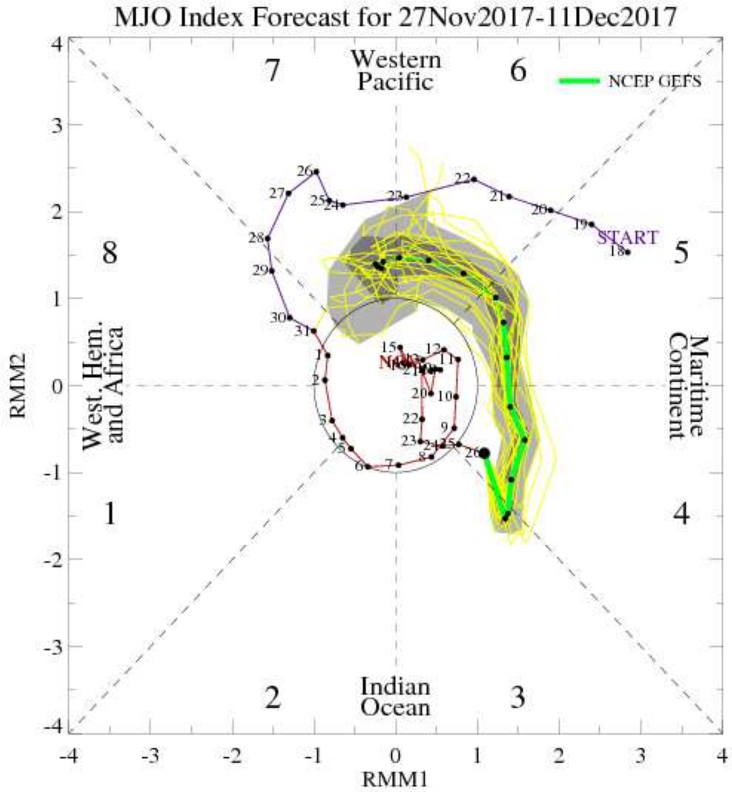


Fig. 2.9.4: MJO during the period 26th-Nov. to 10th Dec.

2.9.4. Brief life history of Ockhi

2.9.4.1. Genesis

At 0300 UTC of 27th, the sea surface temperature (SST) over southwest BoB and adjoining Sri Lanka coast was around 28-29˚C. The Ocean thermal energy was around 60-80 KJ/cm^2 over south of Comorin, 80-100 KJ/cm^2 over Comorin Area and >100 KJ/cm^2 over southwest Sri Lanka. The low level convergence was about 20x10^{-5} second^{-1} to the south of Comorin, the upper level divergence was around 30x10^{-5} second^{-1} to the south of Comorin, and the low level relative vorticity was about 80x10^{-6} second^{-1} to the southeast of Srilanka with vertical extension upto 500 hPa levels. The vertical wind shear of horizontal wind was low to moderate (5-10 knots) over southwest BoB off north Sri Lanka coast, 15-20 knots over east Comorin & adjoining Palk Strait, 20-30 knots over west Comorin and south. The Madden Julian Oscillation (MJO) index was in phase 4 with amplitude >1. The upper tropospheric ridge at 200 hPa level lay along 14^{0}N near 80^{0}E. Under these environmental conditions, a trough of low developed over southwest BoB and adjoining Sri Lanka on 27th November. At 0300 UTC of 28th, similar thermal conditions prevailed over southwest BoB and adjoining Sri Lanka coast. However, dynamical features over southwest BoB off Sri Lanka coast organized. The low level convergence was about 10x10^{-5} second^{-1} to the northeast and south of Sri Lanka. The upper level divergence was around 30x10^{-5} second^{-1} to the southeast of Sri Lanka. The low level relative vorticity increased to 120x10^{-6} second^{-1} over southwest BoB off south Srilanka with vertical extension upto 200 hPa level. The vertical wind shear of horizontal wind was moderate to high (15-30 knots) over southwest BoB and adjoining Sri Lanka coast. The MJO index continued in phase 4 with amplitude >1. The upper tropospheric ridge at 200 hPa level lay along 13^{0}N near 80^{0}E. All these conditions favoured the formation of low pressure area over southwest BoB and adjoining areas of south Sri Lanka & equatorial Indian Ocean in the forenoon (0830 IST) of 28th November.

At 0000 UTC of 29th, the sea surface temperature (SST) over southwest BoB and adjoining Sri Lanka coast was around 28-29˚C. The Ocean thermal energy was around 60-80 KJ/cm^2 over southwest BoB adjoining southeast Sri Lanka & south Comorin area and >80 KJ/cm^2 over north Comorin. However, dynamical features over southwest BoB off Sri Lanka coast further organized. The low level convergence was about 20x10^{-5} second^{-1} to the south of Sri Lanka near 5^{0}N. The upper level divergence increased and was around 40x10^{-5} second^{-1} to the south of Comorin. The low level relative vorticity increased and was about 150x10^{-6} second^{-1} to the south of Sri Lanka and adjoining coast with vertical extension upto 200 hPa level. The vertical wind shear of horizontal wind was high (30 knots) over Comorin and 15-20 knots over southwest BoB off southeast Sri Lanka coast. The wind shear over southwest BOB off southeast Sri Lanka coast showed decreasing tendency of about 10-20 knots during past 24 hrs. It showed increasing tendency of 5-10 knots over Comorin area. The MJO index continued in phase 4 with amplitude >1. The upper tropospheric ridge at 200 hPa level lay along 15^{0}N. All these conditions led to concentration of low into a Depression at 0830 IST of 29th, with centre near 6.5º N/81.8 ºE, about 80 km to the east-southeast of Hambantota (Sri Lanka) and 500 km east southeast of KanyaKumari (Tamil Nadu).

The best track parameters of the systems are presented in Table 2.9.1**.**

Table 2.9.1: Best track positions and other parameters of the Very Severe Cyclonic Storm, 'Ockhi' over the Bay of Bengal during 29 Nov-05 Dec, 2017

Date	**Time (UTC)**	**Centre lat.^{0} N/ long. ^{0} E**	**C.I. NO.**	**Estimated Central Pressure (hPa)**	**Estimated Maximum Sustained Surface Wind (kt)**	**Estimated Pressure drop at the Centre (hPa)**	**Grade**
29/11/2017	0300	6.5/81.8	1.5	1004	25	3	**D**
	0600	6.5/80.4	1.5	1004	25	4	D
	1200	6.2/80.0	1.5	1002	25	4	D
	1800	6.3/79.2	1.5	1002	25	4	D
	2100	6.5/78.6	2.0	1001	30	5	**DD**
30/11/2017	0000	6.7/78.3	2.0	1000	30	6	DD
	0300	7.5/77.5	2.5	999	35	7	**CS**
	0600	7.8/76.9	2.5	998	40	8	CS
	0900	7.9/76.4	3.0	996	45	10	CS
	1200	8.2/75.8	3.0	996	45	10	CS
	1500	8.3/75.4	3.0	996	45	10	CS
	1800	8.5/74.9	3.0	994	45	12	CS
	2100	8.6/74.5	3.0	994	45	12	CS
01/12/2017	0000	8.8/74.0	3.0	992	50	14	**SCS**
	0300	8.9/73.8	3.5	990	55	16	SCS
	0600	9.0/73.4	3.5	989	60	18	SCS
	0900	9.1/73.0	4.0	988	65	21	**VSCS**
	1200	9.2/72.8	4.0	986	65	22	VSCS
	1500	9.3/72.5	4.0	984	65	24	VSCS
	1800	9.4/72.1	4.0	982	70	26	VSCS

	2100	9.5/71.8	4.0	980	75	28	VSCS
02/12/2017	0000	9.6/71.5	4.5	978	80	30	VSCS
	0300	9.7/71.2	4.5	978	80	32	VSCS
	0600	9.8/71.0	4.5	976	85	34	VSCS
	0900	10.2/70.6	4.5	976	85	34	VSCS
	1200	10.5/70.3	4.5	976	85	34	VSCS
	1500	10.8/70.0	4.5	976	85	34	VSCS
	1800	11.1/69.7	4.5	976	85	34	VSCS
	2100	11.3/69.5	4.5	976	85	34	VSCS
03/12/2017	0000	11.7/69.2	4.5	976	85	34	VSCS
	0300	12.1/69.0	4.5	977	80	32	VSCS
	0600	12.3/68.9	4.5	978	75	30	VSCS
	0900	12.4/68.8	4.5	980	75	28	VSCS
	1200	12.9/68.7	4.5	982	75	28	VSCS
	1500	13.1/68.6	4.5	982	75	28	VSCS
	1800	13.5/68.5	4.5	982	75	28	VSCS
	2100	14.0/68.5	4.5	982	75	28	VSCS
04/12/2017	0000	14.5/68.5	4.0	984	70	24	VSCS
	0300	14.7/68.5	4.0	986	65	22	VSCS
	0600	14.9/68.7	4.0	986	65	22	VSCS
	0900	15.2/69.0	4.0	986	65	22	VSCS
	1200	15.7/69.2	3.5	988	60	18	VSCS
	1500	16.1/69.5	3.5	988	60	18	VSCS
	1800	16.5/69.8	3.5	990	55	16	**SCS**
	2100	16.9/70.1	3.5	992	55	14	SCS
05/12/2017	0000	17.3/70.4	3.5	994	50	12	SCS
	0300	17.7/70.7	3.0	996	45	10	**CS**
	0600	18.1/71.0	2.5	998	40	08	CS
	0900	18.3/71.2	2.0	1000	30	06	**DD**
	1200	18.5/71.4	2.0	1002	30	05	DD
	1500	18.8/71.6	1.5	1003	25	04	**D**
	1800	19.2/71.9	1.5	1004	20	03	D
	2100	**Weakened into a well marked low pressure area over northeast and adjoining east central Arabian Sea, south coastal Gujarat and north coastal Maharashtra**					

2.9.4.2. Intensification

As east-northeasterly to easterly winds prevailed over mid to upper tropospheric levels, the system moved westwards, crossed Sri Lanka coast and emerged into Comorin area in the evening (1730 IST) of 29th. At 1800 UTC of 29th, the upper tropospheric ridge ran along latitude 14^{0}N. The upper level winds were nearly easterly over the system region and were becoming east-southeasterly over southeast Arabian Sea. The system thus moved initially nearly westwards and then west-northwestwards. The SST over the region was 28-29 ^{0}C. The Ocean thermal energy was about 100 KJ/cm^{2} over the area. The vertical wind shear was low to moderate (10-20 knots) around the system centre. It was increasing to west and to the south. The low level relative vorticity was around 200 x 10^{-6} s^{-1} to the southwest of the system centre. Low level convergence was around 60 x 10^{-5} s^{-1} to the southwest of the system centre. Upper level divergence was about 50 x 10^{-5} s^{-1} to the southwest of the system center. Under these conditions, the system intensified into a deep depression at 2100 UTC of 29^{th} and lay centered over Comorin area and neighbourhood near 6.5ºN/78.6ºE, about 185 km northwest of Galle (Sri Lanka) and 210 km south-southeast of Kanyakumari (Tamil Nadu).

With the similar favorable environmental conditions, the system moved west-northwestwards and intensified from DD into a CS over Comorin Area within six hours and lay near 7.5ºN/77.5ºE, about 340 km west-northwest of Galle, 60 km south of Kanyakumari, 120 km southwest of Thiruvananthapuram (43372) and 480 km east-southeast of Minicoy (43369) at 0300 UTC of 30^{th} Nov. The observations indicated that there was continuous fall of pressure over entire India, being maximum over southern Peninsular India and Sri Lanka within 4 hPa till 1200 UTC of 29^{th}. It further dropped to 4-6 hPa at 0300 UTC of 30^{th}.There was also continuous negative departure of pressure from normal over entire India, being maximum over south Peninsula (within 4 hPa till 29/1200 UTC and by 8 hPa at 30/0300 UTC).

The upper tropospheric ridge shifted gradually northwards and at 0000 UTC of 1^{st} December, it ran along latitude 17^0N. The winds were nearly southeasterly over southeast Arabian Sea. The SST over the region was 28-30^0C. The Ocean thermal energy was about 100 KJ/cm^2 over the area. The vertical wind shear increased and was moderate (20-25 knots) around the system centre. The low level relative vorticity increased and was about 250x10^{-6} s^{-1} around the system centre. Low level convergence was around 30x10^{-5} s^{-1} to the south of system centre and upper level divergence was about 50 x 10^{-5} s^{-1} to the south of the system centre. MJO index lay in phase 4 with amplitude more than 1. Under these conditions, the system moved west-northwestwards, intensified into a severe cyclonic storm and lay centered over southeast Arabian Sea near latitude 8.8ºN/74.0ºE, about 110 km north-northeast of Minicoy (Lakshadweep Island) at 0000 UTC of 1^{st} Dec.

At 0900 UTC of 1^{st} December, the system moved west-northwestwards, further intensified into a very severe cyclonic storm and lay centred over Lakshadweep area and adjoining southeast Arabian Sea near latitude 9.1ºN/73.0ºE, about 90 km north of Minicoy (Lakshadweep Island). The upper tropospheric ridge ran along latitude 15^0N. The winds at upper level were southeasterly over southeast Arabian Sea. The SST over the region was 28-30 ^{0}C. The Ocean thermal energy was about 100 KJ/cm^2 over the area. The vertical wind shear further increased and was high (20-25 knots) around the system centre. It was decreasing to the north of system centre. The low level relative vorticity was around 250x10^{-6} s^{-1} around the system centre. Low level convergence was around 30x10^{-5} s^{-1} to the southwest of system centre. Upper level divergence also decreased and was about 30 x 10^{-5} s^{-1} to the southwest of the system centre. Though the vertical wind shear was unfavorable and there was decrease in upper level divergence, the system continued to intensify due to favorable relative vorticity, MJO and high Ocean heat content and reached its maximum intensity of 85 knots at 0600 UTC of 2^{nd} Dec. and lay over Lakshadweep area and adjoining southeast Arabian Sea near latitude 9.8ºN/71.0ºE.

At 0600 UTC of 2^{nd}, the SST over the region was 29-30 ^{0}C. The ocean thermal energy was about 75-100 KJ/cm^2 over the area. It decreased towards the north. The low level relative vorticity was around 250x10^{-6} s^{-1} to the south of the system centre. Low level convergence was about 30x10 $^{-5}$ s^{-1} around the system centre. Upper level divergence was about 30 x 10 $^{-5}$ s^{-1} to the southwest of the system centre. The vertical wind shear was high.

From early morning of 3rd December, the system entered into an area of lower Ocean Heat content. At 0300 UTC of 3rd, the SST over the region was 28-29 ^{0}C. However, the ocean thermal energy was about 60-70 KJ/cm^{2} over the area. It was decreasing towards the north. Though the low level relative vorticity was around 300x10^{-6} s^{-1} to the southwest of the system centre, low level convergence was around 30x10 $^{-5}$ s^{-1} to the southwest of the system centre, upper level divergence was about 30 x 10 $^{-5}$ s^{-1} to the northwest of the system centre and the vertical wind shear was moderate to high (15-25 knots) around the system centre and it was increasing towards north. Under these conditions, the system moved north-northwestwards and started weakening. It lay over eastcentral and adjoining southeast Arabian Sea near latitude 12.1ºN and longitude 69.0ºE at 0300UTC of 3rd. The system was steered by peripheral winds in association with anticyclone over BoB.

At 0300 UTC of 4th, the low level relative vorticity was about 300x10^{-6} s^{-1} to the south of the system centre. Low level convergence was about 40x10 $^{-5}$ s^{-1} around the system centre. Upper level divergence was about 70 x 10 $^{-5}$ s^{-1} around the system centre. The vertical wind shear was high (20-30 knots) around the system centre. The wind shear was increasing towards north. The SST over the region was 27-28^{0}C. The Ocean thermal energy was about 30-50 KJ/cm^{2} over the area. It was further decreasing towards the north. Total precipitable water (TPW) imagery at that time indicated cold and dry air entering into the system. The warm and moist air advection to the system centre showed gradual decrease. The system was steered by winds at the periphery of the anti cyclone over BoB and a deep trough in middle and upper tropospheric levels running along 60^{0}E to the north of 17^{0}N. All these features indicated that Ocean heat content supported with high vertical wind shear helped in further weakening of the system with north-northeastward movement.

At 1200 UTC of 4th, the low level relative vorticity decreased and was about 200x10^{-6} s^{-1} to the southeast of the system centre. Low level convergence decreased and was around 30x10 $^{-5}$ s^{-1} to the northeast of the system centre. Upper level divergence decreased and was about 30 x 10 $^{-5}$ s^{-1} to the northeast of the system centre. The vertical wind shear was high (25-30 knots) around the system centre and it showed increasing tendency towards north. The SST over the region was 28-29 ^{0}C. It was decreasing to the north becoming 25-26 ^{0}C off Gujarat coast. The ocean thermal energy was about 30-50 KJ/cm^{2} over the area and it was further decreasing towards the north. There was dry and cold air intrusion of mid-latitude westerlies in the middle and upper tropospheric levels. The TPW imagery at that time indicated cold and dry air entering into the system. The warm and moist air advection to the system centre continued to decrease. Under these environmental conditions, the system continued to weaken. The total precipitable water imageries (TPW) during 29 November-05 December are presented in Fig.2.9.5.

There was gradual increase in dry and cold air intrusion from mid latitude westerlies, decrease in warm & moist air advection into the core of system, increase in vertical wind shear and decrease in Ocean thermal energy as the system moved north-northeastwards. There was also decrease in upper level divergence and lower level convergence. All these features led to weakening of the system into SCS at 1800 of 4th, CS at 0300 UTC of 5th, DD at 0900 UTC of 5th and D at 1500 UTC of same day. Finally, the system weakened into a well marked low pressure area over northeast Arabian Sea and adjoining eastcentral Arabian Sea, south coastal Gujarat and north coastal Maharashtra and crossed south coast of Gujarat between Surat and Dahanu as a well marked low around early morning (0000 UTC) of 6th Dec.

These imageries indicate continuous warm and moist air advection from southeast sector into the system till 30th night. The dry air enveloped the outer core of the system from north and west from 1st December. The same process continued on 2nd also with dry and cold air reaching upto southwest sector in the outer core region. Accordingly, the warm and moist air incursion was limited only from southeast sector. On 3rd, the warm and mosit air incursion from southeast sector further decreased significantly and by midnight of 3rd, the inner core was completely cut off from warm air advection and was completely surrounded by cold dry air. Accordingly, rapid weakening of the system started from early morning of 4^{th}.

To conclude, the intensification/weakening was largely governed by the Ocean heat content. However, the rapid weakening on 4^{th} and 5^{th} Dec was facilitated by dry & cold air intrusion and high vertical wind shear under the influence of a trough in mid-latitude westerlies in middle and upper tropospheric levels running along 60^0E to the north of 17^0N in the morning of 4^{th} Dec.

2.9.4.3. Movement

Under the influence of easterly winds prevailing over mid to upper tropospheric levels, VSCS Ockhi moved initially westwards till 0600 UTC of 29^{th}. Thereafter, it moved west-southwestwards till 1800 UTC of same day. From 2100 UTC of 29^{th}, the system moved west-northwestwards under the influence of east-southeasterly winds prevailing over southeast Arabian Sea. The system moved nearly northwards from 2100 UTC of 3^{rd} to 0300 UTC of 4^{th} and north-northeastwards thereafter, as the system was steered by winds in the periphery of the anticyclone over BoB and a deep trough in middle and upper tropospheric levels running along 60^0E to the north of 17^0N. The twelve hourly movement (speed & direction) of VSCS Ockhi is presented in Fig.2.9.6

The 12 hourly average translational speed of the cyclone was about 15.29 kmph. The system moved very fast during during 0000 to 1200 UTC of 30^{th} under the influence of strong easterly/ east-southeasterly winds prevailing over the region in middle and upper troposphere. The system had a track length of about 2538 km during its life period.

The mean wind in middle and deep layer around the system centre is presented in Fig.2.9.7 & 8. It indicates that the mean deep layer winds between 200-850 hPa levels steered the west-northwestward movement of the system from 1200 UTC of 29^{th} onwards, northward movement during early hours of 4^{th} and north-northeast movement thereafter. The initial westerly movement of the system was in association with the easterlies prevailing over southwest BoB in upper levels. The mean wind speed between 200-850 hpa levels was initially easterly till 1200 UTC of 30^{th}. Thereafter, it became east-southeasterly till 0300 UTC of 1^{st} December and southeasterly till 0000 UTC of 2^{nd}. It then gradually changed becoming southerly by 1200 UTC of 3^{rd} December and then south-southwesterly till it's dissipation. Considering the magnitude of mean wind speed between 200-850 hPa levels, it was 10kts initially, reaching about 13 kts by 1200 UTC of 30^{th}. Thereafter, the wind speed gradually decreased becoming minimum of 7kts at 1500 UTC of 2^{nd} December. It then gradually increased becoming 10 kts till 0000 UTC of 4^{th}. It then increased rapidly reaching upto 20 kts by 1200 UTC of 5^{th}. Considering the mean wind speed between 500-850 hPa levels, during genesis stage the variation was almost similar to that between 200-850 hPa levels. During genesis, it was around 7 kts. It then increased gradually reaching maximum of 12 kts at 1500 UTC of 30^{th} November. It then decreased gradually reaching minimum of 2 kts by about 1500 UTC of 2^{nd}. It then increased gradually reaching to 12 kts by 1200 UTC of 5^{th}. These features suggest that the steering wind changed with intensification/weakening of the system. During SCS and higher intensity stage, the system was steered by the mean wind between 200-850 hPa levels and during D/DD/CS stage, it was steered by 500-850 hPa levels wind. It is mainly due to the fact that with the lower intensity, the vertical extension of the system was less which was also indicated in the vorticity field.

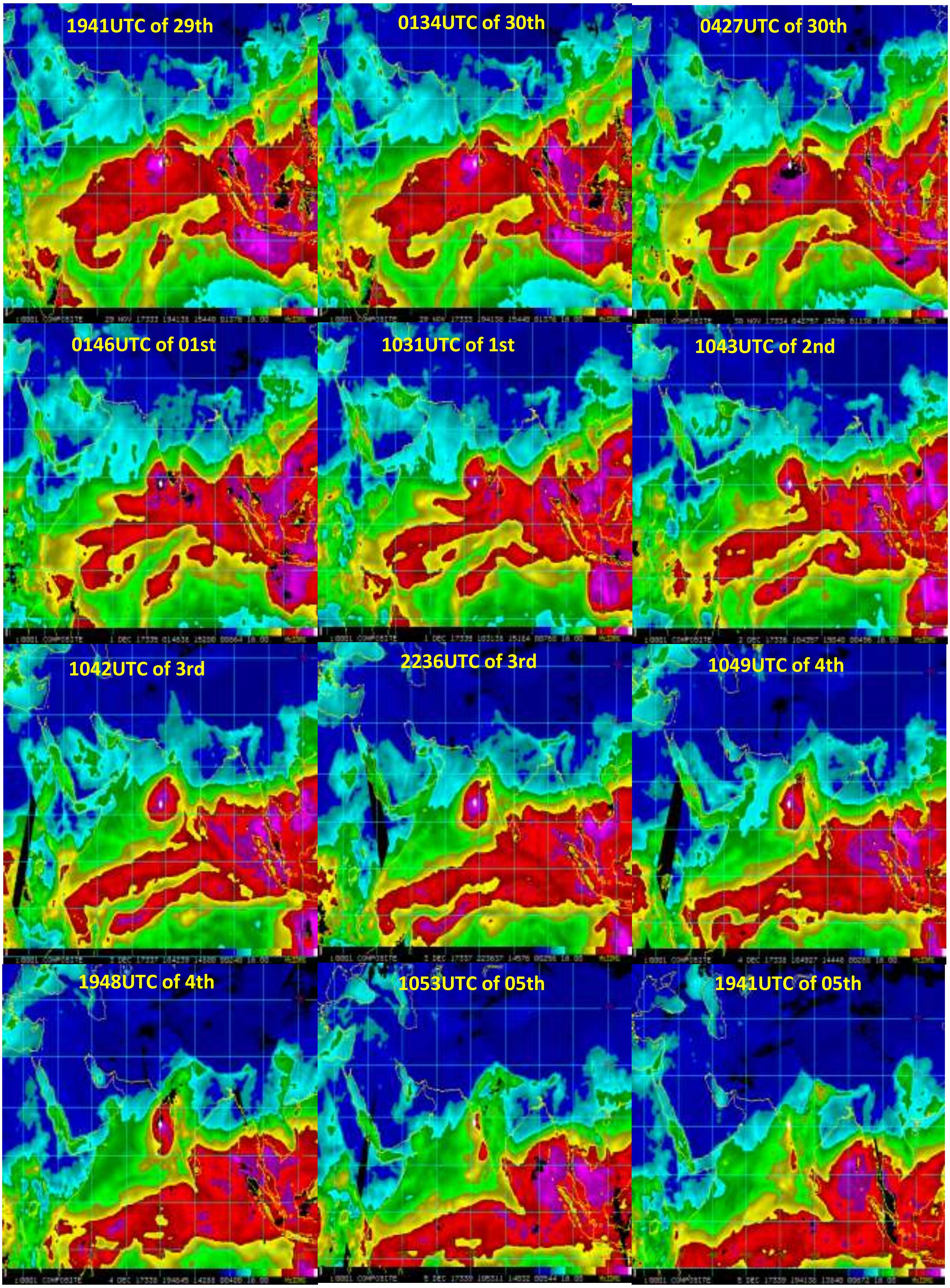


Fig. 2.9.5: Total Precipitable Water Imageries during 29 Nov.-06 Dec., 2017

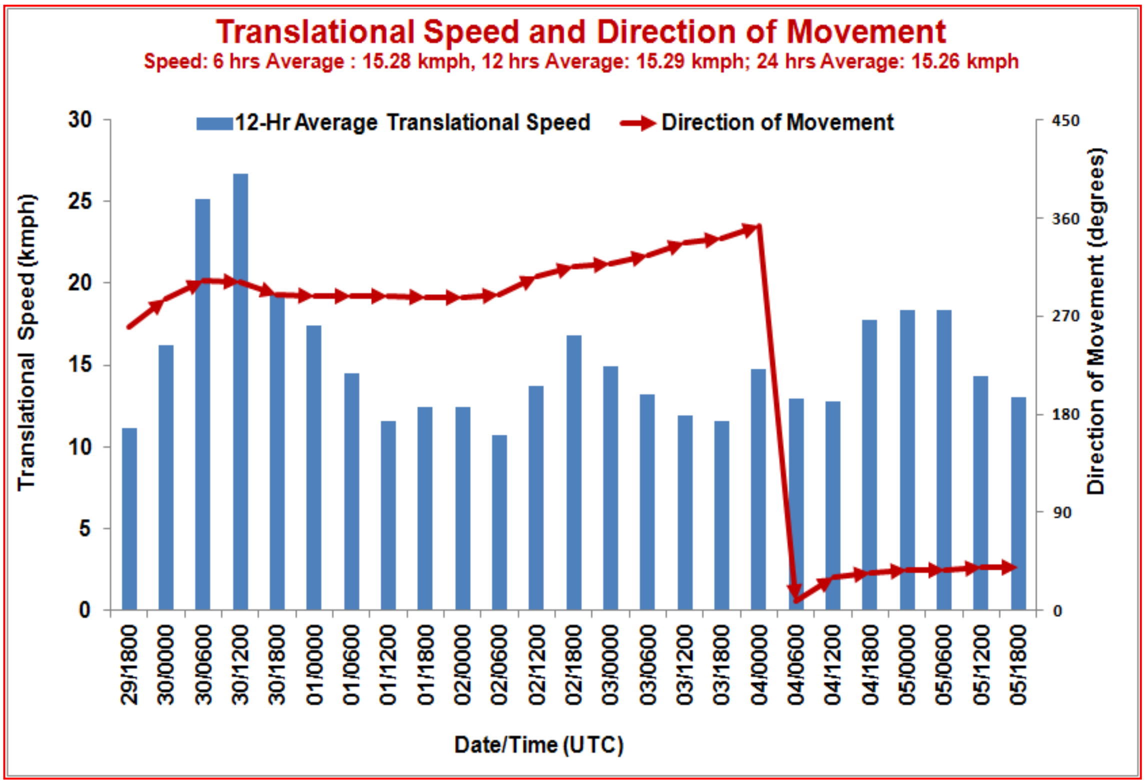
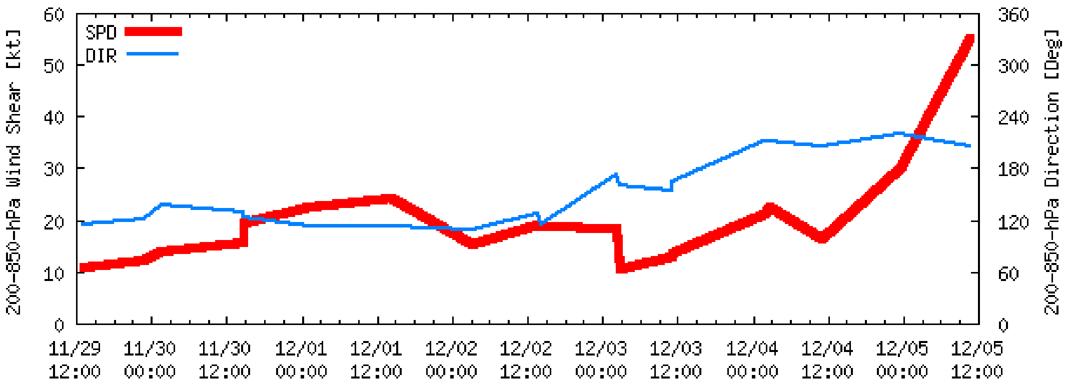


Fig. 2.9.6: Twelve hourly average translational speed (kmph) and direction of movement in association with VSCS Ockhi



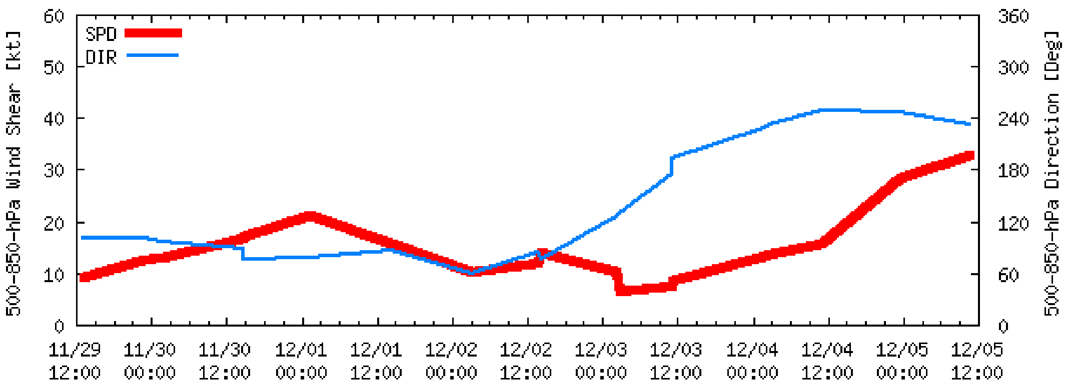


Fig. 2.9.7 Wind shear in the middle and deep layer around the system during 29th Nov. to 05th Dec. 2017.

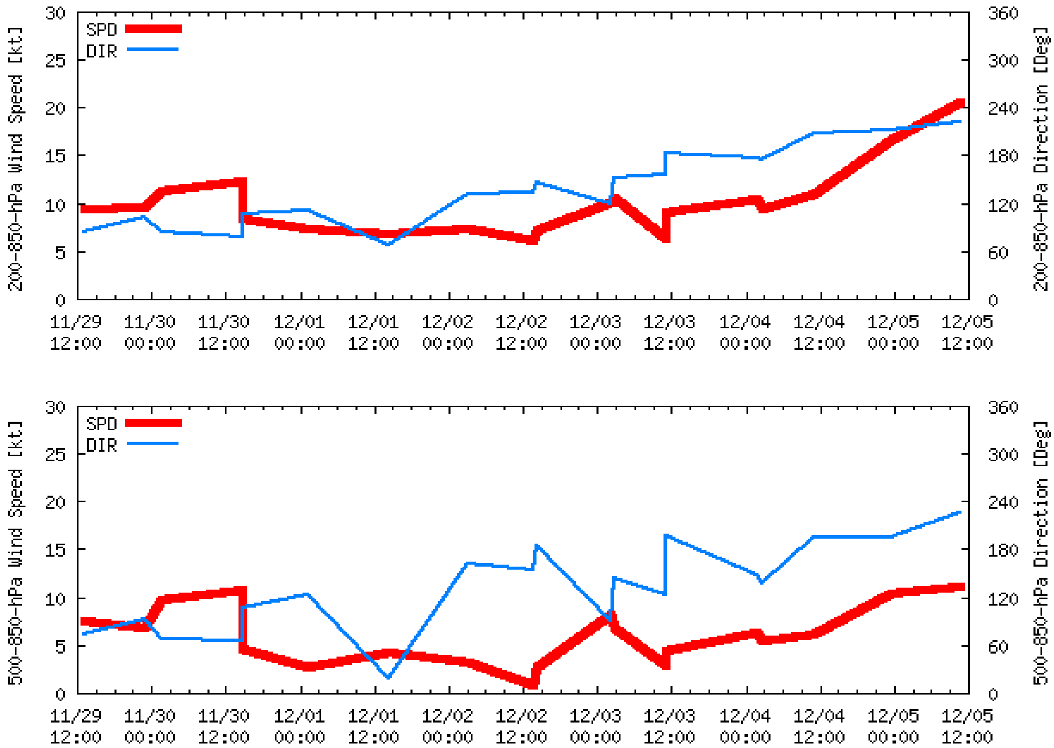


Fig. 2.9.8 Wind speed in the middle and deep layer around the system during 29th Nov. to 05th Dec. 2017.

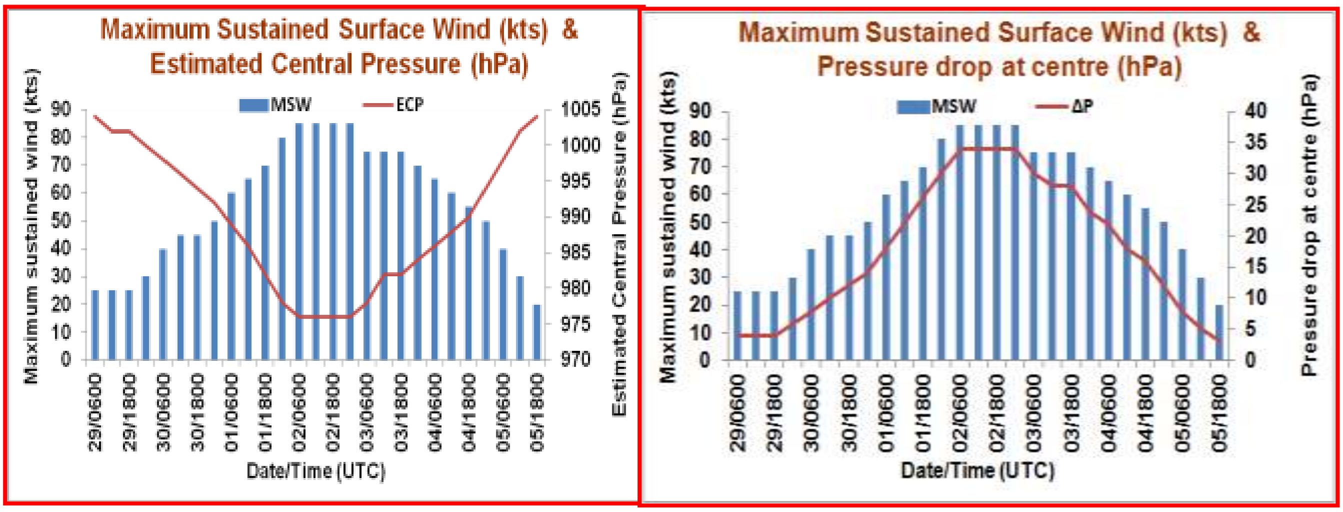


Fig. 2.9.9 (a) Maximum sustained wind speed and Lowest estimated central pressure & Pressure drop at centre

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

The lowest estimated central pressure & pressure drop and the maximum sustained wind speed are presented in Fig. 2.9.9 (a). The lowest estimated central pressure had been 976 hPa during 0600 UTC of 2nd to 0000 UTC of 3rd December. The estimated maximum sustained surface wind speed (MSW) was 85 knots during the same period. The ECP and Vmax graph indicates that the system intensified from 1800 UTC of 29th November (25 knots) to 1200 UTC of 30th (45 knots) maintained its intensity for next six hours and again increased from 1800 UTC of 30th November (45 knots) to 0600 UTC of 2nd December (85 knots), maintained its intensity till 0300 UTC of 30th and started weakening thereafter.

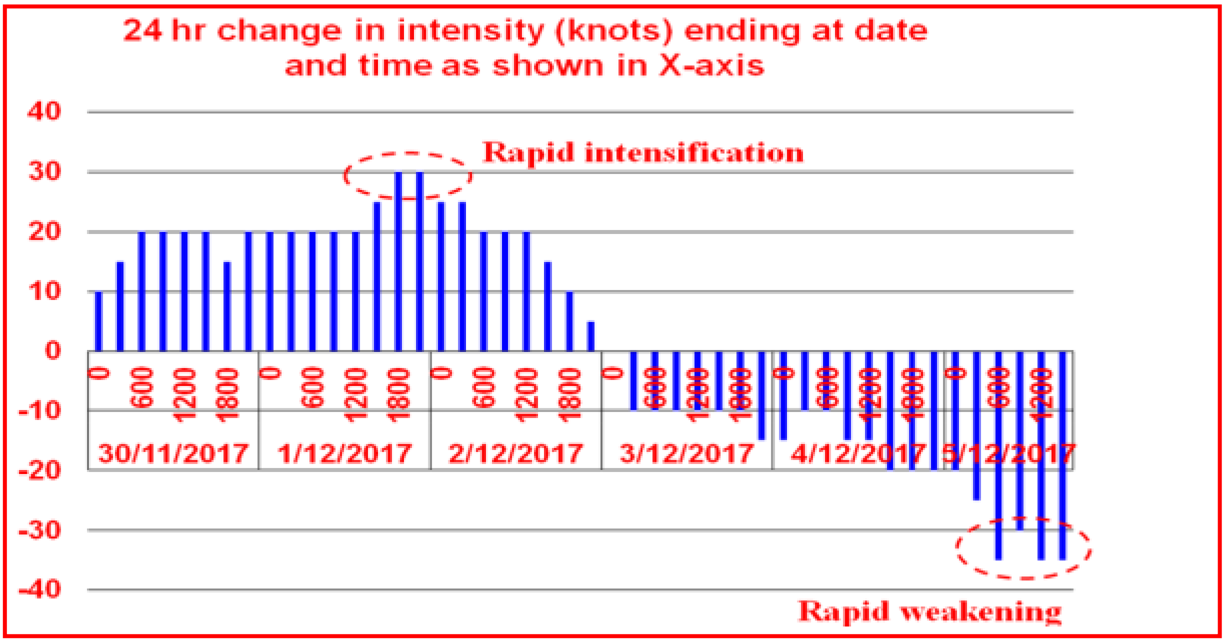


Fig. 2.9.9(b): 24 hour change in intensity (kts) ending at date and time during 30th Nov. to 5th Dec.

The 24 hour change in intensity (kts) ending at date and time is presented in Fig.2.9.9 (b). The system intensified rapidly from 1800 UTC of 30th to 0000 UTC of 2nd (increase in wind speed by 30 kts during past 24 hours). Similarly rapid weakening was observed during 0600 of 4th to 1800 UTC of 5th December. However, the SCIP and RI model of IMD did'nt predict rapid intensification (RI) and rapid weakening (RW). Based on 0000 UTC of 2nd, 3rd and 4th, RI model predicted probability of rapid intensification as Moderate. Though the intensity forecast showed weakening trend. Though it predicted Rapid Weakening (55 to 23 knot) based on 00 UTC of 5th Dec., it still predicted the system to cross the coast as a Depression (23 knots). As discussed earlier, the Ocean Heat Content is one of the most important parameters for intensification/weakening of low pressure systems. The currently available SCIP and RI model of NWP Division of IMD does not take into consideration the Ocean Heat Content as a predictor. HWRF model also underestimated weakening on 5th predicting 52 knots to 33 knots based on 00 UTC of 5th Dec., hence the system to cross as a DD/ marginal CS.

During the movement of TC OCKHI over Comorin, Maldives, Lakshadweep and southeast Arabian Sea during 30th to 4th December, the pressure and wind charts from various self recording instruments of IMD are presented in Fig. 2.9.9 (d). The Vaisala Pressure Sensor at Kanyakumari reported minimum pressure of 997.4 hPa at 0300 UTC of 30th November (Fig. 2.9.9c).

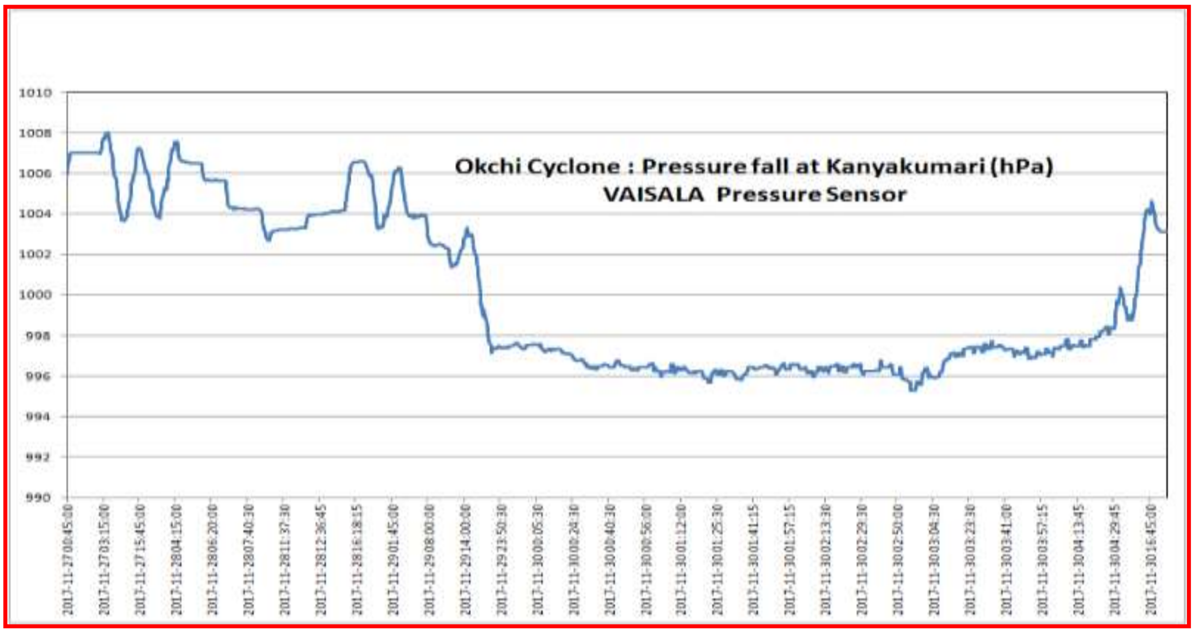


Fig. 2.9.9 (c): Pressure fall at Kanyakumari as recorded by Vaisala Pressure Sensor during 0000 UTC of 27th Nov to 1600 UTC of 30th Nov.

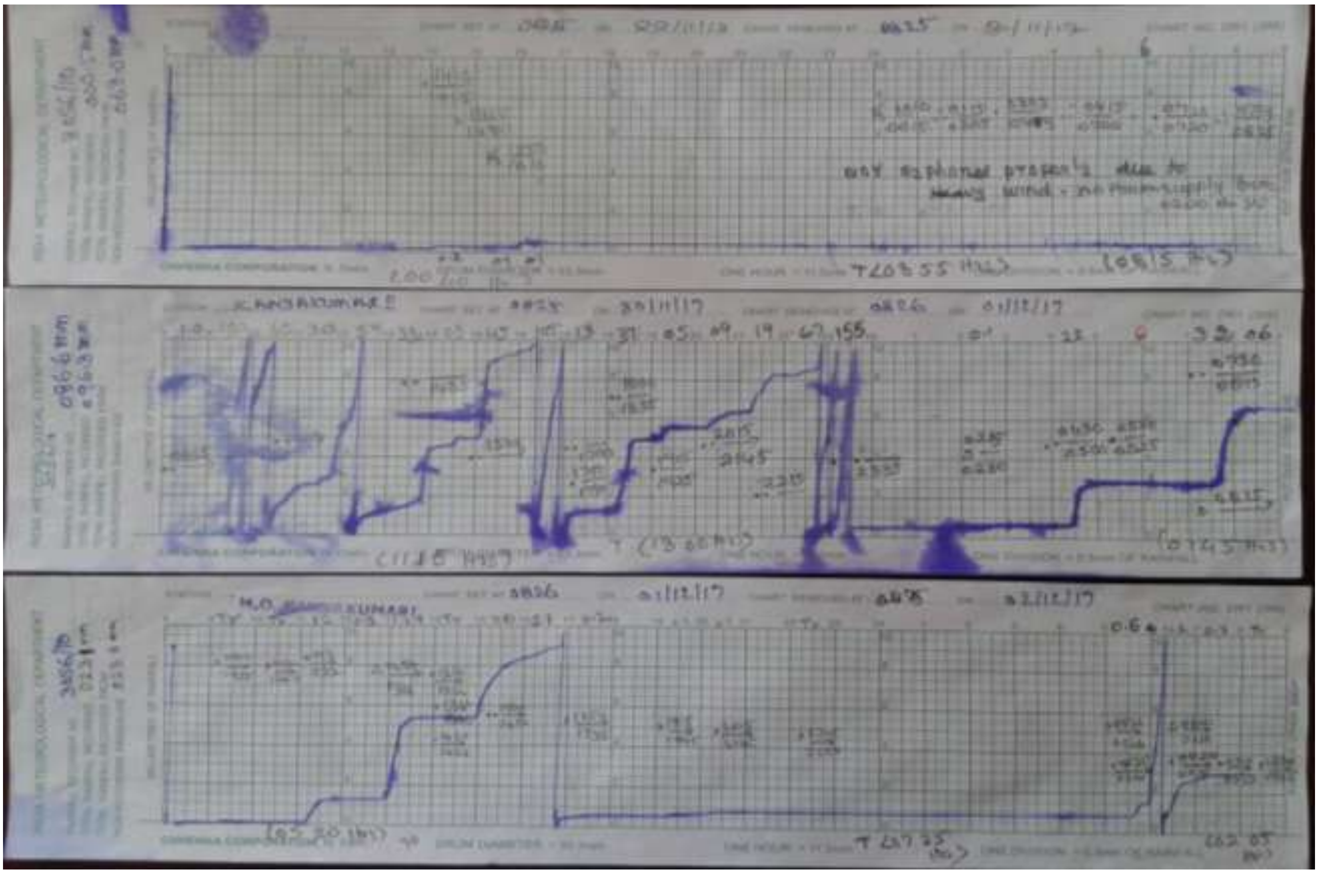


Fig. 2.9.9 (d): Autographic rainfall charts from M.O. Kanyakumari on 29th-30th Nov. and 1st Dec.

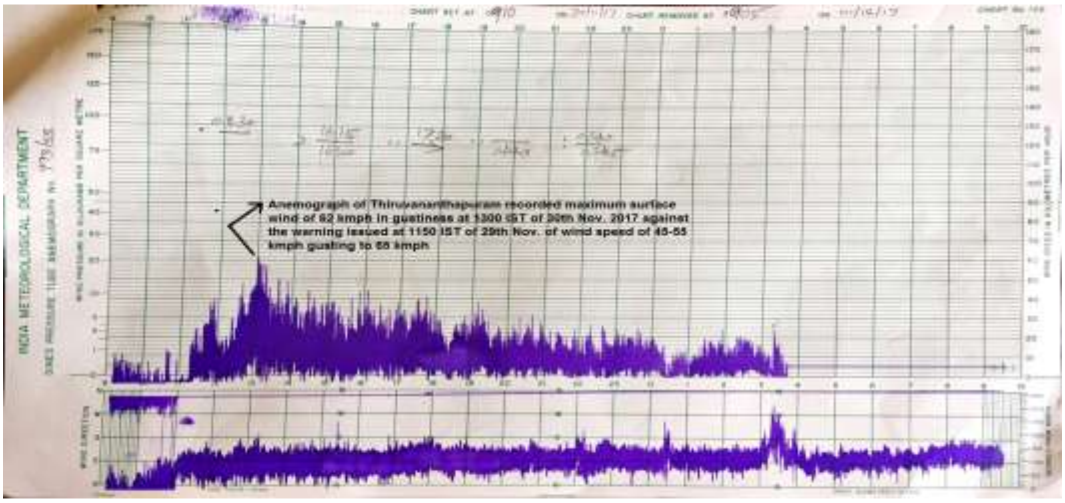


Fig. 2.9.9 (e): Anemograph record of 30th November over Thiruvananthapuram.
It recorded 62 kmph in gustiness at 1300 IST of 30th Nov. The threshold wind speed of 45 kmph was recorded over Thiruvananthapuram from 1230 IST of 30th Nov. Onwards

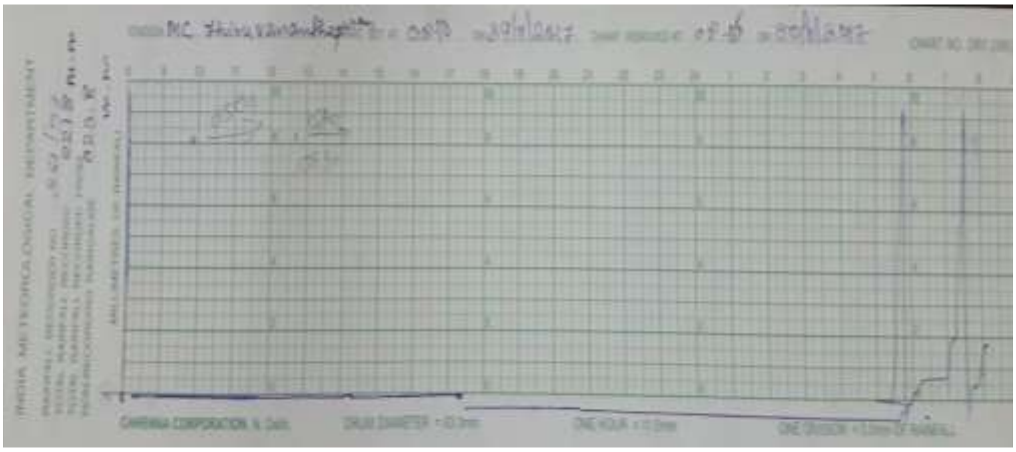


Fig. 2.9.9 (f): Autographic rainfall charts from M.C. Thiruvananthapuram during 29th - 30th Nov.

Fig. 2.9.9 (g): Autographic rainfall charts from M.C. Thiruvananthapuram during 30th Nov. to 1st Dec.

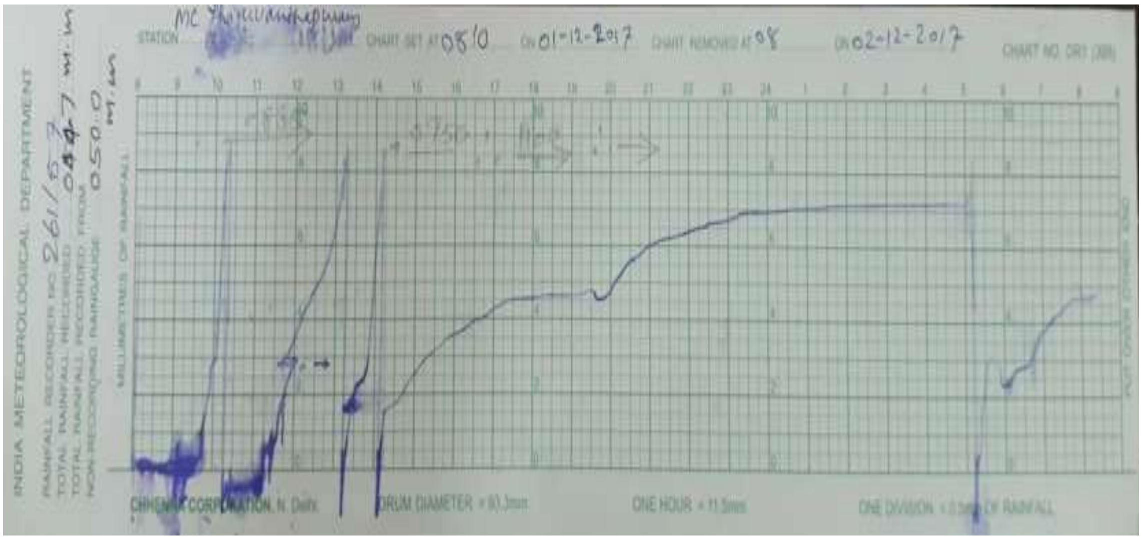


Fig. 2.9.9 (h): Autographic rainfall charts from M.C. Thiruvananthapuram during 1st Dec to 2nd Dec.

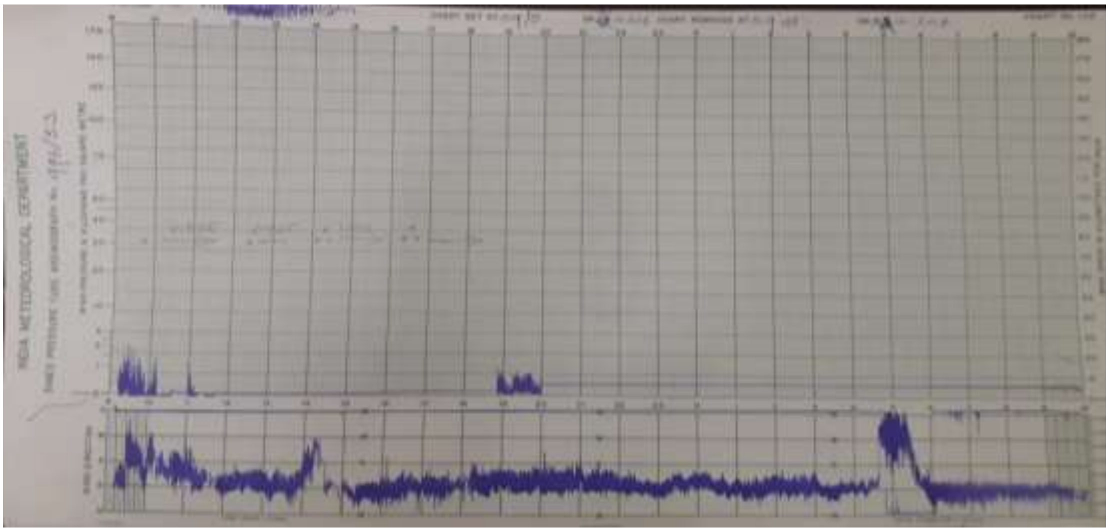


Fig. 2.9.9 (i): Autographic Wind chart from M.C. Thiruvananthapuram on 2nd Dec.

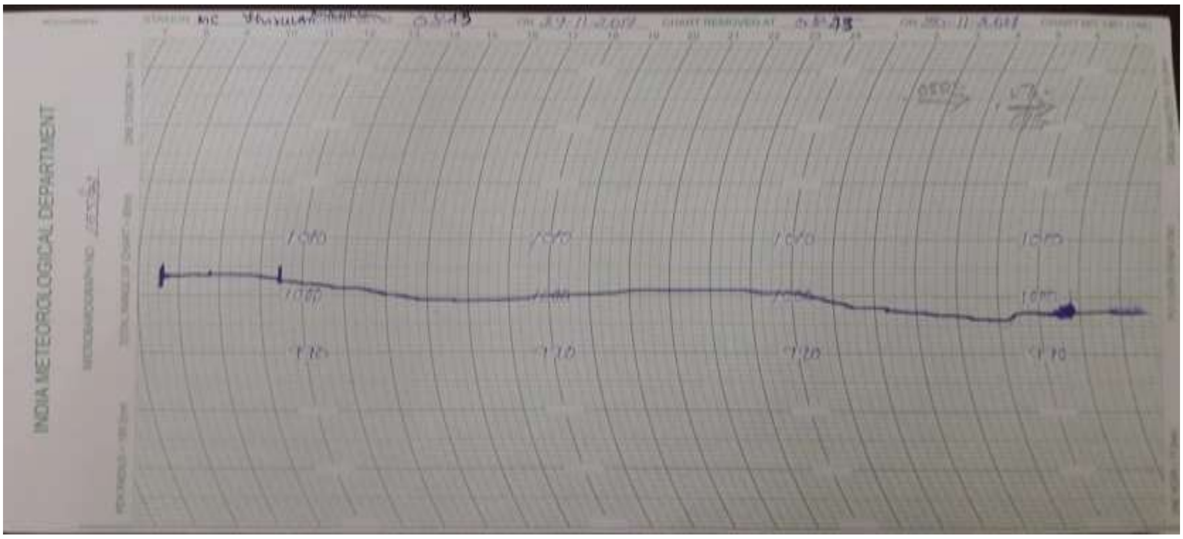


Fig. 2.9.9 (j): Autographic Pressure chart from M.C. Thiruvananthapuram on 30th Nov.

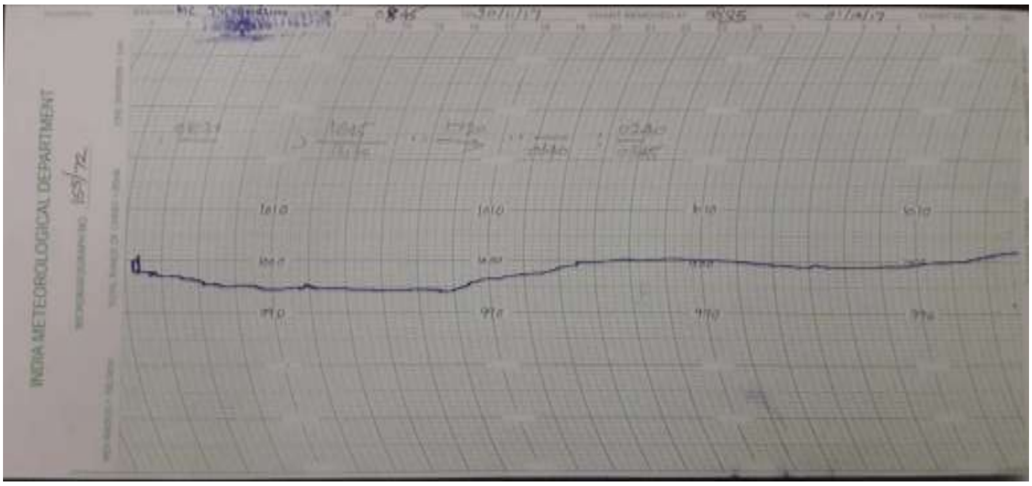


Fig. 2.9.9 (k): Autographic Pressure chart from M.C. Thiruvananthapuram on 1st Dec.

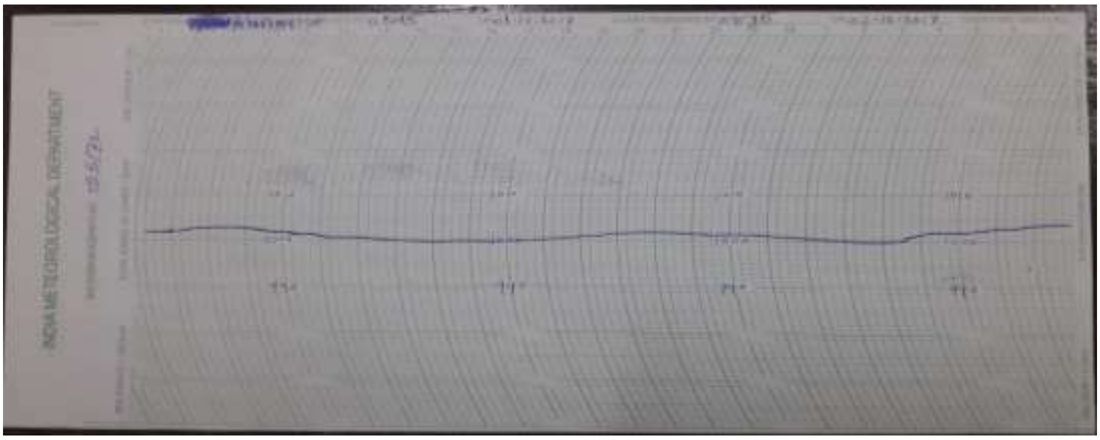


Fig. 2.9.9 (l): Autographic Pressure chart from M.C. Thiruvananthapuram on 2nd Dec.

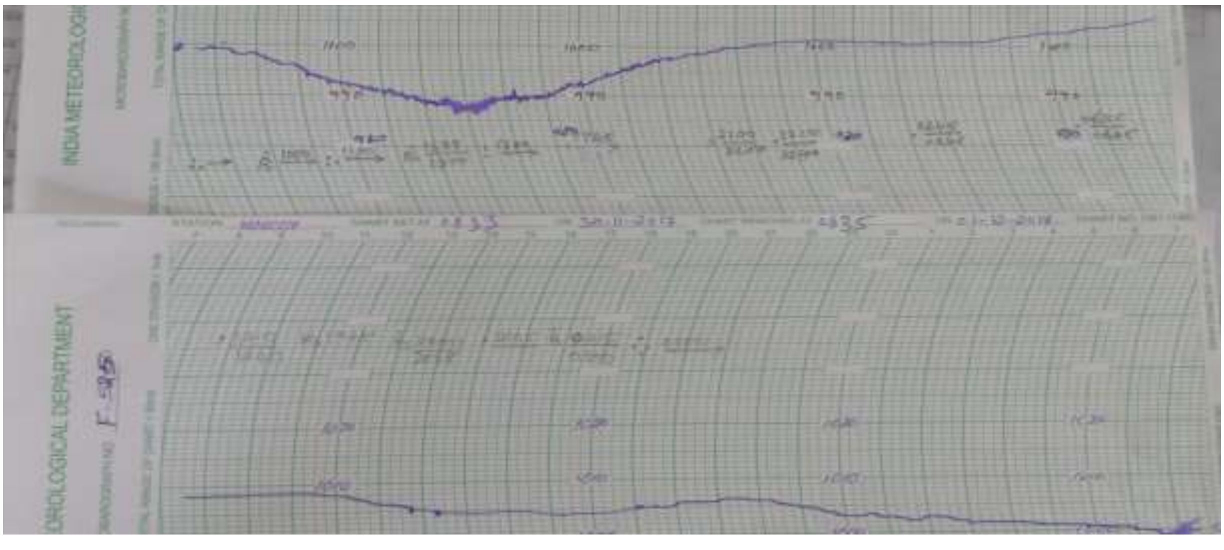


Fig. 2.9.9 (m): Autographic Pressure chart from Minicoy during 30 Nov. to 1st Dec.

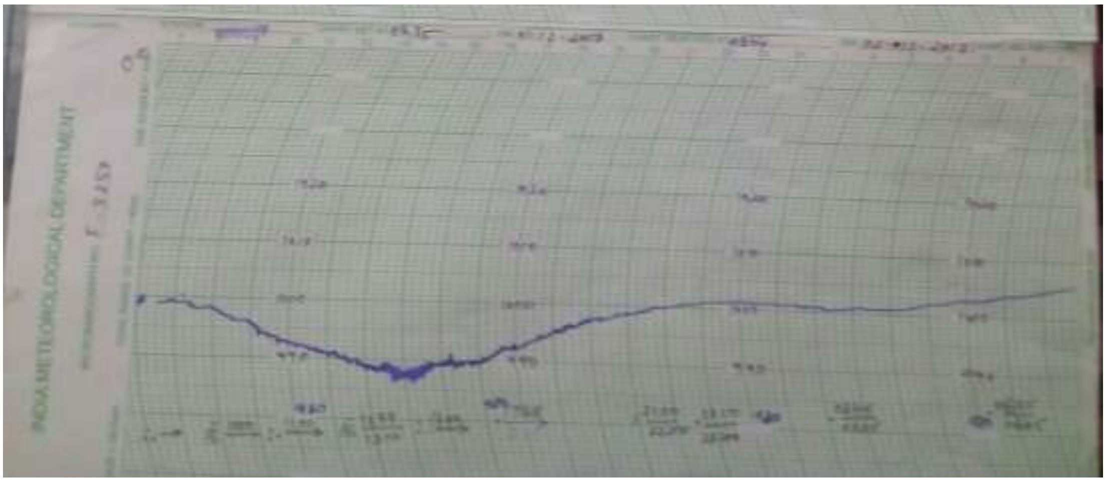


Fig. 2.9.9 (n): Autographic Pressure chart from Minicoy during 1st to 2nd Dec.

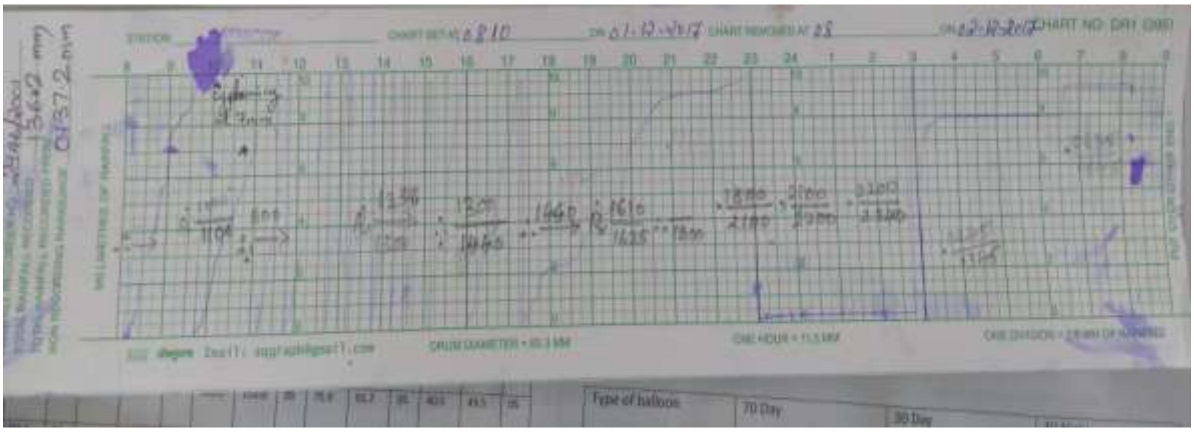


Fig. 2.9.9 (o): Autographic Rainfall chart from Minicoy during 1st to 2nd Dec.

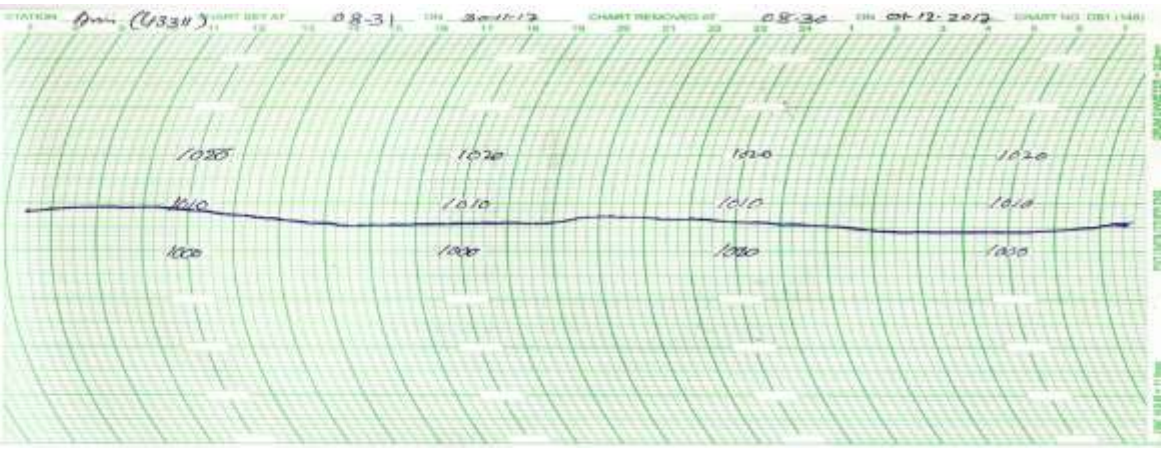


Fig. 2.9.9 (p): Autographic Pressure chart from Amini Divi during 30th Nov.-1st Dec

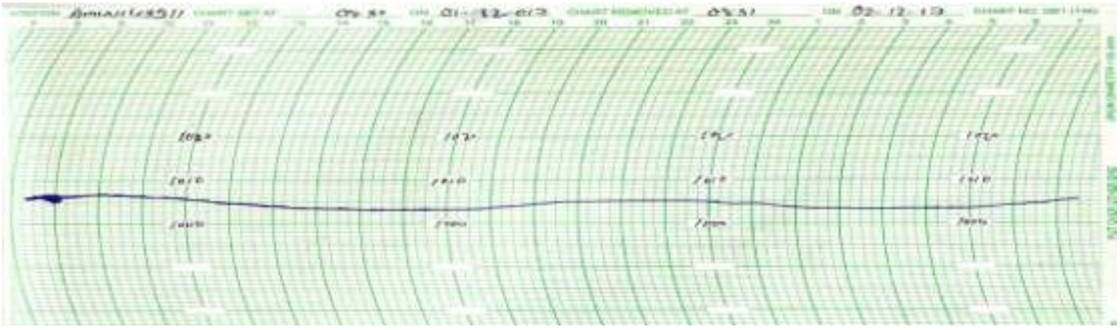


Fig. 2.9.9 (p): Autographic Pressure chart from Amini Divi during 1st Dec-2nd Dec

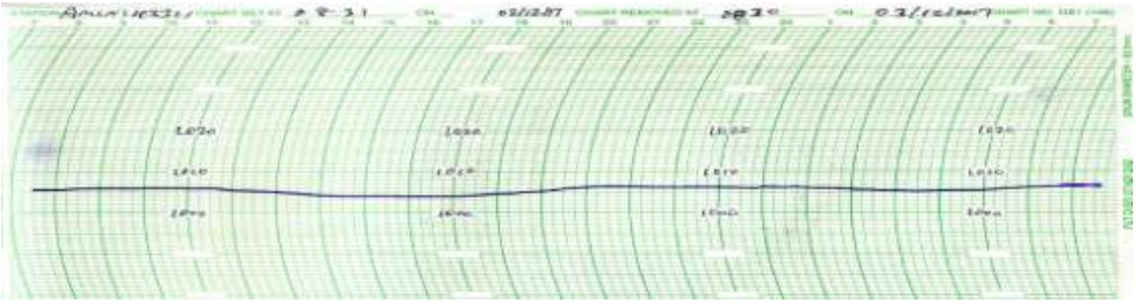


Fig. 2.9.9 (q): Autographic Pressure chart from Amini Divi during 2nd Dec-3rd Dec.

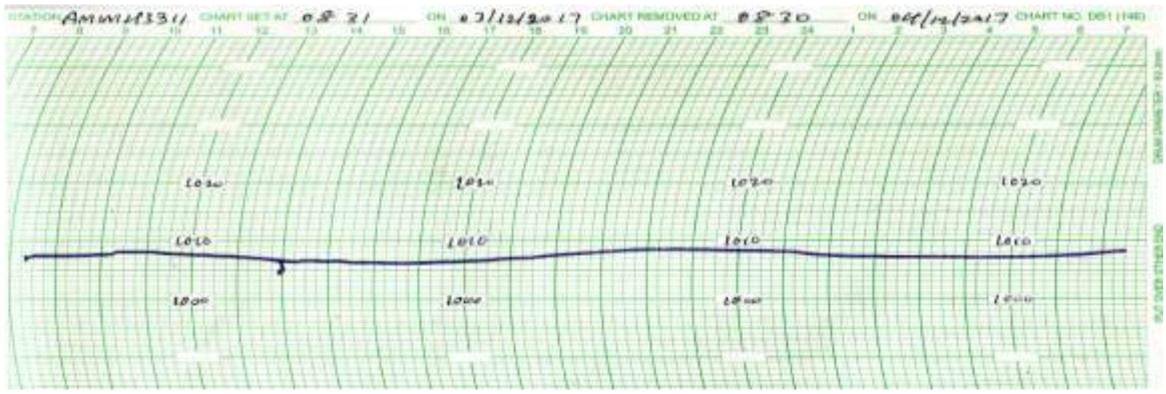


Fig. 2.9.9 (r): Autographic Pressure chart from Amini Divi during 3rd Dec-4th Dec

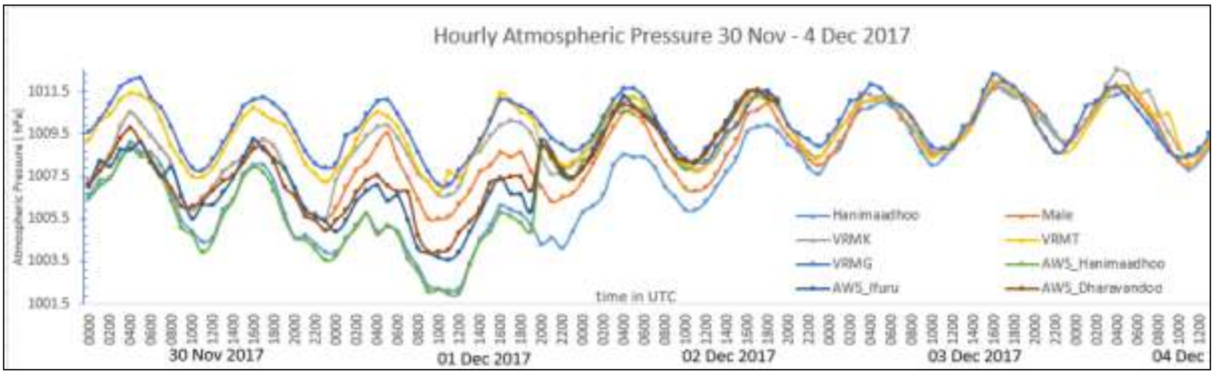


Fig. 2.9.9(s): Hourly Pressure Drop over Maldives during 30th Nov. to 4th Dec.

As the TC OCKHI passed northeastern sector of Maldives, the pressure drop was observed in the station located in the central and northern Maldives. Lowest pressure observed during this period among the local stations in the Maldives was 1001.9hPa recorded in the in the northern-most station (H.Dh. Hanimaadho, WMO location No. 43533) at 1100 UTC of 01 Dec 2017. Hourly pressure drop over Maldives (Source: Maldives Meteorological Department) is presented in Fig. 2.9.9 (s).

2.9.5. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary and polar orbiting satellites were also considered.

2.9.5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and enhanced IR imageries are presented in Fig. 2.9.10. Intensity estimation using Dvorak's technique suggested that the system attained the intensity of T 1.5 at 0600 UTC of 29th November. The system was characterized by loosely defined cloud lines far from a very large area of cold overcast (Shear Pattern). Associated moderate to intense convection lay over southwest BoB and adjoining Sri Lanka & Equatorial Indian Ocean. Thereafter, the system was overland till 1200 UTC of 29th. Hence, T No. could not be estimated. Thereafter, it emerged into Comorin Area. The cloud mass started organising thereafter. At 2100 UTC of 29th, the cloud mass showed curved band pattern measuring 0.45 in logarithmic spiral. The system attained intensity of T 2.0. Associated intense to very intense convection lay over Comorin Area and adjoining Maldives & Equatorial Indian Ocean. At 0300 UTC of 30th, the cloud mass further organized. The system attained intensity of T 2.5. The cloud mass showed curved band pattern measuring 0.60 in logarithmic spiral scale. Associated intense to very intense convection lay between latitude 3ºN to 10 ºN and longitude 72.0ºE to 80.0ºE and the area covering extreme south Tamil Nadu, south Kerala, Gulf of Mannar & Comorin Area. At 0900 UTC of 30th, the intensity was T 3.0. The convection wrapped 0.85 on logarithmic spiral. Associated intense to very intense convection lay between latitude 3ºN to 10 ºN and longitude 72.0ºE to 80.0ºE and the area covering extreme south Tamil Nadu, south Kerala, Gulf of Mannar & Comorin Area. At 0000 UTC of 1st December, the cloud mass further organized. The convection wrapped 0.90 on logarithmic spiral with white banding in enhanced IR. The intensity of the system was T 3.5. Associated broken low/medium clouds with embedded intense to very intense convection lay over area between latitude 5ºN to 13 ºN and longitude 70.0ºE to 78.0ºE. At 0900 UTC of 1st December, intensity became T 4.0. Associated broken low/medium clouds with embedded intense to very intense convection lay over area between latitude 6ºN to 11.5 ºN and longitude 67.0ºE to 75.0ºE. At 0600 of 2nd, the system was characterized by off white eye surrounded by light grey and embedded in medium grey resulting in T 4.5. Associated broken low/medium clouds with embedded intense to very intense convection lay over area between latitude 7ºN to 14.5 ºN & longitude 65.5ºE to 74.0ºE and Lakshadweep area. At 0300 UTC of 3rd December, the system centre was embedded in black and with 2.5^{0} of Central Dense Overcast region yielding T 4.5. Associated broken low/medium clouds with embedded intense to very intense convection lay over area between latitude 9ºN to 14.0 ºN & longitude 66.0ºE to 73.0ºE and Lakshadweep area. At 0300 UTC of 4th, intensity of the system was T 4.0 with disorganisation of cloud. Associated broken low/medium clouds with embedded intense to very intense convection lay over area between latitude 12ºN to 20ºN & longitude 66ºE to 72ºE. Thereafter it showed rapid disorganisation. At 0300 UTC of 5th. Intensity of the system was T 3.0. Associated broken low/medium clouds with embedded intense to very intense convection lay over area between latitude 16ºN to 20.5ºN & longitude 67ºE to 73ºE. At 0600 UTC of 5th, system was characterized by circularly defined cloud lines far from a very small area of cold overcast (Shear Pattern). Intensity of the system was T 2.0. Associated broken low/medium clouds with embedded intense to very intense convection lay over area between latitude 16ºN to 20.5ºN & longitude 67ºE to 73ºE, south Gujarat, north Maharashtra and adjoining Gulf of Cambay. At 1800 UTC of 5th, intensity of the system was T 1.0. Associated broken low/medium clouds with embedded isolated weak convection lay over area between latitude 18ºN to 21ºN & longitude 69ºE, southeast Gujarat, north Konkan and adjoining Gulf of Cambay. IMD satellite positions and corresponding intensity are presented in Table 2.9.2.

Table 2.9.2: Satellite based positions and intensity of VSCS Ockhi

Date/Time (UTC)	Position (lat./long.) in degrees	Dvorak's T.No.	Date/Time (UTC)	Position (lat./long.) in degrees	Dvorak's T.No.
28/1800	6.0/82.8	T 1.0	02/1200	10.4/70.3	T 5.0
28/2100	6.0/82.4	T 1.0	02/1500	10.7/69.8	T 5.0
29/0000	6.0/82.4	T 1.0	02/1800	11.0/69.7	T 5.0
29/0300	6.0/81.5	T 1.0	02/2100	11.3/69.5	T 5.0
29/0600	6.0/81.5	T 1.5	03/0000	11.8/69.2	T 4.5
29/0900	6.0/81.0	T 1.5	03/0300	12.0/69.0	T 4.5
29/1200	6.0/80.1	T 1.5	03/0600	12.3/68.8	T 4.5
29/1500	6.2/79.5	T 1.5	03/0900	12.4/68.7	T 4.5
29/1800	6.3/79.2	T 1.5	03/1200	12.7/68.5	T 4.5
29/2100	6.5/78.6	T 2.0	03/1500	13.0/68.5	T 4.5
30/0000	6.7/78.3	T 2.0	03/1800	13.5/68.5	T 4.5
30/0300	7.5/77.5	T 2.5	03/2100	14.0/68.5	T 4.5
30/0600	7.6/76.6	T 3.0	04/0000	14.4/68.5	T 4.5
30/0900	7.8/76.4	T 3.0	04/0300	14.4/68.6	T 4.0
30/1200	8.3/75.8	T 3.0	04/0600	14.9/68.9	T 4.0
30/1500	8.4/75.3	T 3.0	04/0900	15.1/68.9	T 4.0
30/1800	8.5/74.9	T 3.0	04/1200	15.7/69.2	T 3.5
30/2100	8.6/74.4	T 3.5	04/1500	16.1/69.6	T 3.5
01/0000	8.8/74.0	T 3.5	04/1800	16.5/69.7	T 3.5
01/0300	8.8/73.8	T 3.5	04/2100	17.0/69.8	T 3.5
01/0600	8.9/73.3	T 3.5	05/0000	17.8/70.0	T 3.5
01/0900	8.9/72.9	T 4.0	05/0300	18.8/70.5	T 3.0
01/1200	9.0/72.7	T 4.0	05/0600	18.8/70.8	T 2.5
01/1500	9.1/72.5	T 4.0	05/0900	18.9/71.4	T 2.5
01/1800	9.3/72.0	T 4.0	05/1200	19.2/71.9	T 2.0
01/2100	9.3/71.8	T 4.0	05/1500	19.9/72.0	T 1.5
02/0000	9.5/71.5	T 4.5	05/1800	20.1/72.2	T 1.0
02/0300	9.5/71.2	T 4.5	05/2100	20.3/72.6	T 1.0
02/0600	9.8/71.0	T 4.5	06/0000	LLC	LLC
02/0900	10.2/70.6	T 5.0			

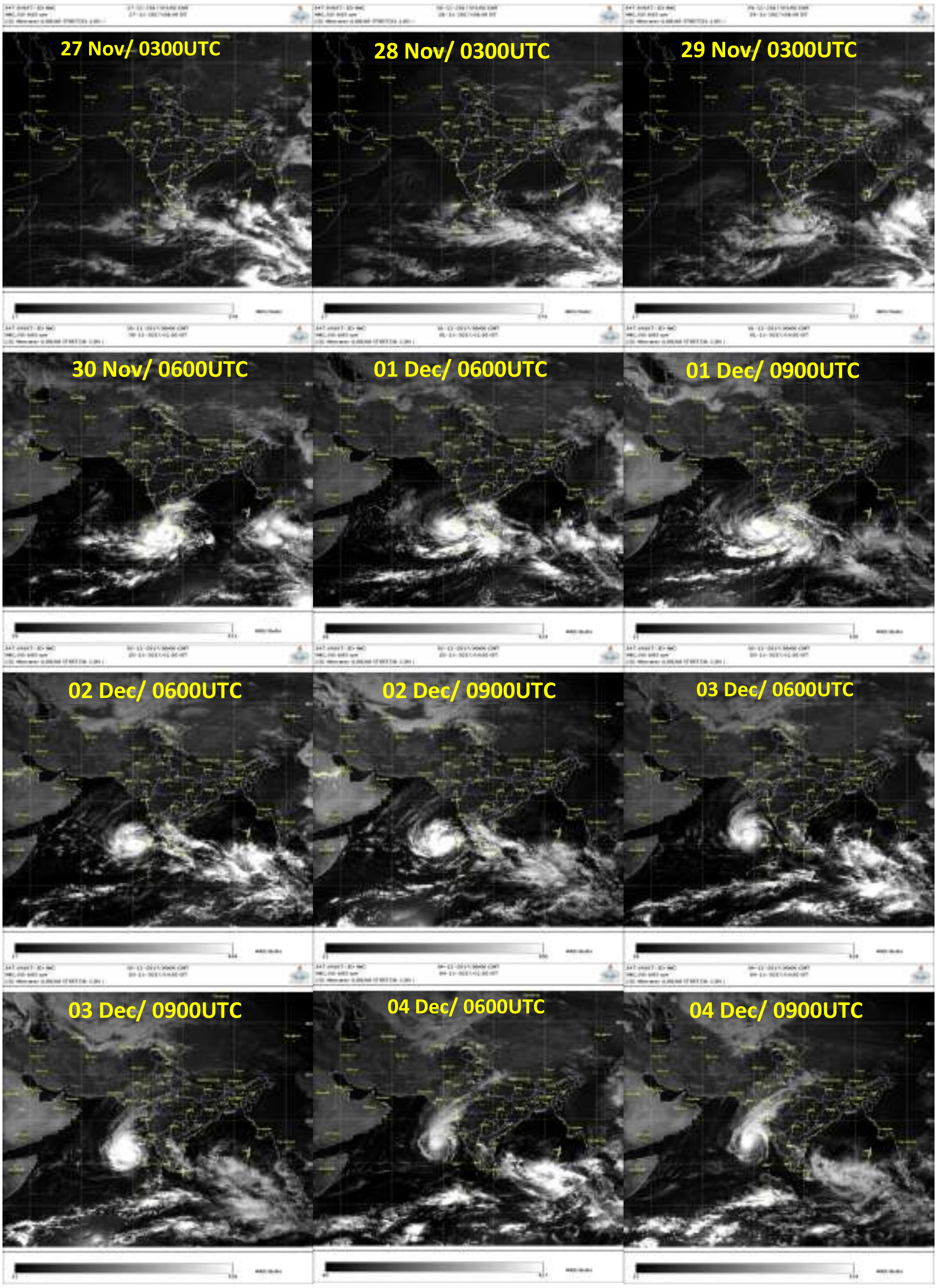


Fig. 2.9.10a: INSAT-3D visible imageries during life cycle of VSCS Ockhi (28 November-05 December, 2017)

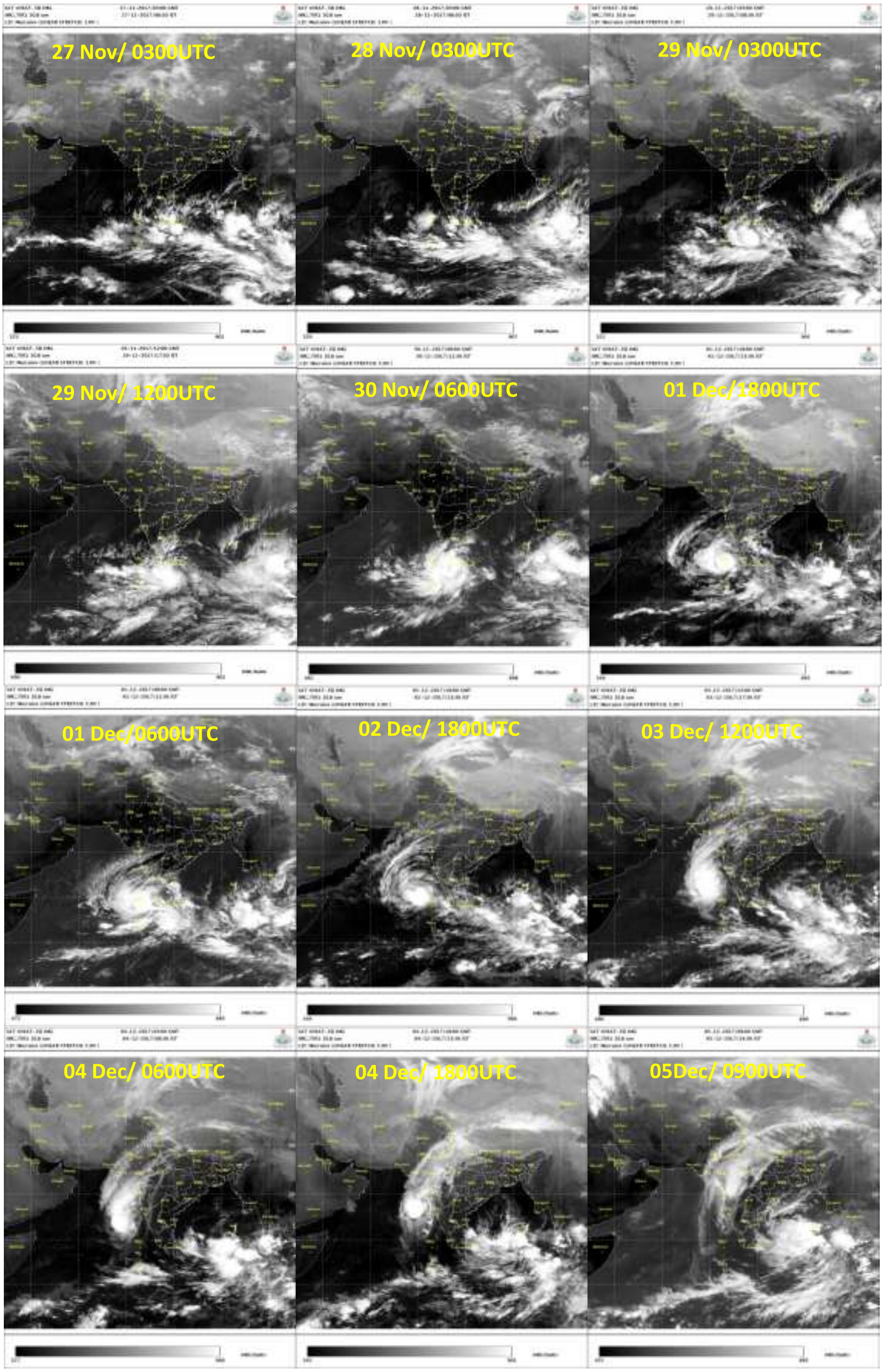


Fig. 2.9.10b: INSAT-3D IR imageries during life cycle of VSCS Ockhi (28 November-05 December, 2017)

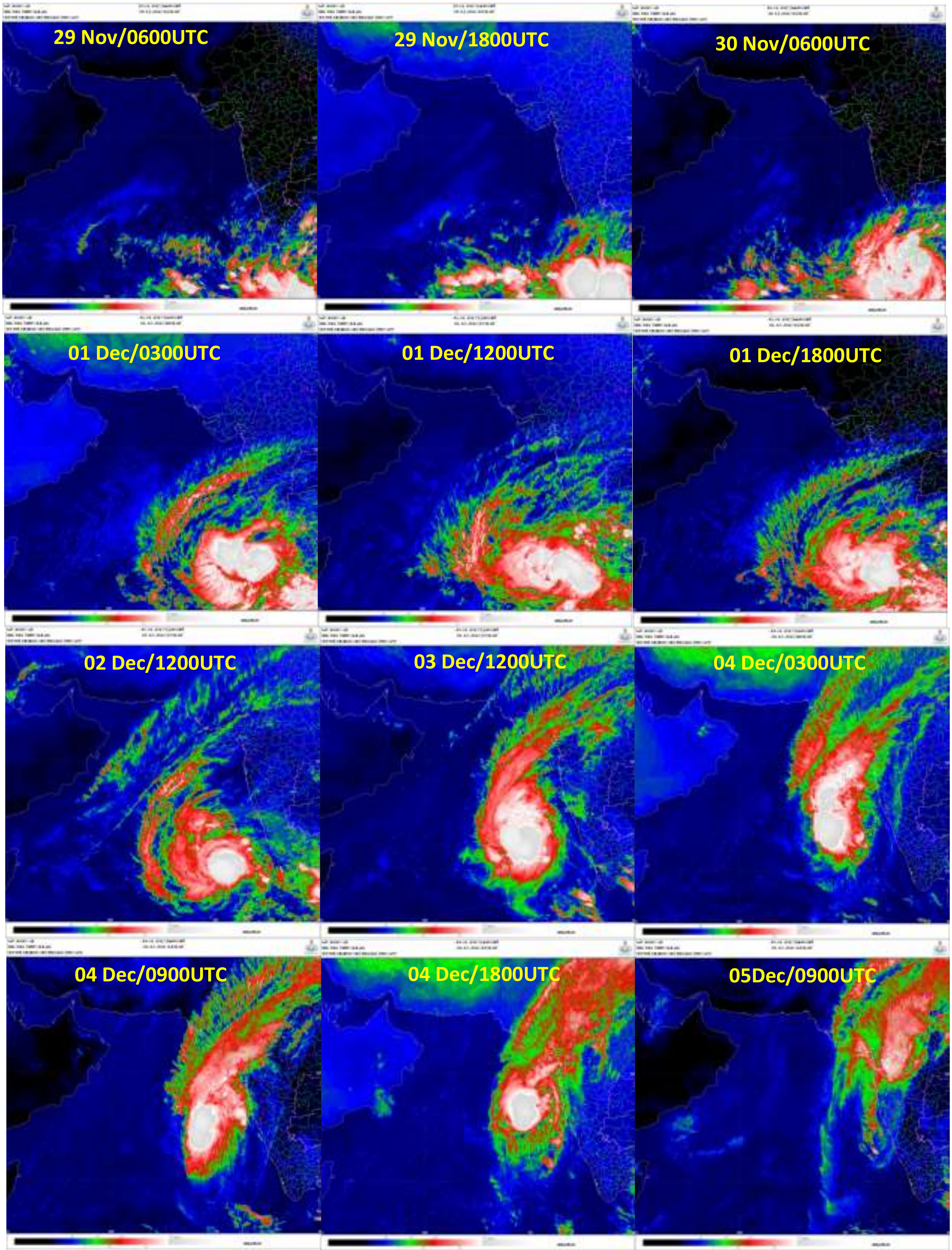


Fig. 2.9.10c: INSAT-3D enhanced colored imageries during life cycle of VSCS Ockhi (28 November-05 December, 2017)

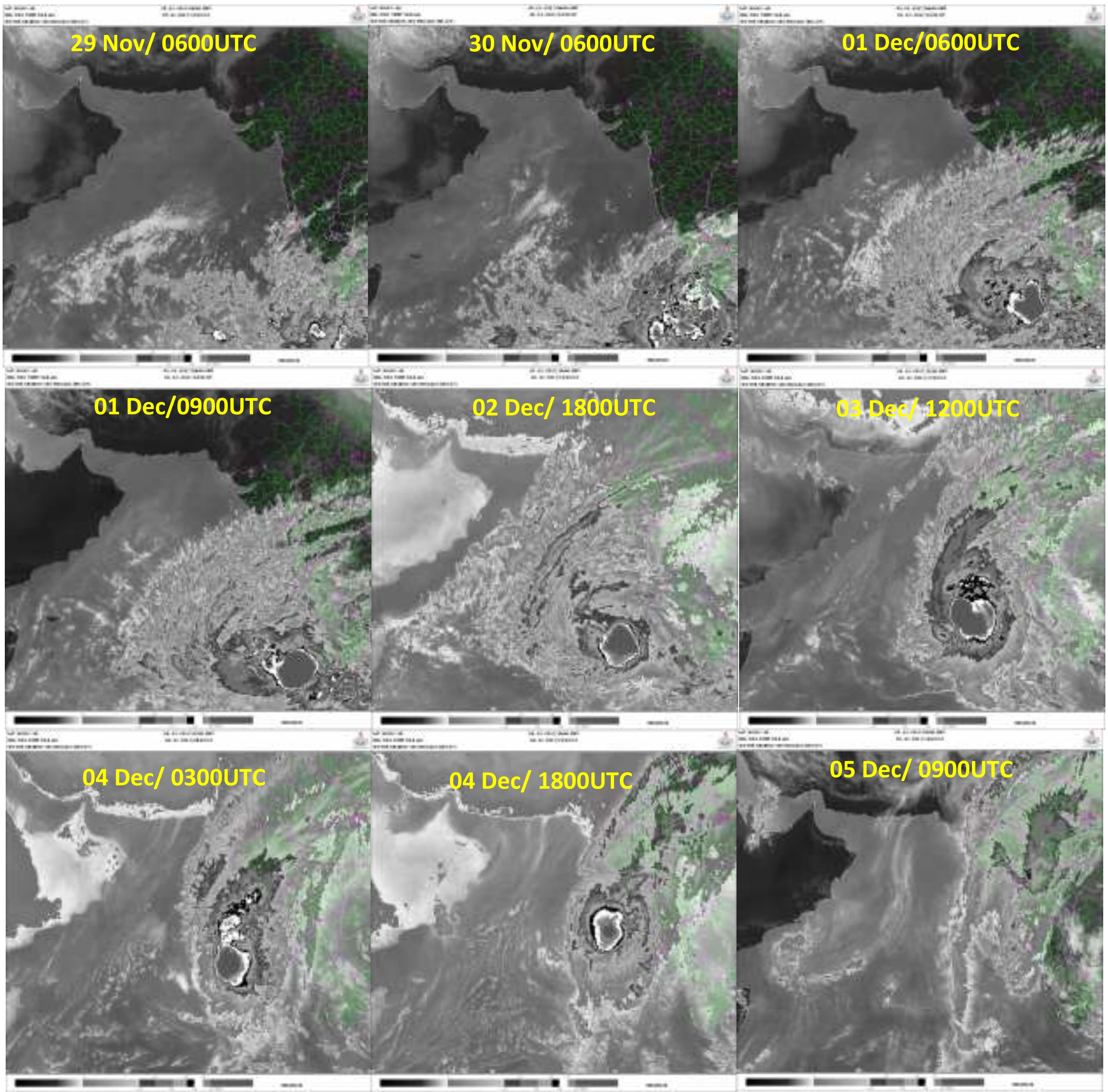


Fig. 2.9.10d: INSAT-3D enhanced IR imageries during life cycle of VSCS Ockhi (28 November-05 December, 2017)

2.9.5.2 Microwave features

F-15, F-16, F-17, GPM and GCOM-W1 microwave imageries of the VSCS Ockhi covering its life period from 26th November to 5th December 2017 are presented in Fig. 2.9.11 (a). These imageries helped in understanding the internal structure of the system and better estimation of location of the system. It could indicate the region of intense convection and hence the rainfall.

The imageries during 2121 UTC of 26th to 1940 UTC of 28th indicate that prior to development of Ockhi, some circulation persisted over south of Sri Lanka that caused rainfall over south of Sri Lanka and adjoining equatorial Indian Ocean on 27th and 28th. At 1940 UTC of 28th, the convection extended upto Comorin area. On 29th morning a small patch of intense convection was seen over southwest BoB and another bigger intense zone was seen over Comorin area.

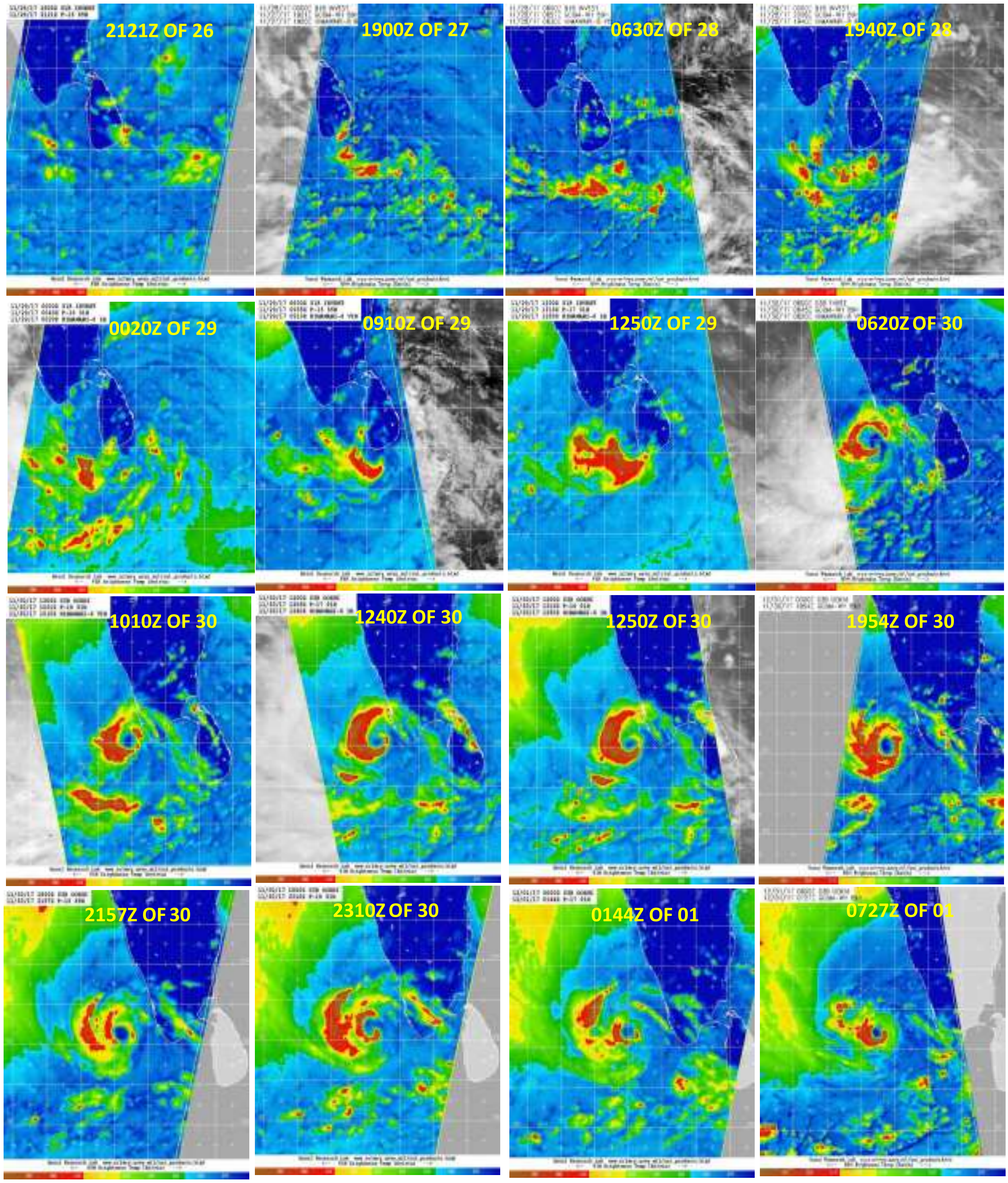


Fig. 2.9.11 (a): Microwave imageries during life cycle of VSCS Ockhi (26th November-1st December)

The convection over Comorin started organising from 0020 UTC of 29th. At 0620 UTC of 30th, the circulation got organised. Spiral structure was seen from 1010 UTC of 30th with spiral bands covering the eye completely by 1954 UTC of 30th. Till 0251 UTC of 3rd, intense convection was seen over western and southern sector of system. Thereafter, convection flared north-north-eastwards. The weakening of the system from 3rd midnight onwards was also well captured in microwave imageries.

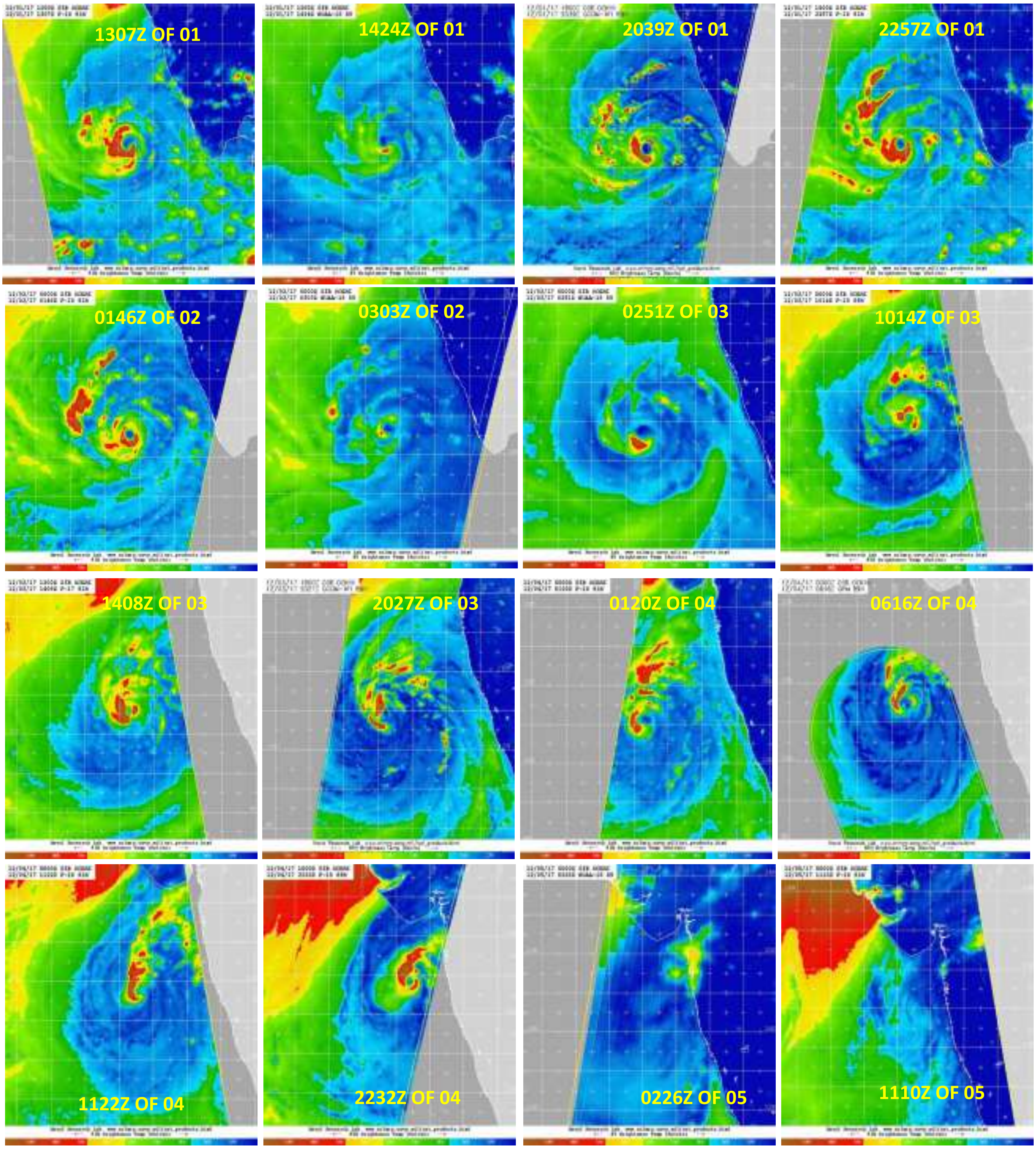


Fig. 2.9.11 (b): Microwave imageries during life cycle of VSCS Ockhi (1st December-5th December)

2.9.5.3: Features observed through SCATSAT imageries

Typical imageries from polar satellite, SCATSAT are presented in Fig. 2.9.12. SCATSAT passes are available twice a day at around 0300 UTC and 1700 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 0259 UTC of 27th indicated cyclonic circulation over southernmost Sri Lanka and adjoining southwest BoB near

5.8^0N/80.7^0E . According to Analog model developed by SAC, ISRO, Ahmedabad the Matching Index (MI) for cyclogenesis was 0.75. (MI>0.6) Stronger winds were seen in southwest and northwest sector. The imagery based on 1438 UTC of 28th indicated large scale cross equatorial flow into the circulation from southeast sector. The circulation centre lay over 6.3^0N/80.7^0E with MI of 0.82. Stronger winds were seen over south and southeast sectors of circulation centre. The imagery based on 0259 UTC of 29th indicated strengthening of system with MI of 0.74. stronger winds were seen to the south of system. However, at 1528 UTC of 29th, the SCATSAT imagery indicated slight weakening of circulation with MI of 0.49. At 0348 UTC of 30th November, it again showed weakening of system with MI of 0.34. Hence, MI was not consistent in predicting cyclogenesis of Ockhi.

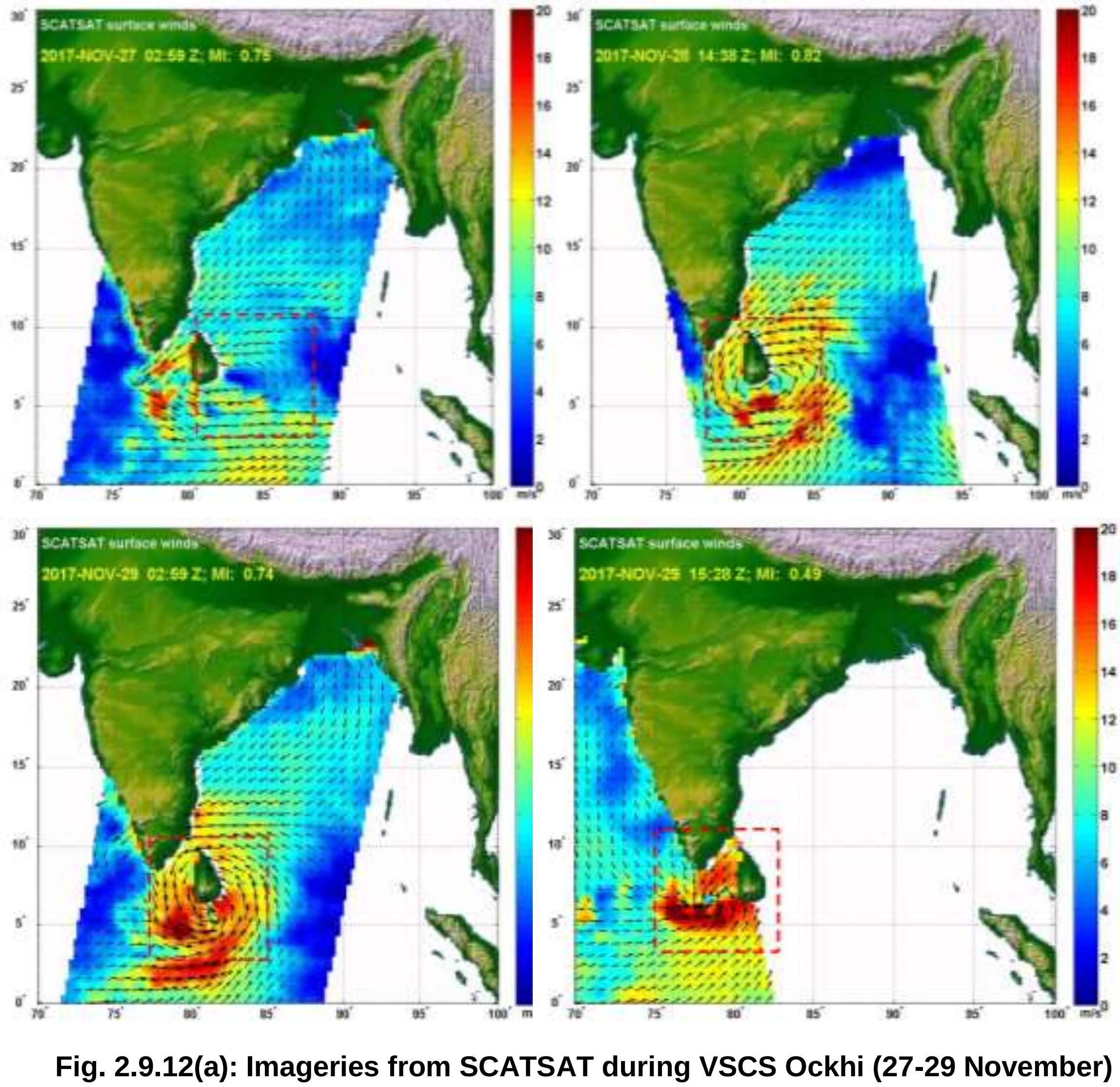


Fig. 2.9.12(a): Imageries from SCATSAT during VSCS Ockhi (27-29 November)

From 0259 UTC of 1st December, it picked up the circulation correctly and suggested MI of 0.73. Stronger winds were seen in eastern sector. At 0348 UTC of 2nd December, strong winds were seen in southwest sector also. On 3rd (1528 UTC) and 4th (0348 UTC) December, the stronger winds were seen around the system centre in all sectors. However, at 1528 UTC of 5th December, strong winds were seen near North Maharashtra coast with MI of 0.62. Thus SCAT Sat imageries based on analog technique for forecast of cyclogenesis (intensification upto T 2.5 or more) could not capture correctly the genesis, intensification and weakening of system. It rather showed weakening during genesis phase. Similarly, during weakening phase on 5th December SCATSAT over-estimated the intensity by indicating MI > 6.0. However, SCATSAT could detect the wind distribution and intensity very well during D/DD/CS stage.

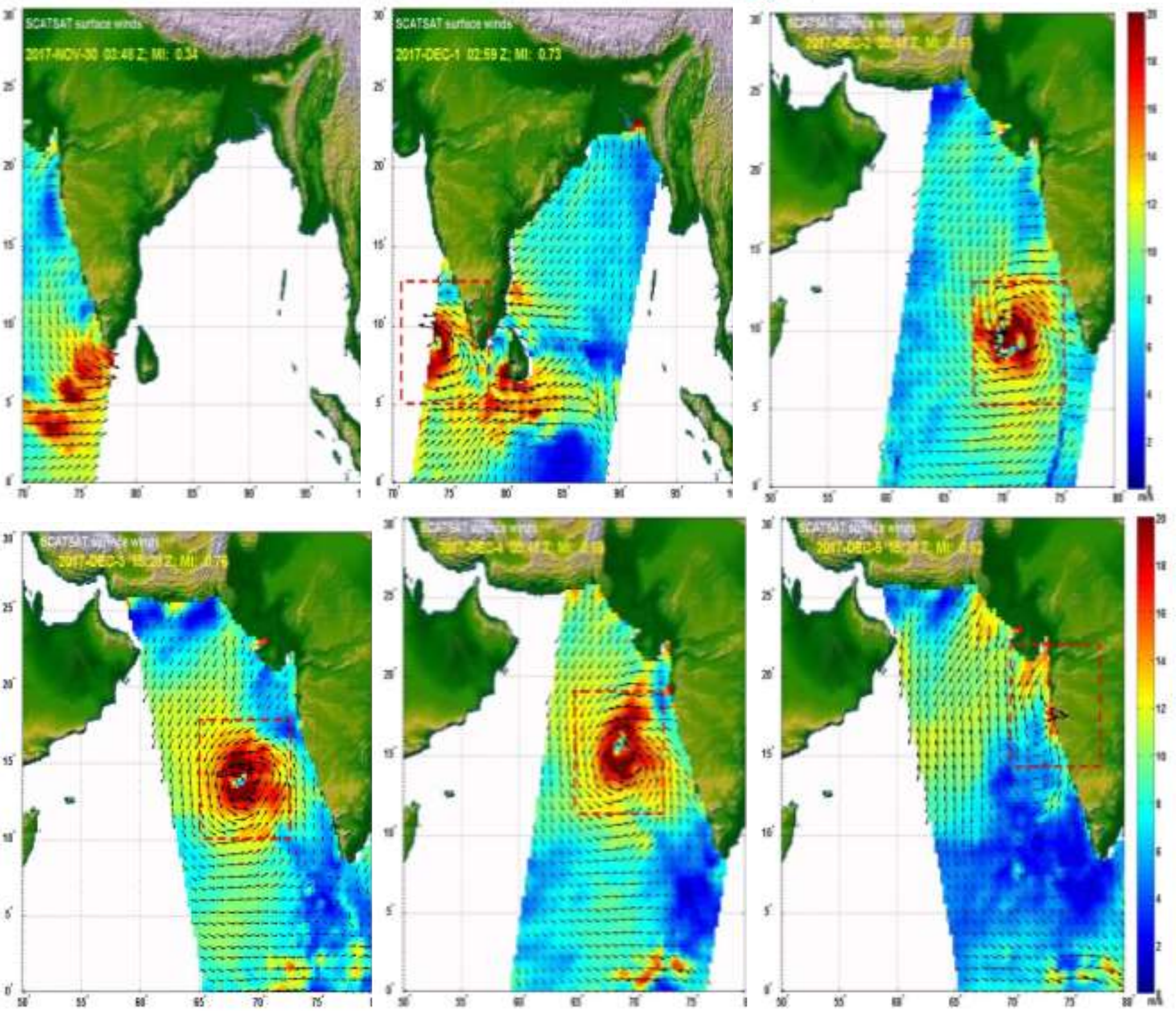


Fig. 2.9.12(b): Imageries from SCATSAT during VSCS Ockhi (30 Nov-05 Dec)

2.9.5.4. Features observed through ASCAT imageries:

Images from ASCAT helped in location of system centre and region of stronger winds. It could capture at 27/1538 UTC, a circulation over southwest BoB off south of Sri Lanka and a fresh circulation centre over southwest BoB off southeast Sri Lanka. This further strengthens that cyclone Ockhi developed from a fresh low pressure area over southwest BoB on 28^{th}. At 1637 UTC of 29^{th}, 1 minute average winds of the order of 30-35 kts were seen over Comorin Area. Corresponding 3-minute average winds are 25-30 kts. At 0454 UTC of 1^{st}, the system was centered over Lakshadweep area near 9.0^0N/74.0^0E and winds of the order of 40-45 kts were seen in the southwest sector. However, at that time winds of 55kts prevailed over the region. Thus as expected, intensity was under-estimated in SCS/VSCS stage. At 1657 UTC of 3^{rd}, it indicated that the system was centered near 13.2^0N /68^0E with maximum winds of 35kts seen in eastern sector. At this time the system was centered near 13.0^0N /68.6^0E with MSW of 75 kts. At 0529 UTC of 4^{th}, it indicated system centered near 14.6^0N /68.8^0E with maximum winds of the order of 40-45 kts in the northeast sector. At 0600 UTC of 4^{th}, the system was centered near 14.9^0N /68.7^0E with MSW of 65 kts. It can be concluded that ASCAT imageries could predict the centre quite accurately. It could also very well detect intensity in the stage of D/DD/CS. It could not pick up intensity of the system correctly in SCS/VSCS stage as expected.

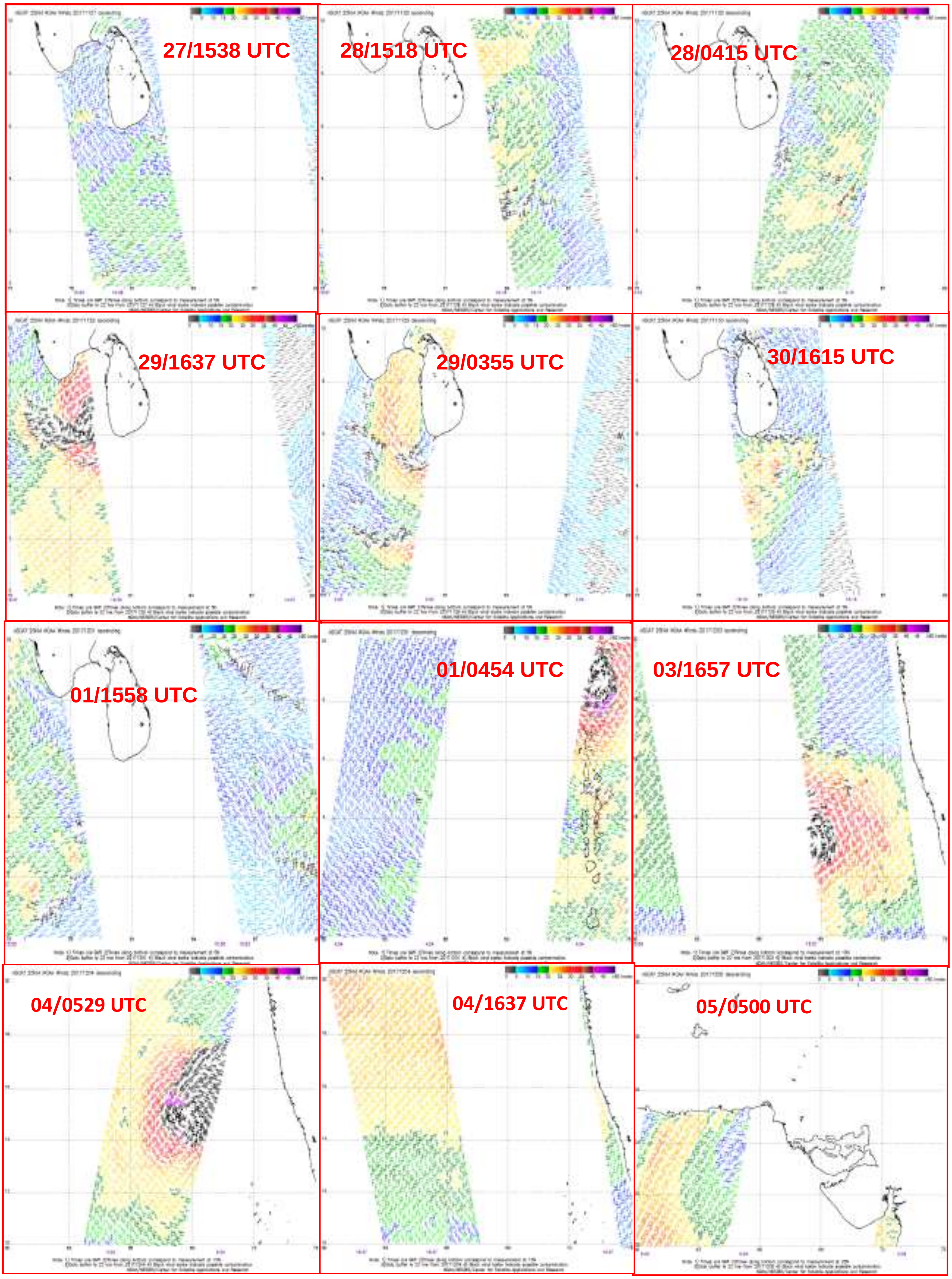


Fig. 2.9.12 (c): ASCAT imageries during life cycle of VSCS Ockhi (27 November-05 December)

2.9.6. Features observed through Radar

As the system developed over southwest BoB off southeast Sri Lanka, emerged into Comorin Area and moved across southeast and eastcentral Arabian Sea, it was well captured by DWR Thiruvananthapuram and Kochi. The associated convection was also detected by DWR Chennai, Karaikal, CDR Goa and DWR Mumbai. However, it was close to DWR Thiruvananthapuram followed by Kochi during genesis and intensification phase. Hence detailed analysis has been made based on the product of these two DWRs. DWR Chennai, Karaikal, Goa and Mumbai being away from the centre of system, could not detect the specific features of genesis and intensification. Typical Radar imageries from these Radars as received are presented in Fig. 2.9.13.

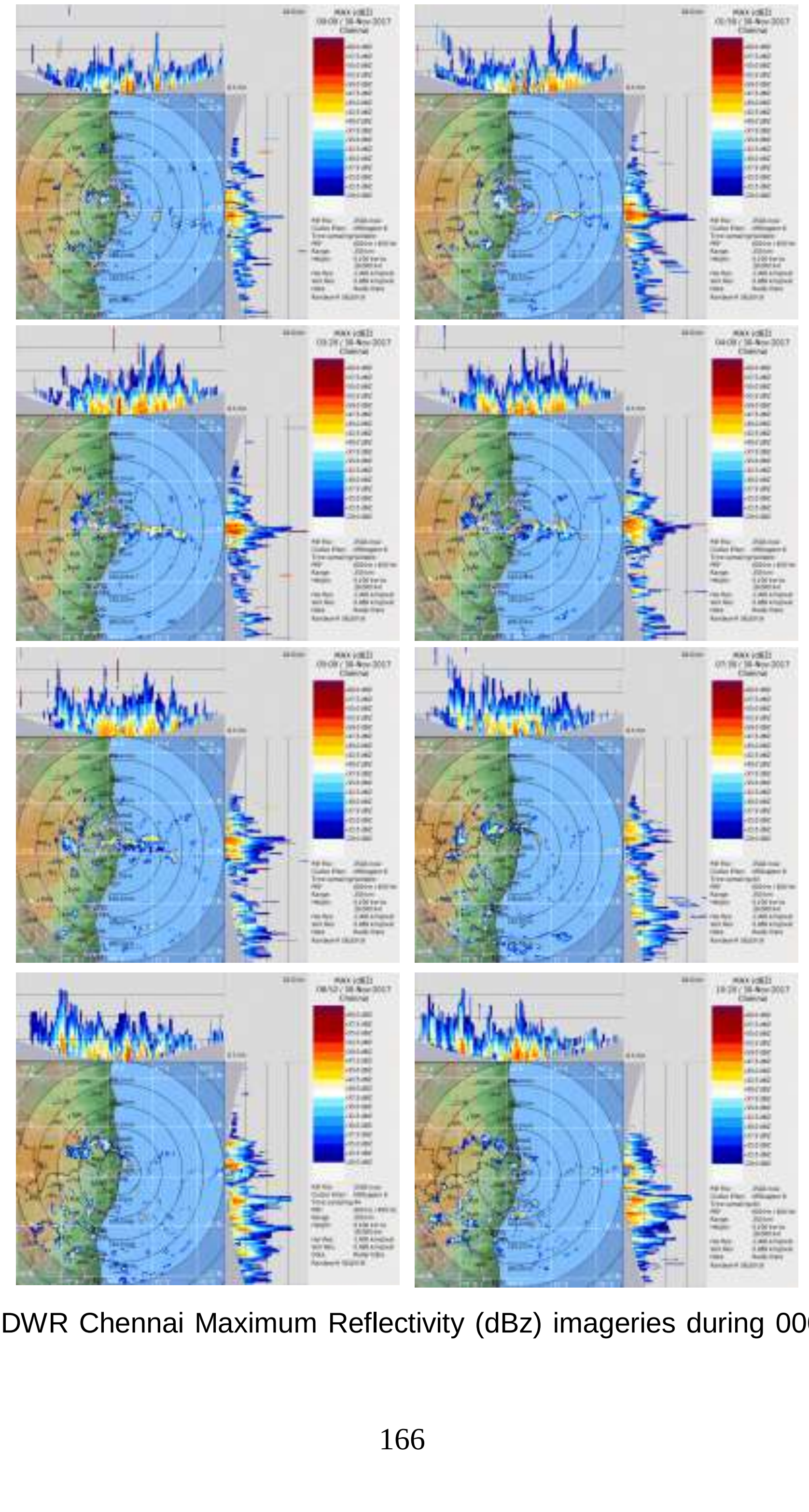


Fig. 2.9.13 (a): DWR Chennai Maximum Reflectivity (dBz) imageries during 0000-1020 UTC of 30th November

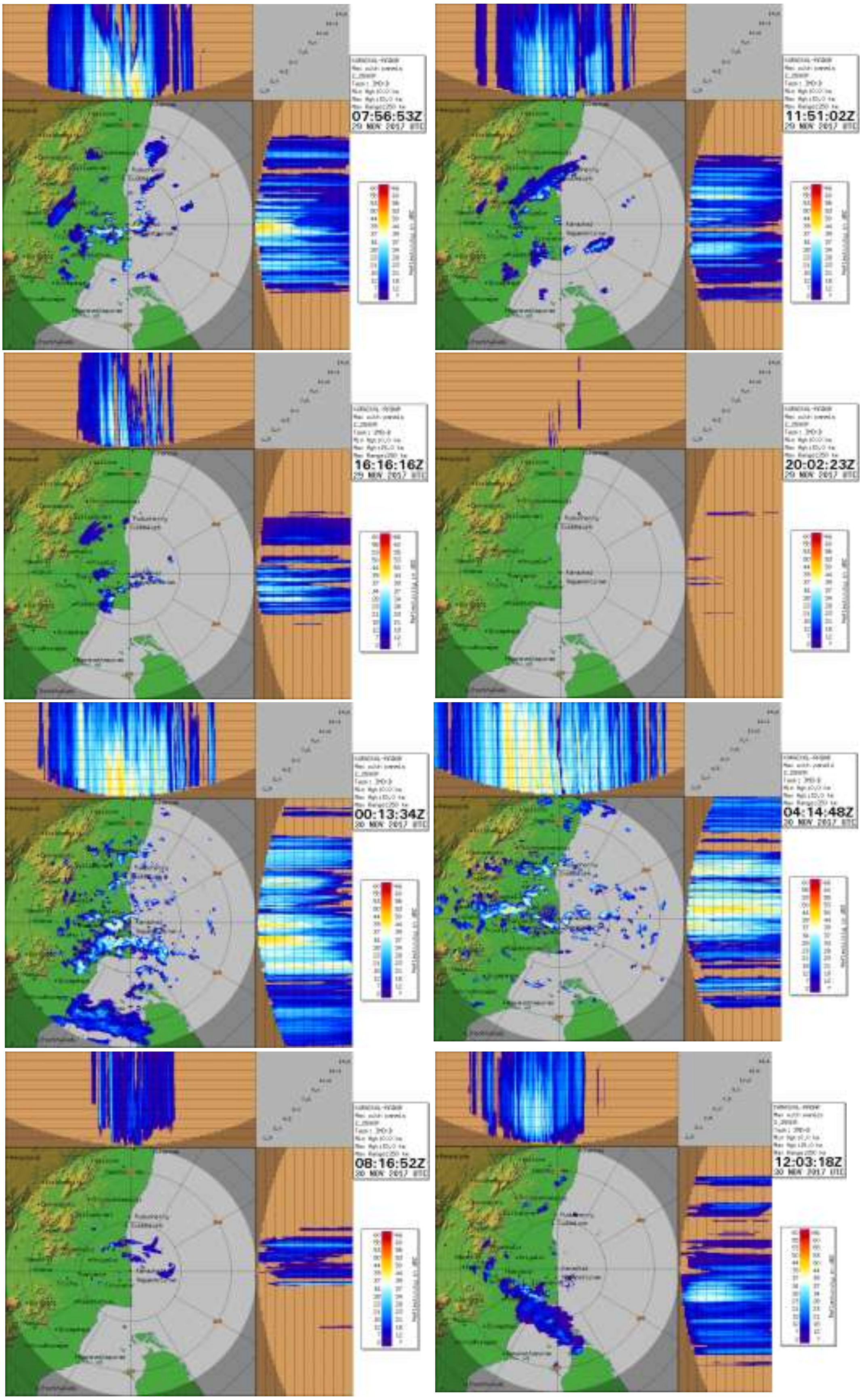


Fig. 2.9.13(b): DWR Karaikal Maximum Reflectivity (dBz) imageries during 0756 UTC of 29th- 1203 UTC of 30th November

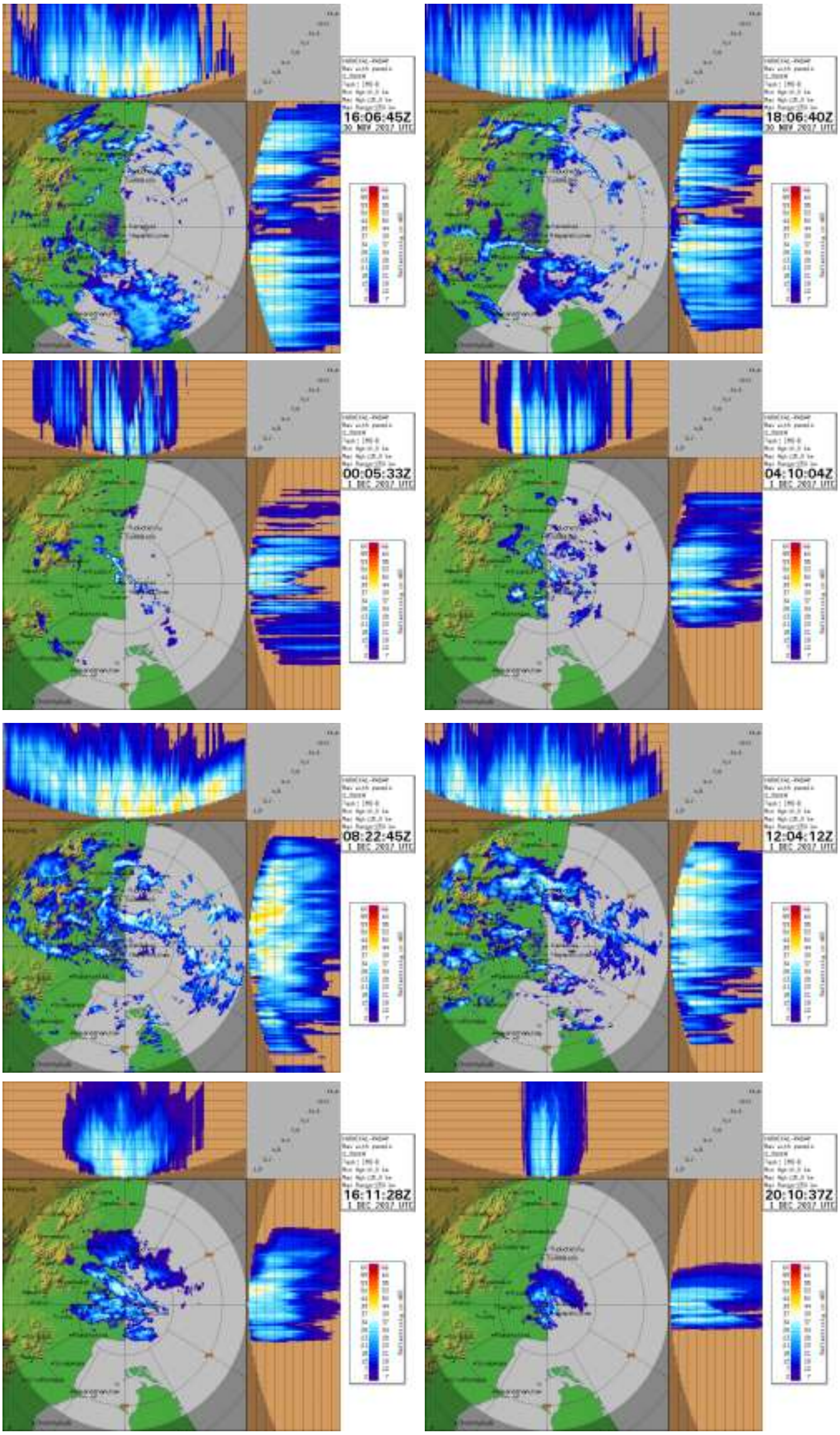


Fig. 2.9.13 (c): DWR Karaikal Maximum Reflectivity (dBz) imageries during 1606 UTC of 30th November -2010 UTC of 1st December

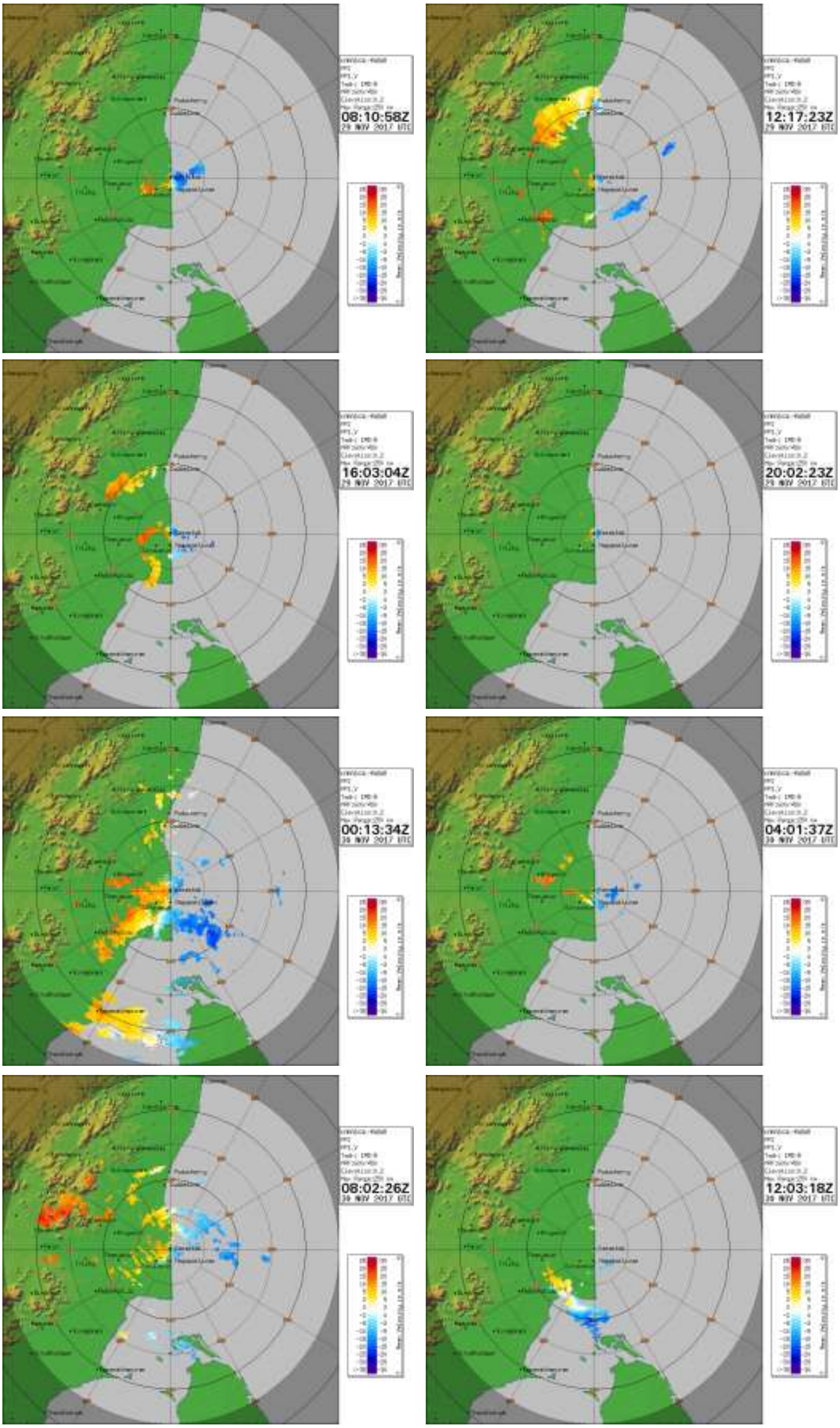


Fig. 2.9.13 (d): DWR Karaikal radial velocity (m/s) imageries during 0810 UTC of 29th - 1203 UTC of 30th November

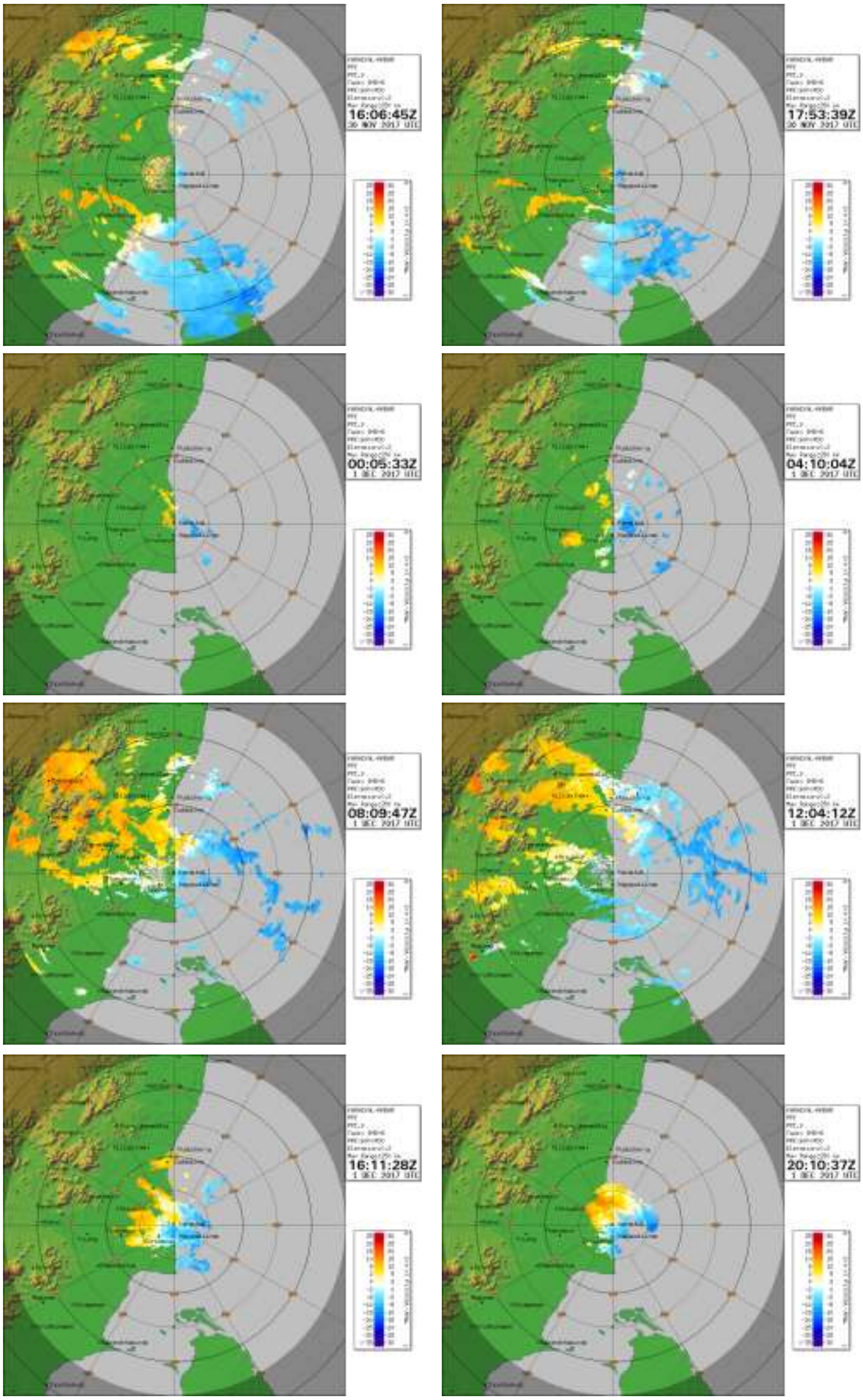


Fig. 2.9.13 (e): DWR Karaikal radial velocity (m/s) imageries during 1606 UTC of 30th November -2010 UTC of 1st December

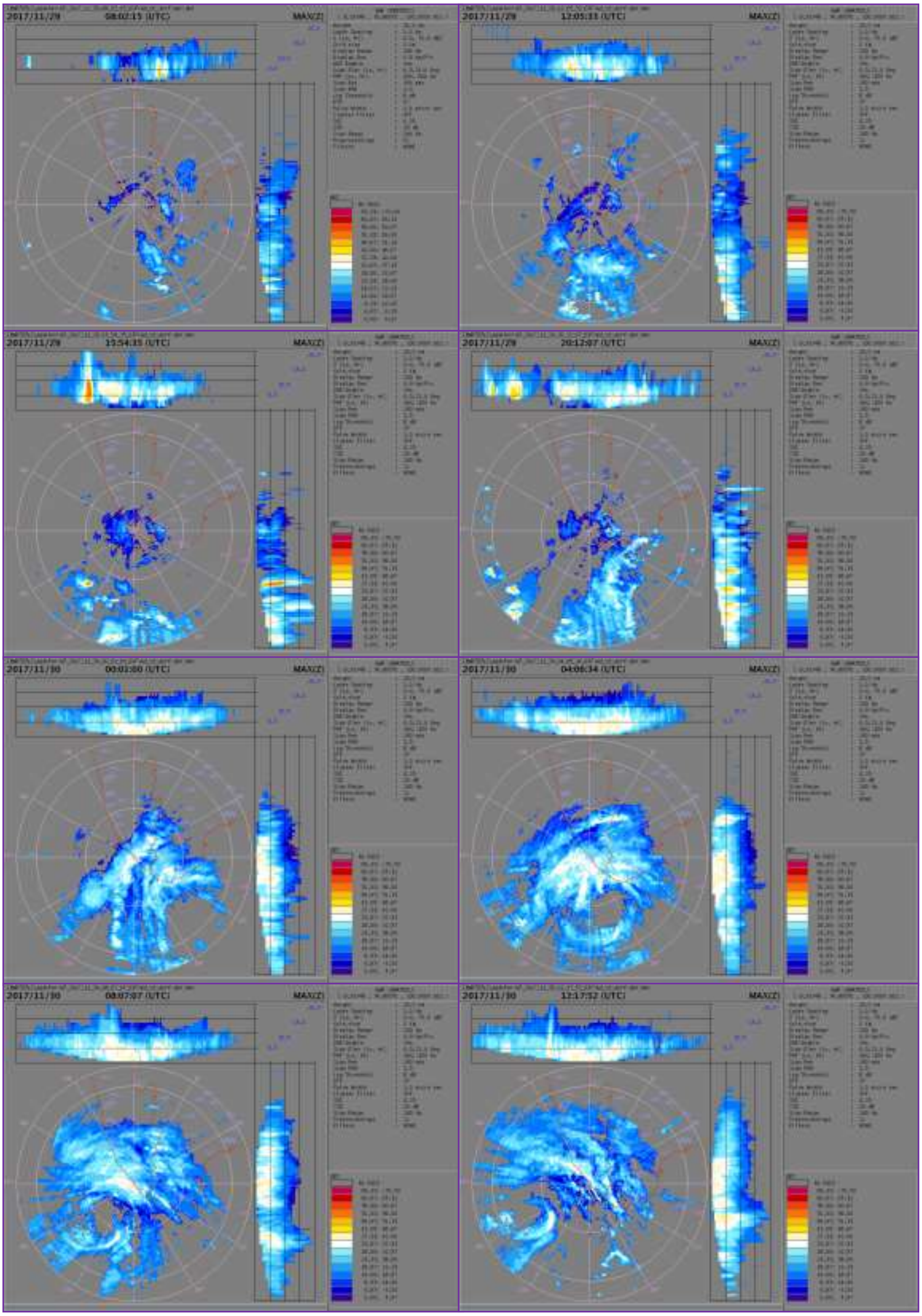


Fig. 2.9.13 (f): DWR Thiruvananthapuram Maximum Reflectivity (dBz) imageries during 0802 UTC of 29th -1217 UTC of 30th November

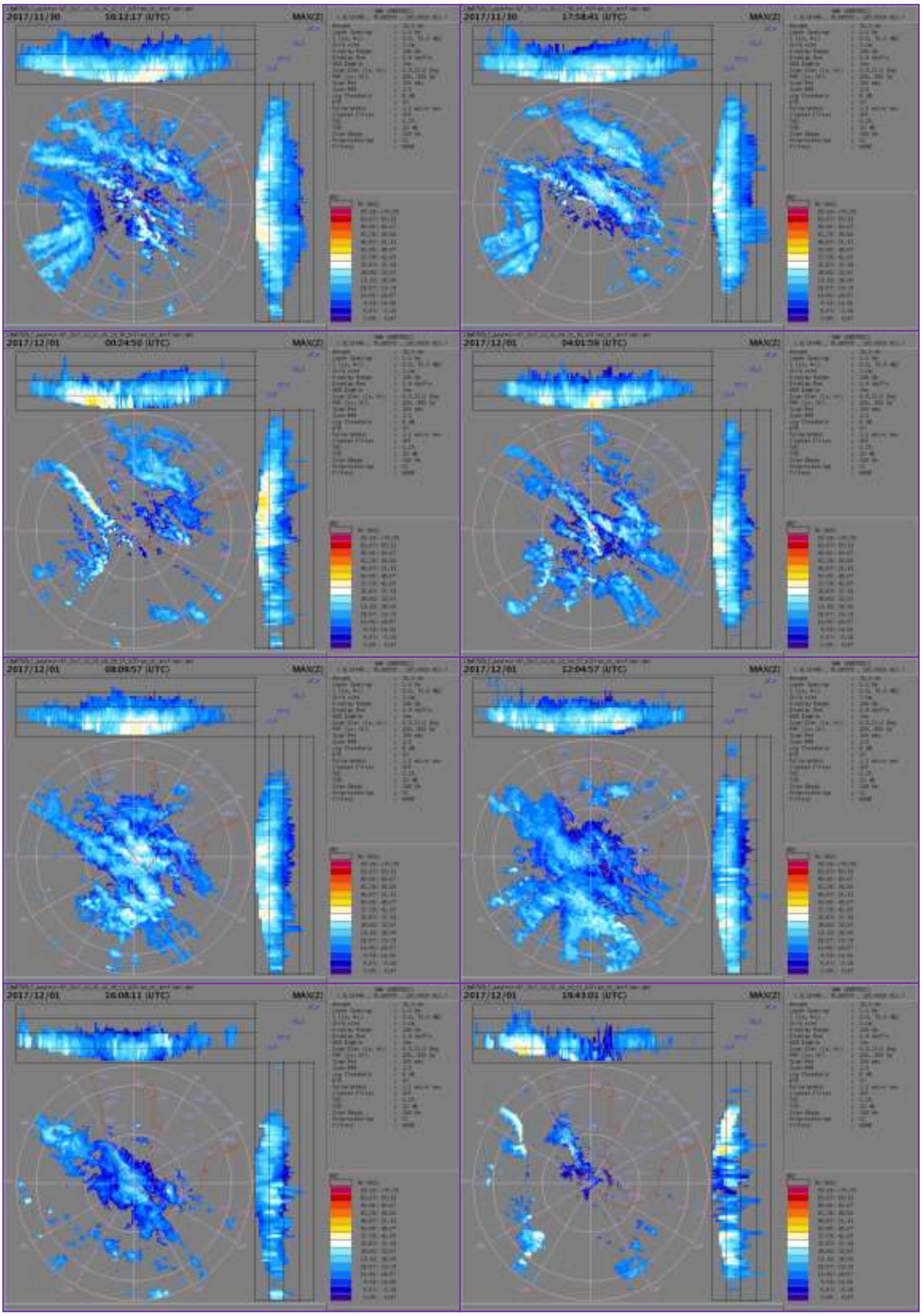


Fig. 2.9.13 (g): DWR Thiruvananthapuram Maximum Reflectivity (dBz) imageries during 1612 UTC of 30th November-1947 UTC of 1st December

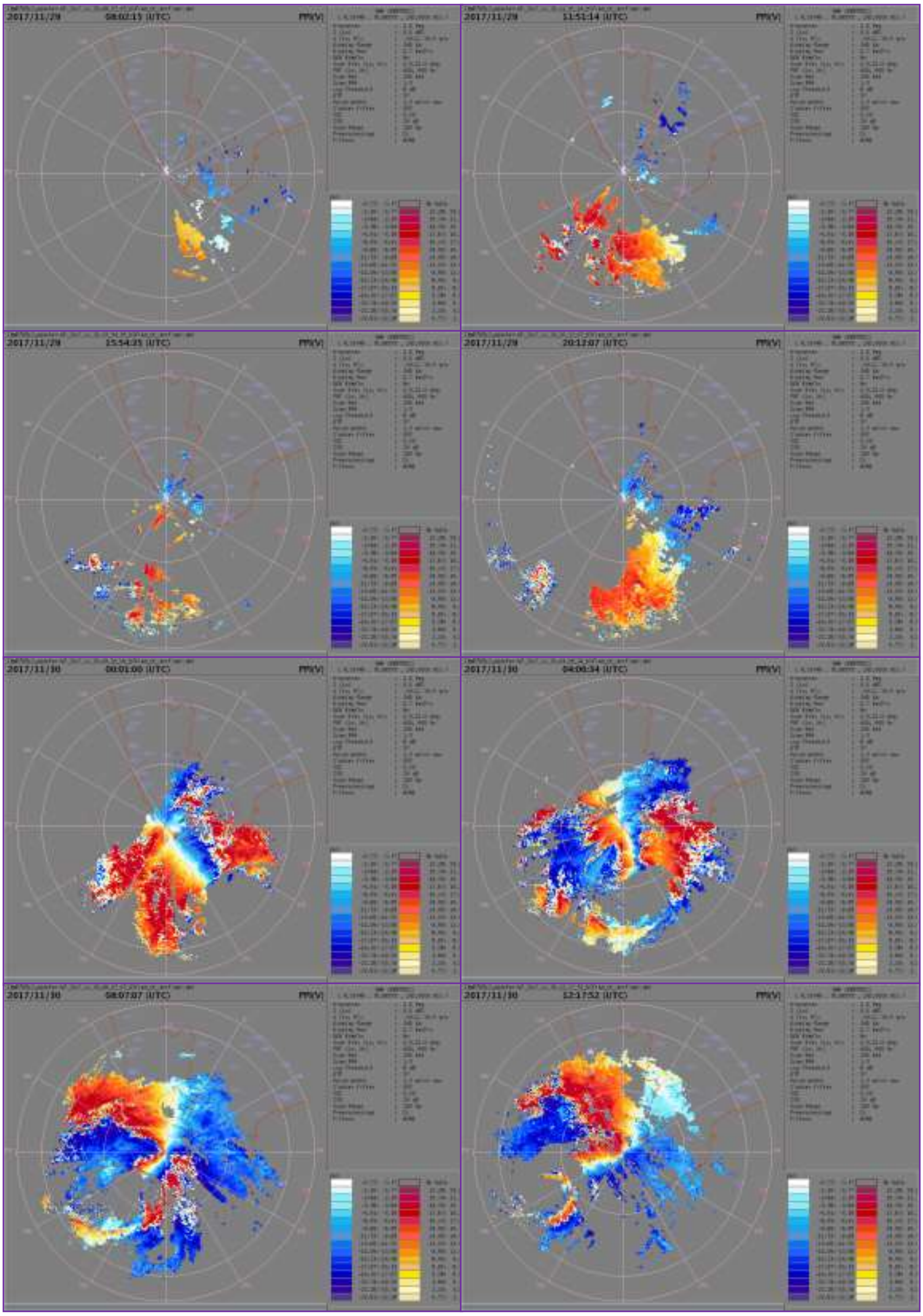


Fig. 2.9.13 (h): DWR Thiruvananthapuram radial velocity (m/s) imageries during 0802 UTC of 29th -1217 UTC of 30th November

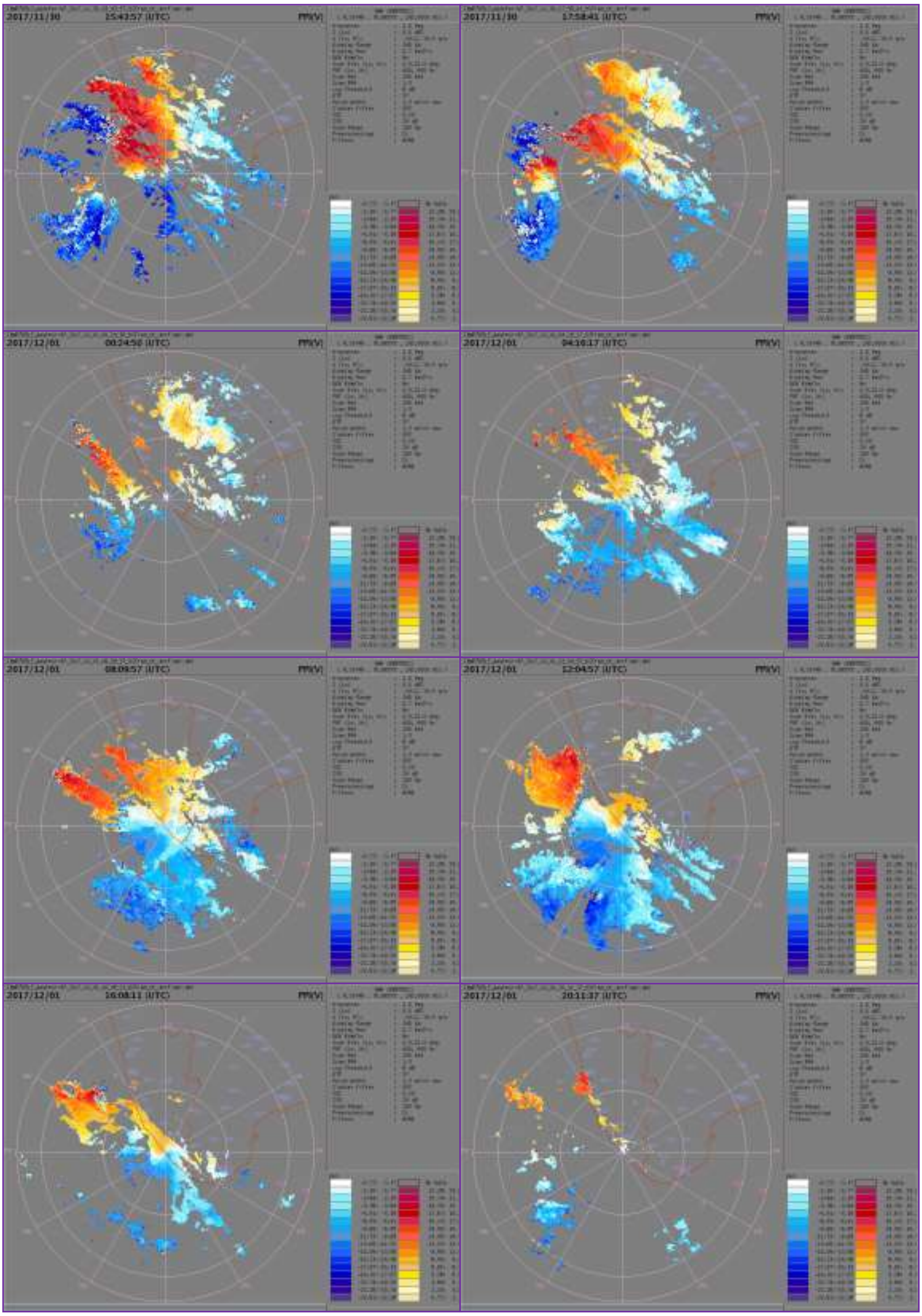


Fig. 2.9.13 (i): DWR Thiruvananthapuram radial velocity (m/s) imageries during 1543 UTC of 30th November-2011 UTC of 1st December

Imageries from CDR Kochi are presented in Fig. 2.9.13 (j). The VSCS Ockhi was captured by CDR Kochi during 0000 UTC of 29th November to 2nd December. The hourly observations from CDR Kochi are presented in Table 2.9.3 & 4.

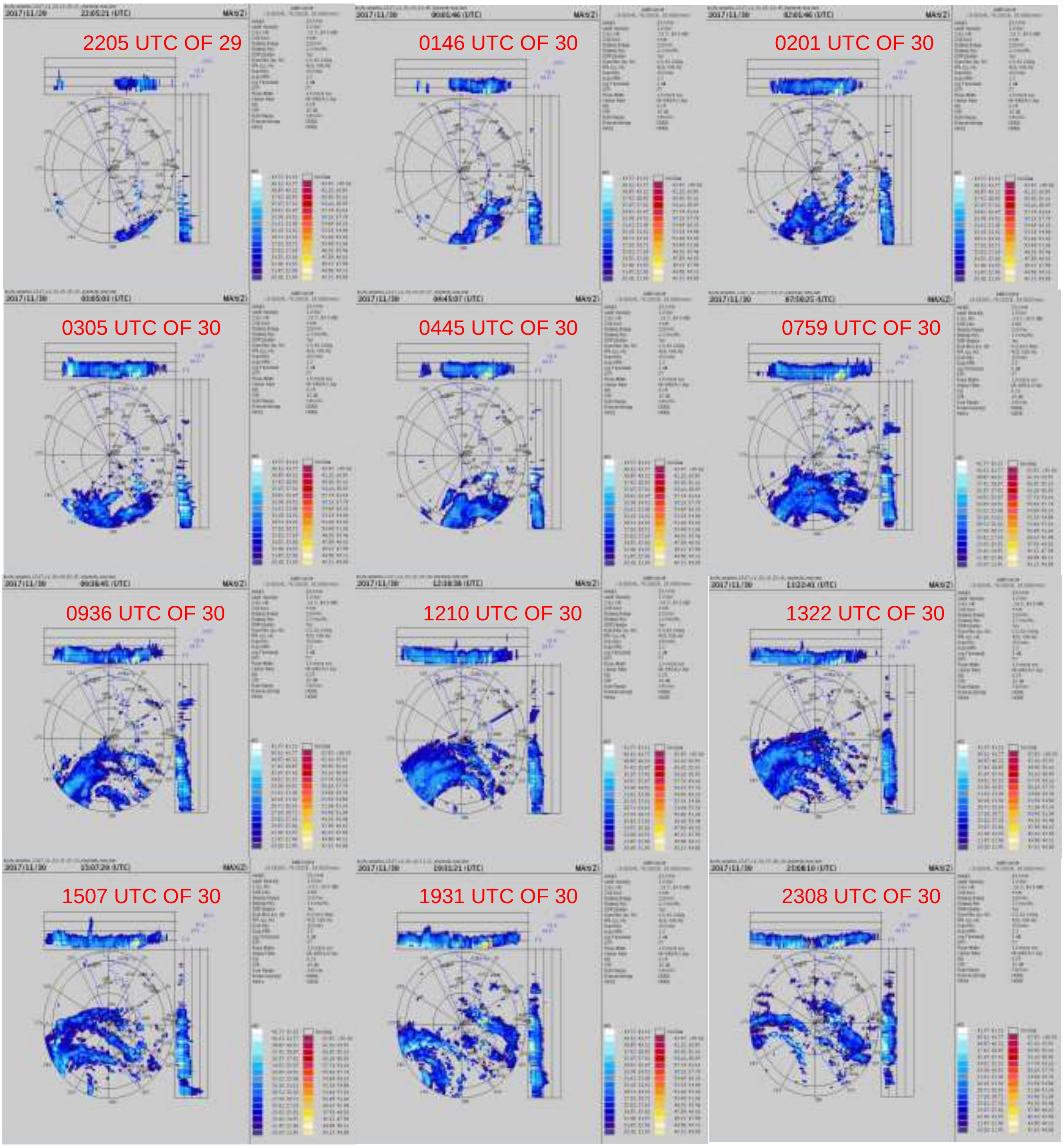


Fig. 2.9.13 (j): CDR Kochi Maximum Reflectivity (dBz) imageries during 2205 UTC of 29th November-2308 UTC of 30th November

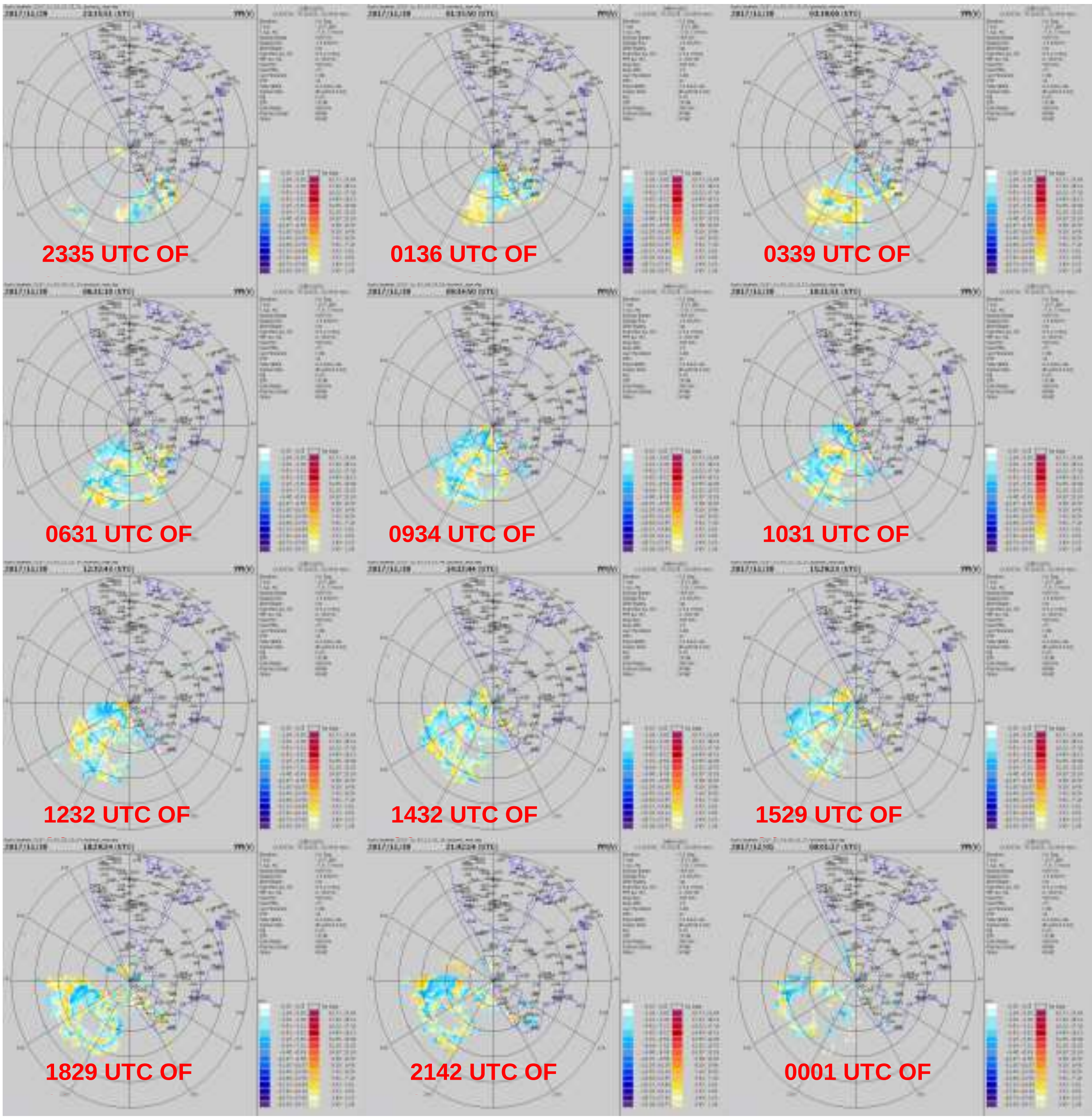


Fig. 2.9.13 (k): CDR Kochi Plan Position Indicator radial velocity (PPI_V) imageries during 2335 UTC of 29th November-0001 UTC of 1st December

As per CDR Kochi Radar observations, maximum radial velocity of 44.7 m/s was recorded at 1907 UTC of 30th November in south-southwest direction (211^0) at a distance of 223 km at a height of 2.92 km above station level. As per the standard procedure the radial velocity has been converted to surface wind. Utilizing the mean wind speed profile, based on dropsonde observations over Atlantic Ocean in the eyewall region of cyclones, radar based radial wind observations at a given height has been converted initially into wind at 700 hPa level (W_{700hPa}) and then at surafce level (W_{10m}). The wind is first converted to 700 hPa level as the WC-130J flies at this level and dropsonde is released into the cyclone field from this level. A suitable conversion factor for changing the radar wind at a given height to the 700 hPa level has been used based on Franklin etal, (2000) and Powel & Black (1990). The standard vertical profile of wind based on dropsonde observation over the north Atlantic has been used for the above purpose.

Table 2.9.3 (a): DWR Kochi observations of maximum sustained surface winds associated with VSCS Ockhi during 29th November-02 December

Date/ Time in UTC	Azimuth (deg)	Range (km)	Height (km)	Latitude (deg)	Longitude (deg)	Radial Velocity in m/s	Conversion factor .	$W_{700\ hPa}$ in m/s	W_{10m}= (7)X0.73 (kt) @1
-1	-2	-3	-4	-5	-6	-7	-8	-9	10
29/0000	196	212	2.64			17.31	1.03	16.81	24
29/2205	155	222	2.9			23.78	1.01	23.54	33
29/2301	175	226	3			18.27	1	18.27	26
30/0101	178	229	3.08			28.53	1	28.53	40
30/0201	200	230	3.11			24.01	1	24.01	34
30/0305	143	237	3.3	Centre ill defined		-32.9	1	-32.9	-47
30/0407	143	213	2.67	7.519	77.242	-28.31	1.03	-27.49	-39
30/0509	179	224	2.95	7.712	77.016	36.14	1.01	35.78	51
30/0609	185	218	2.79	7.827	76.766	37.23	1.02	36.5	52
30/0711	161	207	2.52	7.802	76.546	-38.69	1.03	-37.56	-53
30/0811	193	226	3	7.968	76.339	36.17	1	36.17	51
30/0900	170	236	3.28	8.007	76.159	-39.34	1	-39.34	-56
30/1008	204	223	2.92	8.019	76.004	40.62	1.01	40.22	57
30/1110	201	217	2.77	8.007	75.836	41.09	1.02	40.28	57
30/1210	206	211	2.62	8.058	75.771	40.84	1.03	39.65	56
30/1310	209	207	2.52	8.121	75.629	38.04	1.03	36.93	52
30/1410	224	191	2.15	8.275	75.487	41.74	1.05	39.75	56
30/1507	218	191	2.15	8.287	75.344	43.28	1.05	41.22	58
30/1607	228	221	2.87	8.351	75.176	41.14	1.01	40.73	58
30/1707	231	211	2.62	8.439	74.943	41.95	1.03	40.73	58
30/1807	235	223	2.92	8.439	74.839	42.49	1.01	42.07	60
30/1907	211	223	2.92	8.413	74.698	-44.7	1.01	-44.26	-63
30/1955	241	217	2.77	8.425	74.659	40.64	1.02	39.84	56
30/2057	240	221	2.87	8.553	74.606	42.62	1.01	42.2	60
30/2156	241	221	2.87	8.604	74.477	42.17	1.01	41.75	59
30/2320	226	230	3.11	8.717	74.217	-34.95	1	-34.95	-49

01/0003	266	222	2.9	8.806	74.126	29.09	1.01	28.8	41
01/0102	270	152	1.36	8.819	74.074	30.75	1.07	28.74	41
01/0202	271	179	1.88	8.882	73.944	31.23	1.05	29.74	42
01/0302	252	225	2.98	8.918	73.698	19.96	1	19.96	28
01/0402	259	230	3.11	8.904	73.529	26.29	1	26.29	37
01/0502	260	231	3.14	8.778	73.44	22.64	1	22.64	32
01/0602	197	93	0.51	8.774	73.272	-16.6	1.21	-13.72	-19
01/0702	242	117	0.8	8.773	73.116	-22.48	1.08	-20.81	-29
01/0845	261	50	0.15	8.758	72.961	32.82	0.92	35.67	51
01/0921	263	50	0.15			23.47	0.92	25.51	36
01/1011	264	232	3.17			16.27	1	16.27	23
01/1111	268	102	0.61			28.02	1.06	26.43	37
01/1201	259	237	3.3			15.26	1	15.26	22
01/1301	265	229	3.08			23.77	1	23.77	34
01/1401	221	167	1.64			18.79	1.07	17.56	25
01/1502	269	226	3			22.95	1	22.95	32
01/1607	270	232	3.17			19.93	1	19.93	28
01/1707	268	239	3.36			21.47	1	21.47	30
01/1807	224	207	2.52			-24.35	1.03	-23.64	-33
01/1907	227	218	2.79			-23.97	1.02	-23.5	-33
01/2105	290	232	3.17			23.99	1	23.99	34
01/2140	240	140	1.15			-18.84	1.07	-17.61	-25
02/0028	239	105	0.65			-22.24	1.06	-20.98	-30
02/0104	262	154	1.39			-15.95	1.07	-14.91	-21
02/0204	294	216	2.74			17.86	1.02	17.51	25
02/0307	298	198	2.31			14.41	1.04	13.86	20
02/0407	317	217	2.77	Centre ill defined		19.13	1.02	18.75	27

–ve radial velocity indicates winds were directed towards Radar Station, @1 Powell and Black estimation

Table 2.9.3 (b): Final observations from DWR Kochi of centre and 3-minute average maximum sustained wind (kts) for VSCS Ockhi during 29th Nov.02 Dec

Date/ Time in UTC	Latitude (deg)	Longitude (deg)	W_{10m}= (7)X0.73 (kt)
(1)	(2)	(3)	(4)
29/0000	Centre ill defined		24
29/2205			33
29/2301			26
30/0101			40
30/0201			34
30/0305			-47
30/0407	7.519	77.242	-39
30/0509	7.712	77.016	51
30/0609	7.827	76.766	52
30/0711	7.802	76.546	-53
30/0811	7.968	76.339	51
30/0900	8.007	76.159	-56
30/1008	8.019	76.004	57
30/1110	8.007	75.836	57
30/1210	8.058	75.771	56
30/1310	8.121	75.629	52
30/1410	8.275	75.487	56
30/1507	8.287	75.344	58
30/1607	8.351	75.176	58
30/1707	8.439	74.943	58
30/1807	8.439	74.839	60
30/1907	8.413	74.698	-63
30/1955	8.425	74.659	56
30/2057	8.553	74.606	60
30/2156	8.604	74.477	59
30/2320	8.717	74.217	-49
01/0003	8.806	74.126	41
01/0102	8.819	74.074	41
01/0202	8.882	73.944	42
01/0302	8.918	73.698	28
01/0402	8.904	73.529	37
01/0502	8.778	73.44	32
01/0602	8.774	73.272	-19
01/0702	8.773	73.116	-29
01/0845	8.758	72.961	51
01/0921	Centre ill defined		36
01/1011			23
01/1111			37
01/1201			22
01/1301			34

01/1401		25
01/1502		32
01/1607		28
01/1707		30
01/1807		-33
01/1907		-33
01/2105		34
01/2140		-25
02/0028		-30
02/0104		-21
02/0204		25
02/0307		20
02/0407		27

The centre of the system as observed by DWR Thiruvananthapuram is presented in Table 2.9.4. DWR Thiruvananthapuram could very well detect the centre of the system on 30th November from morning onwards when the system attained the intensity of cyclonic storm over Comorin area.

Table 2.9.4: Hourly observations of centre from DWR Thiruvananthapuram

Time (UTC)	Range (from DWR to centre) km	Centre latitude (deg.)	Centre longitude (deg.)
0:58:16	166.37	7.3814	77.8249
1:55:30	157.4	7.3816	77.6913
2:12:24	144.92	7.4053	77.5185
2:55:02	135.02	7.46	77.4322
4:06:34	112.5	7.5849	77.2123
5:03:47	92.99	7.7097	76.9922
6:01:00	86.28	7.772	76.7327
6:55:49	77.61	7.9044	76.5675
8:07:07	85.43	7.9587	76.355
9:04:20	107.39	7.966	76.0796
9:47:18	114.4	8.0048	75.9772
10:53:25	135.03	8.1132	75.7172
12:03:12	145.18	8.0818	75.6308
13:13:17	148.47	8.1517	75.5754
13:55:56	162.97	8.2369	75.4177
15:04:29	181.62	8.3452	75.2282

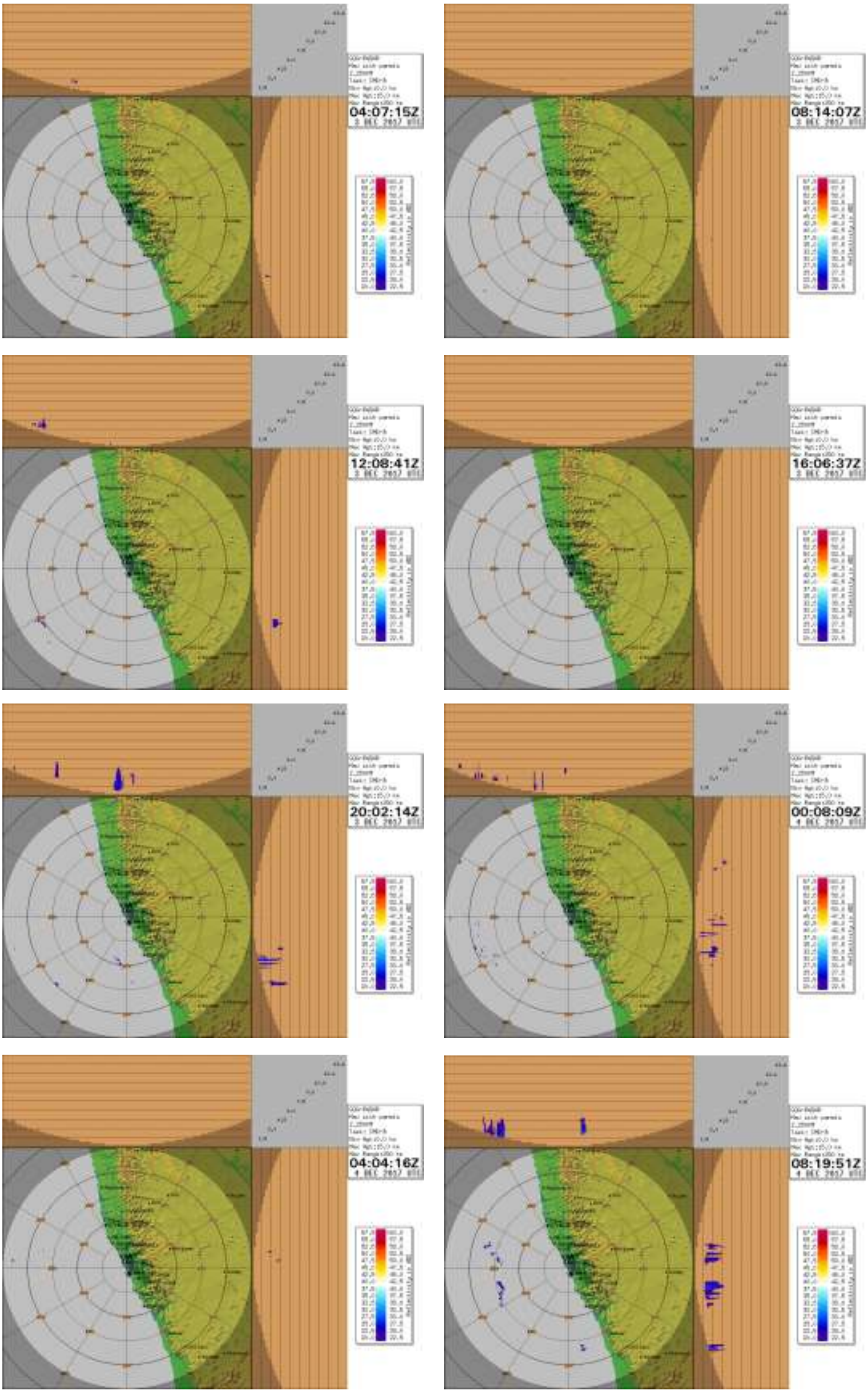


Fig. 2.9.13 (l): DWR Goa maximum reflectivity (dBz) imageries during 0407 UTC of 3rd -0819 UTC of 4th December

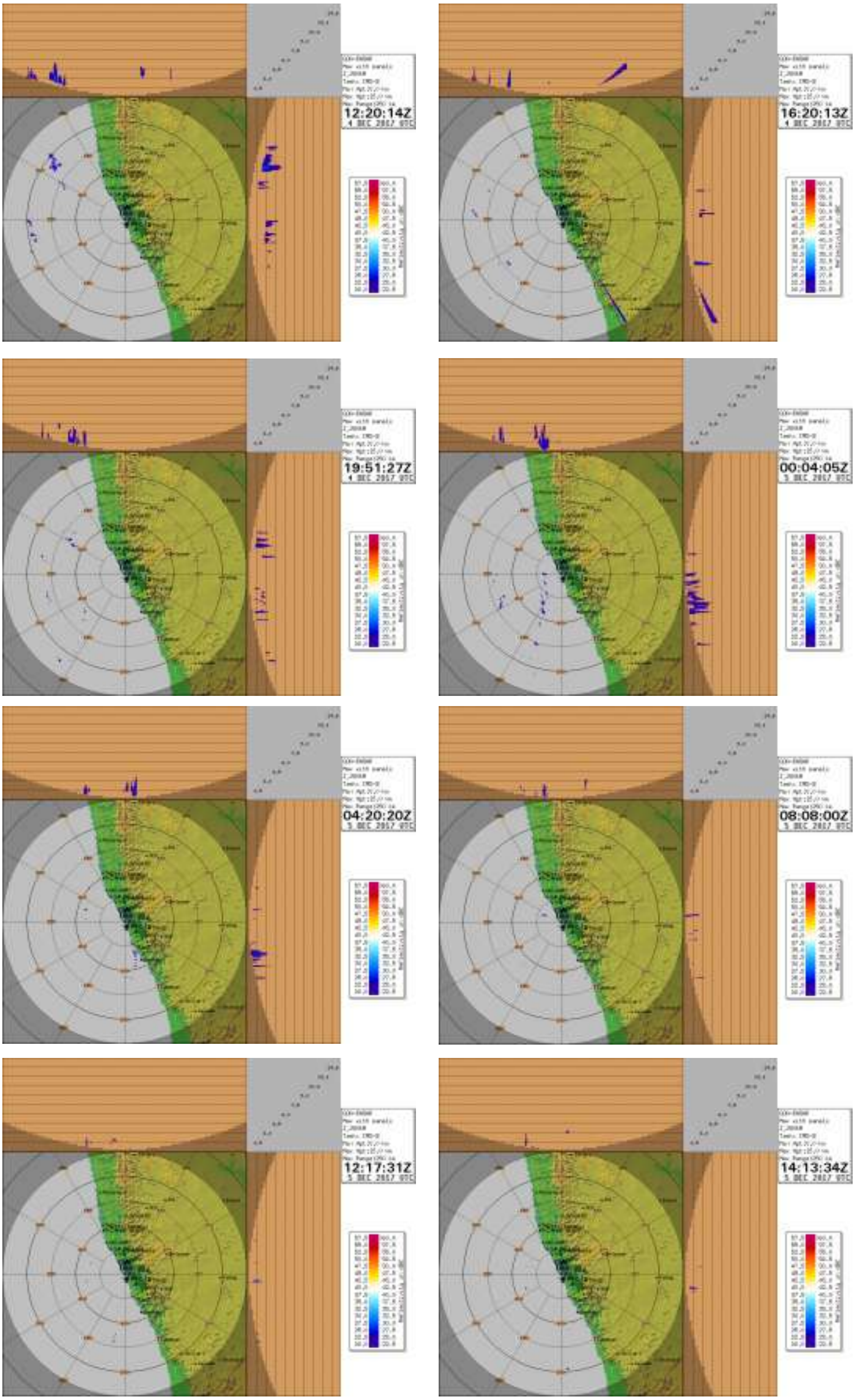


Fig. 2.9.13 (m): DWR Goa maximum reflectivity (dBz) imageries during 1220 UTC of 4th -1413 UTC of 5th December

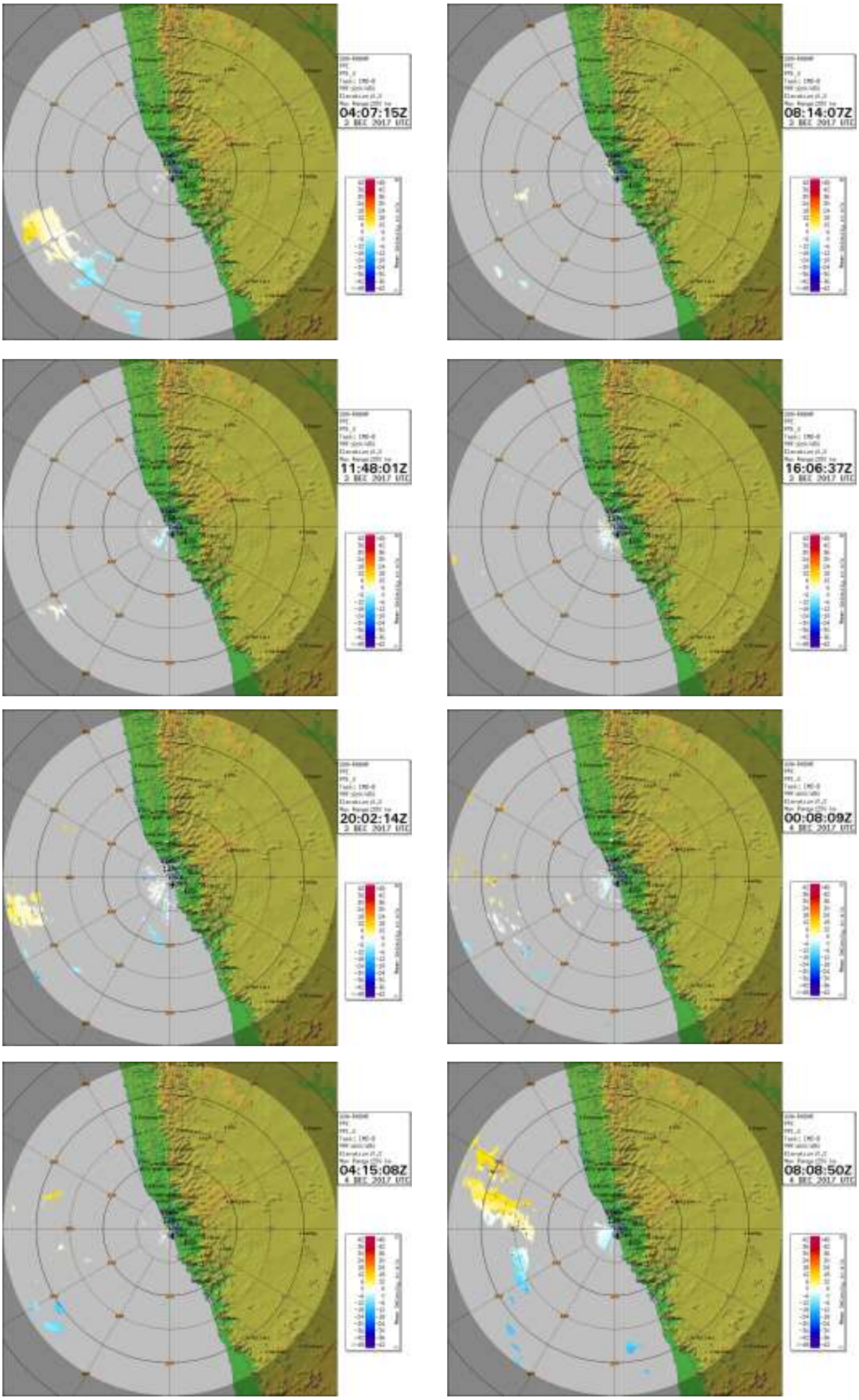


Fig. 2.9.13 (n): DWR Goa Plan Position Indicator (PPI_V) radial velocity (m/s) imageries during 0407 UTC of 3rd -0808 UTC of 4th December

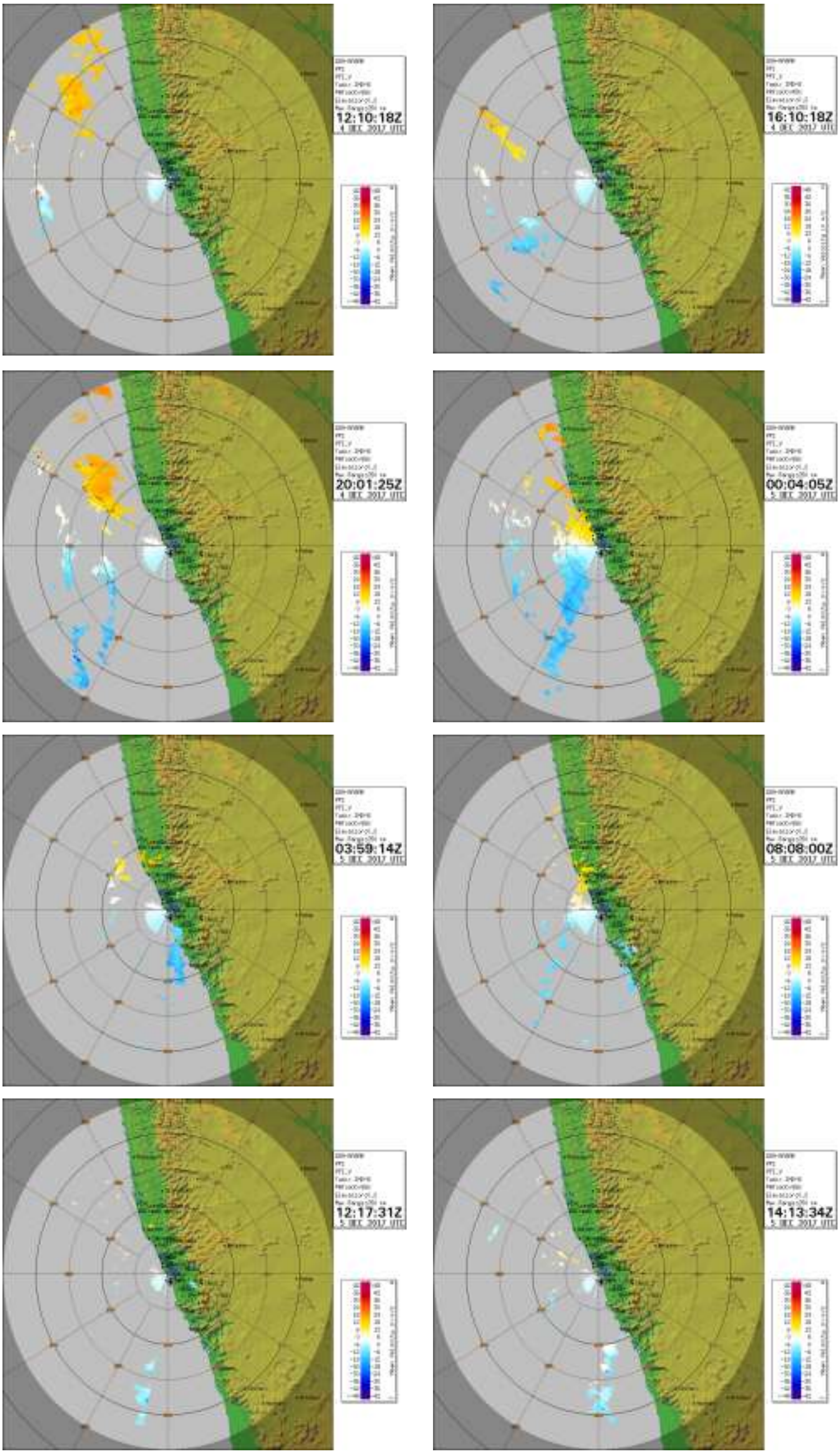


Fig. 2.9.13 (O): DWR Goa Plan Position Indicator (PPI_V) radial velocity (m/s) imageries during 1210 UTC of 4th -1413 UTC of 5th December

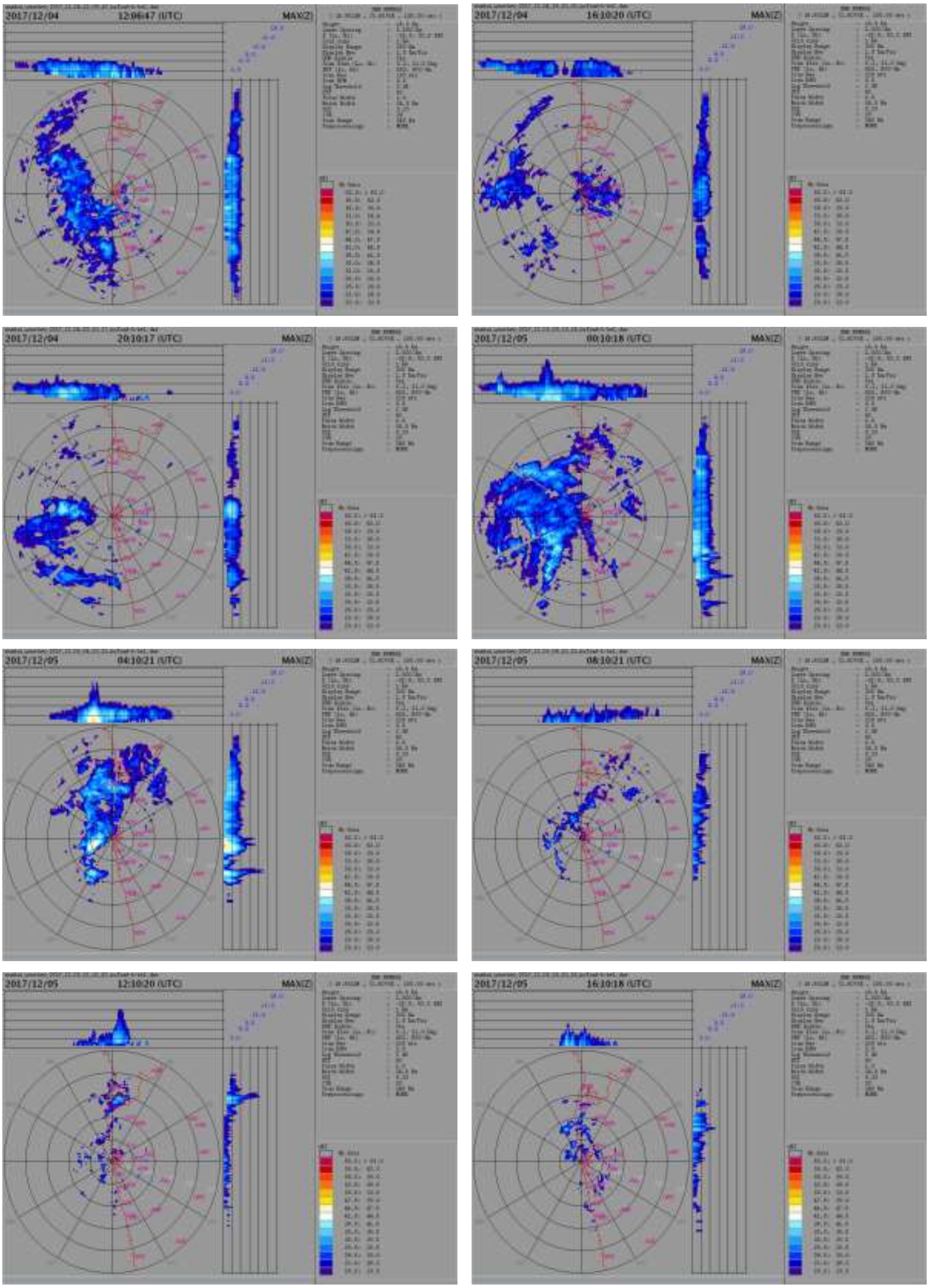


Fig. 2.9.13 (p): DWR Mumbai Max Reflectivity (dBZ) imageries during 1206 UTC of 4th -1610 UTC of 5th December

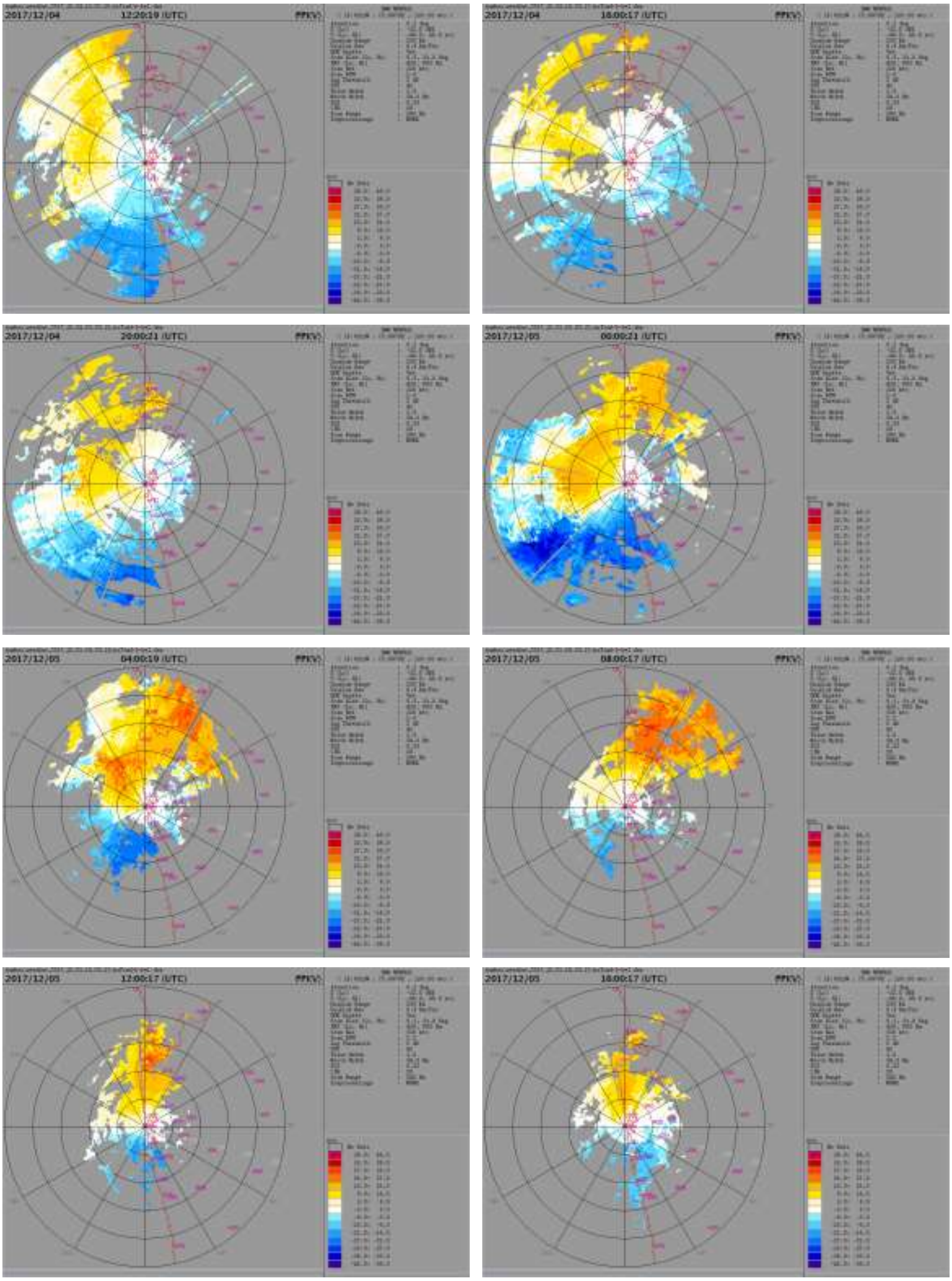


Fig. 2.9.13 (q): DWR Mumbai Plan Position Indicator (PPI_V) imageries during 1220 UTC of 4th - 1600 UTC of 5th December

2.9.7. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 27th November-6th December are presented in Fig. 2.9.14. The forecast field parameters based aforementioned initial conditions are given in Annexure-1. The analysis field based on 0000 UTC observations of 27th showed a feeble trough of low over southwest BoB and adjoining Sri Lanka coast. The forecast field indicated formation of low over Sri Lanka and neighbourhood on 29th, becoming well marked on 30th over the same area and weakening into a low again on 01st December over southwest and adjoining southeast BoB.

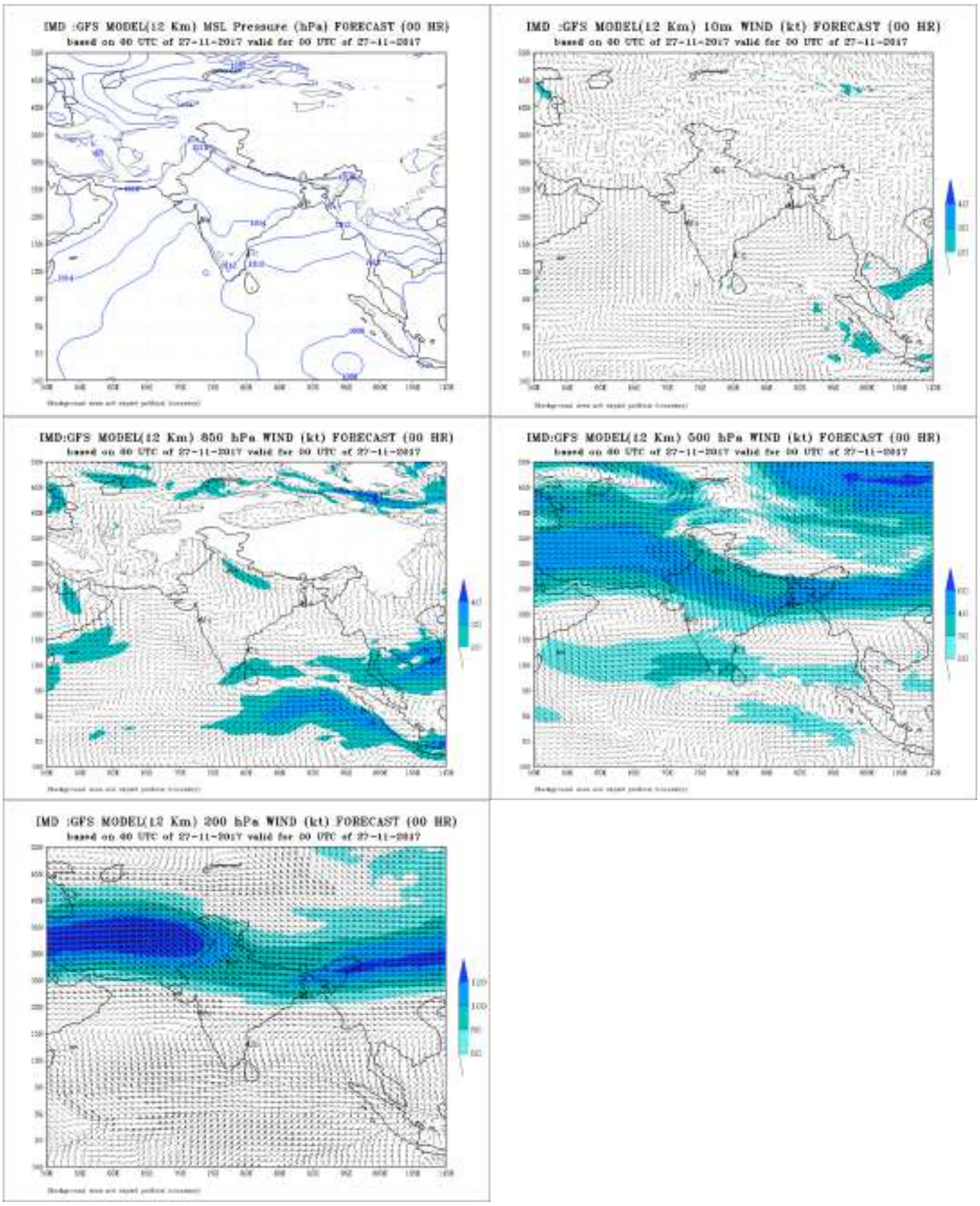


Fig.2.9.14 (a): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 27th November

The analysis field based on 1200 UTC observations of 27th showed an extended low over southwest BoB and adjoining Sri Lanka coast. The forecast field indicated formation of depression over southwest Bob on 29th, moving eastwards and intensifying into deep depression over southwest BoB and adjoining southeast BoB on 30th. On 1st and 2nd it indicated merger with the system coming from Malay Peninsula.

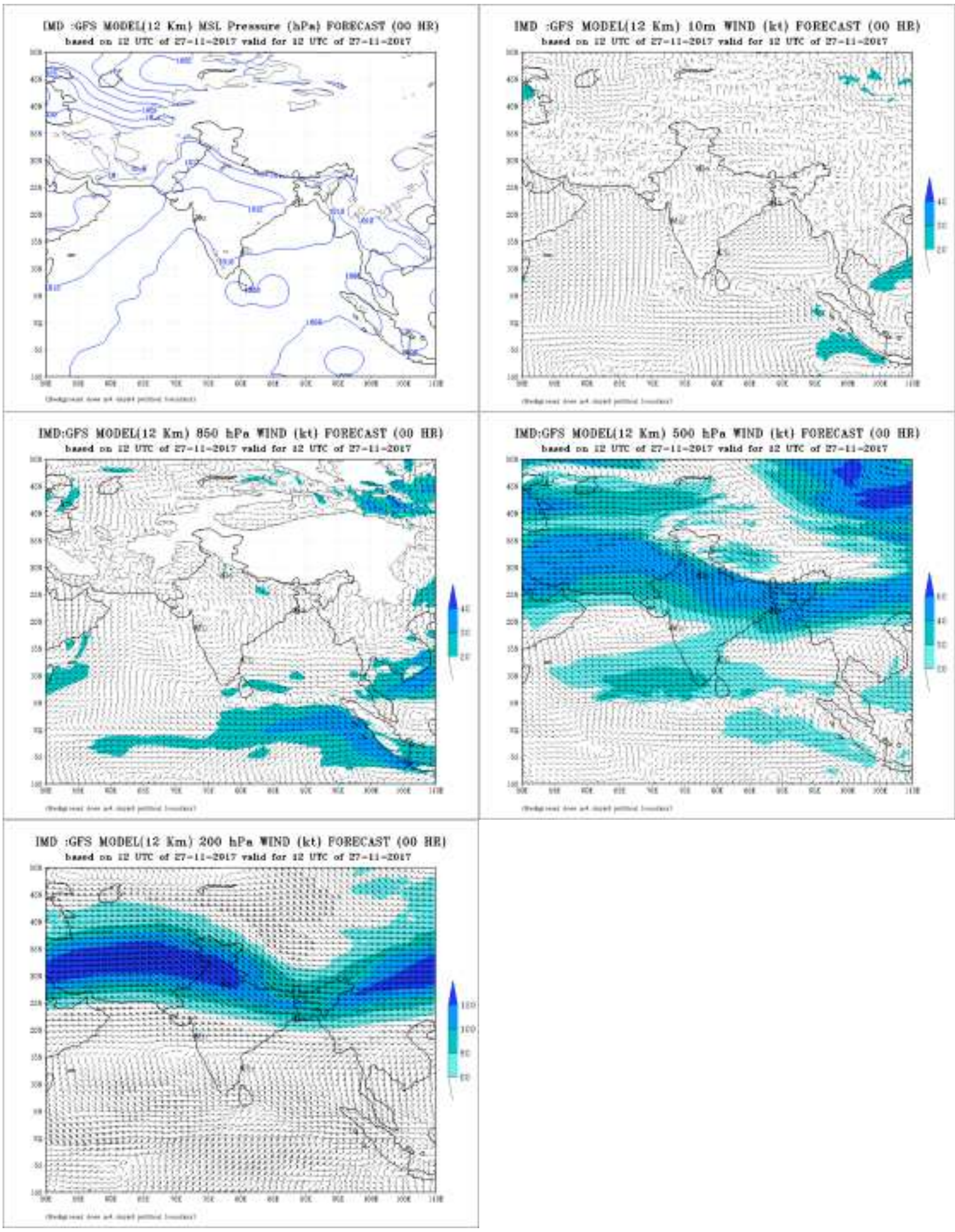


Fig. 2.9.14 (b): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 1200 UTC of 27th November

The analysis field based on 0000 UTC observations of 28th showed a well-marked low over Sri Lanka and neighborhood on 28th. The forecast field showed that it persisted on 30th over the same area, weakened into a low again on 02nd December over SE Bay and become less marked on 04th.

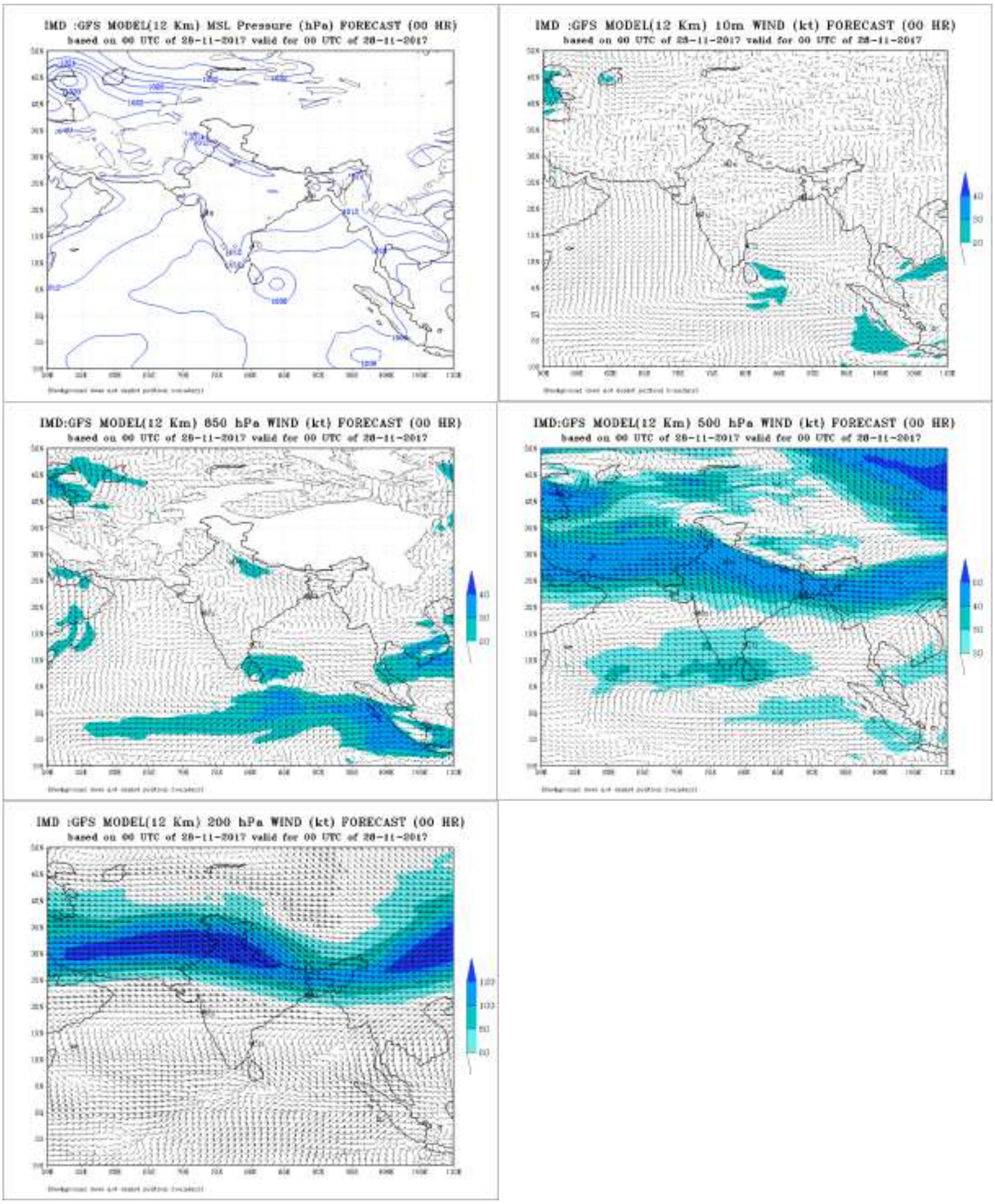


Fig. 2.9.14 (c): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 28th November

The analysis field based on 1200 UTC observations of 28th showed a well-marked low over Sri Lanka and neighborhood on 28th. The forecast field showed that the system moved westwards and lay as Depression over southwest BoB and adjoining southwest Sri Lanka. Moving westwards, it intensified into CS over Comorin on 30th. It moved north-northwestwards and lay as depression over Lakshadweep on 1st. On 2nd and 3rd, it intensified into deep depression over Lakshadweep.

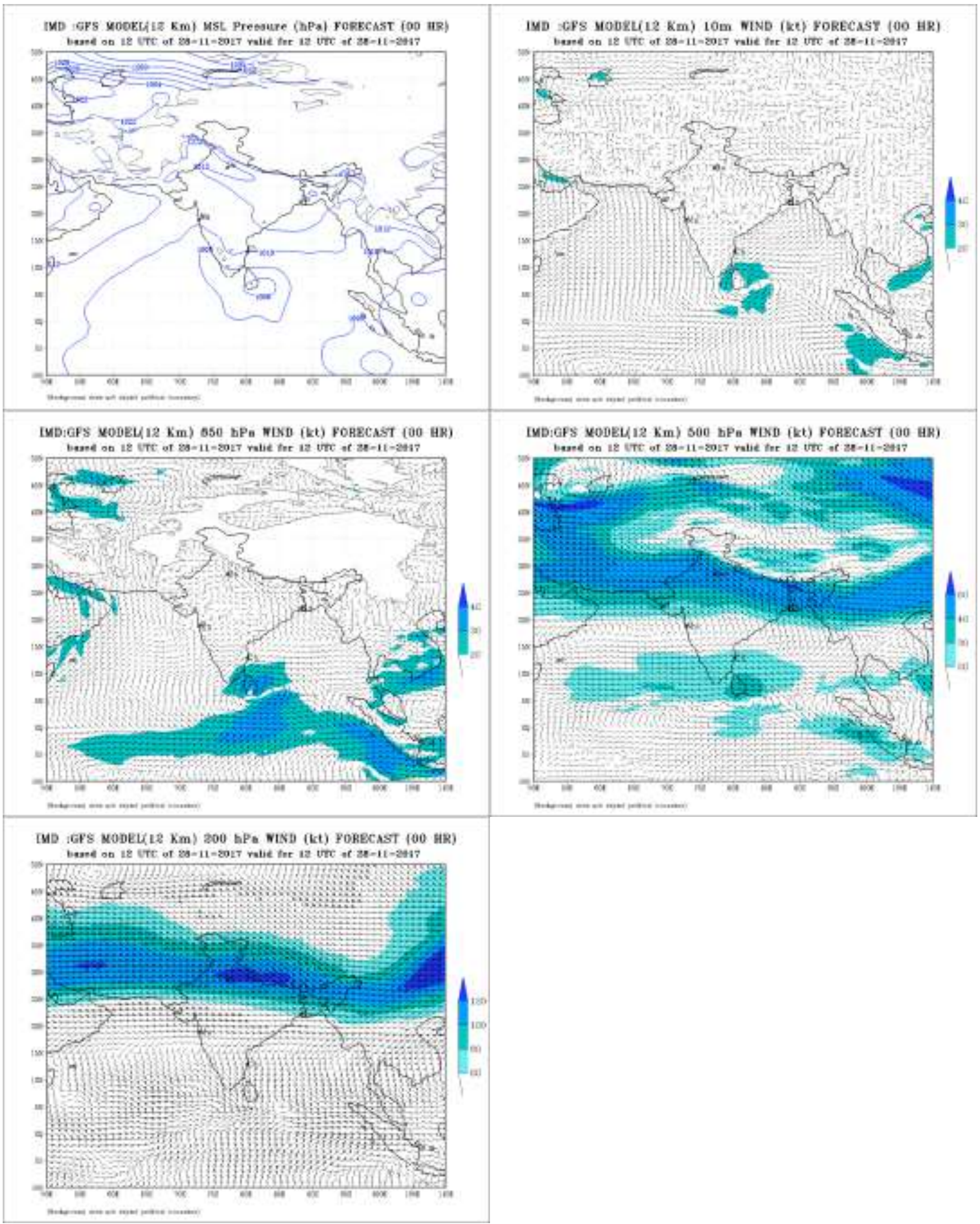


Fig. 2.9.14 (d): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 1200 UTC of 28th November

The analysis field based on 0000 UTC observations of 29th showed a depression over Comorin off extreme southwest Sri Lanka. The forecast field showed that it would move west-northwestwards and intensify into a deep depression on 03rd December over southeast Arabian Sea. Thereafter, it would move in northeast direction and weaken into a depression close to south Maharashtra- Karnataka coasts on 06th December and further into a low pressure area on 07th December over eastcentral BoB.

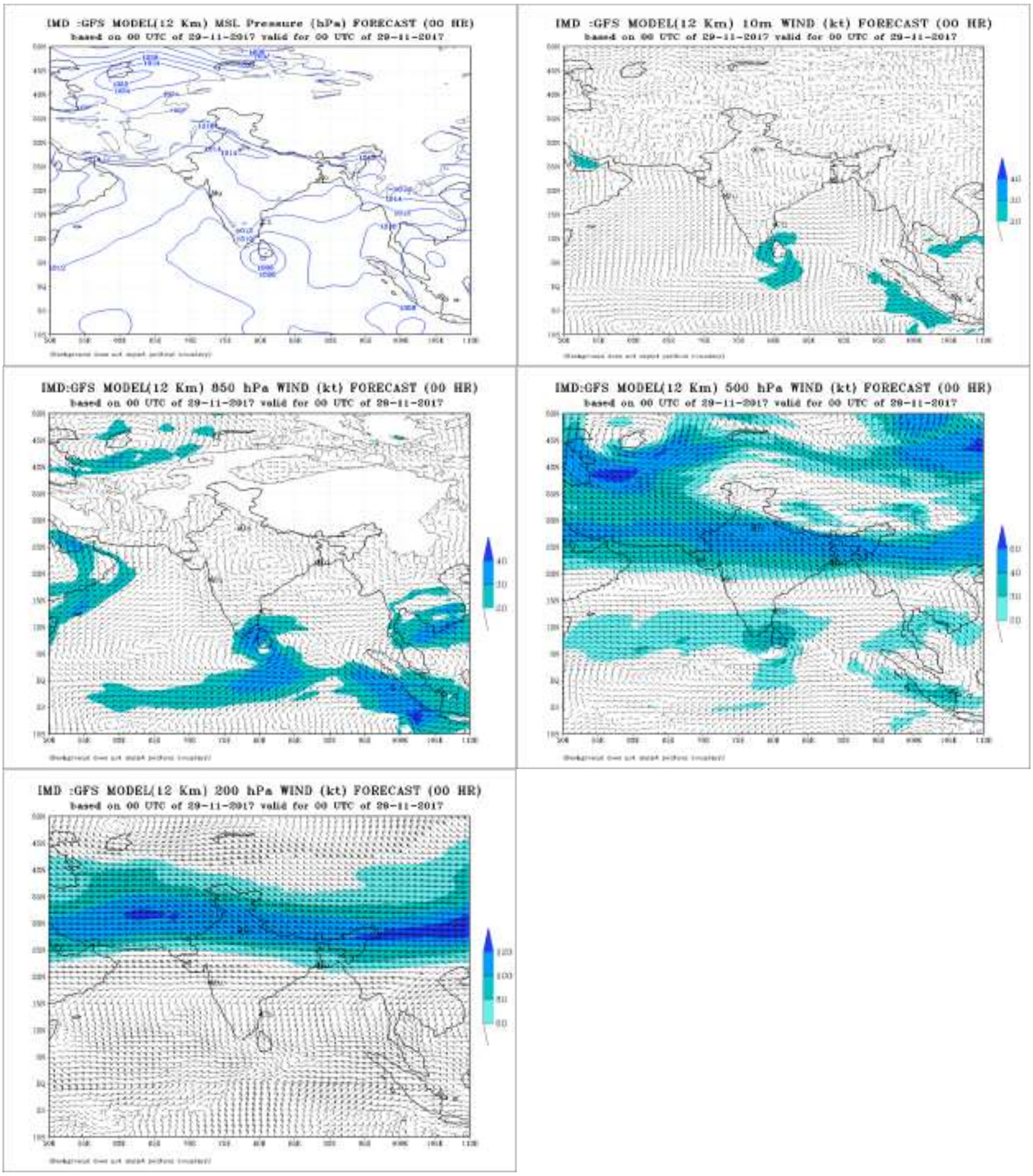


Fig. 2.9.14 (e): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 29th November

The analysis field based on 1200 UTC observations of 29th showed a depression over Comorin off extreme southwest Sri Lanka. The forecast field showed that it moved north-northwestwards and lay as depression over Comorin on 30th. It moved westwards and lay as deep depression over Maldives on 1st. Moving westwards it lay as a CS over southeast AS on 2nd and SCS over southeast AS. Moving northwards, it lay as a deep depression over eastcentral AS on 4th.

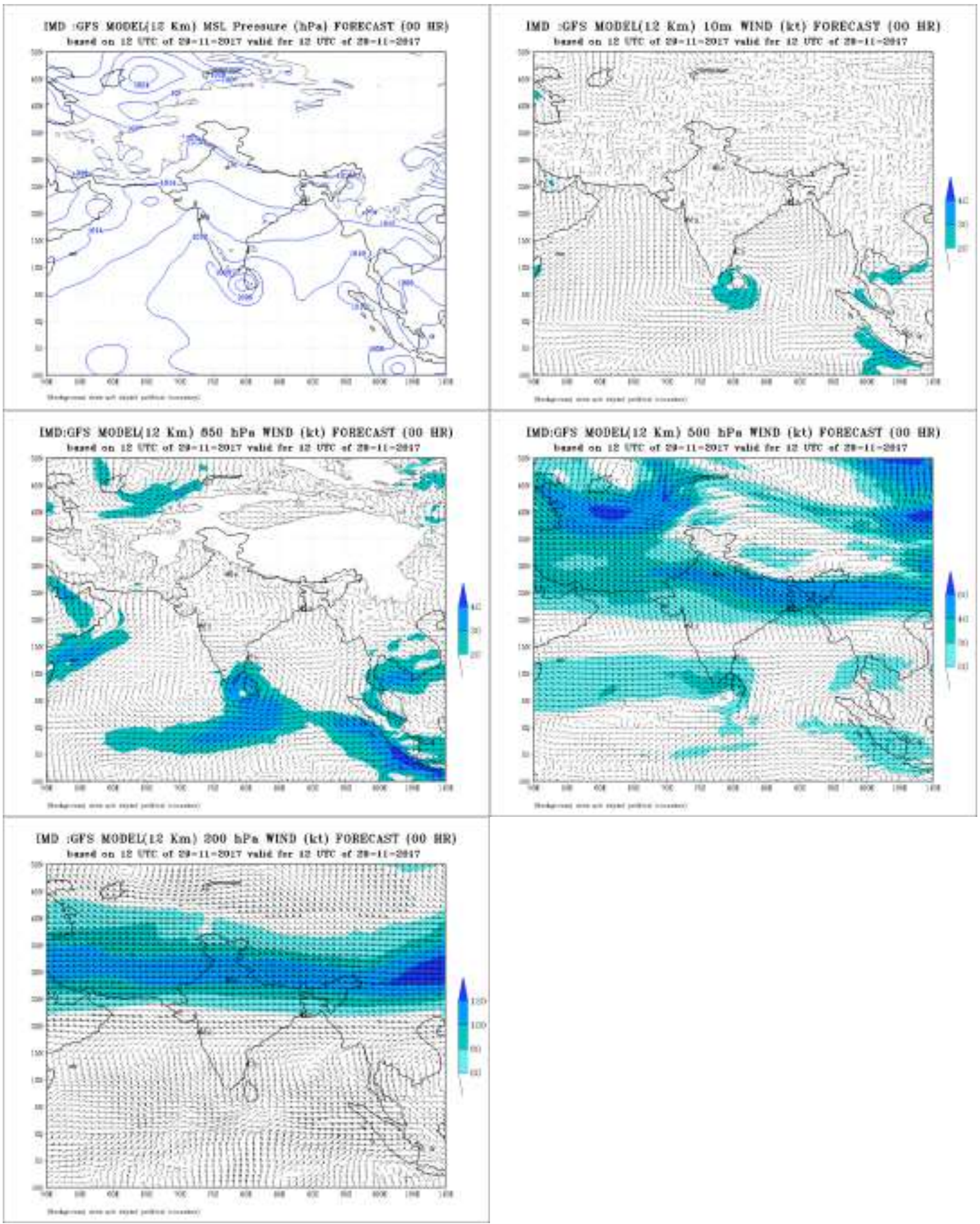


Fig. 2.9.14 (f): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 1200 UTC of 29th November

The analysis based on 0000 UTC of 30th Nov indicated weakening of system and detected as a low over Comorin area to the south of Sri Lanka on 30th. The forecast field indicated that it would move west-northwestwards. Intensify into a deep depression on 01st December over Lakshadweep area and adjoining southeast Arabian Sea. Thereafter it would become a cyclonic storm on 02nd and weaken into a well marked low pressure area on 07th

December over east central Arabian Sea. IMD GFS could not capture the rapid intensification of system from DD and CS during 30th.

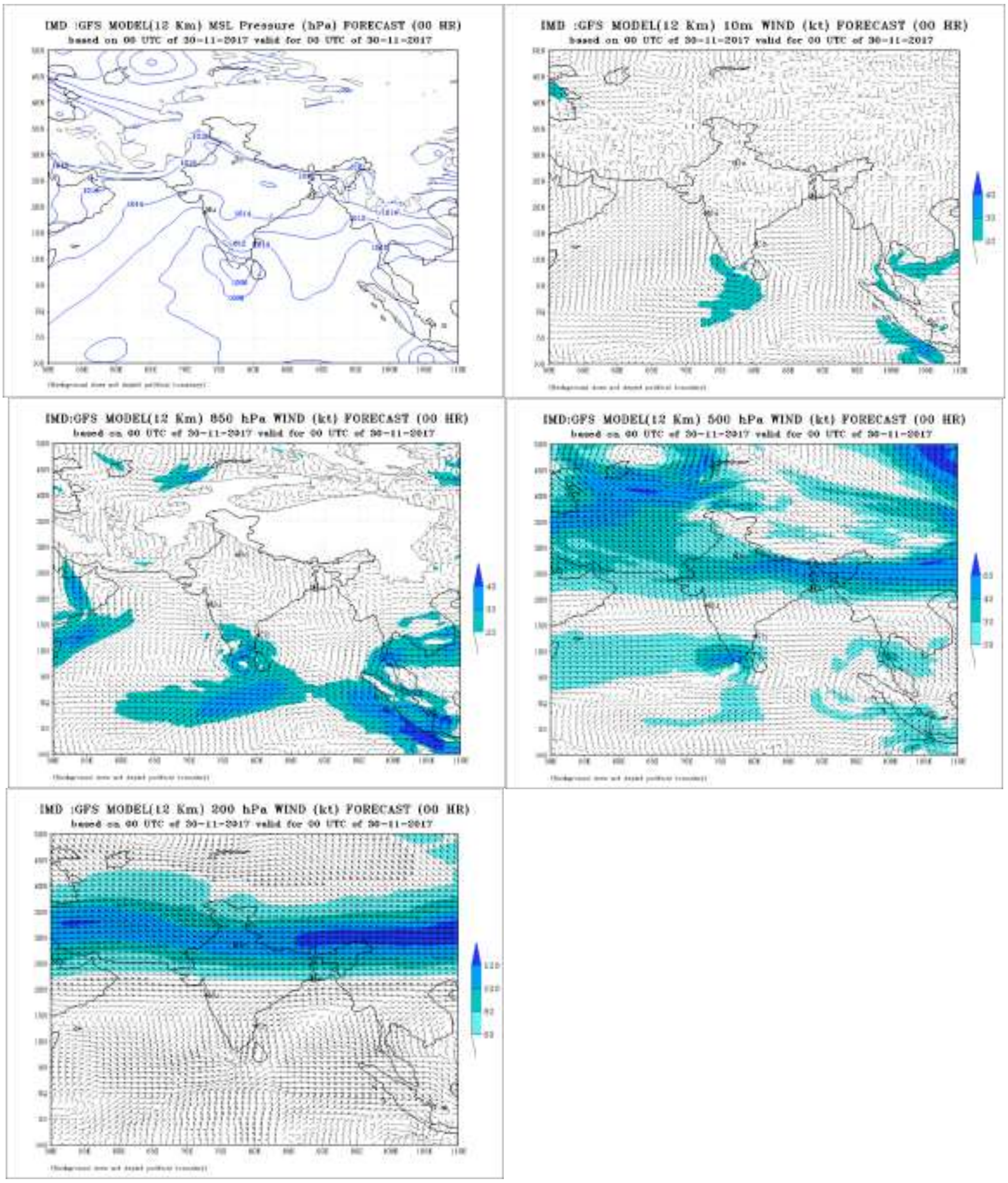


Fig. 2.9.14 (g): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 30th November

The analysis based on 0000 UTC of 1st December indicated cyclonic storm over Lakshadweep Area on 01st December. The forecast field indicated that the system would move northwestwards, intensify further over EC Arabian Sea on 04th. Further moving NNW, it would weaken on 5th and cross south Gujarat north Maharashtra coasts as a low pressure area on 06th. The model underestimated the intensity of the system. However, it could pick up the landfall over south Gujarat north Maharashtra coasts as a low pressure area.

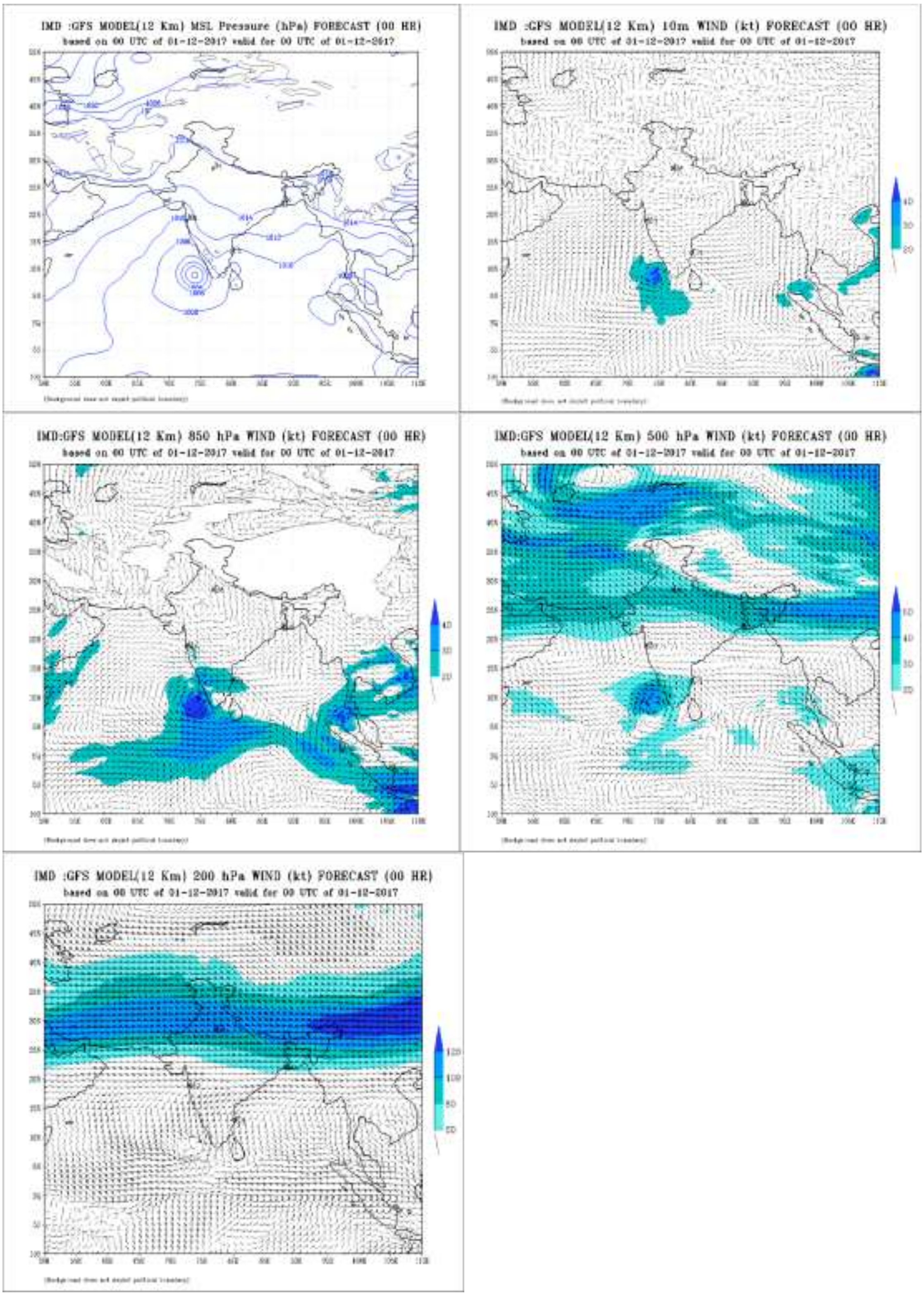


Fig. 2.9.14 (h): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 1st December

The analysis based on 0000 UTC of 2nd December indicated further intensification of system over Lakshadweep Area on 2nd December. The forecast field indicated that the system would move northwestwards till 04th and then move in NNW and weaken on 5th into a deep depression over east central AS. The model picked up the intensification of system over Lakshadweep area and weakening of system over east central AS on 5th correctly.

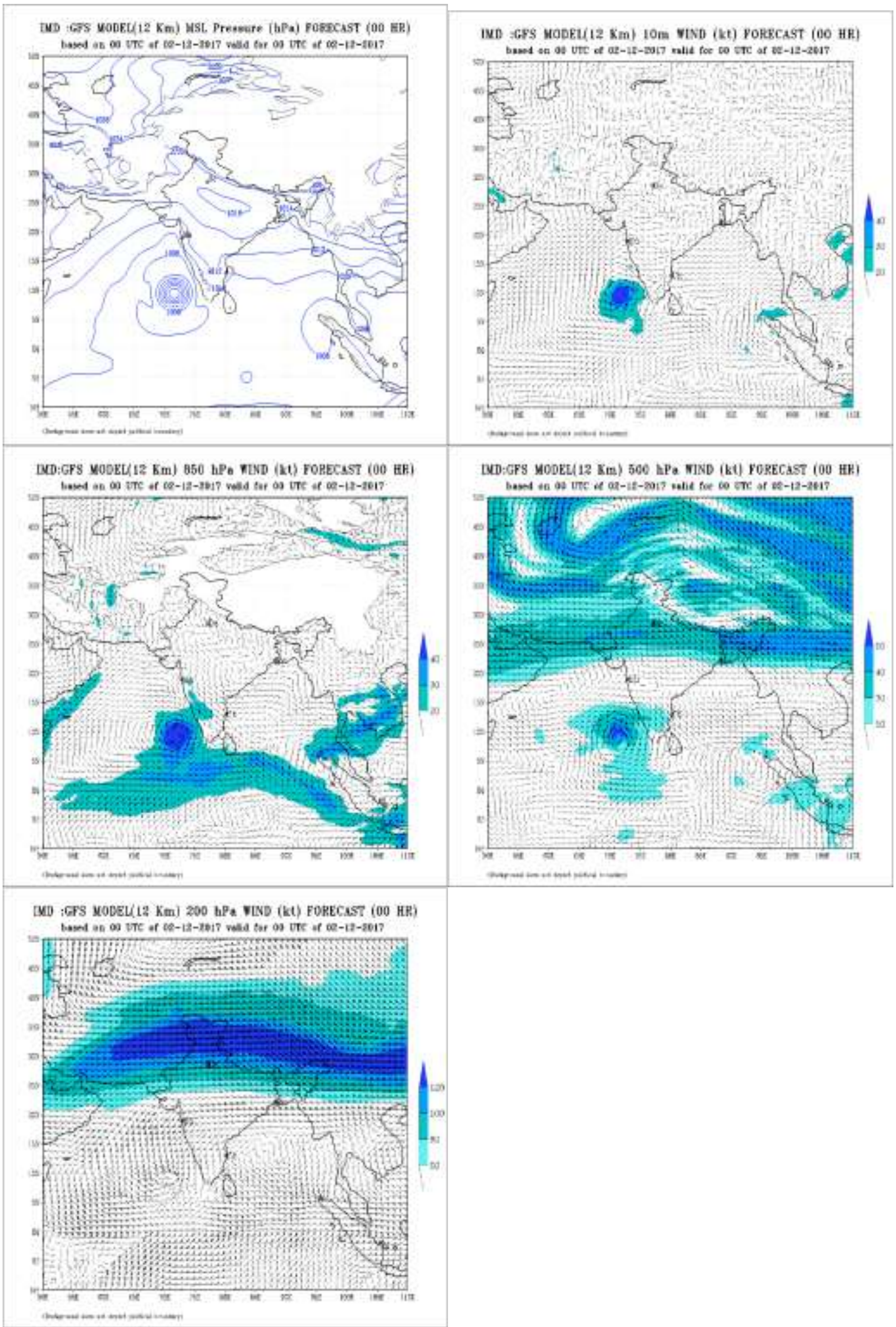


Fig. 2.9.14 (i): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 2nd December

The analysis based on 0000 UTC of 3rd December indicated west-northwestward movement of system. The forecast field indicated that the system would move northwestwards till 04th and then move in NNW and weaken on 5th into a deep depression over eastcentral AS. The model picked up the intensification of system over Lakshadweep area and weakening of system over eastcentral AS on 5th correctly.

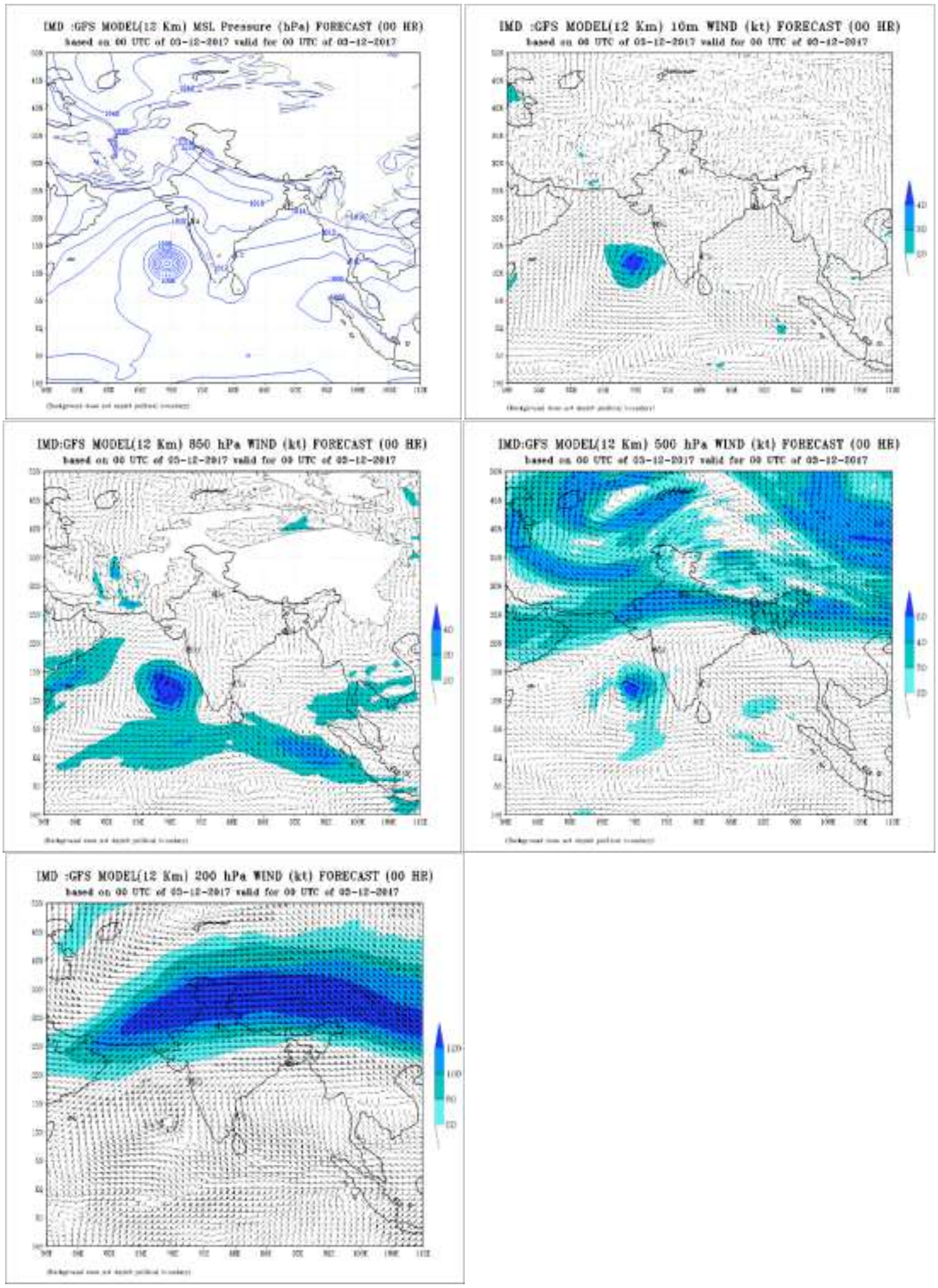


Fig. 2.9.14 (j): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 3rd December

The analysis based on 0000 UTC of 4th December indicated weakening and detected a severe cyclonic storm over eastcentral AS on 4th December. The forecast field indicated that the system would move northeastwards and weaken into a cyclonic storm on 5th over northern parts of EC Arabian Sea and into a well marked low pressure area on 6th off south Gujarat and north Maharashtra coasts. Thereafter, it would cross south Gujarat coast after

0000 UTC of 6th and become less marked after some time. It could capture the trough in westerlies near 50^0E responsible for steering the system north-northeastwards.

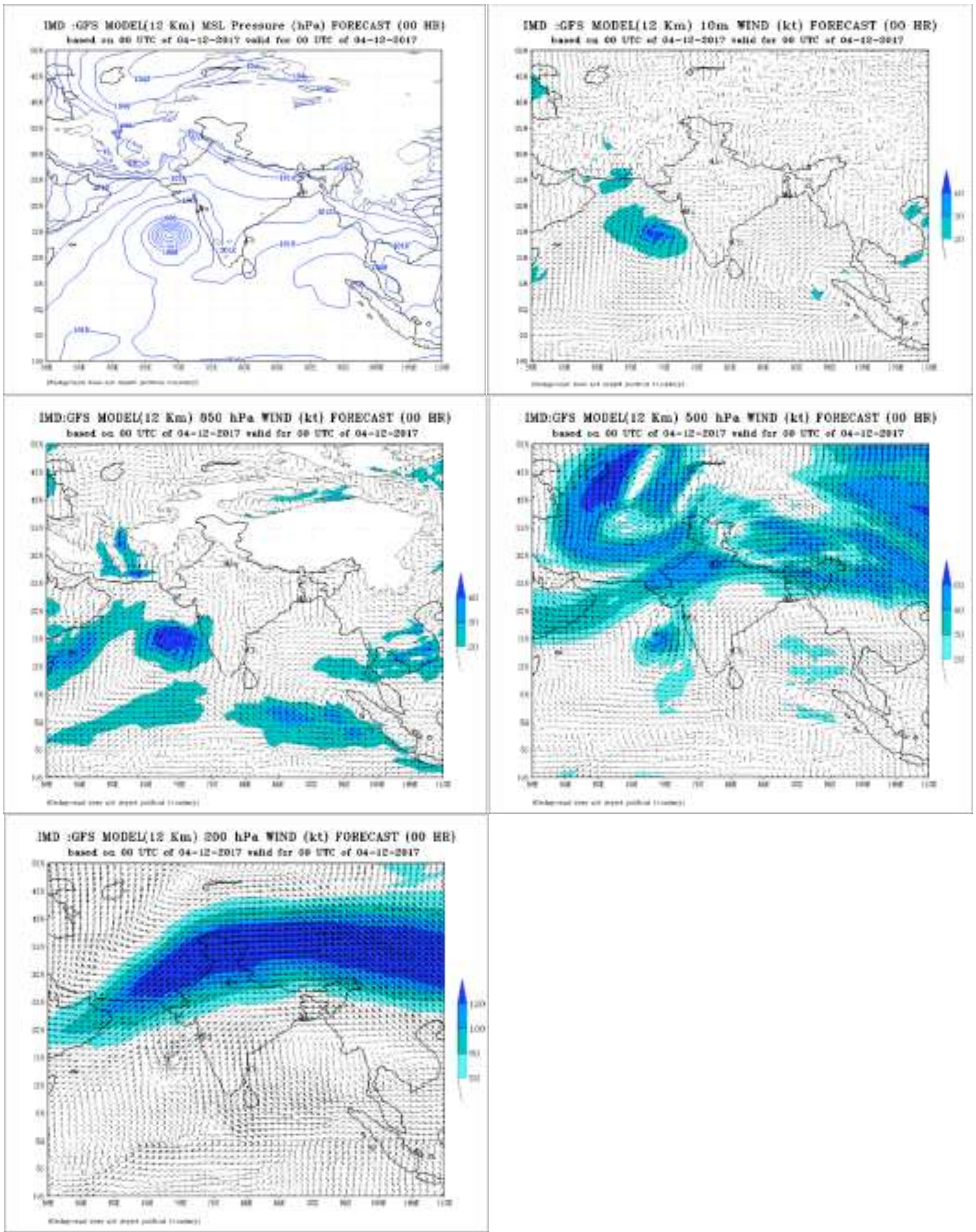


Fig. 2.9.14 (k): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 4^{th} December

The analysis based on 0000UTC of 05th December indicated a cyclonic storm over eastcentral AS on 5th December. The forecast field indicated that the system would move northeastwards and weaken over northern parts of eastcentral AS and into a low pressure area off south Gujarat and north Maharashtra coasts on 6^{th}. Trough in westerlies was well captured by the model. It could also predict that the system would weaken into a low pressure area before crossing south Gujarat and north Maharashtra coasts.

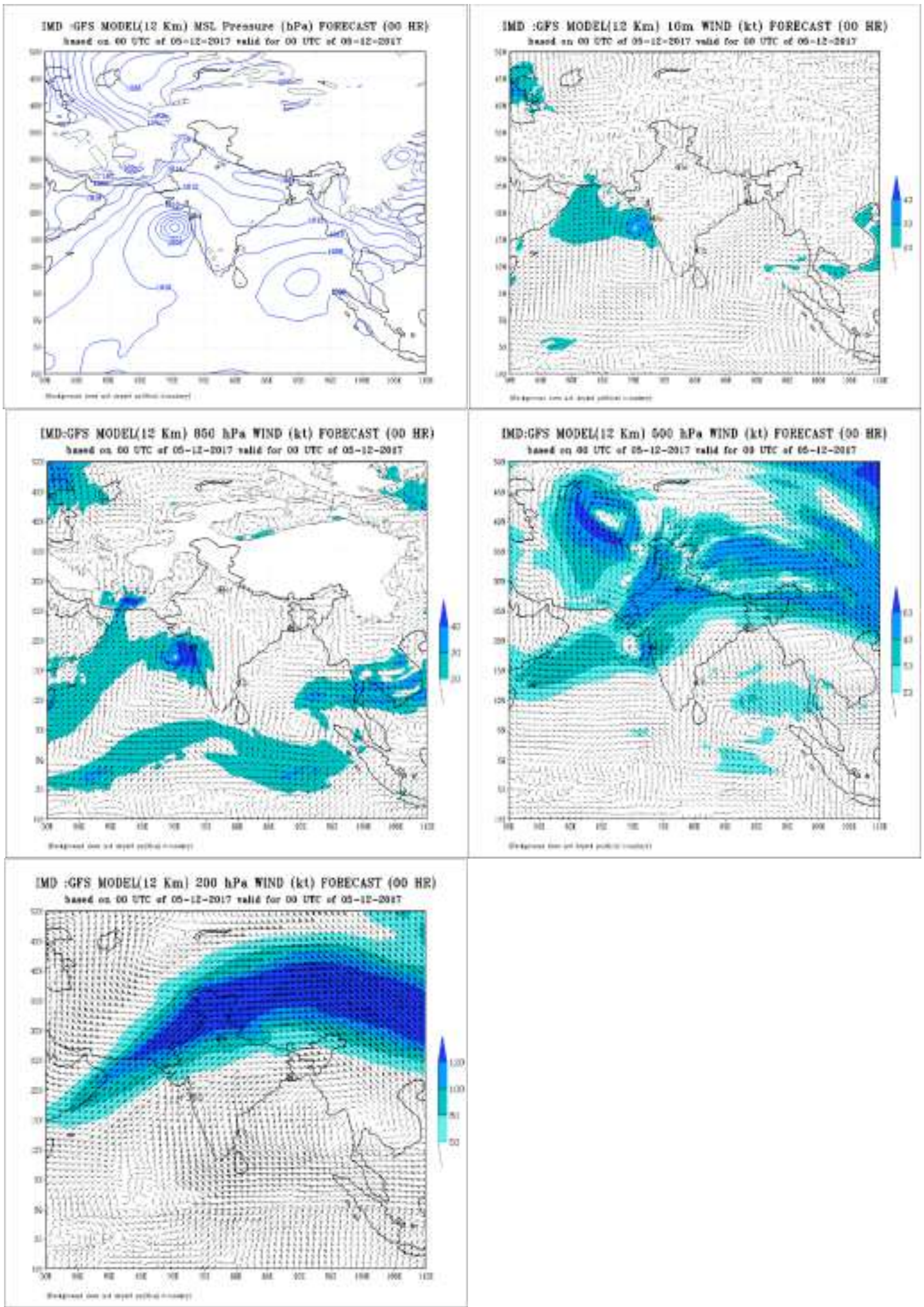


Fig. 2.9.14 (l): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 5th December

The analysis based on 0000UTC of 06th December indicated that the system has weakened into a low over eastcentral and adjoining northeast AS and coastal Maharashtra and south coastal Gujarat.

Hence to conclude, on 27th and 28th IMD GFS didn't show genesis of system. On 29th, it could not capture the rapid intensification of system on 30th. On 30th, it rather showed weakening of system. However, from 1st onwards, it could indicate that the system would intensify further, move northwestwards initially & north-northeastwards from 4th onwards and cross north Maharashtra-south Gujarat coasts as a depression/low.

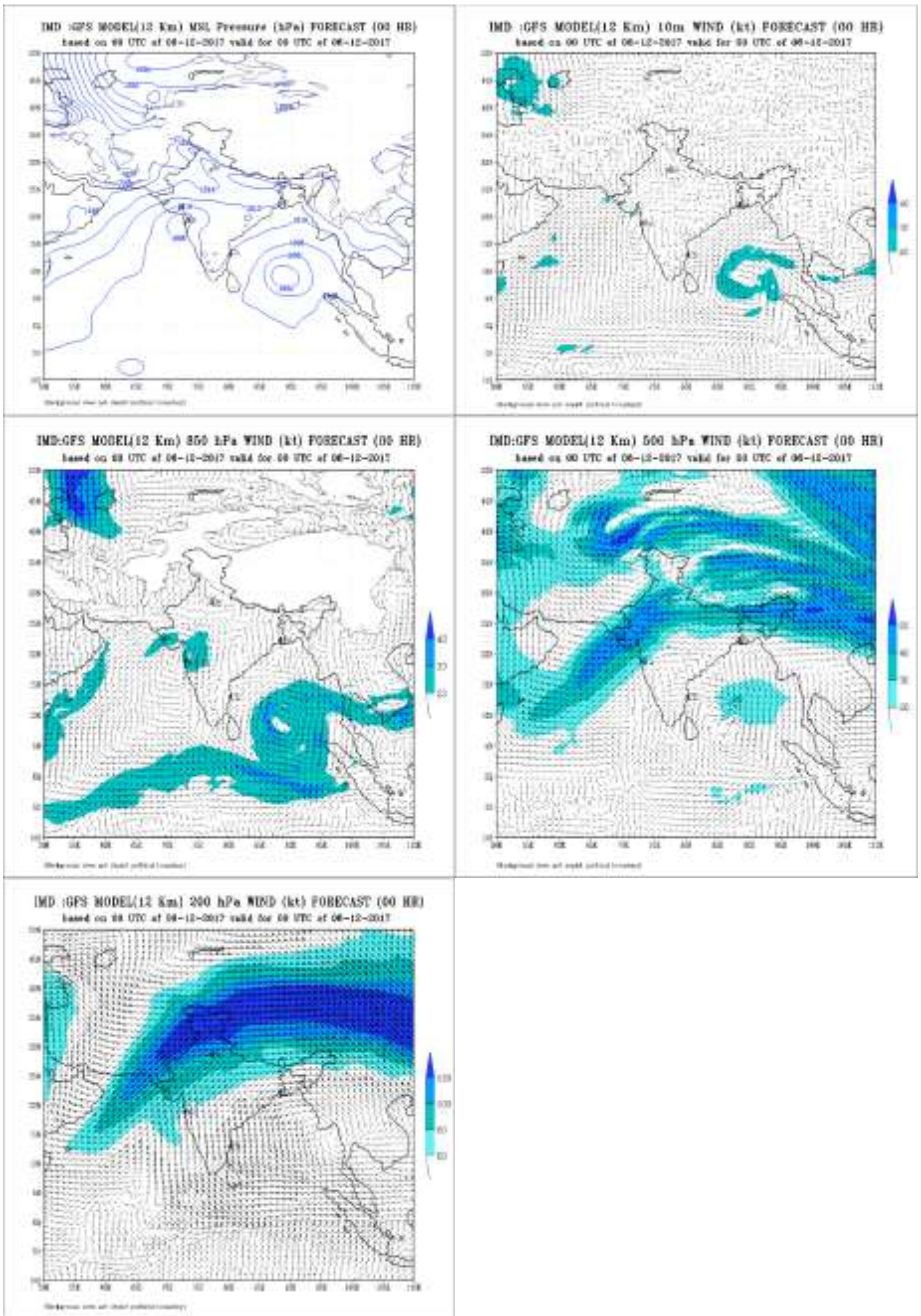


Fig. 2.9.14 (m): IMD GFS analysis of MSLP, 10m wind, 850, 500 & 200 hPa winds based on 0000 UTC of 6th December

2.9.8. Realized Weather:

2.9.8.1 Rainfall:

(a) Indian States:

- It caused isolated heavy rainfall over south Tamil Nadu on 28th and 29th, scattered heavy to very heavy rainfall & isolated extremely heavy rainfall over south Tamil Nadu on 30th Nov. and 1st Dec and isolated heavy to very heavy rainfall on 2nd Dec.
- It caused isolated heavy rainfall over south Kerala on 29th Nov. and 1st Dec. and isolated heavy to extremely heavy rainfall on 30th Nov.
- It caused scattered heavy to very heavy rainfall over Lakshadweep on 01st and 2nd Dec.
- There was heavy rainfall over north coastal Maharashtra and adjoining south coastal Gujarat on 5th Dec.
- There was no heavy rainfall over Tamil Nadu on 27th and over Kerala on 28th.
- It clearly indicates that there was occurrence of two separate spells of heavy rainfall over Tamil Nadu and Kerala in association with the low pressure system (22nd to 28th November) and cyclone, Ockhi 29th November to 5th December).

Rainfall associated with VSCS Ockhi based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in Fig. 2.9.15.

(Rainfall spatial distribution: Isolated places : <25%, A few places: 26-50%, Many places: 51-75%, Most places: 76-100% of total stations in the region;
Quantitative distribution: Moderate rainfall: 15.6-64.4, Heavy rain : 64.5 – 115.5 mm, Very heavy rain: 115.6 – 200.4 mm, Extremely heavy rain: 200.5 mm or more).

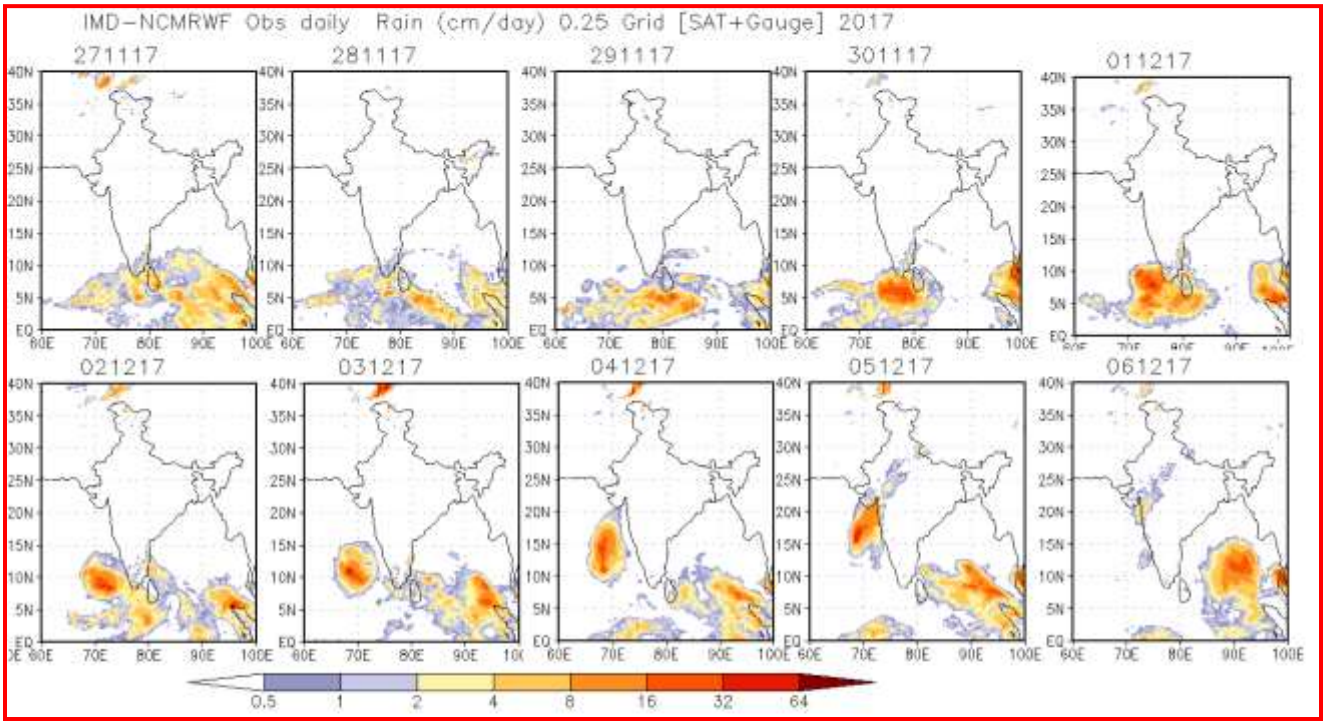


Fig. 2.9.14: IMD-NCMRWF GPM merged gauge rainfall during 27th November– 5th December

Realized 24 hrs accumulated rainfall **(≥7cm)** ending at 0830 hrs IST of date is presented below:

(a) Indian States

27 November 2017

Tamil Nadu & Puducherry: Rameswaram-14, Chembarabakkam-12, Chembarambakkam, Chennai & Sirkali-10 each, Kancheepuram-9, Vedaranyam-8, Poonamalle, Kolapakkam, Chidambaram, Poonamallee, Anaikaranchatram, Kollid and Anna University-7 each.
South Interior Karnataka:-Imangala
Kerala:-Kollam

28 November 2017

Kerala:-Piravam-7

29 November 2017

Tamilnadu & Puducherry:-Nannilam-7

30 November 2017

Tamil Nadu & Puducherry: Vallam, Thuckalay and Puducherry-7 each
Kerala: Aryankavu-15

1 December 2017

Tamil Nadu & Puducherry: Papanasam (District: Tirunelveli)-45, Manimutharu-38, Mylaudy-19, Thenkasi-17, Thuckalay, Pechiparai, Gudalur & Bhoothapandy-16 each, Watrap-15, Maniyachi, Eraniel & Colachel-14 each, Nagercoil, Kodaikanal & Coonoor PTO-13 each, Kuzhithurai, Srivilliputhur, Satankulam, Shencottah, Ayikudi, Coonoor, Samayapuram & Srivaikuntam-12 each, Ottapadiram, Tiruchendur & Kovilpatti each, Tuticorin, Ambasamudram, Uttamapalayam & Kanyakumari-10 each, Radhapuram, Polur, Kovilpatti, Madavaram, Sankarankoil & Sattur-9 each, Arani, Sivaganga, Sivagiri, Uthiramerur, Rajapalayam, Anna University, Grand Anaicut, Uthagamandalam, Chembarabakkam & DGP Office-8 each and Musiri, Vadipatti, K.Paramathi, Karur, Vilathikulam, Anna UTY, Lalgudi, Ambur, Padalur, Panchapatti, Mayanur, Thamaraipakkam, K Bridge, Cholavaram, Nanguneri, Periyakulam, Kalugumalai & Chennai(N)-7 each
Kerala: Aryankavu-26, Myladumpara AGRI-12, Varkala & Punalur-9 each and Trivandrum AERO &, Neyyattinkara-8 each
Lakshadweep: Minicoy-19.

2 December 2017

Tamil Nadu & Puducherry: Sathanur Dam-23, Sirkali-19, Chidambaram & Anaikaranchatram (Kollid)-18 each, Chidambaram AWS-17, Virudachalam & Chengam-15 each, Gingee-14, Mylam AWS & K.M.Koil-14 each, Tirukoilur, Vilupuram, Coonoor PTO & Karaikal-13 each, Cuddalore, Sethiathope & Tiruvannamalai-12 each, Pondicherry-11, Mayanur, Paramathivelur & Polur-10 each, Parangipettai, Kallakurichi, Kodavasal, Nagapattinam, Vanur, Mayiladuthurai, Sankarapuram,& Eraniel, Jayamkondam, Rayakottah, Neyveli AWS, Kuzhithurai, Ariyalur & Tindivanam-9 each, Tiruvaiyaru, Tozhudur, Srimushnam, Valangaiman, Tiruvarur, Ulundurpet, Papanasam (District: Thanjavur) &, Kothagiri-8 each and Harur, Panruti, Needamangalam, Thuckalay, Uthangarai, Nagercoil, Arani & Attur-7 each.
Kerala: Trivandrum AERO-8 and Perinthalamanna & Angadipuram-7 each
Lakshadweep: Minicoy-14

3 December 2017

Tamil Nadu & Puducherry: Tiruvarur-14, Pandavaiyar Head & Kodavasal-13 each, Valangaiman & Nannilam-12 each, Nagapattinam-11, Needamangalam, Kumbakonam, & Karaikal-9 each, Thiruthuraipoondi, Aduthurai AWS & Tiruvadanai-8 each and Thiruvidaimaruthur-7

6 December 2017

Konkan & Goa: Dahanu-10, Talasari & Colaba-8 each and Palghar AGRI-7

Gujarat Region: Umergam & Vapi-9 each and Pardi, Waghai, Vansda & Gandevi ARG-7 each

(b) Maldives:

Heaviest rainfall was 175 millimeters recorded on 30 Nov, at the AWS located in the Ifuru Island. Many islands reported flooding and damage to house hold items ware reported from several islands. Realised rainfall over Maldives is presented in Fig. 2.9.15.

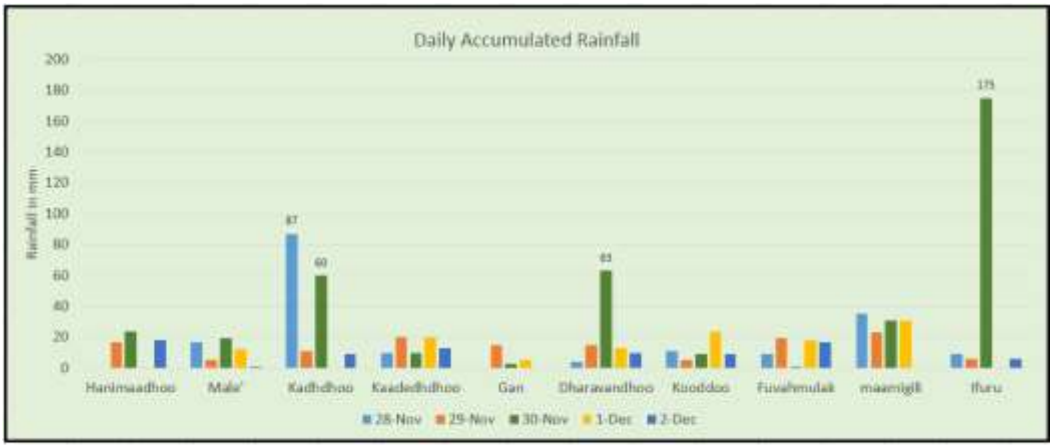


Fig. 2.9.15: Realised Rainfall over Maldives during 28th Nov. -2nd Dec..

2.9.8.2: Realised Wind:

(a) India:

Thiruvananthapuram recorded 62 kmph in gustiness at 1300 IST of 30th Nov. The threshold wind speed of 45 kmph was recorded over Thiruvananthapuram from 1230 IST of 30th Nov. onwards. Anemograph record of Thiruvananthapuram on 30th November is presented in Fig. 2.9.16.

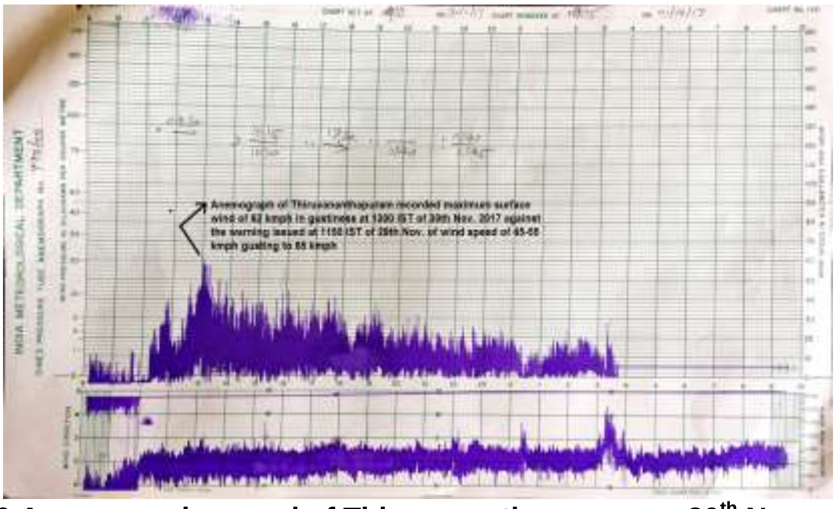


Fig. 2.9.16 Anemograph record of Thiruvananthapuram on 30th November

Gale wind of the order of 65-75 kmph gusting to 85 kmph over Kanyakumari (KYK) and Thiruvananthapuram (TRV) during 30thNov-01stDec 2017 and winds of the order of 100-160 kmph gusting to 180 kmph were observed over Lakshadweep Islands during 01st-02nd Dec.

(b) Maldives:

On 30 November, the AWS station of Alif Dhaalu Maamigili and Baa Dharavandhoo had recorded the maximum gust winds of 56 and 54 miles per hour respectively. Moreover, the strong gust winds of 59 and 51 miles per hour were also recorded at the AWS station of Alifu Dhaalu Maamingili and the National Meteorological Office, Hulhule respectively on 1st of December. In addition the average strong winds of 20 – 30 miles per hour prevailed over the country on the 1st of December. Realised wind over Maldives during 28th Nov to 2nd Dec. is presented in Fig. 2.9.17.

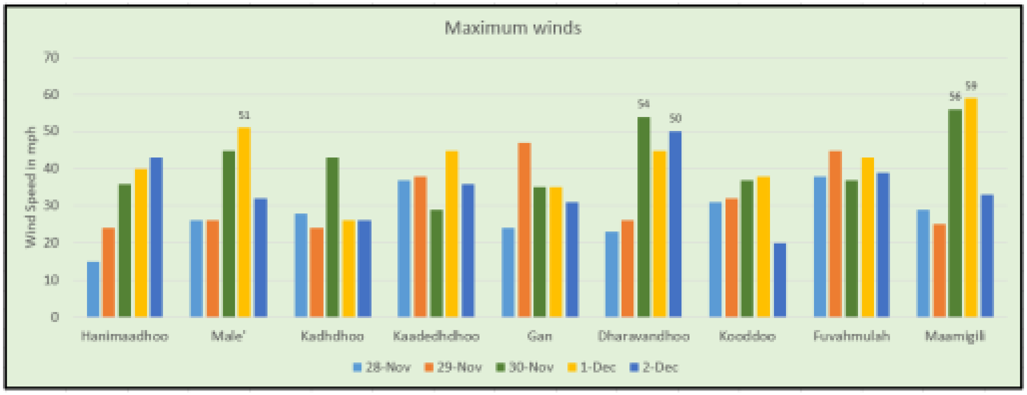


Fig. 2.9.17 Realised wind over Maldives during 28 Nov. to 2nd Dec.

2.9.9. Damage due to VSCS Ockhi

2.9.9.1. Damage over India:

(a) Damage over Tamil Nadu: As per report from Ministry of Home affairs, Govt. of India, about 35 persons lost their lives and 199 went missing. About 6,868 houses were damaged in Tamil Nadu. (Source: http://www.thehindu.com/news/national/tamil-nadu/ockhi-killed-93-damaged-over-10000-houses-minister/article22289551.ece). Several areas of south coastal Tamil Nadu experienced inland flooding and inundation due to heavy to extremely heavy rainfall on 30th Nov and 01st Dec 2017. Gale Wind caused extensive damages to electrical poles, transformers, agricultural plantation, mechanized and country boats of fishermen, houses and roads aside from 5 uprooting of thousands of trees. A few damage photographs are presented in Fig. 2.9.18.

Fig. 2.9.18 (a) Flood hit Kanyakumari (Source: rediff.com, news dated 1st Dec.)

Fig. 2.9.18 (b) Damage due to gale winds over Kanyakumari (Source: M.O. Kanyakumari & *IndiaToday.in, New Delhi, 30th Nov 2017)*

Damage over Kerala: As per report from Ministry of Home affairs, Govt. of India, Kerala state witnessed loss of lives of 75 persons and 137 fisherment went missing. About 3600 houses were damaged by cyclone Ockhi.

Fig. 2.9.18 (c): A car struck in mud at Pampa, Triveni (Source: The New Indian Express 01st Dec 2017)

Fig. 2.9.18 (d): A tree fell over autorikshaw at Sreekanteshwaram in Thiruvananthapuram, (Source:h*ttp://english.mathrubhumi.com/news/kerala/cyclone-ockhi-closes-in-on-kerala-coast-1.2424815)*

Fig. 2.9.18 (e): Trees felling in Thiruvananthapuram, (Source: United News of India, Thiruvananthapuram dated 30th Nov)

Damage over Lakshadweep: No death was reported from Lakshdweep Islands. However normal life at Kalpeni, Minicoy and Kavaratti was badly hit by cyclone.

Fig. 2.9.18 (f): Uprooted trees and flooded streets in Lakshadweep
Source: http://indianexpress.com/article/india/cyclone-ockhi-lakshadweep- islands-suffer-over-rs-500-cr-loss-mp-mohammad-faizal/

Fig. 2.9.18 (g) Damaged Trees in Minicoy (Source: The Hindu dated 3rd Dec 2017)

Fig. 2.9.18 (h) Damaged Trees in Minicoy (Source: Officials M.O. Minicoy)

Damage over Karnataka: No death was reported from Karnataka. As per media reports**,** three houses were damaged and 15 coconut palms were uprooted and some washed away in Ullal, Someshwar-Uchil areas near Mangaluru.
(Source: http://www.thehindu.com/news/national/karnataka/cyclone-ockhi-damages-three-houses-uproots-trees-in-ullal/article21253626.ece)

Fig. 2.9.18 (i) Coconut trees and road side compound wall washed away as high waves lash the sea shore at Someshwara Uchila port near Mangaluru on 3rd December

(b) Damage over Goa: No loss of life reported from Goa. As per media reports about 30 shacks were damaged in Goa. The damage was felt the most at Pernem sub-district bordering Maharashtra. About 12 beaches were affected by sea water.

(c) Maharashtra: Unseasonal rain and inclement weather due to cyclone Ockhi severely impacted grape farms in Maharashtra. As per estimates by Brihanmumbai Municipal Corporation's (BMC) solid waste management (SWM) Department, Cyclone Ockhi dumped more than 80 tonnes of waste from the Arabian Sea on the Mumbai beaches. (Source:http://www.hindustantimes.com/mumbai-news/cyclone-ockhi-has-dumped-80-000-kg-of-trash-on-mumbai-s-beaches-says-bmc/story-xVuWmiAgXzutx7850C39AL.html). The Government of Maharashtra declared holiday

(d) Gujarat: No significant damage was reported from Gujarat

Damage over Maldives:

There were no human casualty during due to this event.

Fig. 2.9.18 (j) A boat and a barge capsized due to rough seas. (b) Trees uprooted due to strong winds

Damage over Sri Lanka:

As per media reports about 27 persons lost their lives due to landslides caused by heavy rains and gale wind associated with VSCS Ockhi (Source: http://micetimes.asia/flooding-in-sri-lanka-and-the-island-of-java-dozens-dead/).

Fig. 2.9.18 (k): Damage due to gale winds over Sri Lanka (Source: http://www.dailymirror.lk/article/Rains-gale-force-winds-wreck-havoc-in-Colombo-141362.html)

2.10. Deep Depression over southeast Bay of Bengal (06--10 December 2017)

2.10.1. Introduction

A low pressure area (LPA) formed over Malay Peninsula and adjoining Andaman Sea in the morning of 30th November, 2017. It lay as a well marked low pressure area (WML) over south Andaman Sea & adjoining Strait of Malacca on 1st December, over Sumatra coast and adjoining south Andaman Sea on 2nd, over southeast Bay of Bengal & adjoining south Andaman Sea and equatorial Indian Ocean on 3rd and 4th and over southeast Bay of Bengal (BoB) & neighbourhood on 5th. It concentrated into a Depression (D) over southeast BoB & neighbourhood in the morning of 6th December. It moved northwards till early hours of 8th. Thereafter, it moved north-northwestwards and intensified into a deep depression (DD) in the early morning of 8th over central BoB. Moving nearly northwards, it weakened into D during the night of same day over westcentral BoB. It started moving north-northeastwards from morning of 9th and weakened into a WML over northwest BoB in the evening of 9th December and into a LPA over north BoB & neighbourhood in the evening of 10th. The observed track of the system is presented in Fig.2.1.

The salient features of the system were as follows:

(i) The system moved nearly north to north-northeastward and weakened over Sea.
(ii) The total life period of the system was 51 hours against the average life period of depression of 65 hours in post monsoon season over the BoB.
(iii) The system caused heavy to very heavy rainfall at isolated places over Odisha and coastal Andhra Pradesh on 15th and heavy rainfall at isolated places on 17th.

IMD mobilised all its resources to monitor the system and regular warnings w.r.t. track, intensity, landfall and associated adverse weather were issued to concerned central and state disaster management agencies, print & electronic media and general public. Regular advisories were also issued to WMO/ESCAP Panel member countries including Bangladesh.

The brief life history, associated weather and forecast performance of IMD/RSMC, New Delhi are presented below.

2.10.2. Brief life history

2.10.2.1. Genesis

A low pressure area (LPA) formed over Malay Peninsula and adjoining Andaman Sea in the morning of 30th November, 2017. It lay as a well marked low pressure area (WML) over south Andaman Sea & adjoining Strait of Malacca on 1st December, over Sumatra coast and adjoining south Andaman Sea on 2nd, over southeast Bay of Bengal & adjoining south Andaman Sea and equatorial Indian Ocean on 3rd and 4th and over southeast Bay of Bengal (BoB) & neighbourhood on 5th. It concentrated into a Depression (D) over southeast BoB & neighbourhood in the morning of 6th December and lay centred near latitude 8.5º N and longitude 88.5 ºE, about 1160 km to the southeast of Machillipatnam and 1250 km south-southeast of Gopalpur. .

Considering the environmental conditions, at 0300 UTC of 6th, the sea surface temperature (SST) over the region was 29-30^{0}C. SST showed decreasing tendency towards north and west. The ocean thermal energy was about 100 KJ/cm^2 over the area. It also showed decreasing tendency towards north. The vertical wind shear between upper and lower levels was high around the system centre. It was increasing towards north and west. The vertical wind shear between middle and lower levels was low (5-10 knots). The low level relative vorticity was around 100 x 10^{-6} s^{-1} to the southwest of system centre. Low level convergence was about 30 x 10^{-5} s^{-1} to the north-northwest of system centre. The upper level divergence was around 30 x 10^{-5} s^{-1} to the north of system centre. The Madden Julian Oscillation (MJO) index lay in phase 5 with amplitude > 1. The upper tropospheric ridge at 200 hPa level ran along 17° N over BoB. A trough ran roughly along Long 65°E to the north of Lat. 18°N at 5.8 km above mean sea level. Eventhough the system lay over favourable ocean thermal conditions, it was embedded in a high wind shear regime. It indicated that the system would not intensify rapidly and its intensification would be limited upto deep depression stage. Further, the system would encounter colder sea, lower ocean thermal energy and increased shear due to the strong upper level winds in association with a deep trough in westerlies near coast. All these conditions indicated weakening of the system near the coast.

2.10.2.2. Intensification and Movement:

At 0300 UTC of 7th, the sea surface temperature (SST) over the region was 28-29^{0}C. SST showed decreasing tendency towards north and west. The ocean thermal energy was about 60-80 KJ/cm^2 over the area. It also showed decreasing tendency towards north and west. The vertical wind shear between upper and lower levels was high around the system centre. It was increasing towards north and west. The vertical wind shear between middle and lower levels was low (5-10 knots). The low level relative vorticity was around 100 x 10^{-6} s^{-1} to the south of system centre. Low level convergence was about 20 x 10^{-5} s^{-1} to the northwest of system centre. The upper level divergence was around 40 x 10^{-5} s^{-1} to the northwest of system centre. The Madden Julian Oscillation (MJO) index lay in phase 5 with amplitude > 1. The upper tropospheric ridge at 200 hPa level ran along 17° N over BoB in association with anti cyclonic circulation over eastcentral BOB. A trough ran roughly along Long 72°E to the north of Lat. 18°N at 5.8 km above mean sea level. Under this scenario, the southeasterly to south-southeasterly winds prevailed over the system at upper level, which suggested the north-northwestward movement of the system. Deep layer mean wind also suggested similar movement of the system. Under these features, the system maintained it's intensity and moved nearly north-northwestward during past 24 hours.

At 0000 UTC of 8th, similar environmental features continued and the system intensified into a deep depression over central BoB near latitude 14.3 ºN and longitude 87.0 ºE, about 590 km south-southeast of Gopalpur and 660 km east-southeast of Machilipatnam. At 1800 UTC of 8th, the system entered the colder sea. SST over the region was 25-26^{0}C. SST showed decreasing tendency towards north and west. The ocean thermal energy was about 50 KJ/cm^2 over the area and the system weakened into a depression over northwest and adjoining northeast BoB. At 0300 UTC of 9th, the low level relative vorticity was around 150 x 10^{-6} s^{-1} around the system centre. Low level convergence was about 30 x 10^{-5} s^{-1} to the northeast of system centre. The upper level divergence was around 40 x 10^{-5} s^{-1} to the northeast of system centre. Though the system entered colder sea region, it maintained it's intensity as there was relative increase in low level relative vorticity, convergence, upper level divergence and moderate wind shear. The upper tropospheric ridge at 200 hPa level ran along 18 ^{0}N over BoB. A trough ran roughly along long 60°E to the north of lat. 25°N at 5.8 km above mean sea level. Under these conditions, the system moved north-

northeastwards and lay centered over northwest BoB near latitude 19.2 ºN and longitude 86.5 ºE, about 170 km east of Gopalpur, 120 km south-southwest of Paradip and 320 km south-southwest of Digha. Moving further north-northeastwards, it weakened into a well marked low pressure area over northwest BoB at 1200 UTC of 9th December.

The best track parameters of the system are presented in Table 2.10.1.

Table 2.10.1: Best track positions and other parameters of the Deep Depression over the southeast Bay of Bengal during 06-10 December, 2017

Date	Time (UTC)	Centre lat.⁰ N/ long. ⁰ E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
06/12/2017	0300	8.5/88.5	1.5	1004	25	4	**D**
	0600	8.8/88.3	1.5	1004	25	4	D
	1200	9.8/88.0	1.5	1004	25	4	D
	1800	10.0/88.0	1.5	1004	25	4	D
07/12/2017	0000	11.1/88.0	1.5	1004	25	4	D
	0300	12.0/88.0	1.5	1004	25	4	D
	0600	12.2/87.9	1.5	1004	25	4	D
	1200	12.8/87.7	1.5	1004	25	4	D
	1800	13.4/87.6	1.5	1004	25	4	D
08/12/2017	0000	14.3/87.0	2.0	1002	30	6	**DD**
	0300	15.0/86.8	2.0	1002	30	6	DD
	0600	15.5/86.7	2.0	1002	30	6	DD
	1200	16.5/86.3	2.0	1002	30	6	DD
	1800	18.0/86.2	1.5	1004	25	4	**D**
09/12/2017	0000	19.0/86.3	1.5	1004	25	4	D
	0300	19.2/86.5	1.5	1004	25	4	D
	0600	19.5/86.7	1.5	1004	25	4	D
	1200	Weakened into a well marked low pressure area over northwest Bay of Bengal at 1200 UTC					

2.10.3. Features observed through satellite and Radar

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and INSAT-3D imageries. Satellite imageries from SCATSAT and international geostationary satellites Meteosat-7 & MTSAT, microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered for monitoring the system.

2.10.3.1 INSAT-3D features

Typical INSAT-3D visible, IR and enhanced colored imageries are presented in Fig. 2.10.1. At 0300 UTC of 6th, intensity of the system was T 1.5. Broken low & medium clouds with embedded moderate to intense convection lay over southeast BoB and adjoining Andaman Sea. Scatterometer wind observations indicated maximum sustained winds of about 25 knots. Broken low & medium clouds with embedded intense to very intense convection lay over southeast & adjoining central BoB, southwest BoB and south Andaman

Sea. The cloud pattern indicated organization. However, majority of cloud mass was displaced northwards from low level circulation centre. At 0000 UTC of 8^{th} , intensity of the system was T 2.0. Broken low & medium clouds with embedded intense to very intense convection lay over BoB between latitude 13.0^0N & 21.0^0N east of longitude 83.0^0E. At 1200

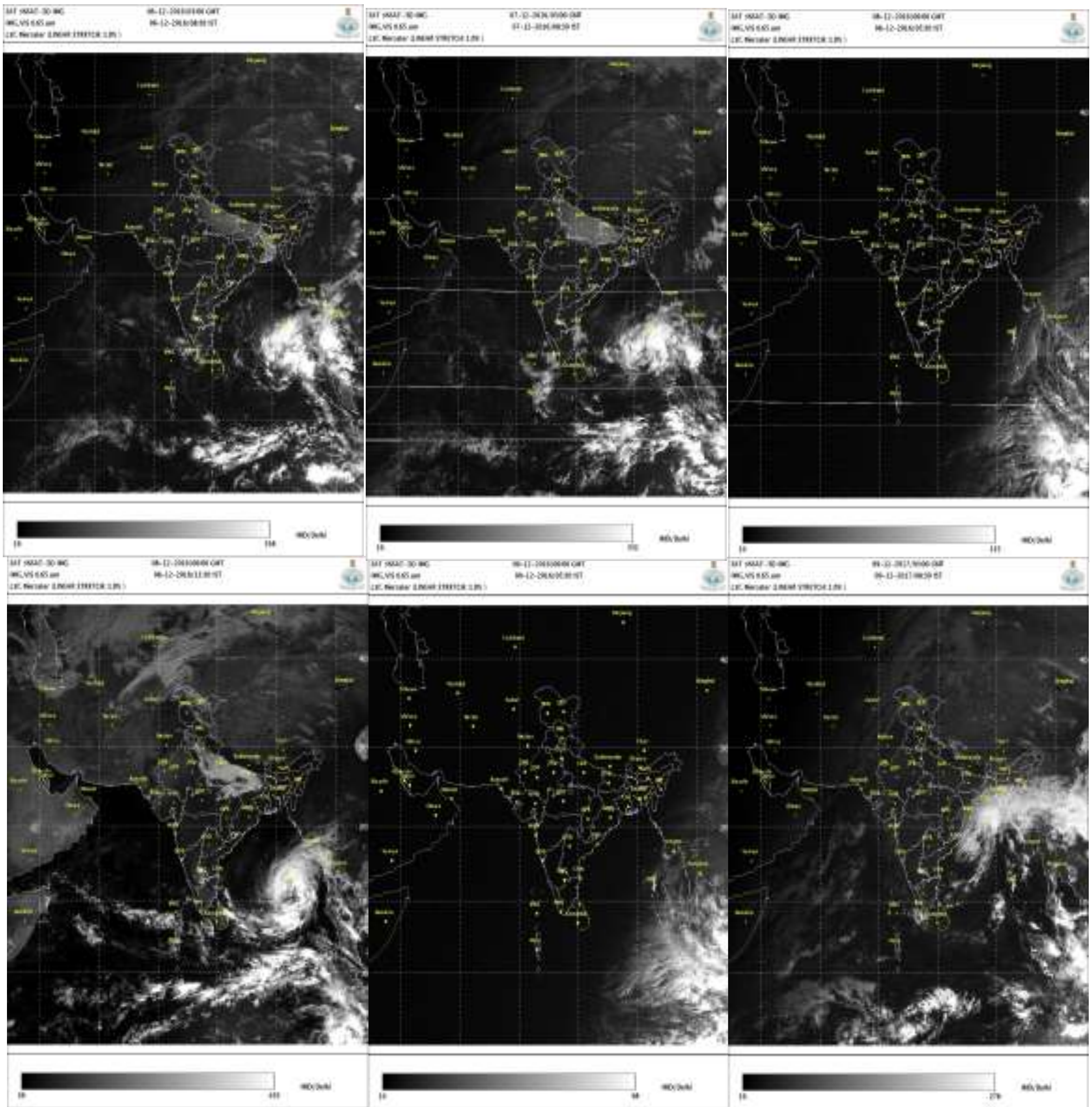


Fig. 2.10.1(a): INSAT-3D Visible imageries of Depression (06-10 December, 2017)

UTC of 8^{th}, broken low & medium clouds with embedded intense to very intense convection lay over BoB between latitude 15.0^0N & 21.5^0N and longitude 83.5^0E & 91.0^0E. At 1800 UTC, the system entered colder sea area and weakened into a depression. At 0300 UTC of 9^{th}, intensity of the system was T 1.5. Broken low & medium clouds with embedded intense to very intense convection lay over BoB between latitude 15.0^0N & 21.5^0N and longitude 83.5^0E & 91.0^0E, coastal Odisha, southwest Bengal and south Bangladesh. Moving north-northeastwards, it weakened into a well marked low pressure area at 1200 UTC of 9^{th} and broken low to medium clouds with embedded moderate to intense convection lay over north Bay, south Bangladesh, Mizoram, Tripura and adjoining areas of Myanmar.

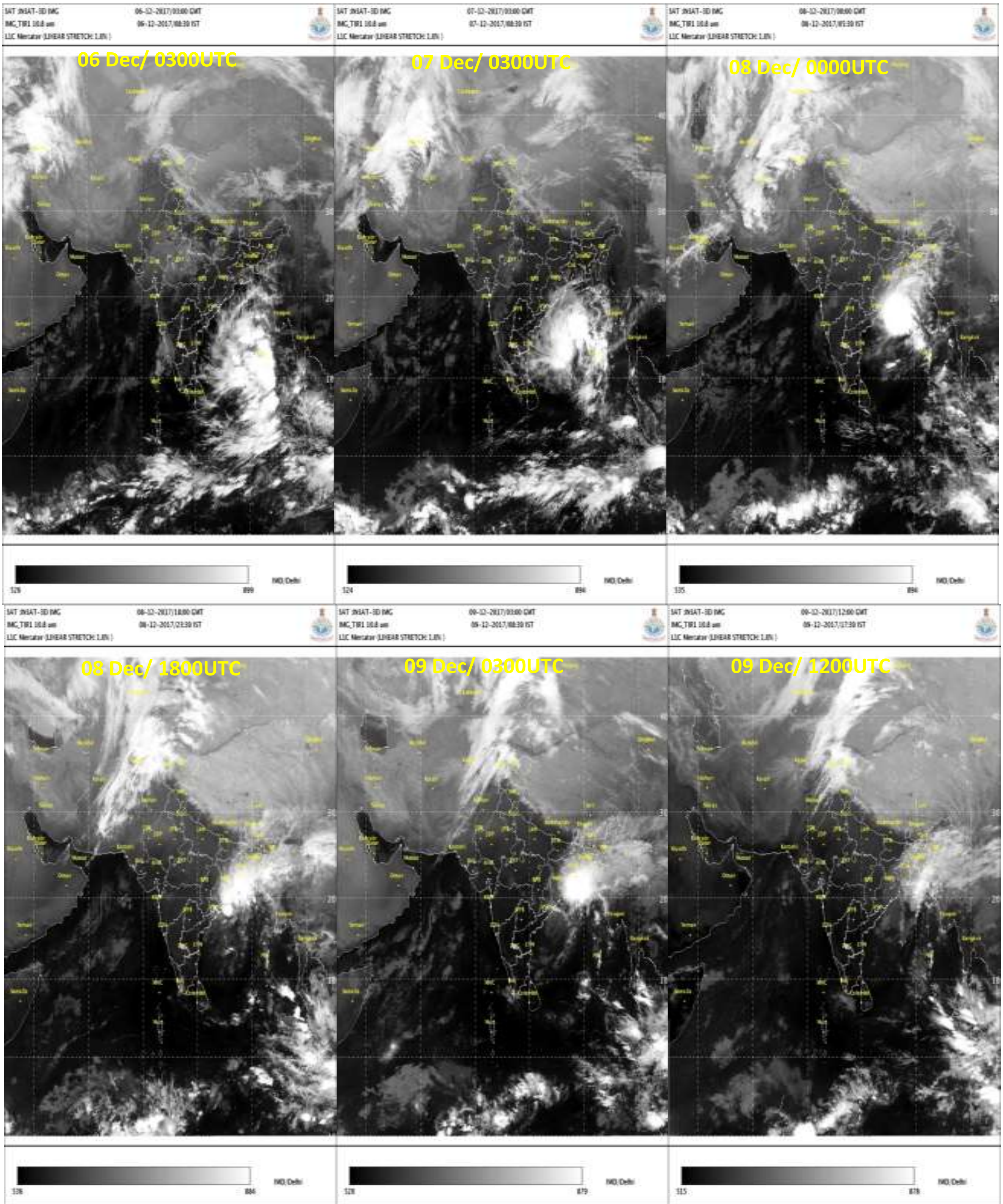


Fig. 2.10.1(b): INSAT-3D IR imageries of Depression (06-10 December, 2017)

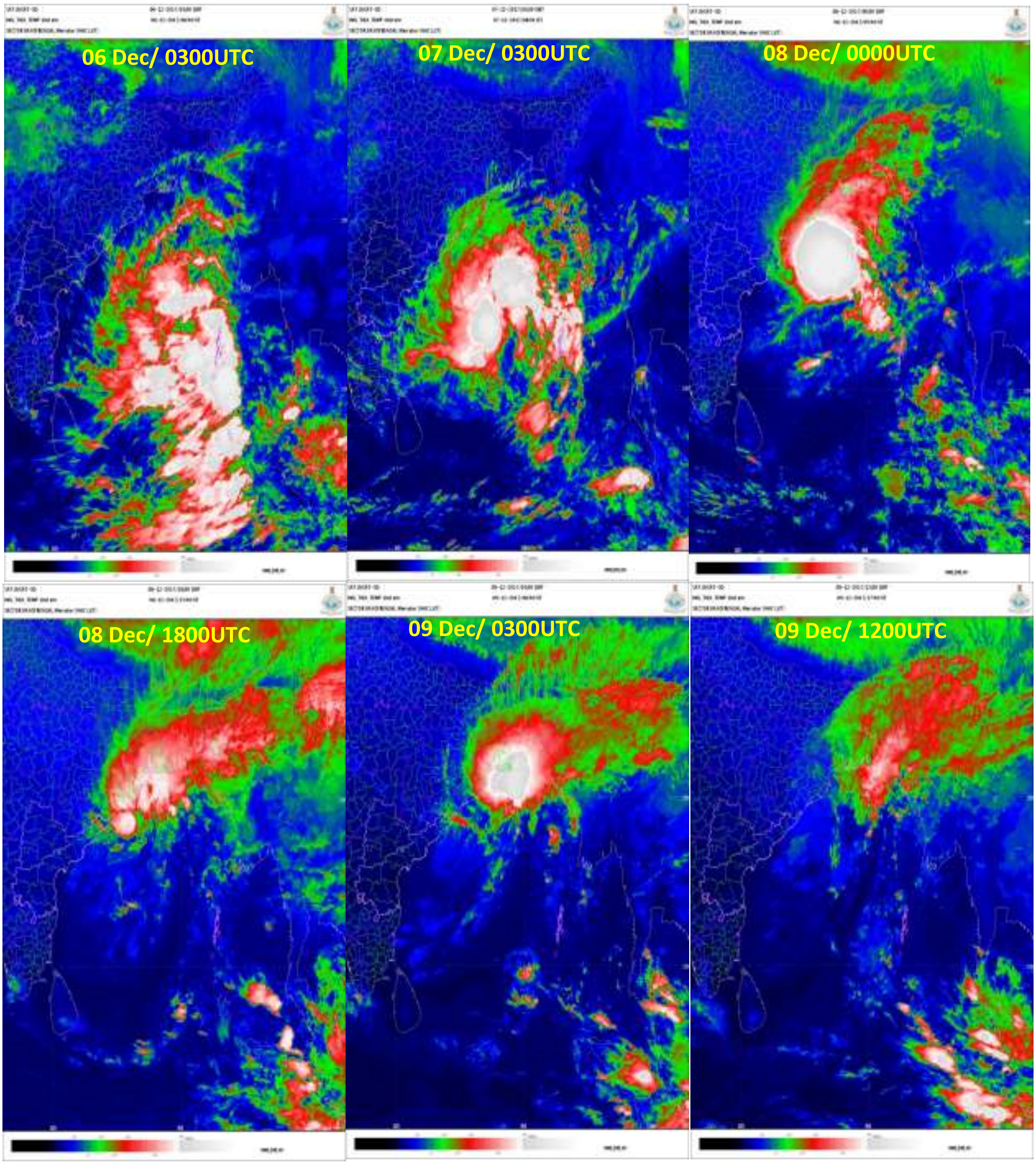


Fig. 2.10.1(c): INSAT-3D enhanced coloured imageries of Depression (06-10 December, 2017)

2.10.3.2. Features observed through Radar

DWR Paradip and Kolkata monitored the system when it was in their range. These imageries were utilized for determining the location and movement of system. Typical DWR imagery from Kolkata Radar is presented in Fig. 2.10.2.

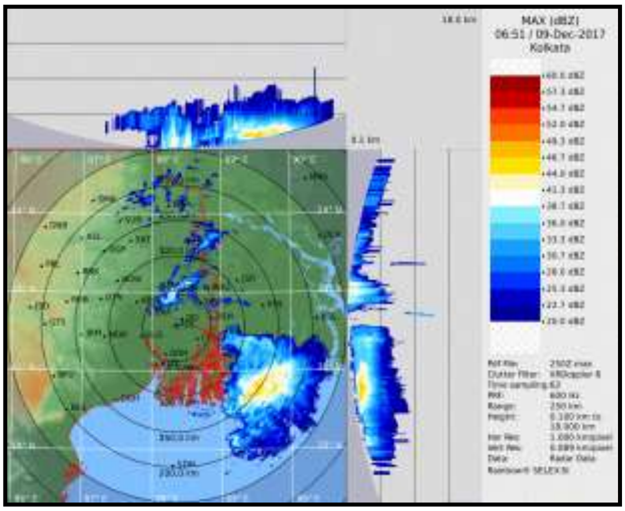


Fig. 2.10.2: Typical DWR imageries during Depression (15-17 November, 2017)

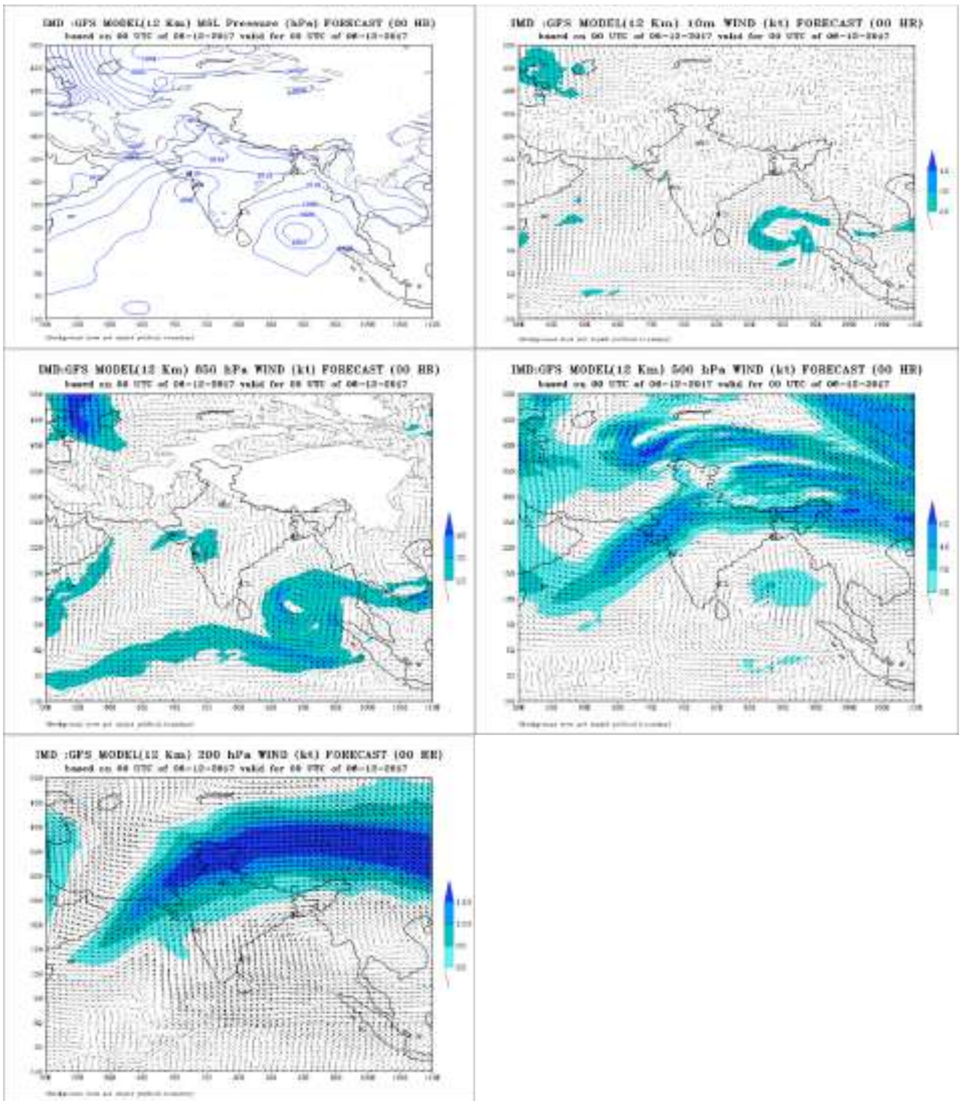


Fig. 2.10.3 (a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 6th December 2017

2.10.4. Dynamical features

IMD GFS (T1534) analysis and forecast of mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.10.3. IMD GFS (T1534) could well simulate the genesis of the system on 6th December, it's north-northeastward movement and dissipation on 9th. It could also capture broad scale features like trough in westerlies along 62^{0}E to the north of 20^{0}N.

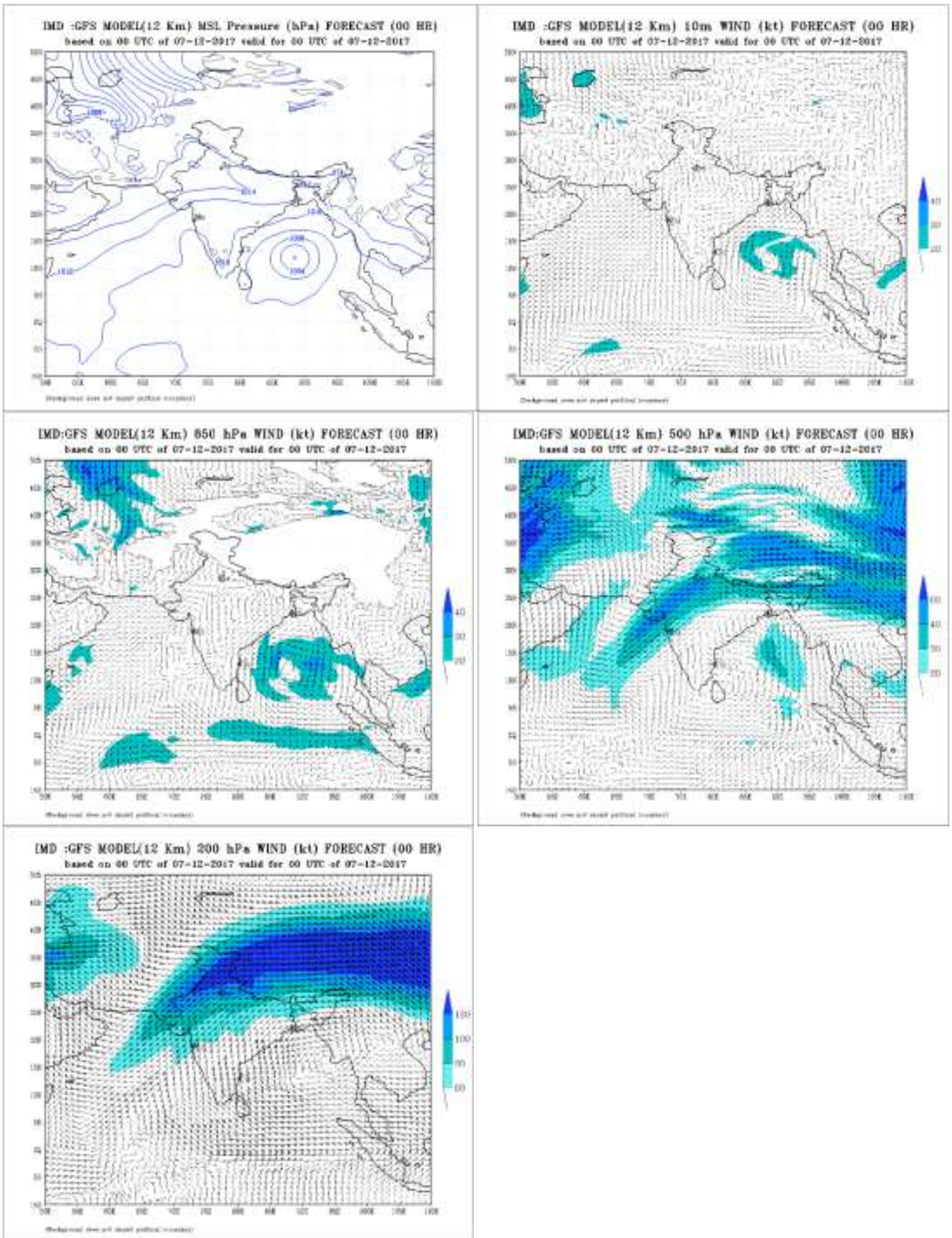


Fig. 2.10.3 (b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 7th December 2017

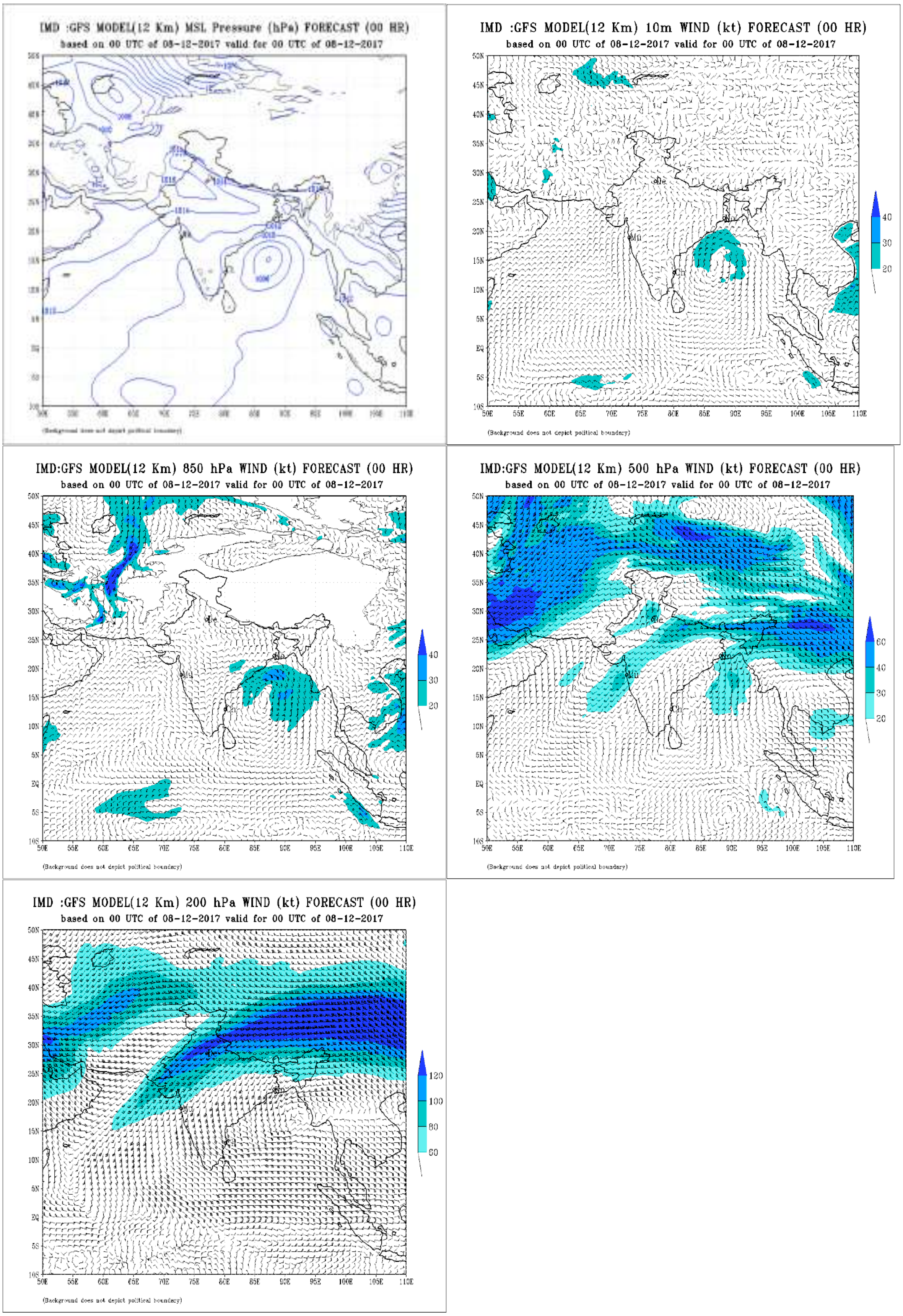


Fig. 2.10.3 (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 8th December 2017

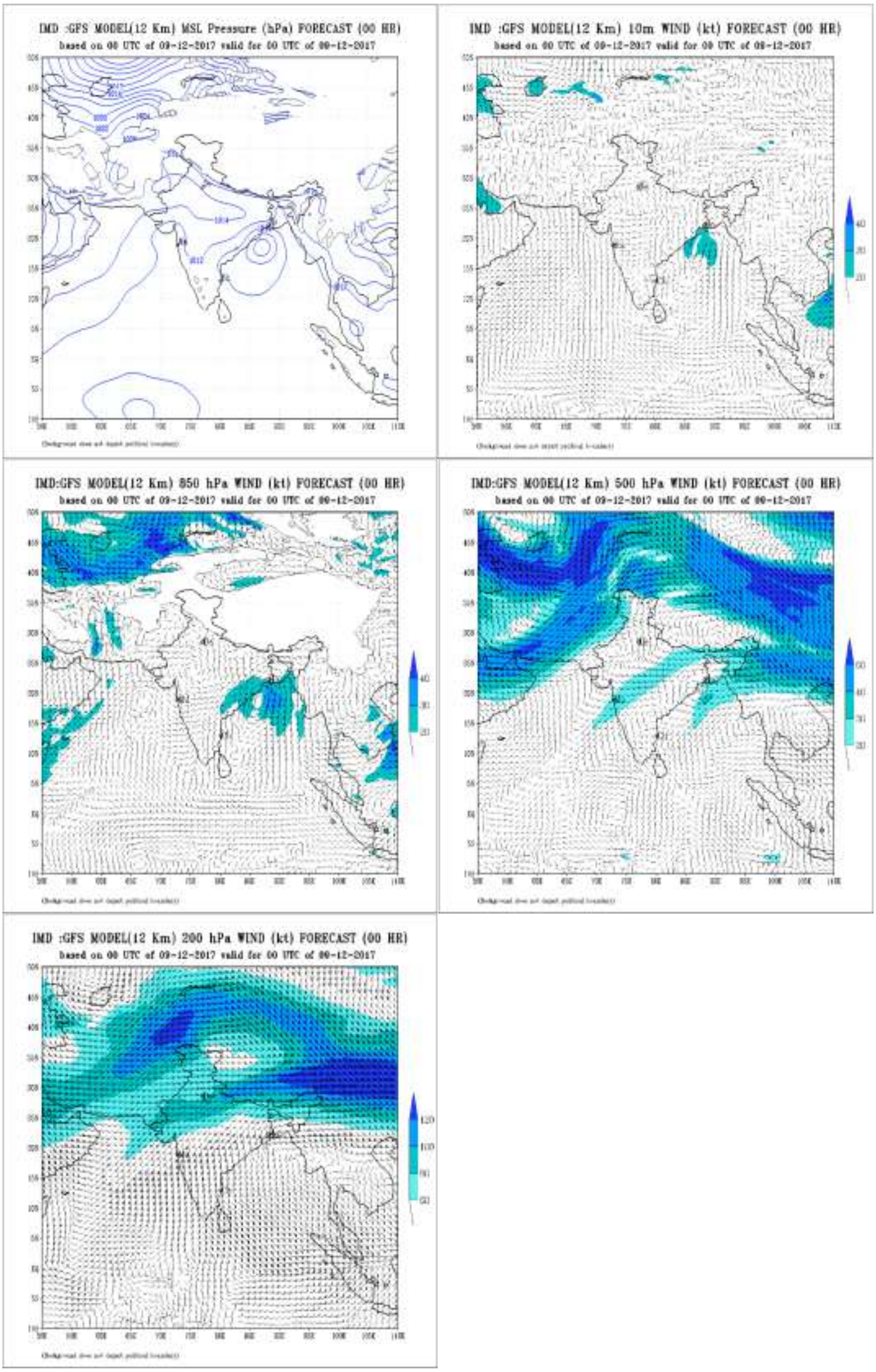


Fig. 2.10.3 (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 9th December 2017

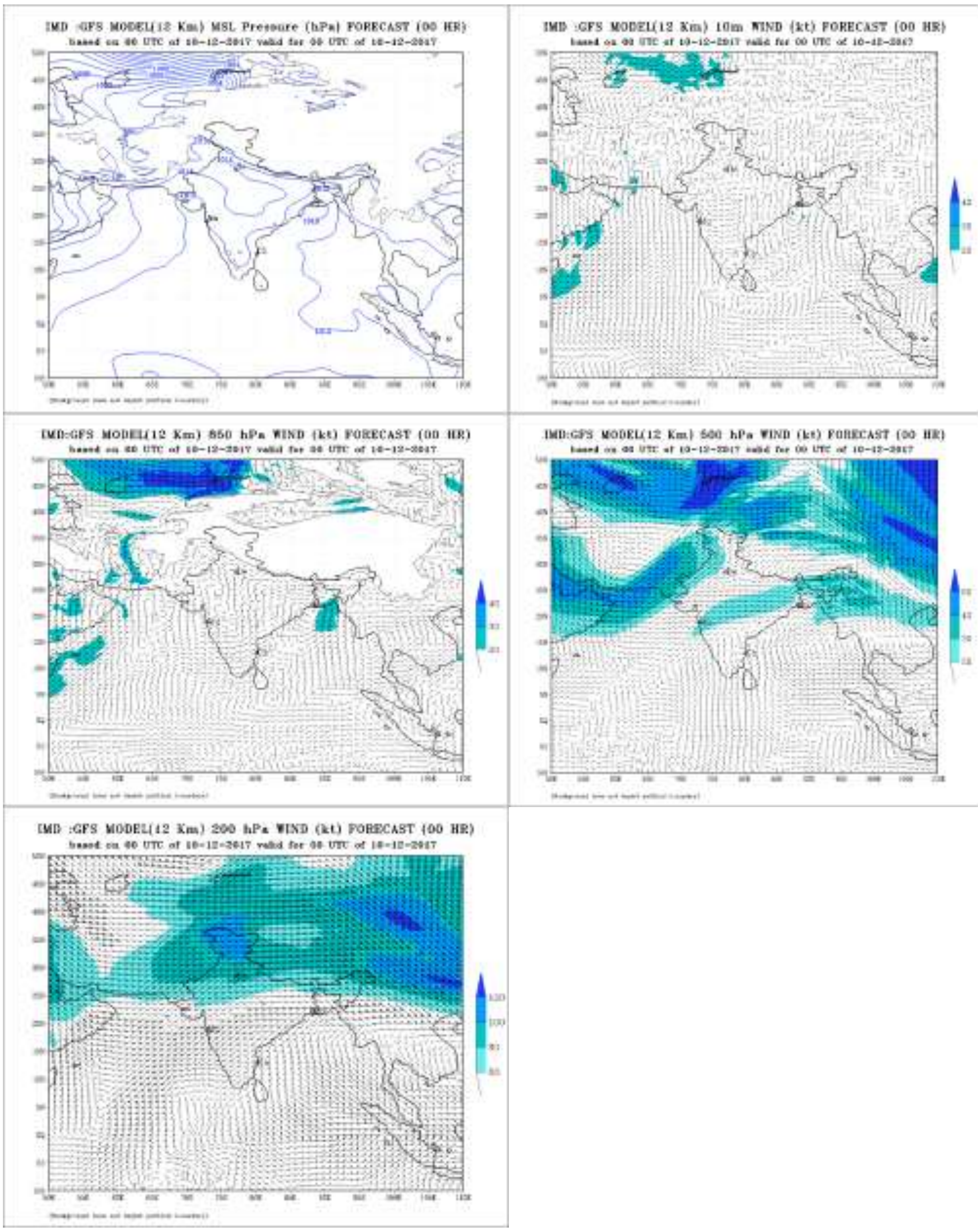


Fig. 2.10.3 (e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th December 2017

2.10.5. Realized Weather

The system caused light to moderate rainfall at few places with isolated heavy falls occurred over Tamilnadu & Puducherry on 6th and 7th Dec. Light to moderate rainfall at many places with isolated heavy falls occurred over coastal Odisha and adjoining districts of interior Odisha on 8th . Light to moderate rainfall also occurred at many places over coastal districts of West Bengal, south Assam, Meghalaya, Mizoram and Tripura with isolated heavy falls over Tripura on 9th. Realized 24 hrs accumulated rainfall (≥5cm) ending at 0830 hrs IST of date during the life cycle of the system is presented below. The rainfall is categorized as: heavy rain: 64.5 – 115.5 mm, very heavy rain: 115.6 – 200.4 mm, extremely heavy rain: 200.5 mm or more.

7 December 2017

Tamilnadu & Puducherry: Virudunagar AWS-11, Sivagiri-6 and Virudhunagar & Sivakasi-5 each

8 December 2017

Tamilnadu & Puducherry: Gobichettipalayam-8, Rajapalayam-7, Srivilliputhur-6, Kovilpatti-5

9 December, 2017

Odisha: Kakatpur- 12 cm, Gop- 11 cm; Paradeep, Puri & Astaranga -10 cm each, Balikuda & Kujanga -9 cm each; Niali -8 cm; Satyabadi & Tirtol- 7 cm each; Alipingal, Krishnaprasad, Nimpara & Jagatsinghpur - 6 cm each; Marsaghai, Derabis, Raghunathpur & Pipili - 5 cm each.

10 December, 2017

Assam: Karimganj & Amraghat-5 cm each.

Mizoram: Serchip – 6 cm.

Tripura: Kailashahar -7 cm, Arundhutinagar & Gokulpur-5 cm each.

The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig. 2.10.4.

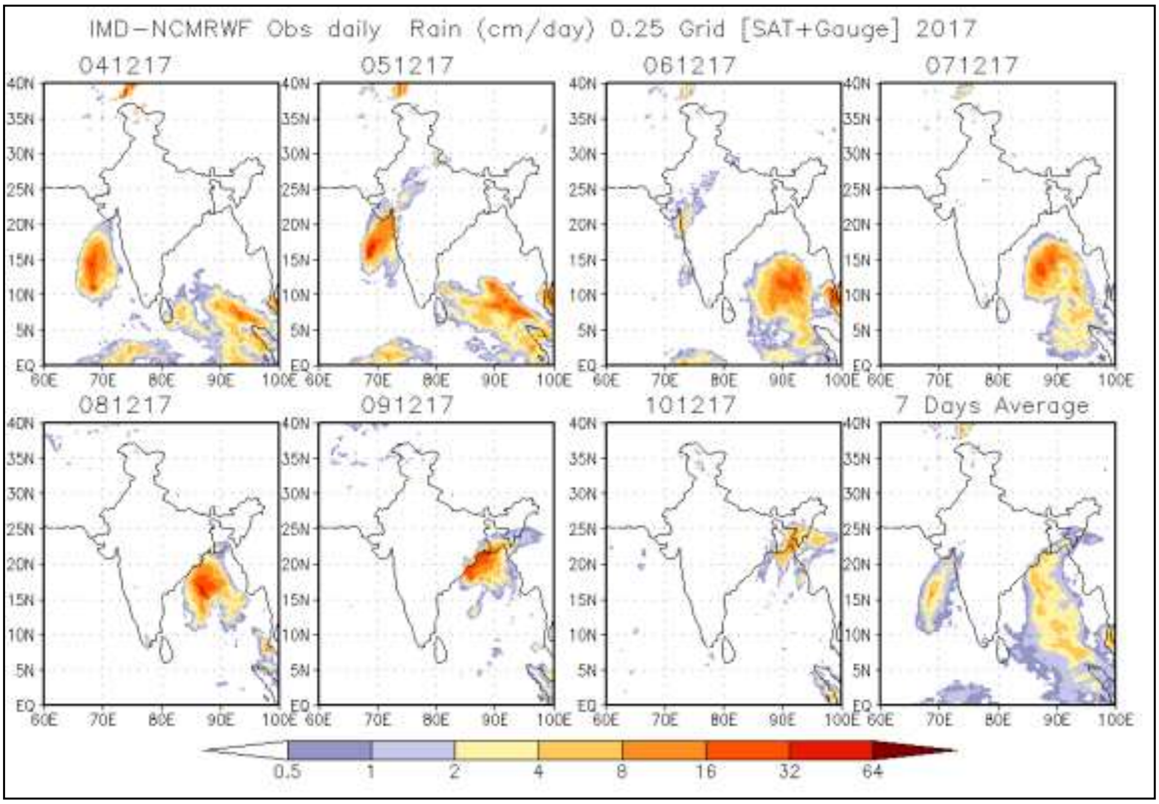


Fig. 2.10.4: Daily rainfall distribution ending at 0300 UTC (0830 IST) of date based on merged grided rainfall data of IMD/NCMRWF during 06-10 December, 2017

CHAPTER-III

Performance of operational NWP models for forecasting tropical cyclones over the North Indian Ocean during the year 2017

3.1. Introduction:

India Meteorological Department (IMD) operationally runs two regional models, WRF and HWRF for short-range prediction and one Global model T1534L64 for medium range prediction (10 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. 23^0 S to 46^0 N long 40^0 E to 120^0 E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 9 km. The boundary conditions are updated at every six hours interval. The HWRF model (resolution 18 km, 6 km and 2 km) is used for cyclone track prediction in case of cyclone situation in the north Indian Ocean. IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), UKMO (UKMet), JMA (Japan Meteorological Agency). Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

In addition to the above NWP models, IMD also run operationally “NWP based Objective Cyclone Prediction System (CPS)”. The method comprises of five forecast components, namely (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) 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 index (RII). 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 2017 are presented and discussed.

Global models are also run at NCMRWF. These include unified model (NCUM) adapted from UK Meteorological Office. Apart from the observations that are used in the earlier system, the new observations assimilated at NCMRWF include (i) Precipitation rates from SSM/I and TRMM (ii) GPSRO occultation (iii) AIRS and AMSRE radiances (iv) MODIS winds. Additionally ASCAT ocean surface winds and INSAT-3D AMVs are also assimilated. NCUM (N768/L70) model features a horizontal resolution of 17km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. NCUM is a grid point model which has a Non-hydrostatic dynamics with a deep atmosphere suitable for all scales. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. It features mass-flux for shallow convection with convective momentum transport, non-local mixing and entrainment for boundary layer. NCMRWF Ensemble Prediction System (NEPS) is a global medium range probabilistic forecasting system adapted from UK MET Office. The configuration consists of four cycles of assimilation corresponding to 00Z, 06Z, 12Z 18Z and 10-day forecasts are made using the 00Z initial condition. The N400L70 forecast model consists of 800x600 grid points on the horizontal surface and has 70 vertical levels. Horizontal resolution of the model is approximately 33 km in the mid-latitudes. The 10 day control forecast run starts with N768L70 analysis of the deterministic assimilation forecast system and 44 ensemble members start from different perturbed initial conditions consistent with the uncertainty in initial conditions. The initial perturbations are generated using Ensemble Transform Kalman Filter (ETKF) method (Bishop et al., 2001).

An important component common to both the deterministic and ensemble model is that they do not use any TC relocation in the analysis.

3.2. Cyclonic storm ‘Maarutha’ over the Bay of Bengal during 15-17 April 2017

3.2.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for Maarutha

Figure 3.1 shows the predicted zone of cyclogenesis. Grid point analysis and forecasts of GPP correctly predicted the cyclogenesis zone over south west Bay of Bengal 96 hrs before its formation. Fig. 3.2 presents the area average analysis and GPP forecasts.

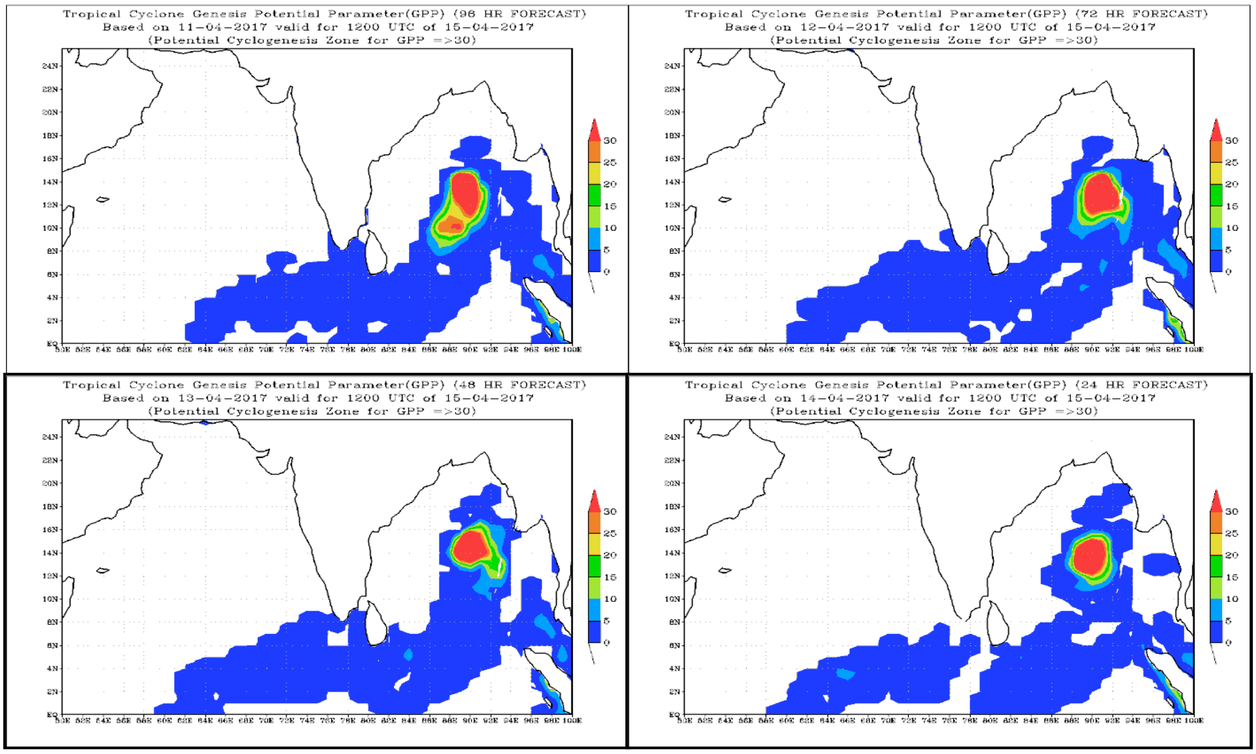


Fig.3.1: Predicted zone of cyclogenesis based on 1200 UTC of 11th - 14th April.

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for: (i) Developed system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0. From Fig.3.2, GPP ≥ 8.0 (threshold value for intensification into cyclone) indicated its potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

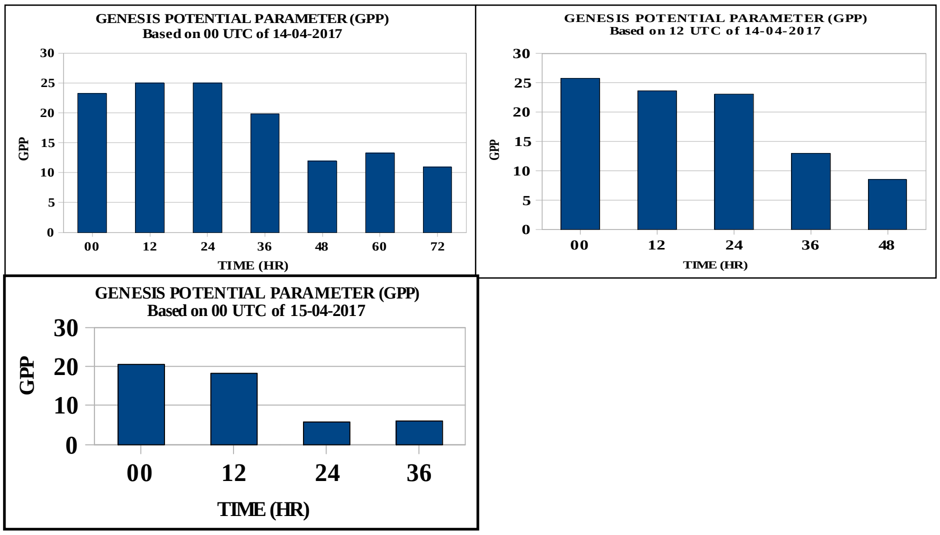


Fig. 3.2: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 14th and 15th April.

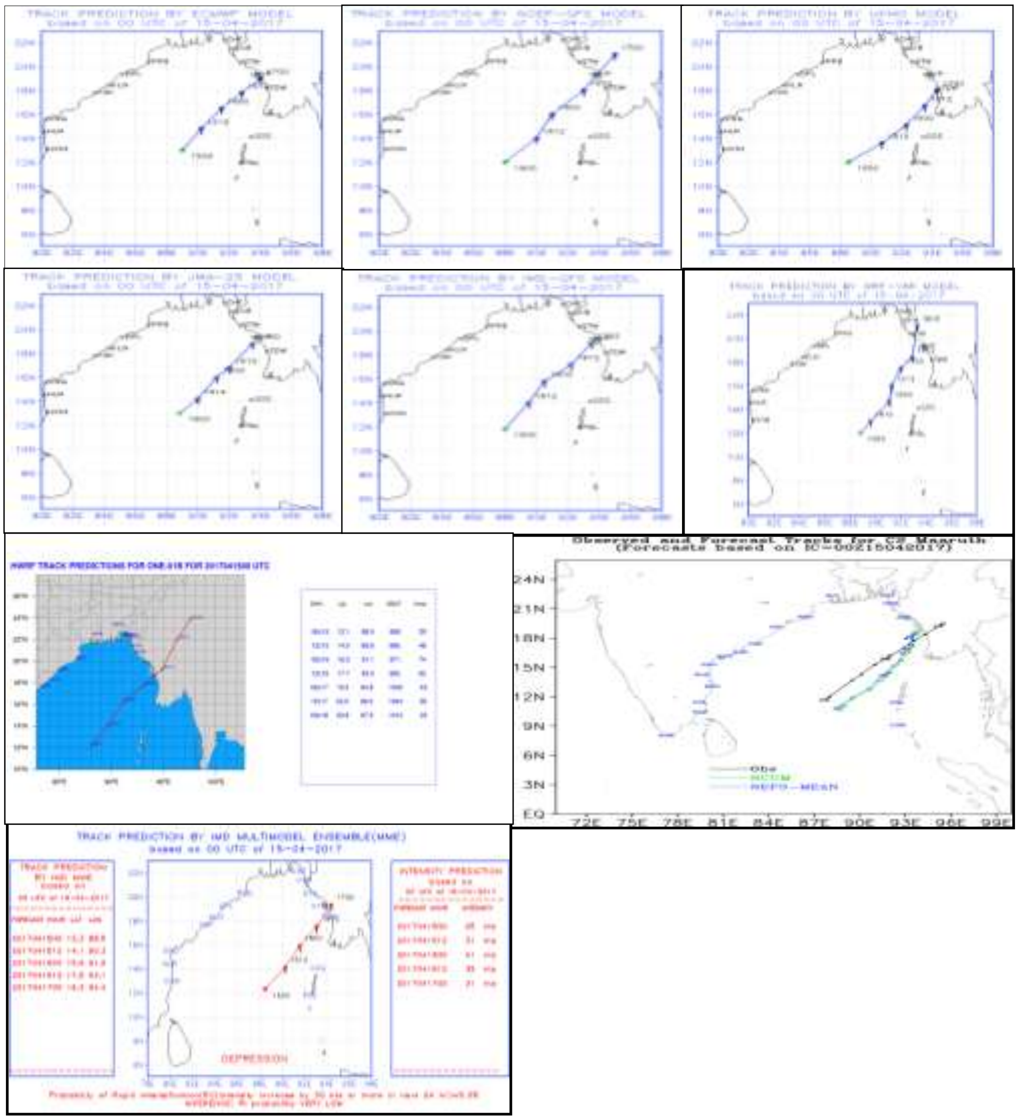


Fig.3.3. (a): Track prediction by NWP models based on 0000 UTC of 15th April, 2017

3.2.2 Track prediction by NWP models

Based on initial conditions of 0000 UTC of 15th, most of the models except JMA, IMD GFS and NCUM suggested landfall over Myanmar between Thandwe and Kyaukpyu. Many models like JMA, IMD GFS and NCUM predicted no landfall. However, only NCEP GFS and HWRF predicted landfall time around 1800 UTC around 42 hours prior to landfall. Most of the models (ECMWF, UKMO, JMA, IMD GFS, WRF and MME) were predicting landfall between 0000 to 1200 UTC of 17th. The tracks forecast by different models based on 0000 UTC of 15th April are presented in Fig. 3.3(a).

Based on initial conditions of 0000 UTC of 16th, ECMWF, NCEP GFS, UKMO, HWRF and MME predicted landfall close to Thandwe. Models like JMA and WRF predicted no landfall. However, only UKMO and HWRF predicted landfall time around 1800 UTC. Even 18 hours prior to landfall many models (ECMWF, NCEP and MME) predicted early rainfall. IMD GFS and JMA could not capture fast movement and predicted delayed landfall time. The track forecasts by different models based on 0000 UTC of 16th April are presented in Fig. 3.3(b).

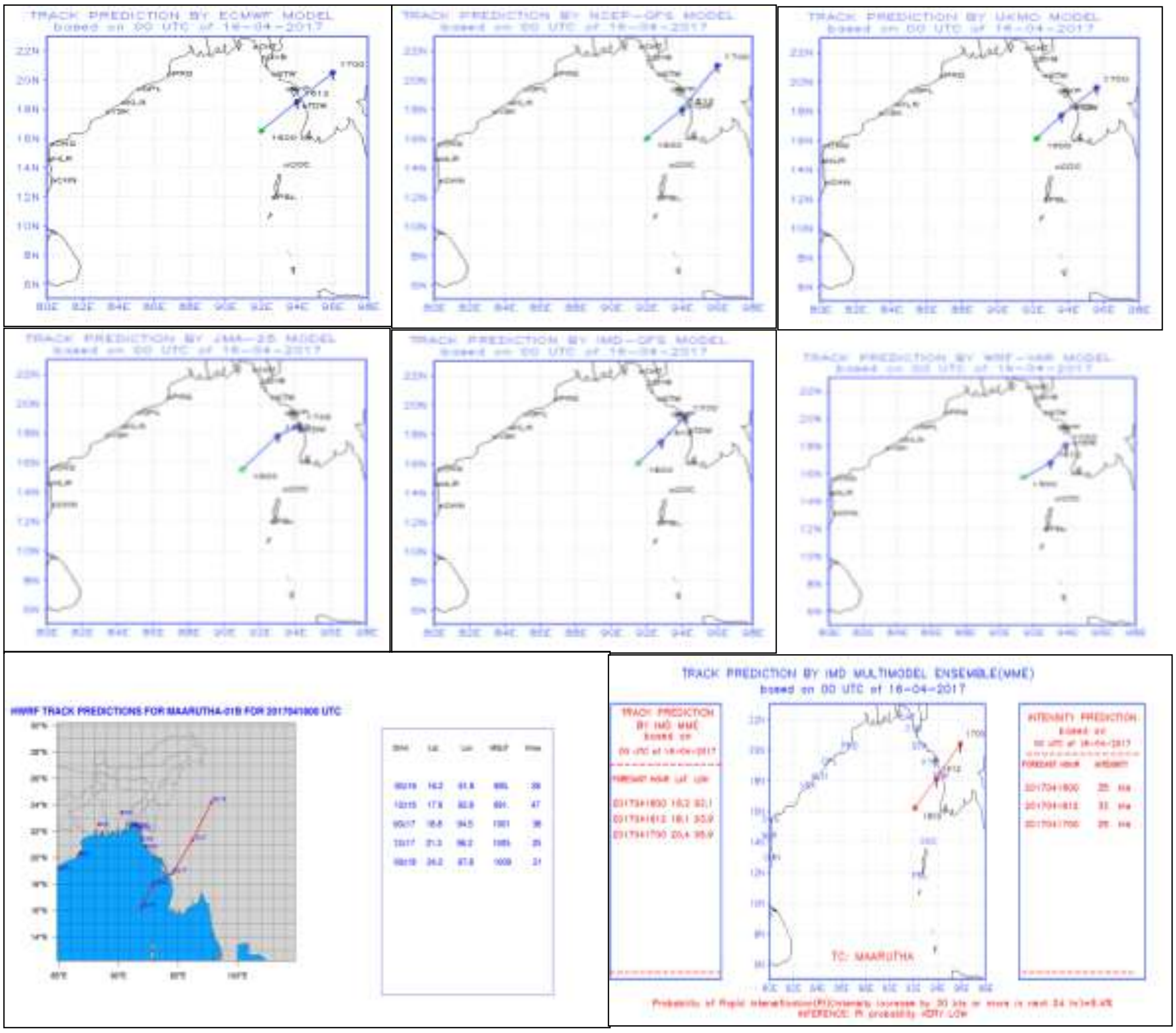


Fig.3.3 (b): Track prediction by NWP models based on 0000 UTC of 16th April, 2017

Hence to conclude, even 18 hours prior to landfall, most of models failed to capture landfall time correctly as Maarutha was a fast moving system. The landfall and track forecast errors as compared to operational forecast have been exceptionally higher for all lead periods as discussed in following sections.

3.2.3: Track and intensity forecast errors by various Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in Table 3.1. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 3.2 (a-b). From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of MME were significantly less for all lead periods. The track frecast errors for HWRF were the least for 36 and 48 hours lead period. Table 3.2(a) and (b) indicate show that DPE was largely contributed by ATE, that is errors in speed of movement of the storm, whereas CTE shows that forecast tracks were close to the observed track.

Table-3.1: Average track forecast errors (Direct Position Error (DPE)) in km

Models	Lead time →			
	12 hr	24 hr	36 hr	48 hr
IMD-GFS	100(3)	160(3)	186(2)	217(1)
IMD-WRF	112(3)	176(3)	310(2)	431(1)
JMA	65(3)	133(3)	168(2)	224(1)
NCEP	64(3)	117(3)	117(2)	175(1)
UKMO	78(3)	101(3)	151(2)	209(1)
ECMWF	55(3)	84(3)	119(2)	167(1)
IMD-HWRF	114(4)	115(3)	111(2)	81(1)
IMD-MME	46(3)	75(3)	110(2)	117(1)
NCUM	220	215	240	233
NCEP	190	228	230	271
Operational Error	**3**	**41**	**60**	

Table-3.2 (a). Average cross-track forecast errors (CTE) in km

Models	Lead time →			
	12 hr	24 hr	36 hr	48 hr
IMD-GFS	42	68	54	110
IMD-WRF	32	17	69	108
JMA	18	33	38	95
NCEP	30	69	66	155
UKMO	67	62	53	28
ECMWF	23	55	66	73
IMD-HWRF	58	42	51	28
IMD-MME	11	22	28	66
NCUM	140	120	160	122
NCEP	105	80	110	105

Table-3.2(b). Average along-track forecast errors (ATE) in km

Models	Lead time →			
	12 hr	24 hr	36 hr	48 hr
IMD-GFS	91	143	178	187
IMD-WRF	107	175	301	417
JMA	58	126	164	203
NCEP	56	90	89	81
UKMO	34	74	136	207
ECMWF	50	52	97	150
IMD-HWRF	92	103	98	75
IMD-MME	37	71	106	97
NCUM	165	170	215	198
NCEP	142	242	178	272

Landfall point and time forecast errors are presented in Table 3.3 and 3.4. For lead period of 18hrs, landfall point forecast error was the least by HWRF and ECMWF followed by JMA. For lead period of 42 hrs, the landfall point forecast error was the least by UKMO followed by IMD MME and HWRF.

Table-3.3: Landfall point forecast errors (km) of NWP Models at different lead time (hr)

Model	Forecast Lead Time (hour) →			
	06:30 hr	18:30 hr	30:30 hr	42:30 hr
	16April/12z	16April/00z	15April/12z	15April/00z
IMD-GFS	***	65	NLF	NLF
IMD-WRF	***	NLF	85	221
JMA	***	18	21	NLF
NCEP	***	25	69	109
UKMO	***	25	31	31
ECMWF	***	16	75	69
IMD-HWRF	40	16	65	40
IMD-MME	***	25	40	40

**** - No landfall

Table-3.4: Landfall time forecast errors (hour) at different lead time (hr)

Forecast Lead Time (hour) →	06:30 hr	18:30 hr	30:30 hr	42:30 hr
Based on	16April/12z	16April/00z	15April/12z	15April/00z
IMD-GFS	***	+03:30	NLF	NLF
IMD-WRF	***	NLF	+11:30	+25:30
JMA	***	+05:30	-01:30	NLF
NCEP	***	-04:30	+05:30	-01:30
UKMO	***	-01:30	-01:30	+15:30
ECMWF	***	-05:30	+05:30	-01:30
IMD-HWRF	-00:30	+02:30	+05:30	+01:30
IMD-MME	***	-03:30	+05:30	+02:30

('+' indicates delay landfall, '-' indicates early landfall; '***'-No landfall)

Intensity prediction:

The intensity forecasts of IMD-SCIP model and HWRF model are presented in Table 3.5. The errors were SCIP model were the least. The probability of rapid intensification (RI) index of IMD is shown in Table 3.6. It correctly predicted no RI for cyclone, Maarutha.

Table-3.5: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-SCIP (AAE)	3.7(3)	6.5(2)	5.0(1)	-
IMD-SCIP (RMSE)	4.8	8.5	5.0	-
IMD-HWRF (AAE)	10.8(4)	19.0(3)	20.0(2)	23.0(1)
IMD-HWRF (RMSE)	12.6	22.1	20.1	23.0

The figure in paranthesis represents the No. of observations verified.

Table 3.6: Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes(kt) occurred in 24h
00/15.04.2017	5.2 %	VERY LOW	15
12/15.04.2017	9.4 %	VERY LOW	10
00/16.04.2017	9.4 %	VERY LOW	-20

Intensity prediction by SCIP model is presented in Fig. 3.4. The SCIP model underpredicted the intensity of the system.

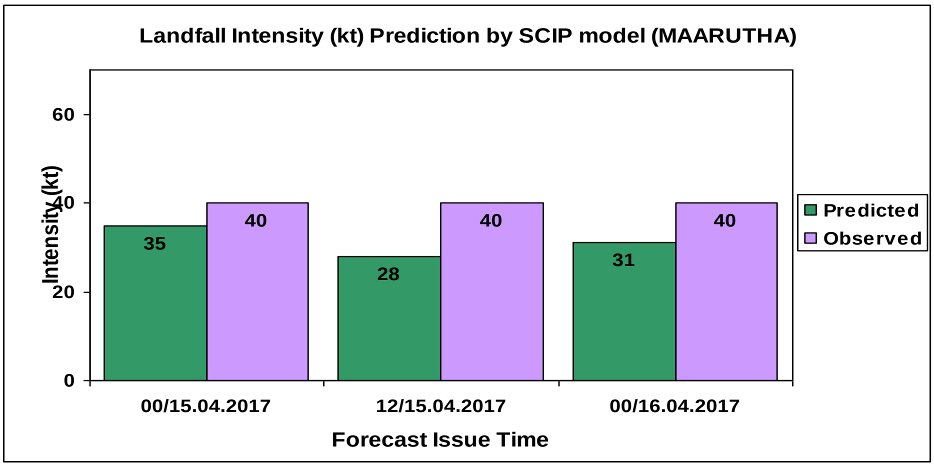


Fig.3.4: Intensity prediction by SCIP Model

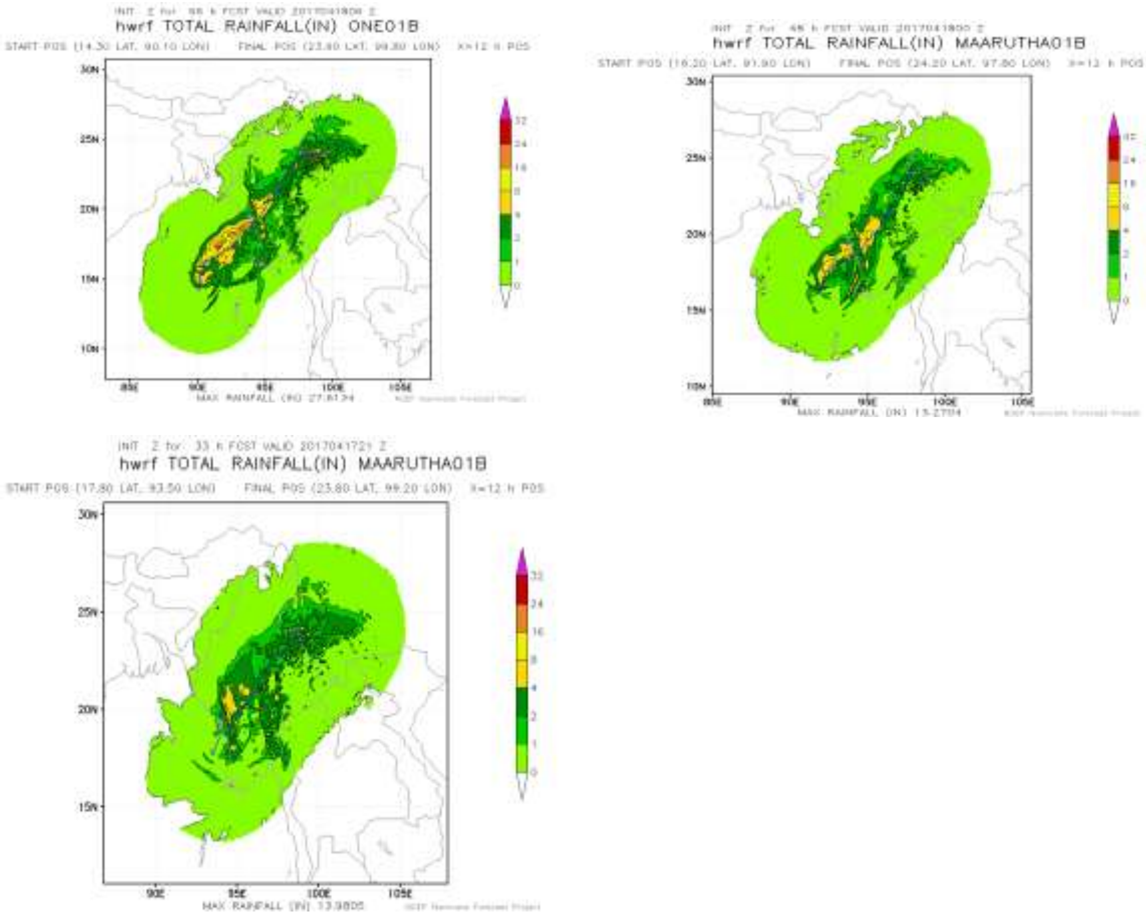


Fig.3.5: HWRF rain swath (inch) based on 15/1200, 16/0000 and 16/1200 UTC initial conditions.

3.2.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model is presented in Fig.3.5. Rainfall associated with the system decreased near landfall. The system caused more rainfall during initial stages.

3.3. Severe Cyclonic Storm ‘Mora’ over the Bay of Bengal during 28-31 May 2017

3.3.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for MORA

Fig.3.6 (a-f) shows the predicted zone of cyclogenesis for SCS Mora.

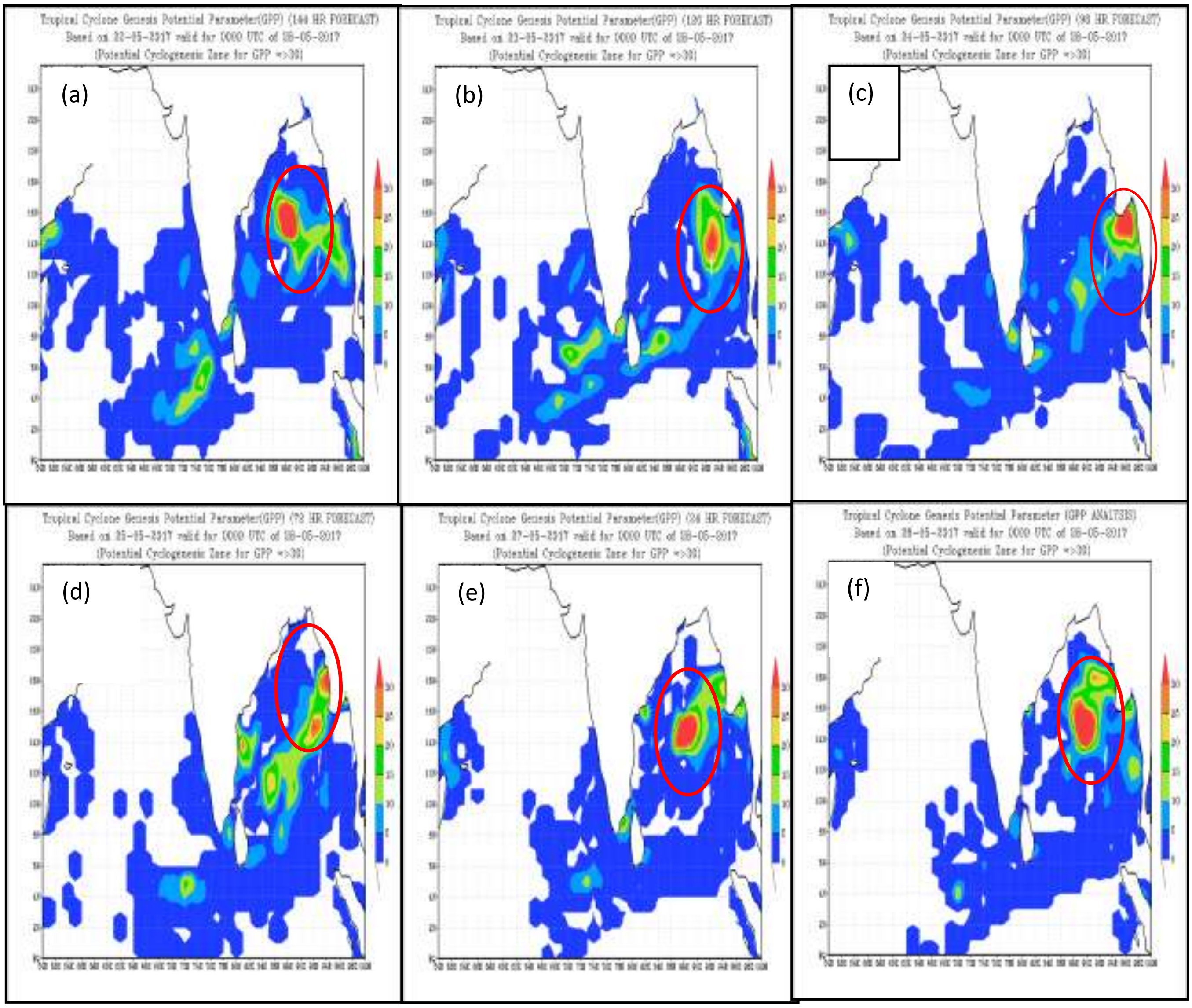


Fig. 3.6 (a-f): Predicted zone of cyclogenesis based on 0000 UTC of 22nd to 28th May 2017.

The model could predict cyclogenesis zone correctly about 24 and 144 hours in advance. However, for 72, and 120 hours lead period it failed to predict cyclogenesis zone correctly.

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for (i) Developed system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0.

The forecasts of GPP (Fig. 3.7) showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0). However, based on 0000 & 1200 UTC analysis of 28th, the model predicted weakening trend after 24 hours. Actually the system didn't weaken till landfall.

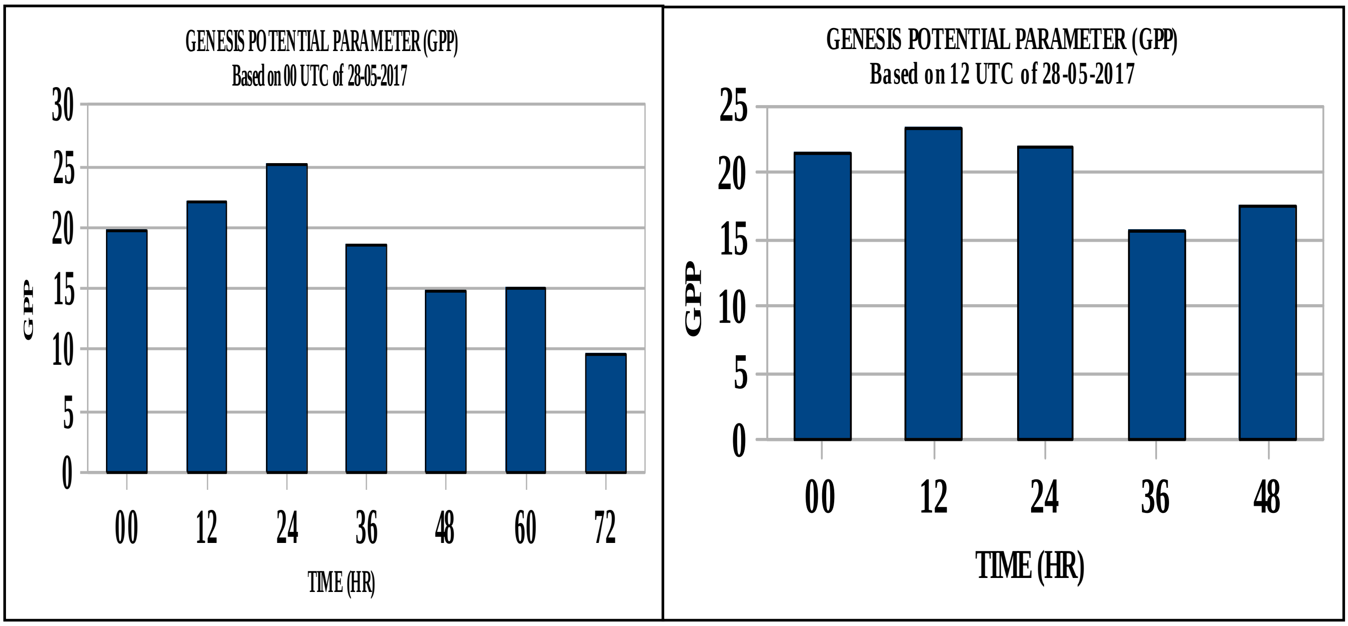


Fig. 3.7: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 28th May, 2017

3.3.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.3.8. Based on initial conditions of 0000 UTC of 28th May, ECMWF predicted landfall to the south of Chittagong. WRF-VAR, HWRF and MME predicted landfall to the south of Cox's Bazar. UKMO predicted landfall near Sittwe with overall movement of cyclone similar to observed track. NCEP-GFS, IMD-GFS and JMA were predicting north-northwestward movement and landfall near Dhaka over southwest Bangladesh. Only, WRF-VAR, HWRF, UKMO and MME were predicting landfall in the morning of 30th. ECMWF predicted landfall around night of 29th.

Based on the initial conditions of 0000 UTC of 29th May, ECMWF, UKMO, WRF-VAR, HWRF and MME predicted landfall close to south of Chittagong in the morning of 30th. NCEP-GFS, IMD-GFS and JMA predicted landfall over southeast Bangladesh. But MME predicted probability of Rapid Intensification as HIGH and the system didn't show rapid intensification.

Hence to conclude models like IMD GFS, NCEP GFS and JMA had eastward bias and were predicting landfall over southeast Bangladesh near Dhaka. ECMWF, MME, HWRF and UKMO were unanimous about landfall point and time close to Chittagong. But models were not unanimous about intensity during landfall.

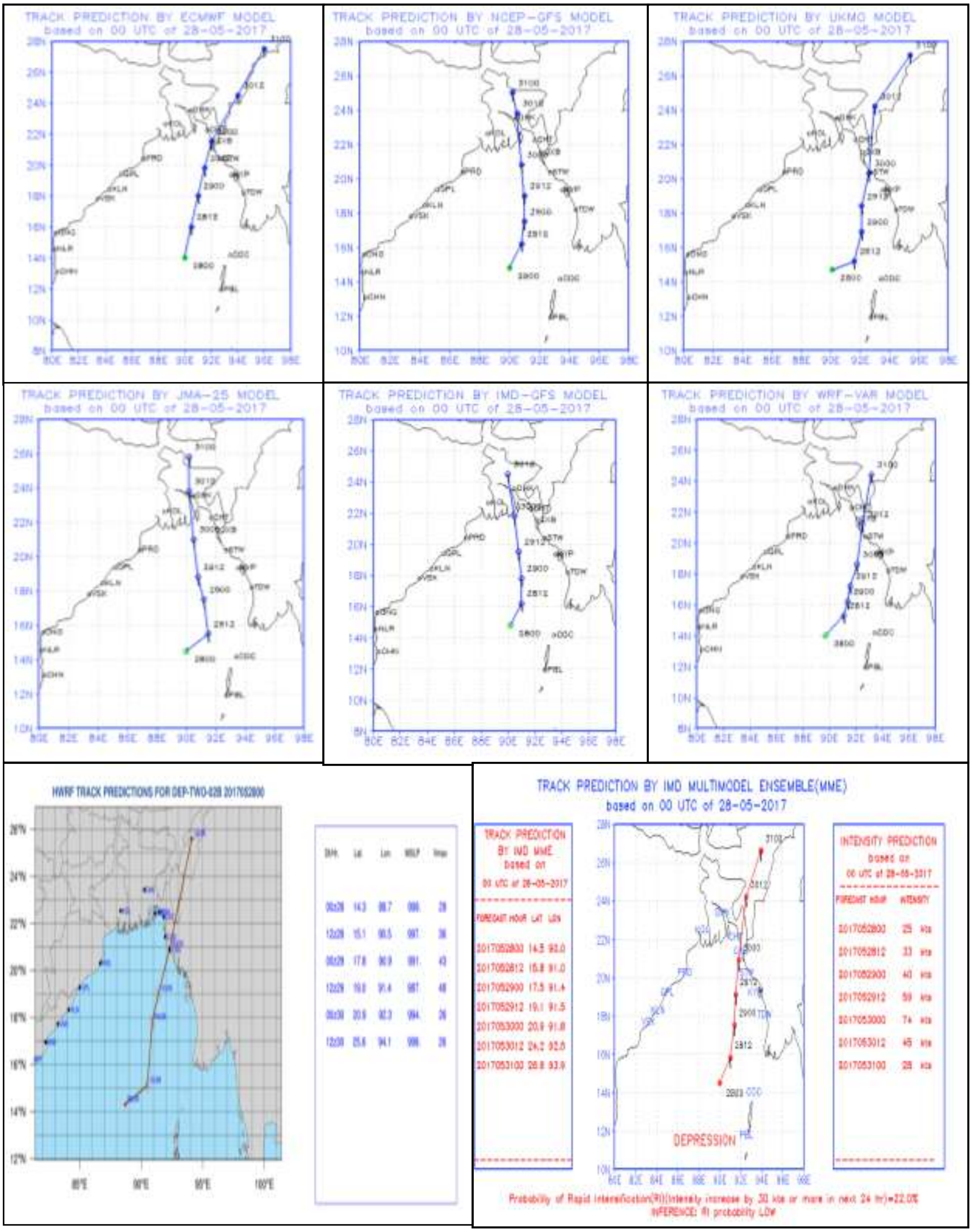


Fig. 3.8 (a): NWP model track forecast based on 0000 UTC of 28th May

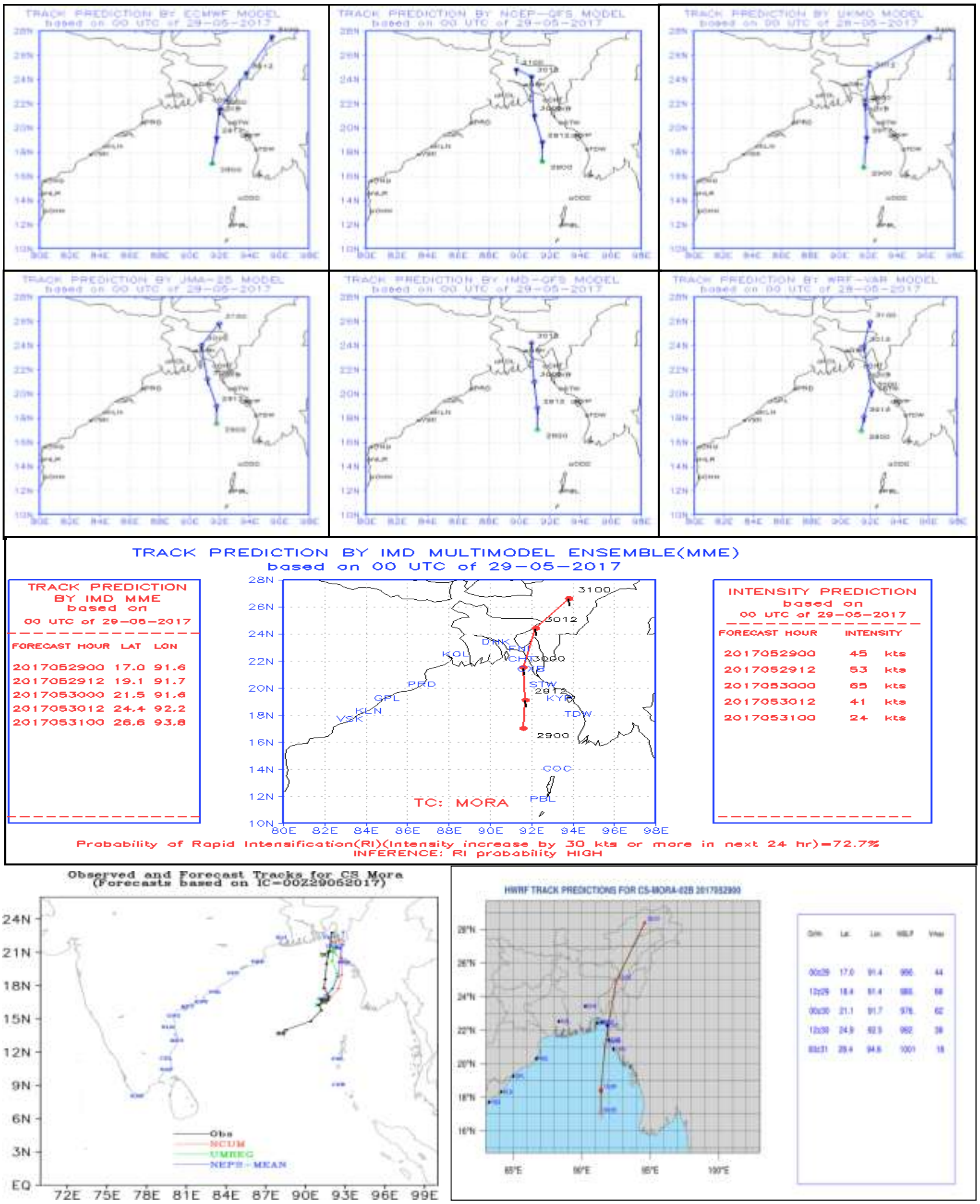


Fig. 3.8 (b): NWP model track forecast based on 0000 UTC of 29th May

3.3.3. Ensemble Prediction System

The probabilistic and deterministic track forecast by Meteorological Service of Canada (MSC) and National Centre for Environment Prediction (NCEP) and consolidated forecast by these centres based on initial conditions of 0000 UTC of 28th May are presented in **Fig. 3.9(a)**. MSC predicted 20-40% strike probability over southeast Bangladesh and adjoining Myanmar Region. NCEP members showed 60-80% strike probability over southwest Bangladesh and 20-40 % strike probability over southeast coast of Bangladesh. All members ensemble showed 20-40% strike probability over Bangladesh coast. The ensemble forecast was widespread.

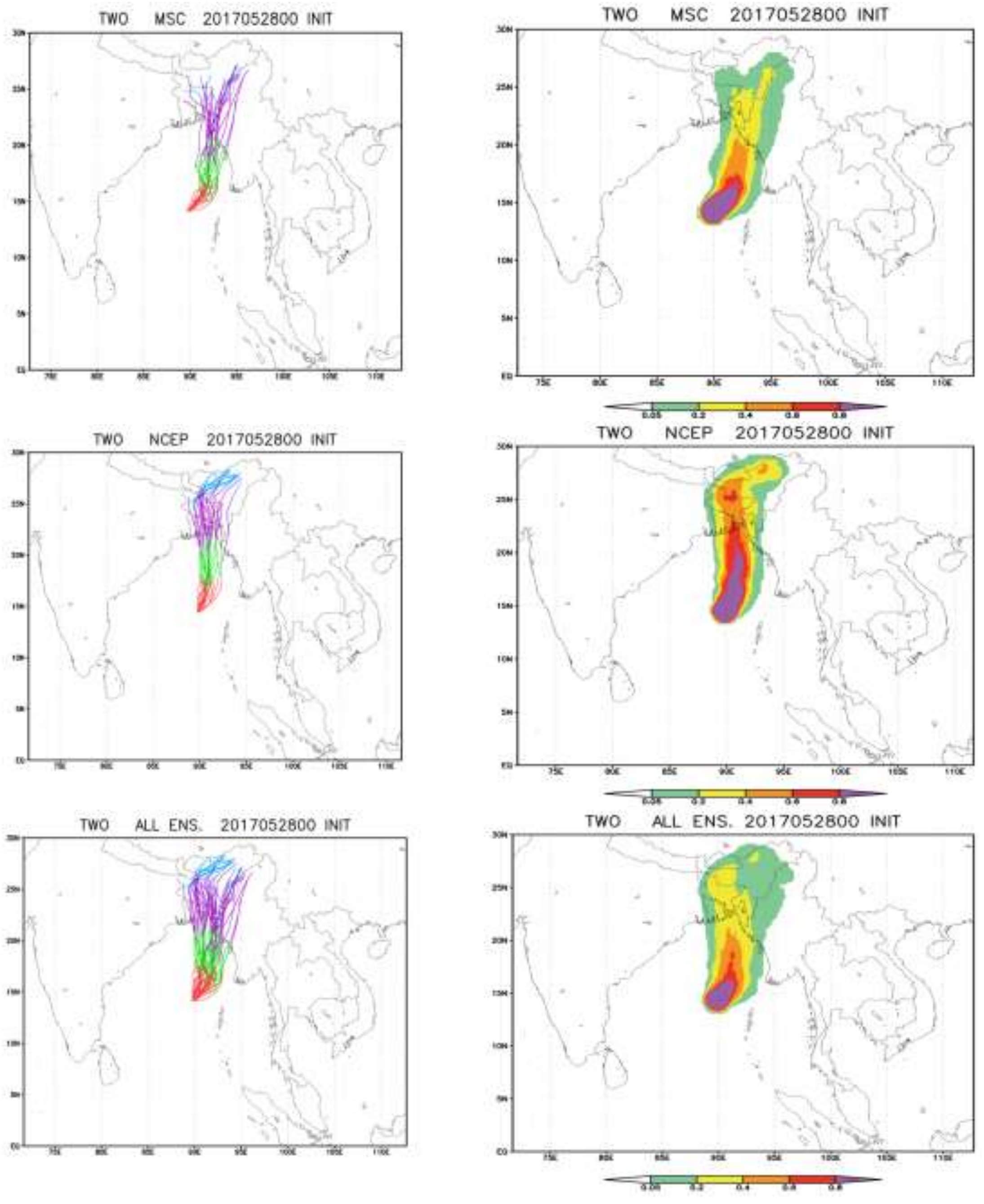


Fig. 3.9 (a): EPS track and strike probability forecast based on 0000 UTC of 28th May, 2017.

MSC and NCEP probabilistic and deterministic tracks based on 0000 UTC of 29th May are presented in **Fig. 3.9 (b).** MSC ensemble members predicted 60-80 % strike probability over southeast Bangladesh close to south of Chittagong. However, NCEP ensemble members predicted 80-100 % strike probability to the north of Chittagong. All ensemble members were predicting 60-80 % strike probability over southeast Bangladesh close to south of Chittagong.

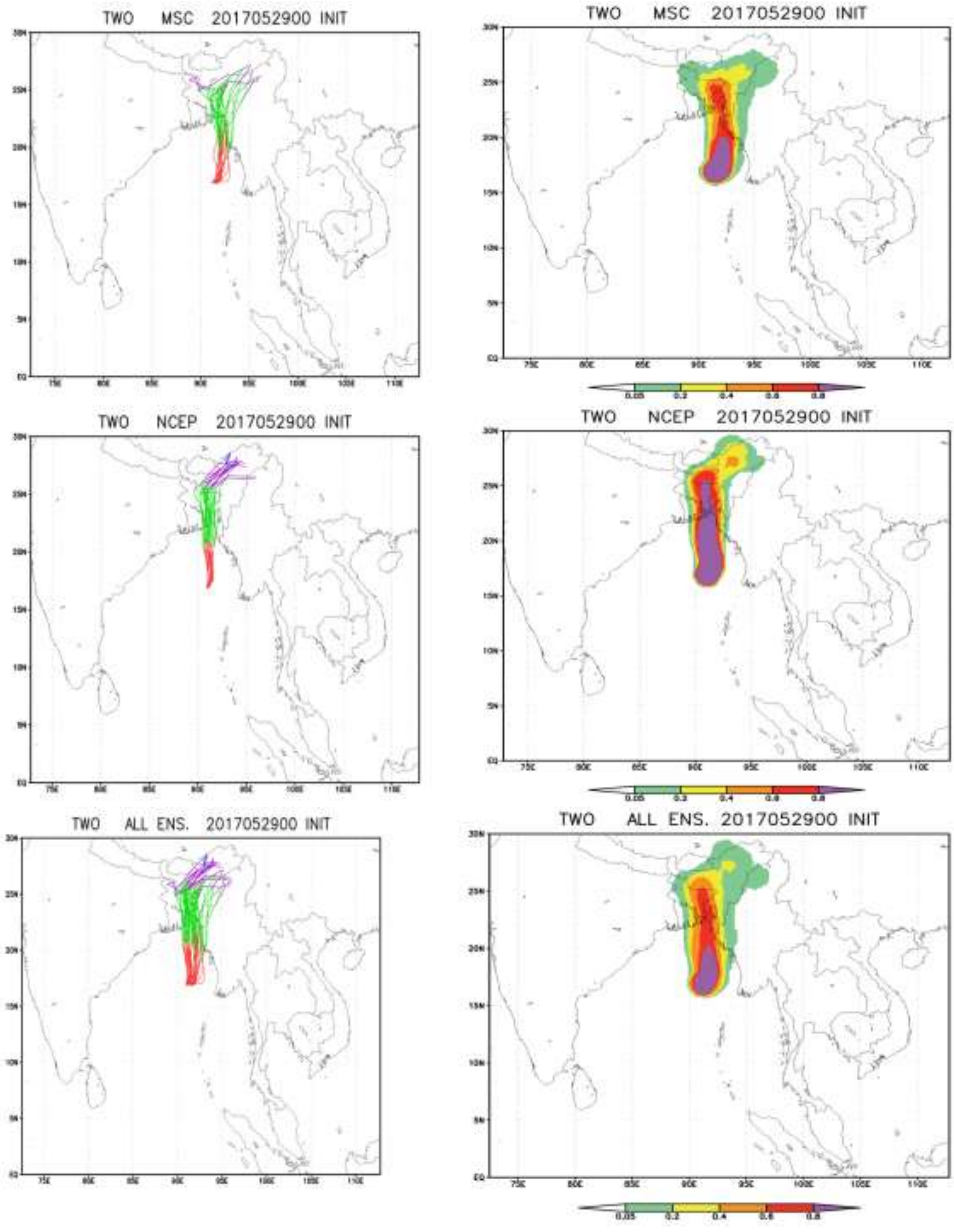


Fig. 3.9 (b): EPS track and strike probability forecast based on 0000 UTC of 29th May, 2017

UKMO and NCEP probabilistic and deterministic tracks based on 1200 UTC of 29th are presented in **Fig. 3.9 (c).** Ensembles from UKMO predicted 60-80 % strike probability over southeast Bangladesh. Ensembles from NCEP predicted 80-100 % strike probability over southeast Bangladesh. All ensemble members were predicting 80-100% strike probability over southeast Bangladesh close to south of Chittagong.

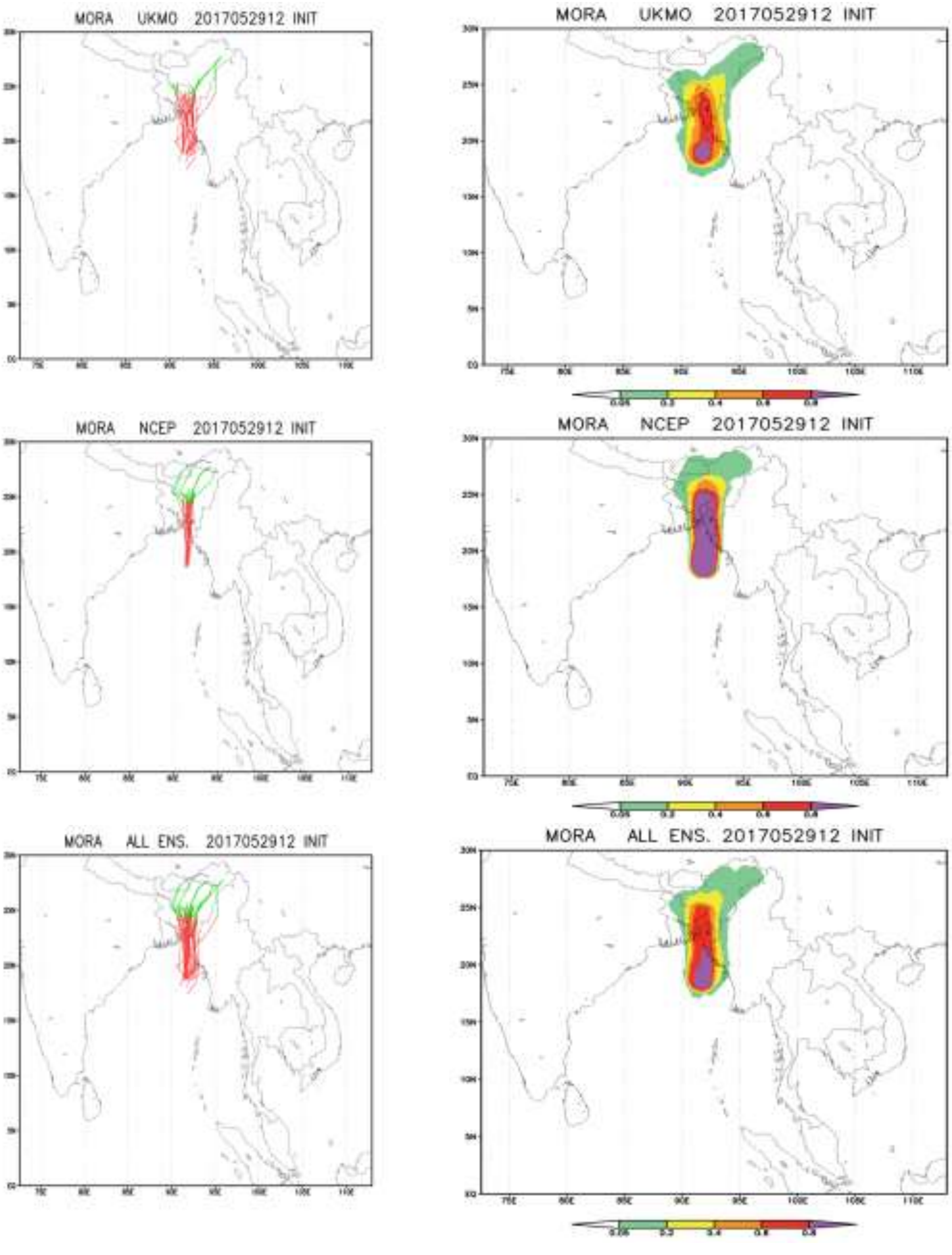


Fig. 3.9 (c): EPS track and strike probability forecast based on 1200 UTC of 29th May, 2017

12 hours prior to landfall both UKMO and NCEP members were predicting landfall close to south of Chittagong. However, 24 and 48 hours prior to landfall, MSC predicted landfallfall over southeast Bangladesh while NCEP members predicted landfall pver southwest Bangladesh.

Composite forecast track based on various initial conditions by HWRF and observed track is presented in Fig.3.10. It is seen that HWRF could predict predict landfall over southeast Bangladesh close to Chittagong based on initial conditions of 0600 UTC of 28th to 0000 UTC of 30th. However, based on 0000 UTC initial conditions 960 hours prior to landfall), it predicted landfall near Teknaf.

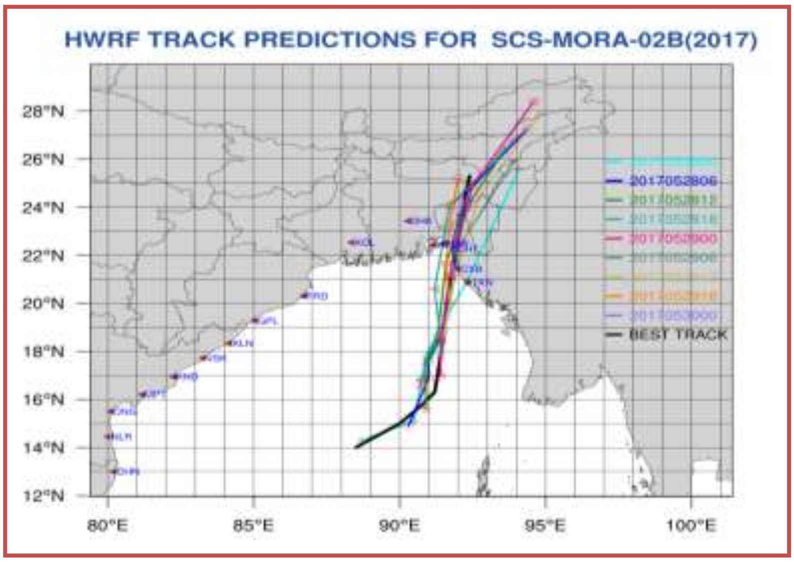


Fig. 3.10: Observed track and forecast tracks by HWRF based on initial conditions during 0000 UTC of 28th to 30th May

Table 3.7: Average track forecast errors (Direct Position Error (DPE)) in km

Lead time	12 hr	24 hr	36 hr	48 hr	60 hr
IMD-GFS	58(4)	110(4)	136(3)	189(2)	225(1)
IMD-WRF	79(4)	112(4)	160(3)	290(2)	335(1)
JMA	76(4)	60(4)	111(3)	146(2)	208(1)
NCEP	43(4)	81(4)	120(3)	149(2)	178(1)
UKMO	100(4)	119(4)	55(3)	98(2)	81(1)
ECMWF	68(4)	82(4)	139(3)	81(2)	185(1)
IMD-HWRF	47(9)	49(7)	79(6)	30(4)	114(2)
IMD-MME	53(4)	66(4)	44(3)	43(2)	30(1)
NCUM	127(5)	113(3)	135(2)	214(2)	234(1)
UMERG	124(2)	75(2)	94(2)	175(1)	-
NEPS	93(2)	101(2)	130(2)	151(1)	250(1)
ACCESS	51(3)	66(1)	125(1)	-	

( ): Number of forecasts verified; -: No forecast issued

3.3.4. Track and intensity forecast errors by various NWP Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in Table 3.7. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 3.8 (a-b). From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of HWRF were the least followed by MME for 12, 24 & 48 hours lead period. Average track errors of IMD-MME were the least followed by UKMO and HWRF for 60 hours lead period.

Table 3.8 (a). Average cross-track forecast errors (CTE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr
IMD-GFS	39	97	132	187	221
IMD-WRF	24	50	63	92	141
JMA	33	42	103	134	177
NCEP	28	77	110	119	148
UKMO	53	53	44	76	76
ECMWF	36	49	103	42	160
IMD-HWRF	14	11	9	22	72
IMD-MME	20	27	28	36	29
NCUM	85	65	135	170	225
UMERG	60	50	85	145	-
NEPS	58	68	135	148	240
ACCESS	35	65	98	-	-

Table 3.8(b). Average along-track forecast errors (ATE) in km

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr
IMD-GFS	38	49	27	26	42
IMD-WRF	64	97	140	269	304
JMA	64	33	40	54	109
NCEP	28	26	39	89	99
UKMO	77	99	23	55	27
ECMWF	46	57	84	62	93
IMD-HWRF	119	132	177	144	205
IMD-MME	47	60	23	16	10
NCUM	68	78	50	79	60
UMERG	100	58	48	102	-
NEPS	59	68	39	39	80
ACCESS	40	10	79	-	-

Above tables show that DPE was largely contributed by ATE that is the errors in speed of movement of the storm, whereas CTE shows that forecast tracks were close to the observed track.

Landfall point and time forecast errors are presented in Table 3.9 and 3.10. Landfall point forecast errors were the least by IMD-MME, WRF-VAR and ECMWF followed by HWRF for various lead periods. Landfall time errors were the least for HWRF for all lead periods except for 60 hours.

Table 3.9: Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	**16:30 hr**	**18:30 hr**	**40:30 hr**	**52:30 hr**
Based on	**29 May/12z**	**29 May/00z**	**28 May/12z**	**28 May/00z**
IMD-GFS	108	144	155	156
IMD-WRF	25	11	59	143
JMA	25	128	158	155
NCEP	108	144	138	138
UKMO	119	11	115	196
ECMWF	25	56	105	56
IMD-MME	25	30	105	25
HWRF	56	73	44	114

Landfall Point Error: Landfall Forecast Point- Actual Landfall Point, **: No forecast issued

Table-3.10. Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	**16:30 hr**	**18:30 hr**	**40:30 hr**	**52:30 hr**
Based on	**29 May/12z**	**29 May/00z**	**28 May/12z**	**28 May/00z**
IMD-GFS	+01:00	+02:30	-02:00	-02:30
IMD-WRF	+02:30	+02:00	+07:30	+05:30
JMA	-01:30	+02:30	+00:30	+01:00
NCEP	+00:30	+02:30	+02:30	+01:30
UKMO	-09:30	-03:30	-05:30	-03:30
ECMWF	-04:30	-04:30	-01:00	-04:30
IMD-MME	-02:30	-00:30	+01:30	-01:30
HWRF	0	0	0	-4:00

Landfall Time Error: Landfall Forecast Time- Actual Landfall Time, -: No forecast issued

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table 3.11. The errors by IMD-SCIP were the least followed by HWRF. The probability of rapid intensification (RI) index of IMD is shown in Table 3.12. 24 hours prior to landfall it predicted HIGH probability of rapid intensification. 36 and 48 hours prior to landfall it predicted probability of rapid intensification as LOW. However, the system didn't show any rapid intensification.

Table 3.11: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP and HWRF models (Number of forecasts verified is given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr
IMD-SCIP (AAE)	4.5(4)	7.0(3)	5.5(2)	14.0(1)
IMD-HWRF (AAE)	7.3(9)	7.4(7)	5.8(6)	13.0(4)
IMD-SCIP (RMSE)	5.2(4)	7.5(3)	6.5(2)	14.0(1)
IMD-HWRF (RMSE)	9.5(9)	8.5(7)	6.4(6)	14.5(4)

( ): No of forecasts verified

Table 3.12: Probability of Rapid intensification

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes (kt) occurred in 24h
00/28.05.2017	22 %	LOW	20
12/28.05.2017	22 %	LOW	20
00/29.05.2017	72.7 %	HIGH	15

3.3.5. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.3.11**.

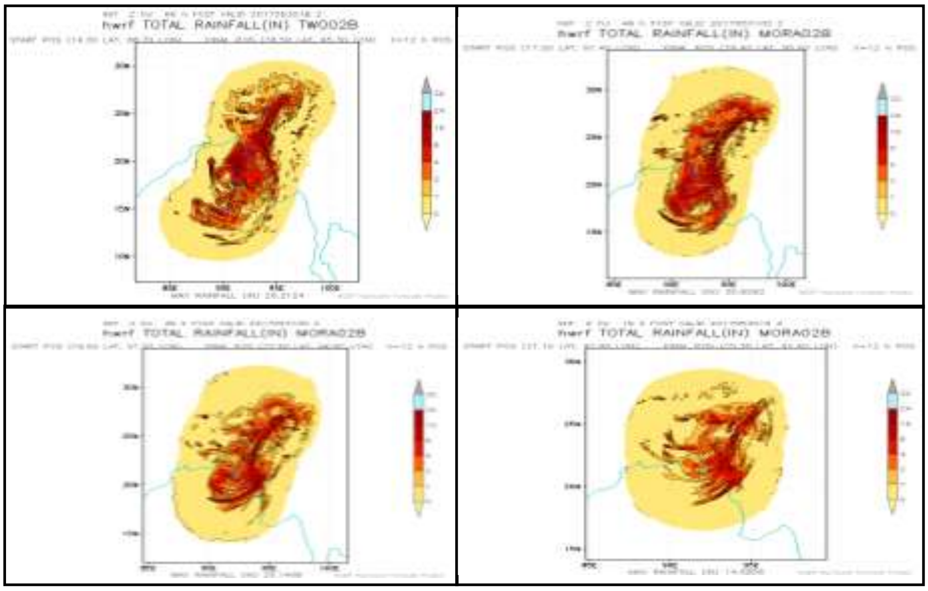


Fig.3.11: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 28th-30th May, 2017.

It indicates that HWRF model could capture the occurrence of rainfall over parts of southeast Bangladesh, Myanmar and northeastern states like Assam, Manipur, Nagaland, Mizoram, Arunachal Pradesh based on initial conditions of 0000 UTC of 28th -30th.

3.3.6. Storm surge forecast

IMD predicted storm surge forecast based on guidance from Indian National Centre for Ocean Information Services (INCOIS) Advance Circulation (ADCIRC) model and Indian Institute of Delhi. IMD predicted Storm surge of about 1 to 1.5 m height above astronomical tide at the time of landfall over low lying areas of Bangladesh between Sitakund and Uttar Jaldi at the time of landfall. Storm surge forecast by INCOIS is presented in **Fig.3.12**.

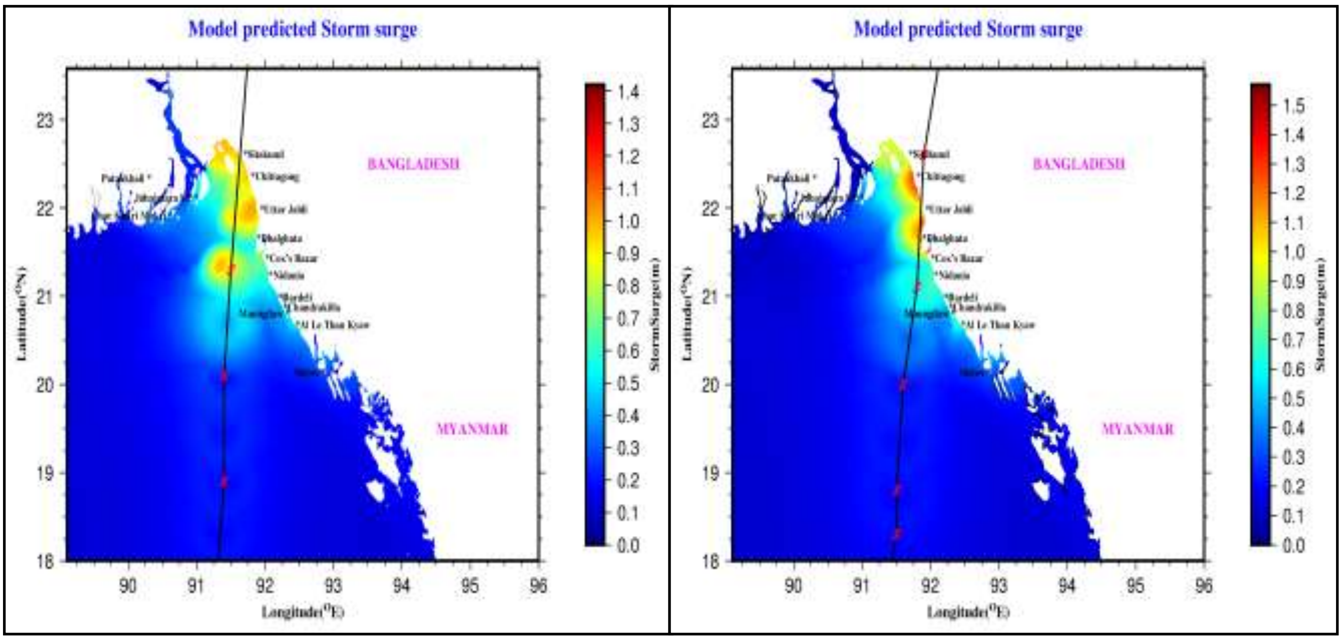


Fig. 3.12: Storm Surge Forecast issued by INCOIS on 29th and 30th May, 2017.

3.4. Cyclonic storm 'Ockhi' over the Bay of Bengal during 29 November-5 December 2017

3.4.1 NWP Guidance on Genesis:

Numerical Weather Prediction Model guidance from various models including IMD GFS, ECMWF, NCUM, NEPS and JMA during 21st to 30th November is discussed in Table 3.13. The NWP charts from IMD GFS model are placed at Annexure-2, ECMWF charts are placed at Annexure-3, NCUM at Annexure-4, NEPS at Annexure-5 and JMA at Annexure-6.

Table 3.13: Numerical weather Prediction Model guidance during 21st-30th November.

Date/Time	Model Analysis
21/00	IMD GFS indicated an Ext LPA over SW Bay on 24th which also becomes less marked the following day. Another low forms on 25th & 26th over southern parts of SE Bay. NCUM indicated LPA over Comorin on 21st becoming insignificant on 22nd. Low over SE BoB on 23rd. Low over south Andaman Sea movig westwards during 24th-26th. NEPS indicated a LPA over Gulf of Thailand and Ex. LPA over Comorin Area off SW Sri Lanka on 21st and LPA over SE BoB on 23rd becoming insignificant thereafter. JMA didn't indicate any cyclogenesis during 21-26.
22/00	IMD GFS indicated an LPA over SE Bay on 26th moving WNW and lay as LPA over SW BoB on 27th. NCUM indicated two LPAs over SE and SW BoB during 23rd – 26th. NEPS indicated LPA on 22nd, 23rd & 25th over Gulf of Thailand, EC BoB and SE BoB respectively. JMA didn't indicate any cyclogenesis during 22-27.
23/00	IMD GFS indicated an LPA over SE BoB during 26th-27th moving westwards & becoming WML on 28th over SE Bay NCUM indicated an Ext low over SW BoB and LPA over SE AS on 25th. On 27th 2 LPAs over SW BoB NEPS indicated LPA over SE BoB on 23rd moved nearly northwards & lay over EC BoB on 24th. No system on 25th & 26th. LPA over Gulf of Thailand on 27th . 2 LPAs over SE BoB & south Andaman Sea. JMA indicated no cyclogenesis during 23-28.
24/00	IMD GFS indicated Ext LPA over SE BoB on 24th becoming insignificant on 24th. A fresh LPA over SW BoB moving westwards from 26th to 29th. WML over south Kerala on 29th. NCUM indicated LPA over SW BoB on 25th, LPA SE BoB on 26th. Moved WNWwards and lay over SW BoB on 27th becoming insignificant on 28th. Ext LPA over Maldives on 29th. NEPS indicated a CS over north Andaman Sea and an LPA over Thailand on 24th. LPA over SW BoB on 25th becoming insignificant on 26th. Fresh LPA over SW BoB on 27th moving towards north Tamil Nadu till 29th. Another LPA over SW BoB on 29th. JMA indicated no cyclogenesis during 24-29.
25/00	IMD GFS indicated LPA over SW BoB on 25th. Moved westwards & lay as LPA off SE Sri Lanka coast on 26th, LPA over SW Sri Lanka on 27th, Ex. Low over Comorin on 28th becoming low on 28th over Comorin and DD over Maldives on 29th. ECMWF indicated no depression on 29th and 30th. NCUM indicated LPA over equatorial Indian Ocean on 25th. Fresh low over Thailand on 26th. Moving nearly westwards lay as low over SE BoB on 27th, D over SW BoB on 28th, Low over SW BoB off south TN coast on 29th, LPA over Lakshadweep on 30th. Another fresh LPA over south Andaman Sea on 30th. NEPS indicated LPA over SE BoB on 25th becoming less marked on 26th. Fresh Ext. LPA over SE BoB on 27th. Moved WNWwards and lay as CS over SW BoB on 28th. Moved westwards & lay as DD over north TN coast on 29th and LPA over north Kerala on 30th.

	JMA indicated an Ex. LPA over SW AS on 28th becoming less marked thereafter.
25/12	IMD GFS indicated LPA over SW BoB on 25th. Moved westwards & lay as LPA over SW BoB on 26th. Moved nearly westwards & lay as LPA over Comorin on 27th. Lay as WML over SW BoB off SW Sri Lanka coast on 28th. Moved NNWwards & lay as LPA over Comorin on 29th. Another fresh LPA over SE BoB on 29th. Two LPAs over SE BoB on 30th. ECMWF indicated LPA over SW BoB on 25th. On 26th, it moved westwards lay over Comorin & fresh LPA over SW BoB off NE Sri Lanka coast. On 27th, both became insignificant. On 28th, LPA over SW BoB which persisted till 30th/12Z. On 29th, Ex.LPA over SE AS. Moved WNWwards & lay over SE As on 30th. NCUM indicated an Ex.LPA over Lakshadweep & LPA over SW BoB off SW Sri Lanka coast on 25th. On 26th, LPA over Comorin. No system on 27th. On 28th, LPA over Lakshadweep & SE AS. On 29th, LPA over SE BoB & SW BoB. D over SE BoB, LPA over Comorin & another LPA over equatorial Indian Ocean adj Maldives on 30th. NEPS indicated no system. JMA indicated Ex.Low over SW AS on 27th.
26/00	IMD GFS indicated an LPA over Maldives & Ex. LPA over South Sri Lanka on 27th. LPA over Comorin & fresh LPA over SE BoB on 28th. Ex. LPA over Maldives and another over south Andaman Sea on 29th. Ext. LPA over SE AS & WML over north Andaman Sea on 30th. Ext. LPA over SE As & DD over south Andaman Sea o 1st. ECMWF indicated LPA over Comorin on 26th, moved WSWwards lay over Maldives on 27th & 28th, insignificant on 29th & 30th and moved westwards lay as Ext. LPA over SE AS on 1st . It also indicated fresh LPA over SW BoB on 27th, persisted over same area on 28th, insignificant on 29th & 30th and again persisted over same area on 1st. NCUM indicated an LPA over SW BoB off SE Sri Lanka coast & another off south Sri Lanka on 26th. Ex. LPA over Maldives on 27th, insignificant on 28th. Fresh LPA over south Andaman Sea on 28th, insignificant on 29th, LPA over SW BoB on 30th & 1st. On 1st a fresh LPA over SE AS. NEPS indicated LPA over SW BoB and another over SW AS on 26th. Insignificant on 27th & 28th. Fresh Ex. LPA over SE AS on 29th, moved northwards lay as Ex. LPA over SE AS on 30th, moved westwards las as Ex. LPA over SE AS on 1st. It also indicated fresh LPA over SW BoB on 29th, insignificant on 30th. Fresh LPA over SE BoB on 1st. JMA indicated Ex. LPA over SW AS on 26th. No significant system thereafter.
26/12	IMD GFS indicated LPA over Lakshadweep on 26th becoming insignificant on 27th. Fresh LPA over SE BoB on 27th. Fresh LPA over south Andaman Sea on 28th. On 29th, LPA over south Andaman Sea and Fresh LPA over SW BoB off Sri Lanka coast. On 30th, Ext LPA over Comorin and LPA over SE BoB. On 1st, LPA over SE AS and CS over south Andaman Sea. ECMWF indicated LPA over South Sri Lanka on 26th becoming D on 27th and LPA on 28th over same area. On 29th, moved WNWwards & lay as Ext Low over Maldives. It moved NNWwards & lay as LPA over Maldives and fresh LPA over Sri Lanka on 30th. On 1st, two D/DD seen over SE AS and SE BoB. NEPS indicated no cyclogenesis during 26 Nov – 1 Dec. JMA indicated LPA over Comorin on 27th becoming insignificant on 28th and again developing as LPA on 29th.
27/00	IMD GFS indicated feeble LPA over Maldives on 27th. Fresh Ext LPA over SW BoB and LPA over Gulf of Thailand on 28th. On 29th, LPA over SW BoB. On 30th, LPA over SW BoB and fresh D over Gulf of Thailand. On 1st, D/DD over south Andaman Sea & fresh LPA over SE BoB. On 2nd, DD over SE BoB. ECMWF indicated LPA over Comorin on 29th moved WNWwards lay as D over Lakshdweep on 30th, moved westwards lay as CS over SE AS on 1st and 2nd. It also indicated fresh LPA over Sri Lanka on 30th becoming insignificant thereafter. It also showed fresh D over southeast BoB on 1st moving WNWwards and lay as DD over SE BoB on 2nd.

	NCUM indicated LPA over north Andaman Sea on 27th becoming insignificant on 28th, 29th. LPA over Comorin on 28th becoming insignificant on 29th. Fresh LPA over SW BoB off SE SriLanka and another off SW Sri Lanka on 30th. On 1st Ext LPA over Comorin and fresh LPA over south Andaman Sea. On 2nd, LPA over Comorin and LPA over SE BoB NEPS indicated a D over EC AS and DD over SW BoB on 27th. Both becoming insignificant till 2nd. On 2nd, fresh Ext LPA over south Andaman Sea. JMA indicated LPA over Comorin on 28th & 29th becoming WML on 30th and insignificant thereafter.
27/12	IMD GFS indicated Ext LPA over SW BoB on 27th becoming WML over same area on 28th. On 29th WML over SE BoB, lay as D over SE BoB on 30th, DD over SE BoB on 1st . Ext LPA over Thailand on 29th becoming D over south Andaman Sea on 30th & 1st. On 2nd both merged and lay as D over SE BoB. ECMWF indicated LPA over Sri Lanka on 28th , moved WSWwards lay as LPA over Comorin on 29th, moved NNWwards lay as D over Lakshadweep on 30th, moved WNWwards lay as CS over southeast AS on 1st and 2nd. It also indicated LPA over SE BoB on 28th, insignificant on 29th. Fresh LPA over south Andaman Sea on 30th, moved WNWwards lay as D over SE BoB on 1st, moved westwards and lay as CS over SE BoB on 2nd. NCUM indicated LPA over SW BoB off south Sri Lanka on 27th, LPA over SW BoB off SE Sri Lanka on 28th, LPA over SW BoB off south Sri Lanka on 29th, fresh Ex LPA over Lakshadweep and LPA persisted over SW BoB on 30th. On 1st fresh D over south Andaman Sea becoming SCS over SE BoB on 2nd. NEPS indicated no cyclogenesis during 27th to 2nd. JMA indicated LPA overSW BoB on 27th, 28th and over Comorin on 29th and 30th.
28/00	IMD GFS indicated LPA over Gulf of Thailand and adjoining Malay Peninsula on 29th, becoming D over south Andaman on 30th and DD over south Andaman Sea on 1st. Moved WNWwards lay as DD over SE BoB on 2nd , moved WNWwards and lay as D over SE BoB. It also indicated WML over SW BoB on 28th. Moved westwards lay as WML over south Sri Lanka on 29th, D over Comorin on 30th becoming WML over Comorin on 1st and low over same area during 2nd-3rd. ECMWF indicated Extended LPA over south Sri Lanka on 29th , moved WNWwards lay as DD over Comorin on 30th, moved NWwards lay as CS over southeast AS on 1st, moved WNWwards lay as SCS on 2nd and 3rd. It also indicated fresh DD over south Andaman Sea on 1st, moved westwards lay as CS over SE BoB on 2nd, moved WNWwards and lay as SCS over SE BoB on 3rd. NCUM indicated Ex. LPA over SW BoB on 28th becoming insignificant on 29th & 30th. Fresh Ex Low over SE AS on 1st , becoming insignificant on 2nd and again as Ex. Low on 3rd. It also indicated fresh LPA over south Andaman Sea on 30th, moved northwards lay as D over north Andaman Sea on 1st, moved westwards lay as D over SE BoB on 2nd, moved westwards lay as D over SE BoB on 3rd.
28/12	IMD GFS indicated LPA over Gulf of Sumatra on 28th, moved WNWwards lay over south Andaman Sea as Ex LPA on 29th, moved NNWwards lay over SE BoB as D on 30th, moved ENEwards lay as DD over SE BoB on 1st, moved WNWwards lay as DD over SE BoB on 2nd, moved WNWwards lay as DD over SW BoB on 3rd. It also indicated another LPA over SW BoB off Sri Lanka on 28th, moved WNWwards lay as D over Comorin on 29th, DD on 30th & weakening from 1st onwards, moved WNWwards lay as D over Lakshadweep on 2nd and D over SE AS on 3rd. ECMWF indicated Low over Comorin on 28th, moved WNWwards lay as DD over Comorin on 29th, moved WNWwards lay as SCS over SE AS on 1st, moved WNWwards lay as SCS over SE AS on 2nd, moved WNWwards lay as CS over EC AS on 3rd. It also indicated D over Andaman Sea on 30th, moved westwards lay as DD over southeast BoB on 1st, moved WNWwards lay as CS over SE BoB on 2nd and moved WNWwards lay as SCS over SE BoB on 3rd.

	NCUM indicated LPA over Lakshadweep on 28th becoming insignificant thereafter. It also indicated an Ex LPA over SW BoB off SW Sri Lanka on 28th, moved WNWwards lay as LPA over SW BoB off south Sri Lanka on 29th, moved WNWwards lay as LPA over Comorin on 30th, moved WNWwards lay as Es. LPA over Lakshadweep on 1st, insignificant on 2nd, fresh LPA over SE AS on 3rd. NEPS indicated no cyclogenesis during 28-3rd. JMA indicated WML over SW BoB off SE Sri Lanka on 28th, moved WNWwards lay as WML over Comorin on 29th & 30th, moved WNWwards lay as D over Lakshadweep on 1st becoming insignificant thereafter.
29/00	IMD GFS indicated WML over SW BoB off south Sri Lanka on 29th, moved westwards lay as DD over Comorin on 30th, moved NWwards lay as D over Comorin on 1st, moved WNWwards lay as D over Lakshadweep on 2nd, moved NNWwards lay as D over Lakshadweep on 3rd, moved WNwwards lay as D over SE AS on 4th. It also indicated D over south Andaman Sea on 1st, moved WNWwards lay as DD over SE BoB on 2nd, moved WNWwards lay as CS over SE BoB on 3rd , moved WNwwards lay as CS over SE BoB on 4th. ECMWF indicated LPA over SW BoB and another over south Sri Lanka on 29th, merged and moved westwards and lay as CS over Comorin on 30th, moved WNWwards lay as SCS on 1st and 2nd, moved WNWwards lay as CS over SE AS on 3rd, moved Nwwards lay as CS over EC AS on 4th. It also indicated D over south Andaman Sea on 1st, CS over southeast BoB on 2nd, 3rd and 4th.. NCUM indicated LPA over SW BoB south of Sri Lanka on 29th, moved WNWwards lay as D over Comorin on 30th, moved WNWwards lay as D over Maldives on 1st, moved WNwwards lay as SCS over SE AS on 2nd, moved WNWwards lay as SCS over EC AS on 3rd , moved northwards lay as SCS over EC AS on 4th. It also indicated LPA over north Andaman Sea on 30th, fresh LPA over south Andaman Sea on 1st, moved westwards lay as D over south Andaman Sea on 2nd, moved WNWwards lay as DD over SE BoB on 3rd , moved WNWwards lay as CS over SE BoB on 4th. NEPS indicated D over Comorin on 30th, moved westwards lay as D over Maldives on 1st, moved NWwards lay as CS over SE AS on 2nd, moved NNWwards lay as SCS over EC AS on 3rd , moved westwards lay as SCS over EC AS on 4th. JMA indicated D over SW BoB off SW Sri Lanka coast on 29th, moved WNWwards lay as D over Comorin on 30th, moved WNWwards lay as CS over Lakshadweep off north Kerala coast on 1st, moved WNWwards lay as DD over Lakshadweep on 2nd, becoming insignificant thereafter.
29/12	IMD GFS indicated D over SW BoB & adjoining Comorin on 29th, moved westwards lay as DD over Comorin on 30th, moved WNWwards lay as D over Maldives on 1st, moved WNWwards lay as DD over SE AS on 2nd, moved NNWwards lay as CS over EC AS on 3rd, moved NNEwards lay as DD over EC AS on 4th.(Recurvature) It also indicated D over south Andaman Sea on 1st, moved NWwards layas D over SE BoB on 2nd, moved WNWwards lay as D over SE BoB on 3rd, moved WNWWards lay as D over SE BoB on 4th. ECMWF indicated D over Comorin on 29th, moved WNWwards lay CS over southeast AS near south Kerala coast on 30th, moved WNWwards lay as SCS over southeast AS on 1st, moved WNWwards lay as SCS over SE AS on 2nd, moved WNWwards lay as SCS over EC AS on 3rd, moved WNWwards lay as DD over EC AS on 4th. It also indicated another D over southeast BoB on 2nd and 3rd. NCUM indicated D over SW BoB off south Sri Lanka on 29th, moved NWwards lay as DD over Comorin on 30th, moved WNWwards lay as D over Lakshadweep on 1st, moved NWwards lay as DD over Lakshdweep on 2nd, moved WSWwards lay as DD over SE AS on 3rd, moved westwards lay as SCS over EC AS on 4th. It also indicated LPA over Malay Peninsula on 1st, persisting over same area on 2nd, moved WNWwards lay as D over south Andaman Sea on 3rd, moved westwards lay as D over south Andaman Sea & adjoining SE BoB on 4th. NEPS indicated no cyclogenesis during 29-4th.

	JMA indicated DD over SW BoB off south Sri Lanka on 29th, moved WNWwards lay as DD over Comorin off south Kerala coast on 30th, moved WNWwards lay as CS over Lakshadweep on 1st, moved WNWwards lay as CS over EC AS on 2nd.
30/00	IMD GFS indicated LPA/WML over Comorin on 30th, moved WNWwards lay as DD over Lakshadweep off south Kerala coast on 1st, moved WNWwards lay as D over Lakshadeep on 2nd, moved WNWwards lay as DD over EC AS on 3rd& 4th over EC AS, moved westwards lay as D over EC AS on 5th. ECMWF indicated a cyclonic storm over Comorin Area on 30th, which moving west-northwestwards intensify into a severe cyclonic storm on 01st December over Lakshadweep area and adjoining SE Arabian Sea. It then moved northeastwards and weakens further into a depression on 5th and weakened into well marked low on 6th and less marked by 07th over EC Arabian Sea. It also indicated low over south Andaman Sea and adjoining Malay Peninsula on 30th Nov. which moving westward becomes a depression on 05th December SE Bay. Further moving north-westwards, it becomes depression on 07th over SW Bay. It lies off south coastal Andhra Pradesh at 0000 UTC on 08th December as a deep depression/ CS and crosses south Andhra Pradesh coast (near about lat. 160 N) around 0000 UTC of 8th Dec. and weakens gradually thereafter. NCUM indicated DD over SW BoB south of Sri Lanka on 29th, moved WNWwards lay as SCS over Comorin off south Kerala coast on 30th, moved WNWwards lay as SCS over Lakshadweep on 1st, moved WSWwards lay as SCS over SE AS on 2nd, moved NNWwards lay as SCS over EC AS on 3rd, moved NNWwards lay as SCS over EC AS on 4th, moved NEwards lay as SCS over NE AS on 5th. NEPS indicated LPA over WC BoB on 30th & SCS over Thailand on 30th. Fresh CS over Comorin on 1st, moved WNWwards lay as CS over Lakshadweep on 2nd, moved NNWwards lay as CS over EC AS on 3rd, moved northwards lay as SCS over EC AS on 4th, moved NNWwards lay as CS over EC AS on 5th.
30/12	IMD GFS indicated D over Comorin on 30th, moved WNWwards lay as CS over Lakshadweep on 1st, moved WNWwards lay as CS over SE AS on 2nd, moved NWwards lay as CS over EC AS on 3rd, moved NNWwards lay as CS over EC AS on 4th, moved ENEwards lay as D over EC AS on 5th (Recurvature). It also indicated LPA over Malay Peninsula on 30th, moved WNWwards lay as LPA over south Andaman Sea on 1st, moved WNWwards lay as LPA over SE BoB on 2nd & 3rd, moved WNWwards lay as D over SW BoB on 4th, moved NWwards lay as D over SW BoB on 5th. NCUM indicated SCS over Comorin off south Kerala coast on 30th, moved WNWwards lay as SCS over north Kerala coast on 1st, moved WNWwards lay as SCS over SE AS on 2nd, moved NWwards lay as SCS over EC AS on 3rd, moved NEwards lay as SCS over EC AS (recurvature) on 4th, moved NNEwards lay as D over south Gujarat on 5th. It also indicated LPA over Malay Peninsula on 30th, moved westwards lay as LPA over south Andaman Sea on 1st, moved WNWwards lay as LPA over south Andaman Sea on 2nd, moved SWwards lay as LPA over SE BoB on 3rd, moved NNWwards lay as LPA over SE BoB on 4th, moved NNWwards lay as DD over SE BoB on 5th.

Hence to conclude there were limitations in NWP model guidance in prediction of genesis (formation of depression) and its intensification into CS over Comorin area. Most of the models including GFS, JMA, NCUM & NEPS indicated limitation in predicting genesis and intensification of OCKHI. There was over warning over BOB and AS even during formation of OCKHI over Comorin area. No system was predicted over Comorin. The ECMWF products analyses indicated limitation in predicting genesis and intensification of OCKHI before 29th. Among all the models, ECMWF was better, but it could also indicate intensification based on 0000 UTC of 29th only.

3.4.2 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for Ockhi

The predicted zone of cyclogenesis for VSCS Ockhi based on 0000 UTC initial conditions during 27th to 30th November is presented in Fig. 3.13. The analysis based on 0000 UTC of 27th indicated a potential zone for cyclogenesis over southwest BoB off Sri Lanka coast and another over Comorin Area. The zone over south Comorin moved westwards and the zone near Sri Lanka hovered near south Sri Lanka during next 5 days. The zone to the east of Sri Lanka become extended on 28th, reduced intensity on 29th and again elongated on 30th ,1st & 2nd while moving southwestwards.

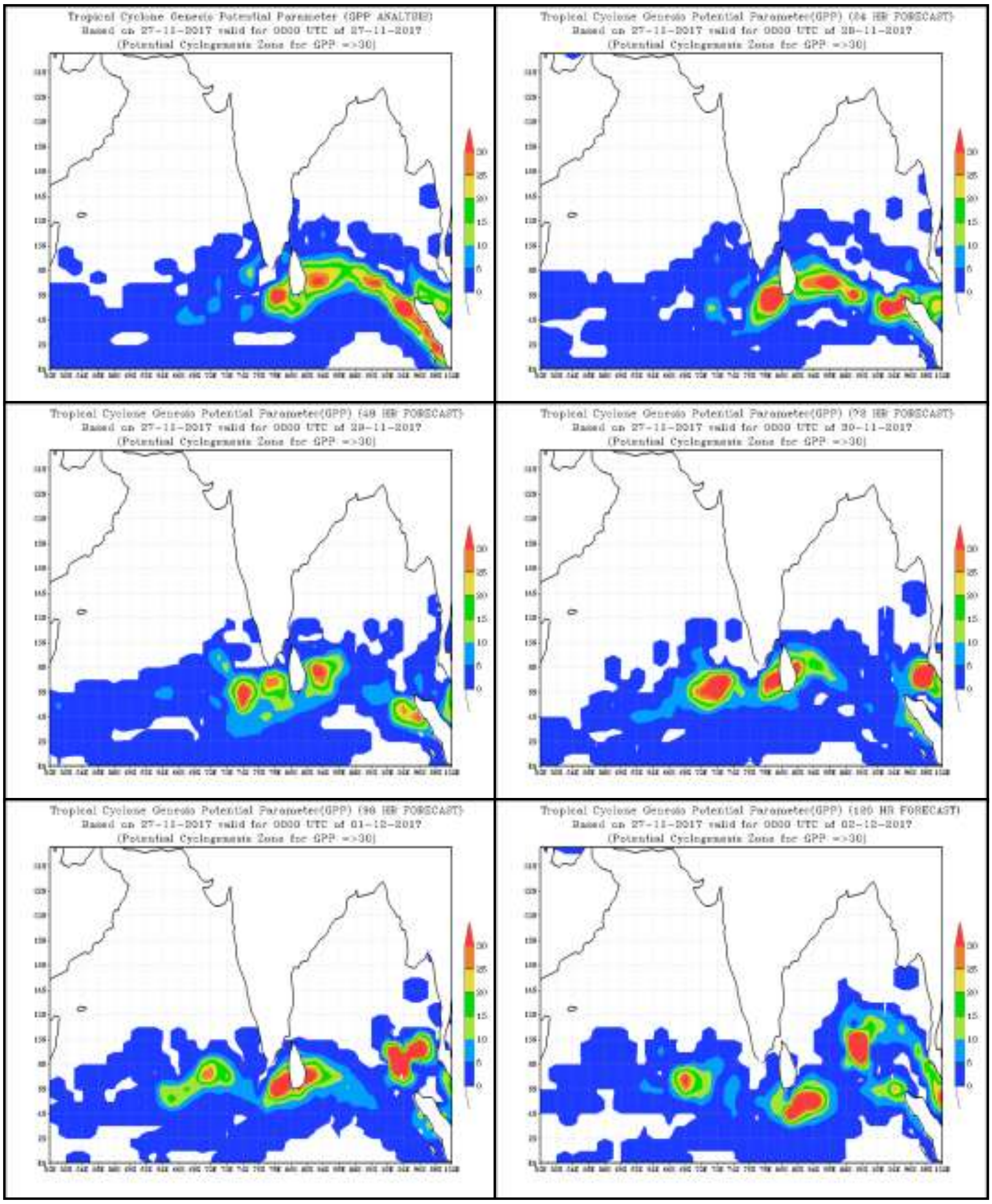


Fig. 3.13 (a): GPP analysis and forecast based on 0000 UTC of 27th November.

GPP analysis and forecast based on 1200 UTC of 27th November indicated two potential zones of cyclogenesis one each over southwest BoB and the other over Comorin area on 27th. The zone over Comorin became insignificant on 28th, appeared again on 29th & 30th and becoming insignificant thereafter. The other over southwest BoB off southeast Sri Lanka persisted till 2nd December. It also indicated potential zone of cyclogenesis over Andaman Sea on 30th with westwards movement till 2nd over southeast BoB. On 2nd, it indicated more potential of cyclogenesis over southeast BoB rather than southwest BoB or Arabian Sea.

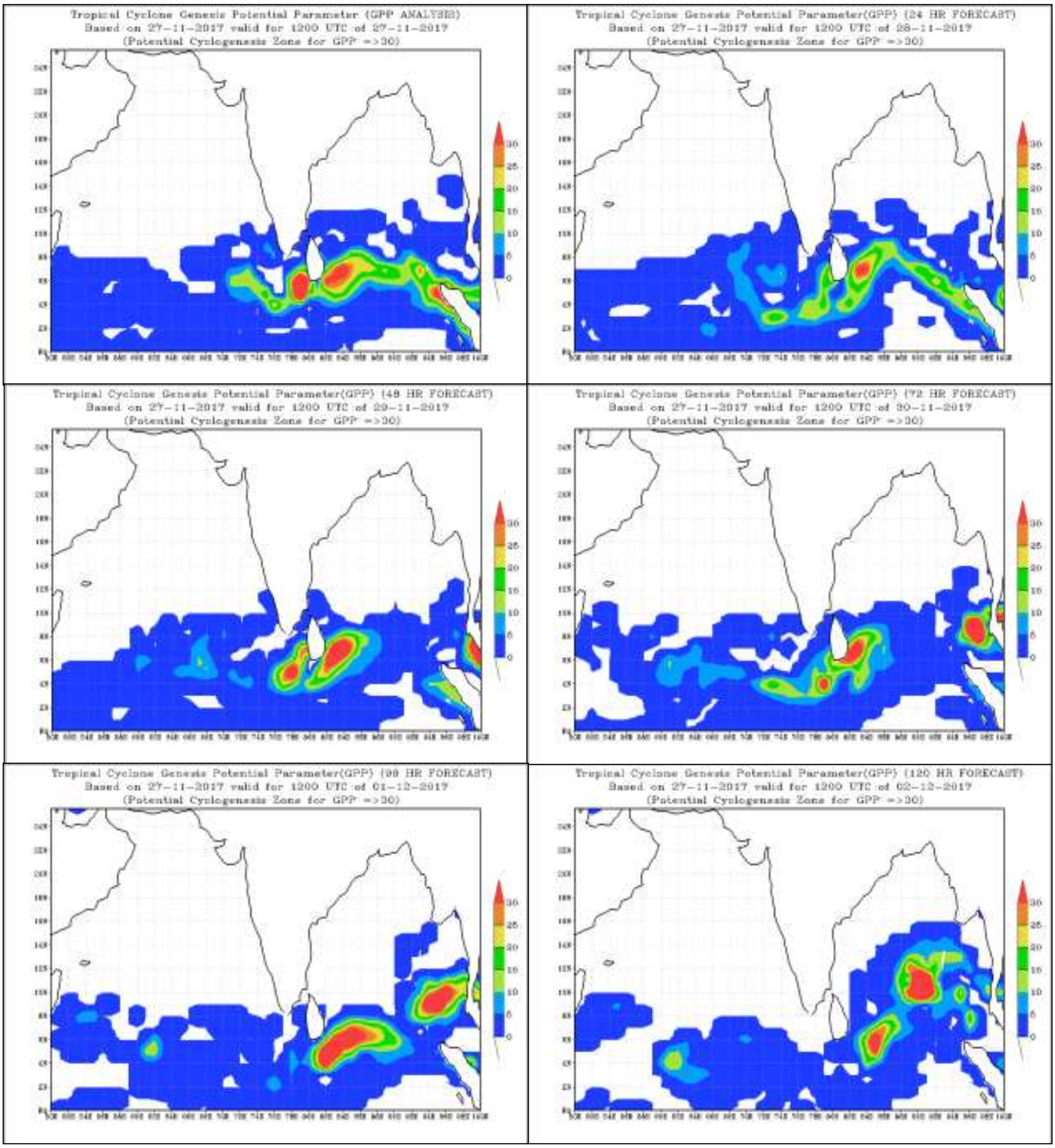


Fig. 3.13 (b) : GPP analysis and forecast based on 1200 UTC of 27th November.

The analysis based on 0000 UTC of 28th indicated an elongated zone of cyclogenesis over southwest BoB off Sri Lanka coast moving westwards and signs of weakening from 1st onwards.

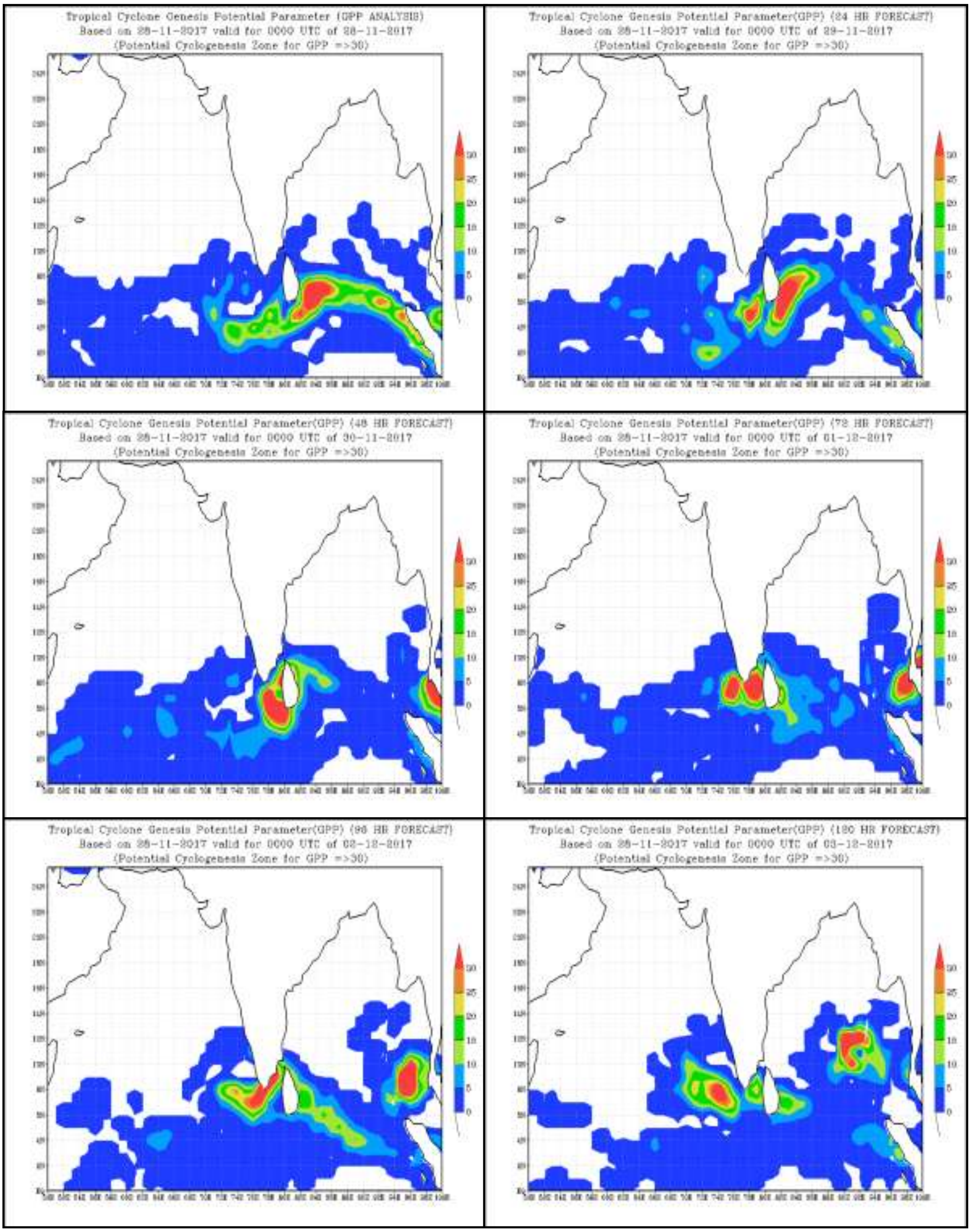


Fig. 3.13 (c): GPP analysis and forecast based on 0000 UTC of 28th November.

The GPP analysis and forecast fields based on 1200 UTC of 28th, indicated a potential zone for cyclogenesis over southwest BoB off southeast Sri Lanka and another off southwest Sri Lanka on 28th. On 29th the potential zone of cyclogenesis lay over Comorin area and thereafter it moved north-northwestwards across Lakshadweep Islands and southeast Arabian Sea. It also indicated a potential zone over Andaman Islands on 30th which moved west-northwestawards and lay over southeast and adjoining southwest Bay of Bengal on 2nd Dec., but with lesser intensity as compared to the zone over Arabian Sea.

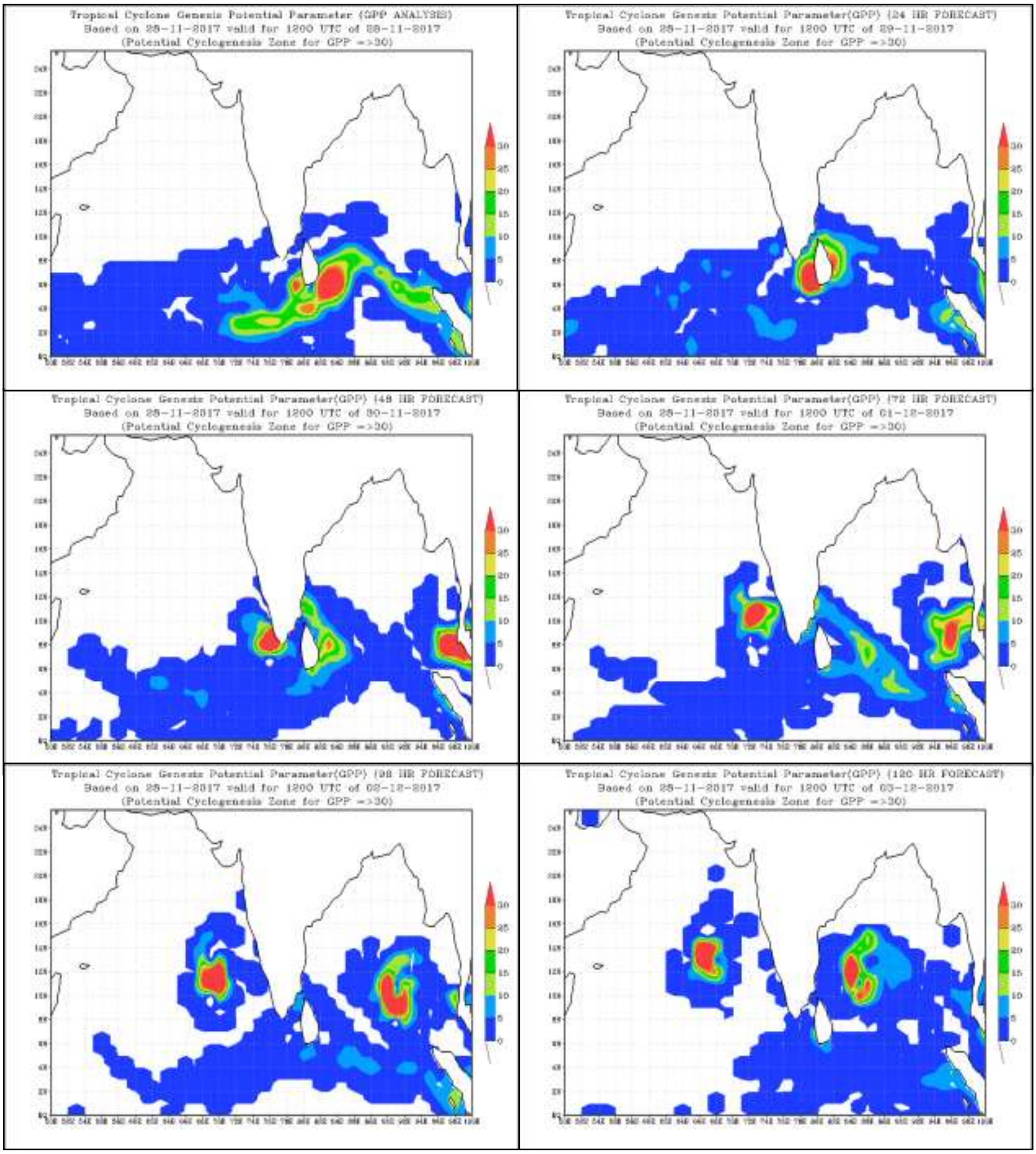


Fig. 3.13 (d): GPP analysis and forecast based on 1200 UTC of 28th November.

The analysis based on 0000 UTC of 29th indicated a potential zone of cyclogenesis over southwest BoB & Sri Lanka moving westwards till 30th and west-northwestwards thereafter reaching eastcentral Arabian Sea on 4th December. The cyclogenesis was predicted well but with reduced area gradually. At the same time it was showing another potential zone from south Andaman Sea.

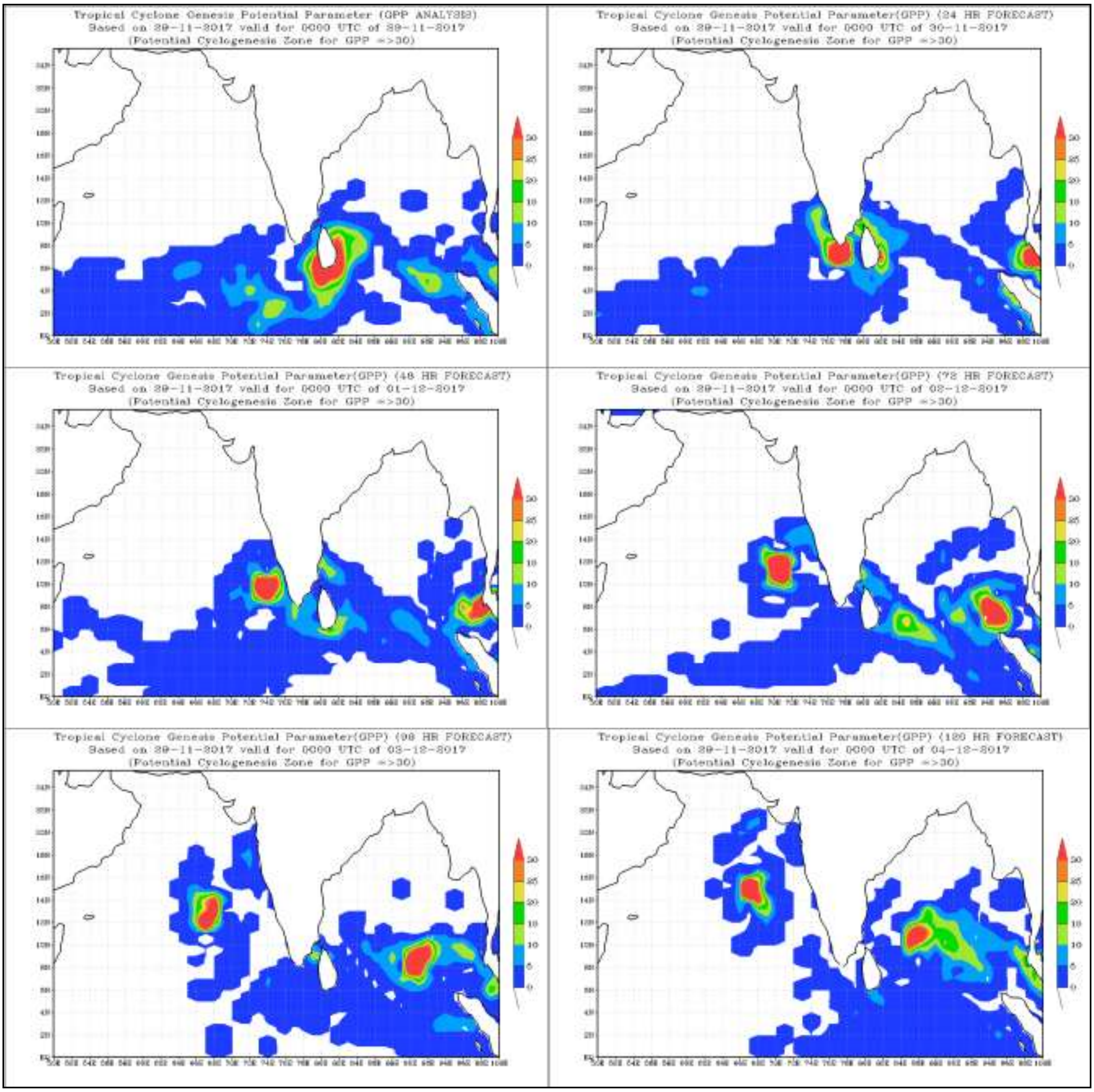


Fig. 3.13 (e): GPP analysis and forecast based on 0000 UTC of 29th November.

The analysis and forecast field based on 1200 UTC of 29th indicated a significant zone over Comorin on 29th which moved northwestwards and persisted over southeast Arabian Sea till 3rd Dec. becoming insignificant on 4th. It also indicated another potential zone for cyclogenesis over Andaman Sea on 30th moving west-northwestwards and reaching southwest BoB off south Andhra Pradesh coast on 4th.

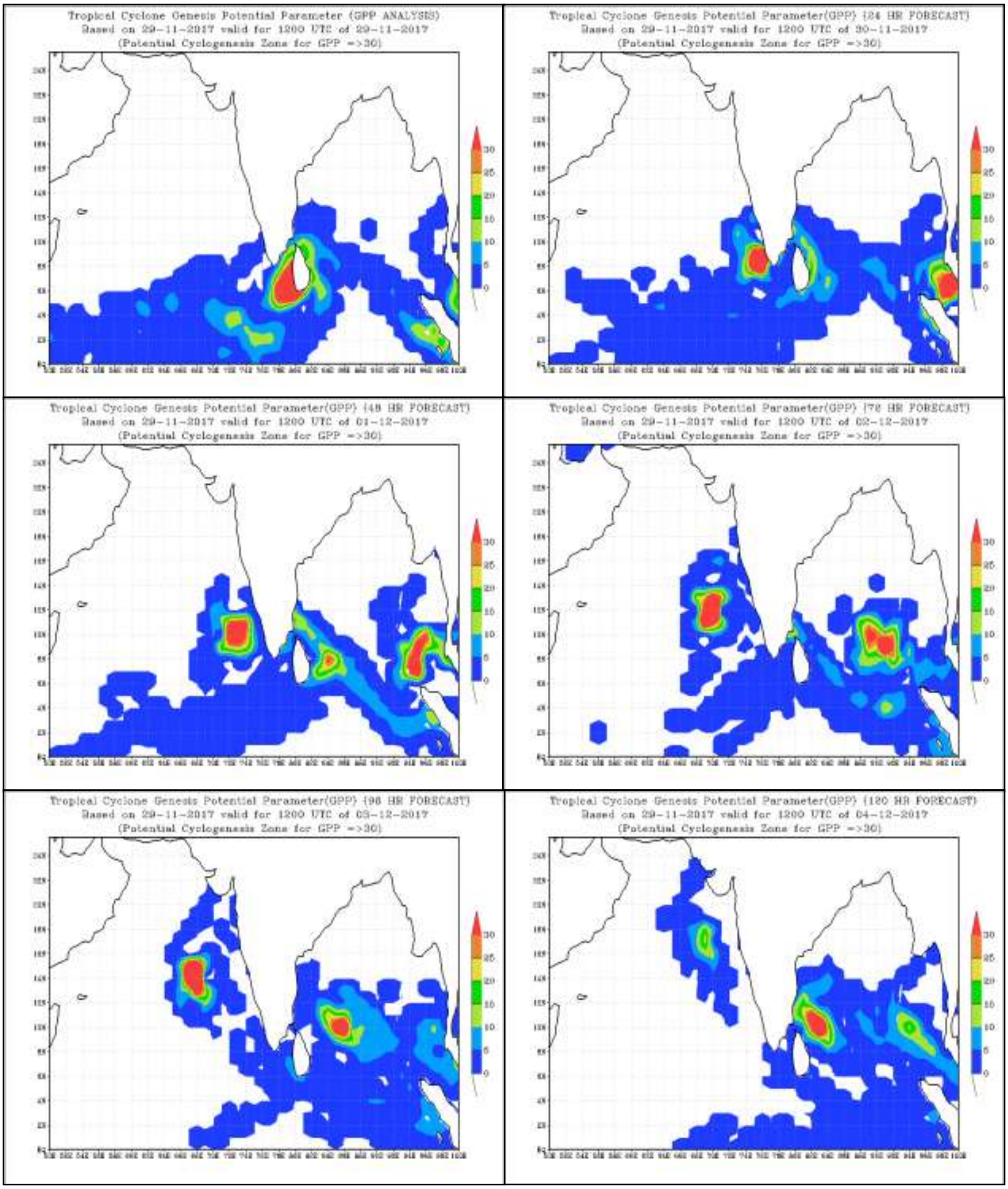


Fig. 3.13 (f) : GPP analysis and forecast based on 1200 UTC of 29th November.

The analysis based on 0000 UTC of 30th indicated a potential zone of cyclogenesis over Comorin Area on 30th moving west-northwestwards till 3rd December, north-northeastwards from 4th onwards and weakening over eastcentral AS on 5th December. At the same time, it was showing another zone moving westward from south Andaman Sea and reaching southwest Bay off north Tamilnadu based on 6th December.

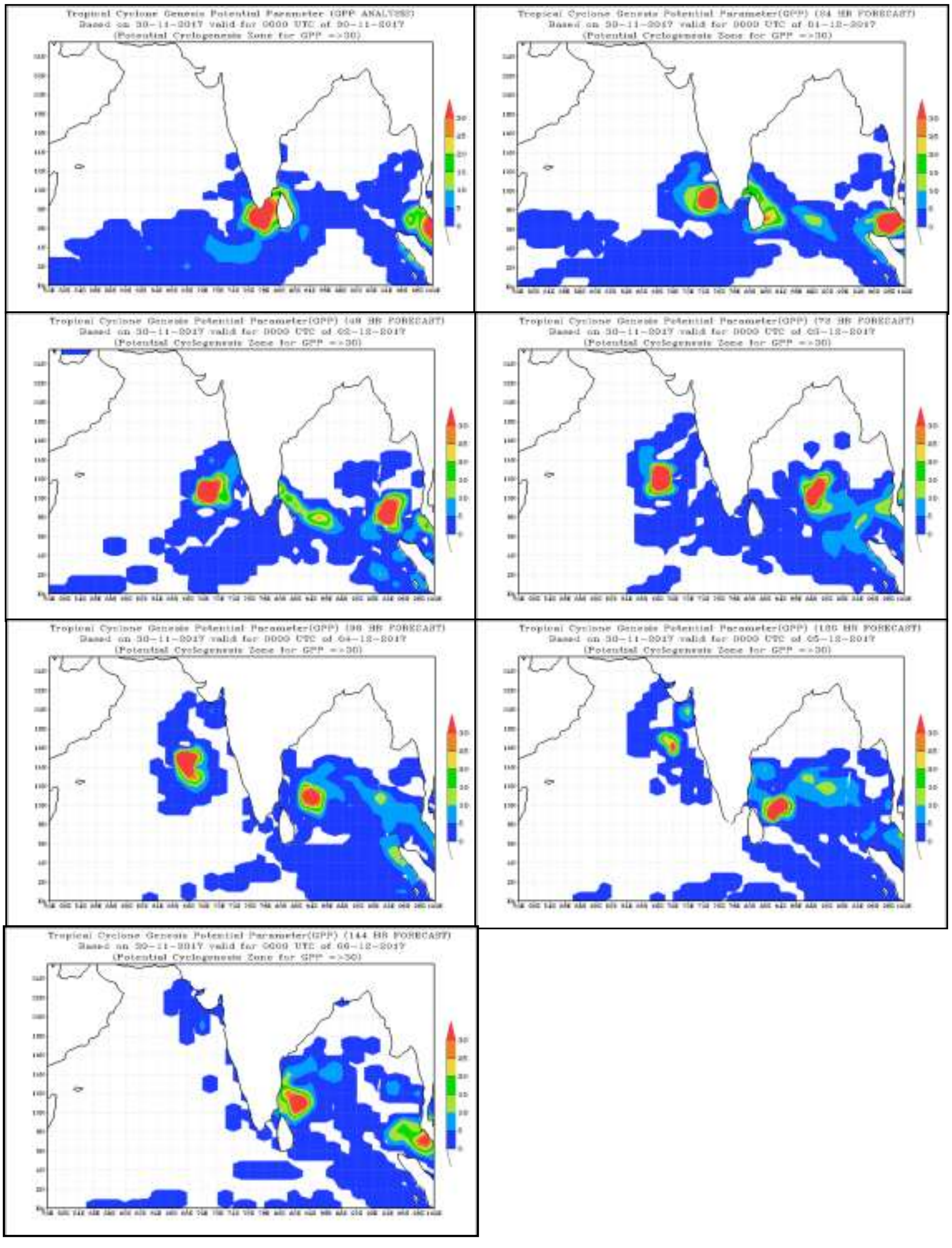


Fig. 3.13 (g): GPP analysis and forecast based on 0000 UTC of 30th November

Area Average GPP:

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for developed system is that average GPP ≥ 8.0 .Based on 0000 UTC analysis of 30th, the model predicted favourable GPP for next 96 hours (i.e. upto 4th December) and weakening thereafter during next 12 hours (by 1200 UTC of 4th December). The model underestimated the intensity of system beyond 96 hours. The system started weakening from 0000 UTC of 4th but maintained cyclonic storm (≥34 Kts) intensity till 0600 UTC of 5th.

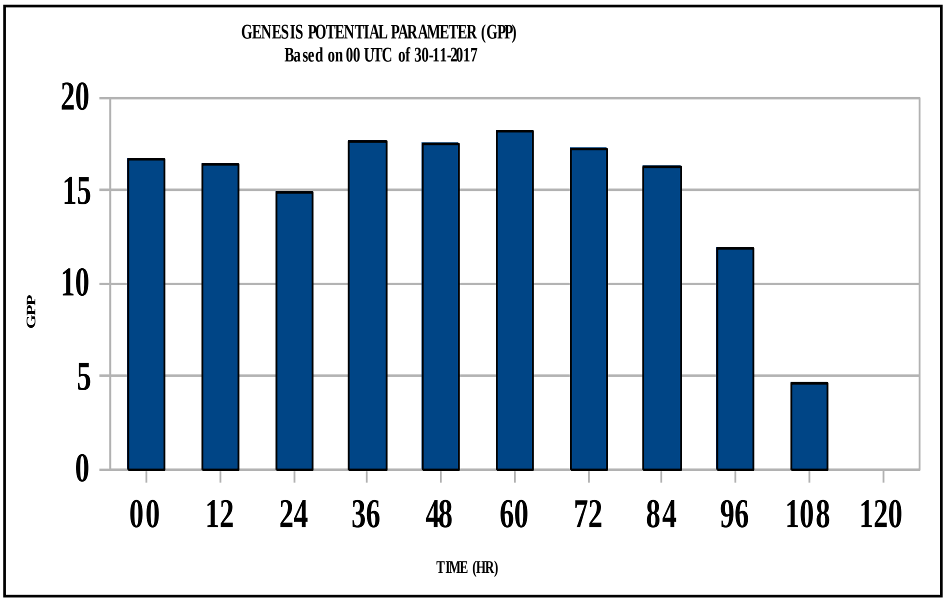


Fig. 3.14: Area average analysis and forecasts of GPP based on 0000 UTC of 30th November, 2017

However, the product based on 0000 UTC of 30th Nov. was made available by the time the system was already a cyclonic storm. According to NWP Division, the calculation of GPP is valid for open sea only and the GPP shows over estimation over land and land locked sea areas.

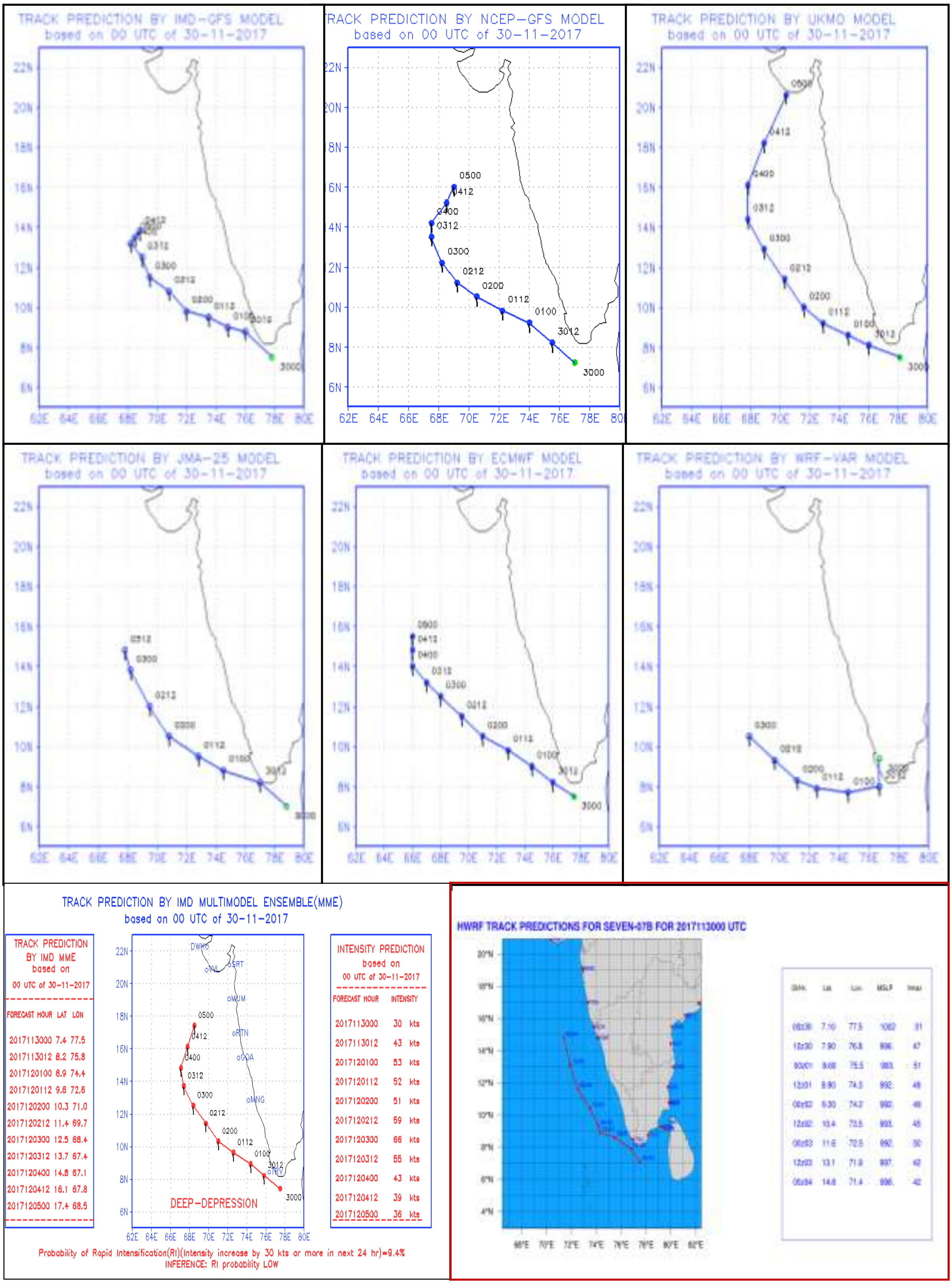
It has been observed that Ocean Heat Content (OHC) was one of the most important parameter for cyclogenesis and intensification/weakening. The currently used GPP however does not take into consideration the OHC and is based on other Gray parameters derived from IMD GFS model analysis and forecast. As the performance of GFS model was not satisfactory, the GPP derived from it could not meet the requirement.

3.4.3 Track prediction by NWP models

3.4.3.1. Track prediction by Deterministic models

Track prediction by various NWP models is presented in Fig. 3.15. Based on initial conditions of 0000 UTC of 30th November, all models were predicting west-northwestwards movement with weakening over eastcentral AS. The models were not unanimous about the time of weakening. The models and MME indicated northeastward recurvature also. Only UKMO indicated movement towards Gujarat.

Based on the initial conditions of 0000 UTC of 1st December, NCEP GFS indicated landfall near Dahanu, north Maharashtra in the afternoon of 5th December. All other models indicated weakening of system over eastcentral AS around 1200 UTC of 5th with JMA indicating weakening of system at 1200 UTC of 4th, HWRF at 0000 UTC of 5th and WRF VAR at 0000 UTC of 4th. All models except WRF-VAR and HWRF indicated movement towards south Gujarat-north Maharashtra coast



TRACK PREDICTION BY IMD MME based on 00 UTC of 30-11-2017		
FORECAST HOUR	LAT	LON
2017113000	7.4	77.5
2017113012	8.2	75.8
2017120100	8.9	74.4
2017120112	9.6	72.6
2017120200	10.3	71.0
2017120212	11.4	69.7
2017120300	12.5	68.4
2017120312	13.7	67.4
2017120400	14.8	67.1
2017120412	16.1	67.8
2017120500	17.4	68.5

INTENSITY PREDICTION based on 00 UTC of 30-11-2017	
FORECAST HOUR	INTENSITY
2017113000	30 kts
2017113012	43 kts
2017120100	53 kts
2017120112	52 kts
2017120200	51 kts
2017120212	59 kts
2017120300	66 kts
2017120312	55 kts
2017120400	43 kts
2017120412	39 kts
2017120500	36 kts

Fig. 3.15 (a): NWP model track forecast based on 0000 UTC of 30th November

.

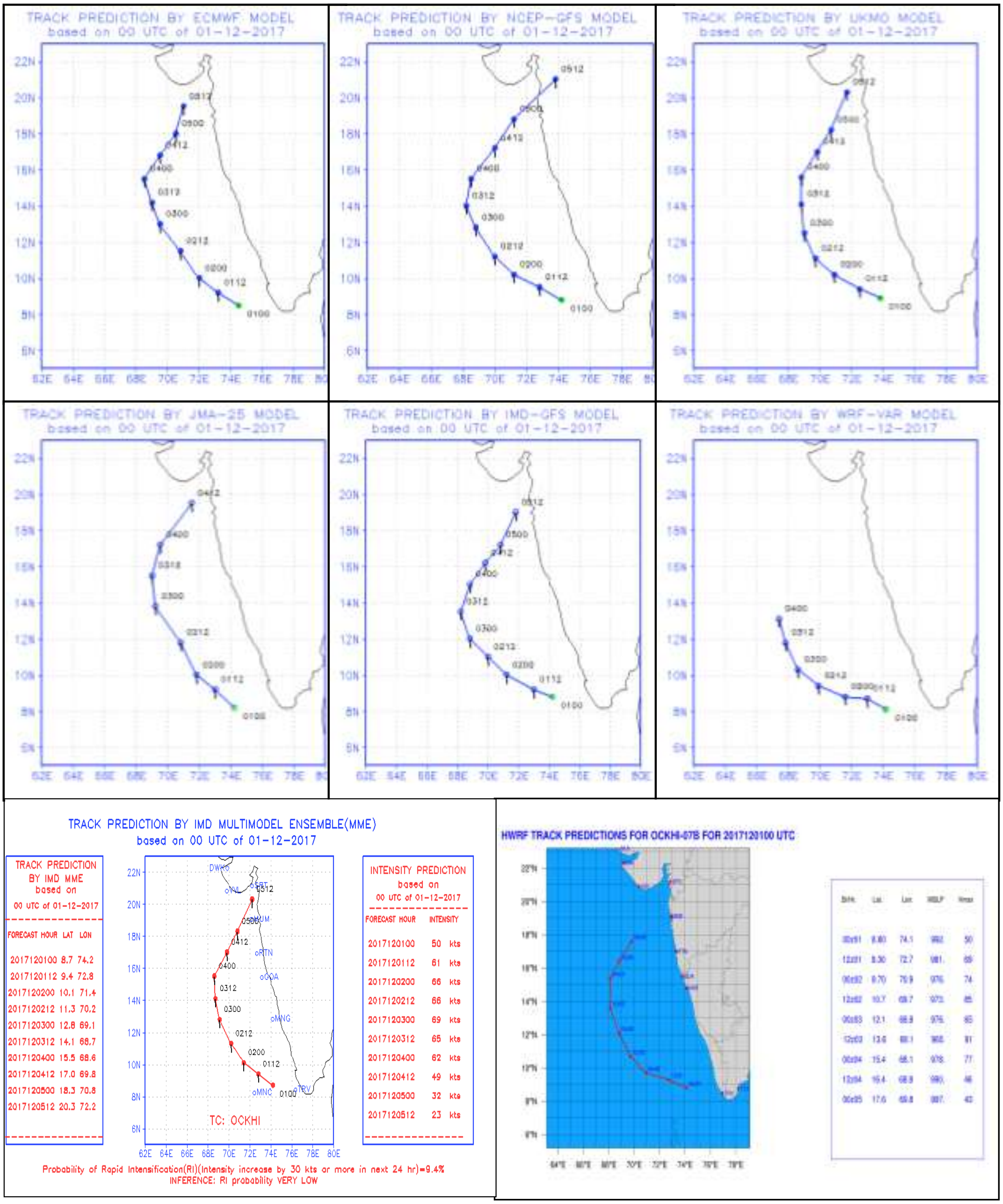


Fig. 3.15 (b): NWP model track forecast based on 0000 UTC of 1st December

Based on the initial conditions of 0000 UTC of 2nd December, NCEP GFS, ECMWF and MME indicated weakening of system over eastcentral BoB. All other models including UKMO, JMA, IMD GFS indicated landfall of system between Mumbai and Dahanu over north Maharashtra between 0800 to 1200 UTC of 5th. HWRF however indicated landfall near Surat around 0300 UTC of 5th December.

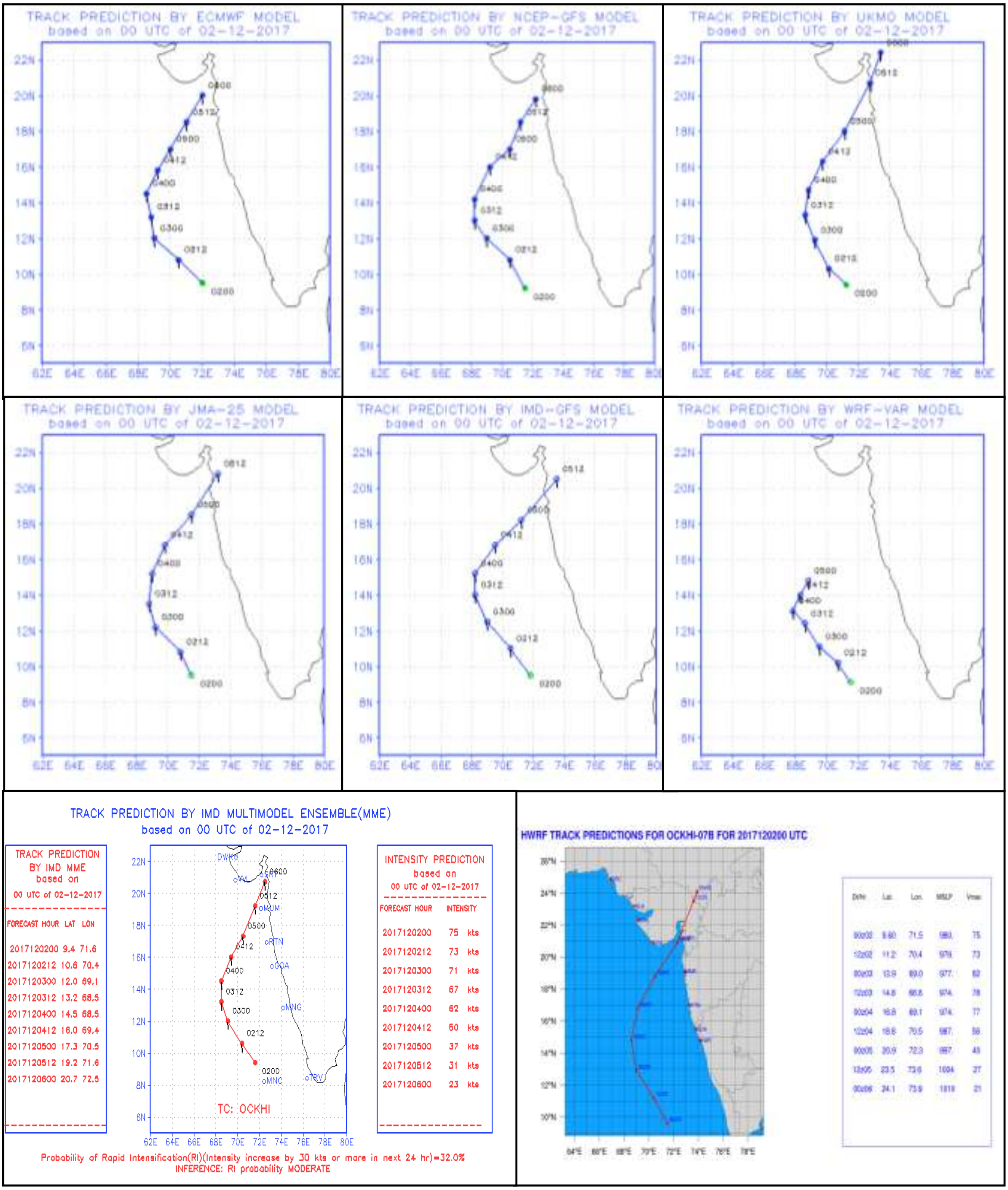


Fig. 3.15 (c): NWP model track forecast based on 0000 UTC of 2nd December

Based on the initial conditions of 0000 UTC of 3rd December, all models except WRF-VAR and IMD GFS indicated landfall between Surat and Dahanu around night of 5th December.

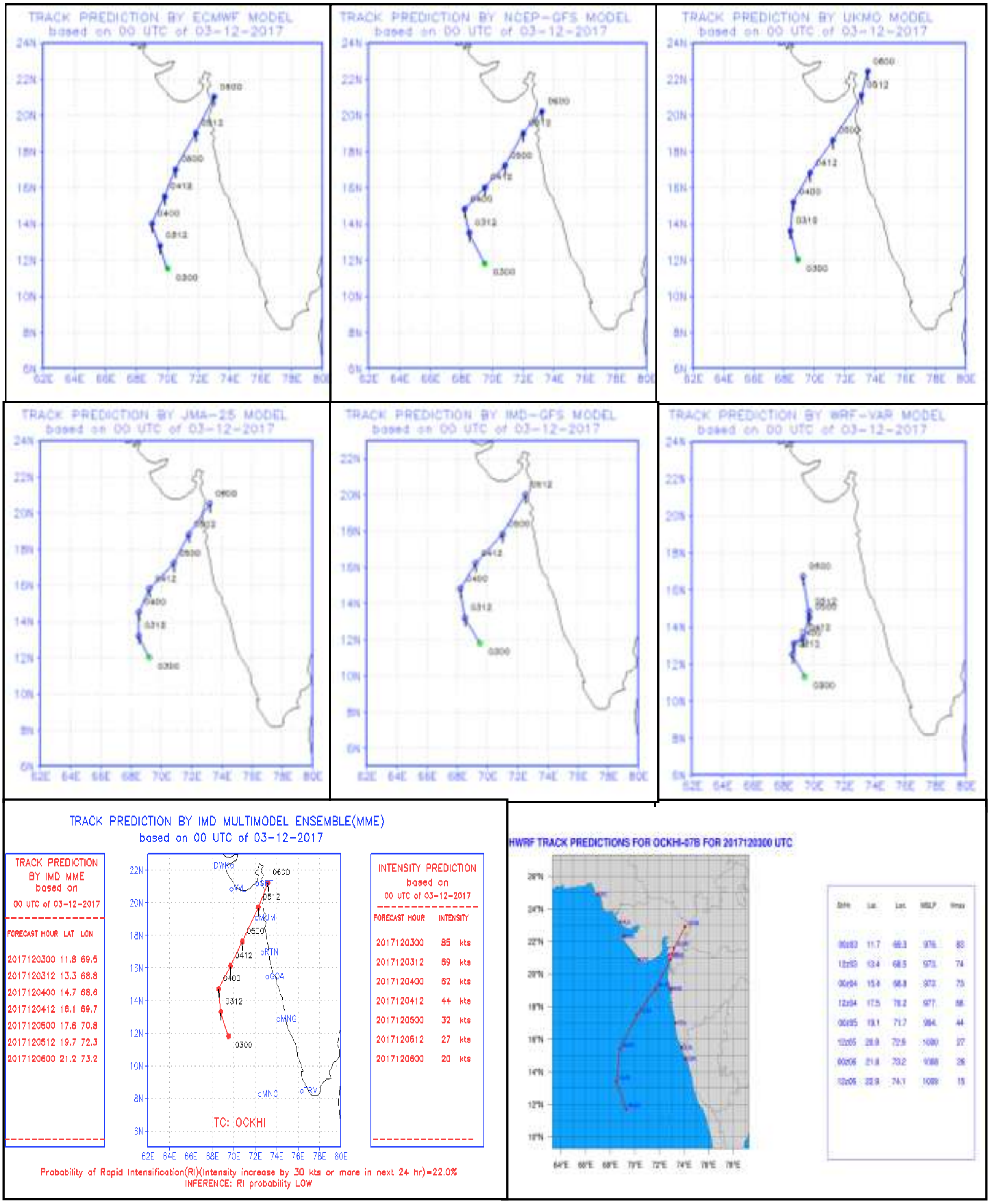


Fig. 3.15 (d): NWP model track forecast based on 0000 UTC of 3rd December

Based on the initial conditions of 0000 UTC of 4th December, all models except WRF-VAR and HWRF indicated landfall between Surat and Dahanu around night of 5th December. HWRF indicated landfall near to east of Veeraval.

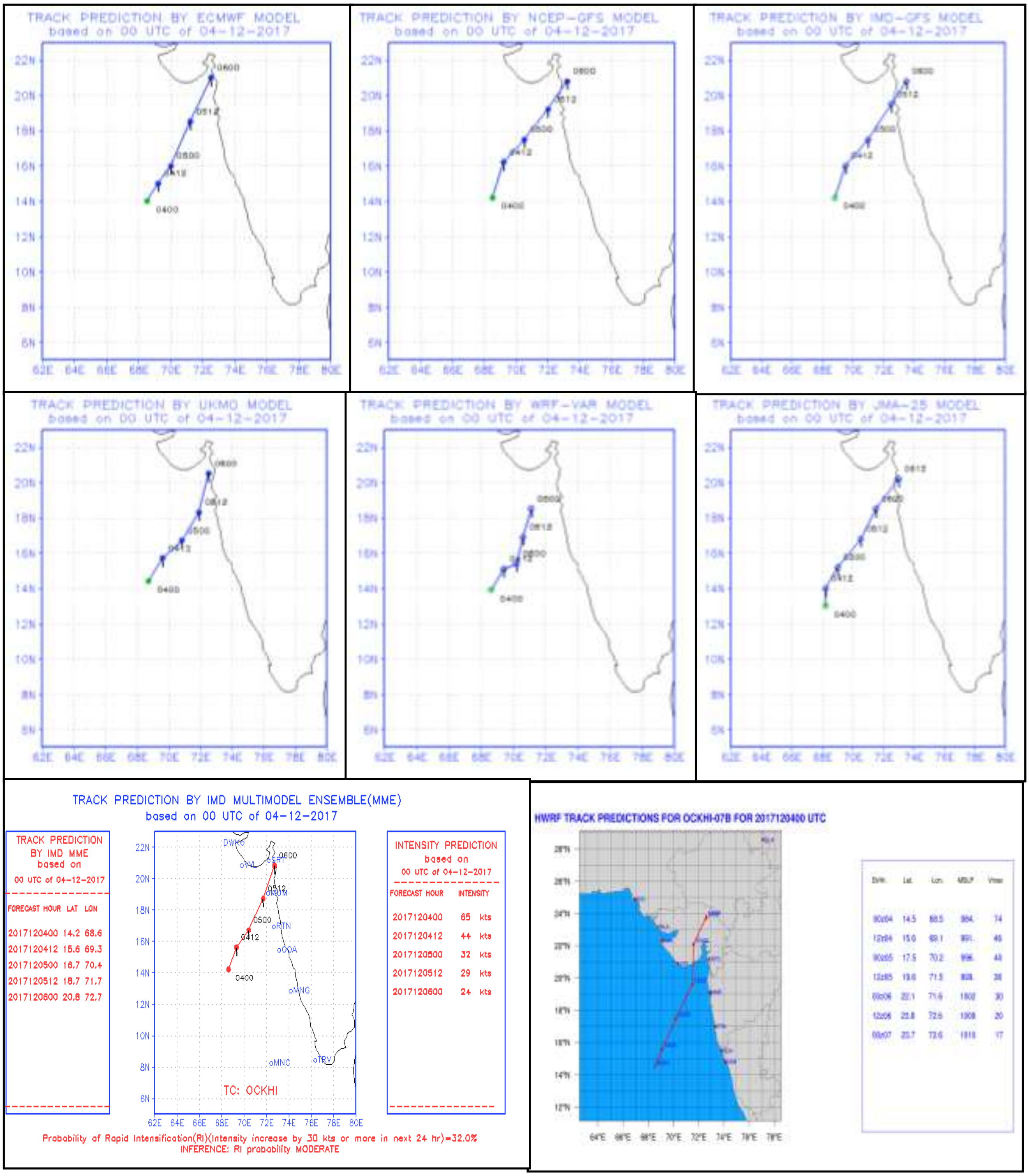


Fig. 3.15 (e): NWP model track forecast based on 0000 UTC of 3rd December

Based on the initial conditions of 0000 UTC of 5th December, all models except HWRF indicated weakening over eastcentral AS close to south Gujarat and north Maharashtra coast between Surat and Dahanu. HWRF indicated landfall over Gujarat to the east of Veeraval.

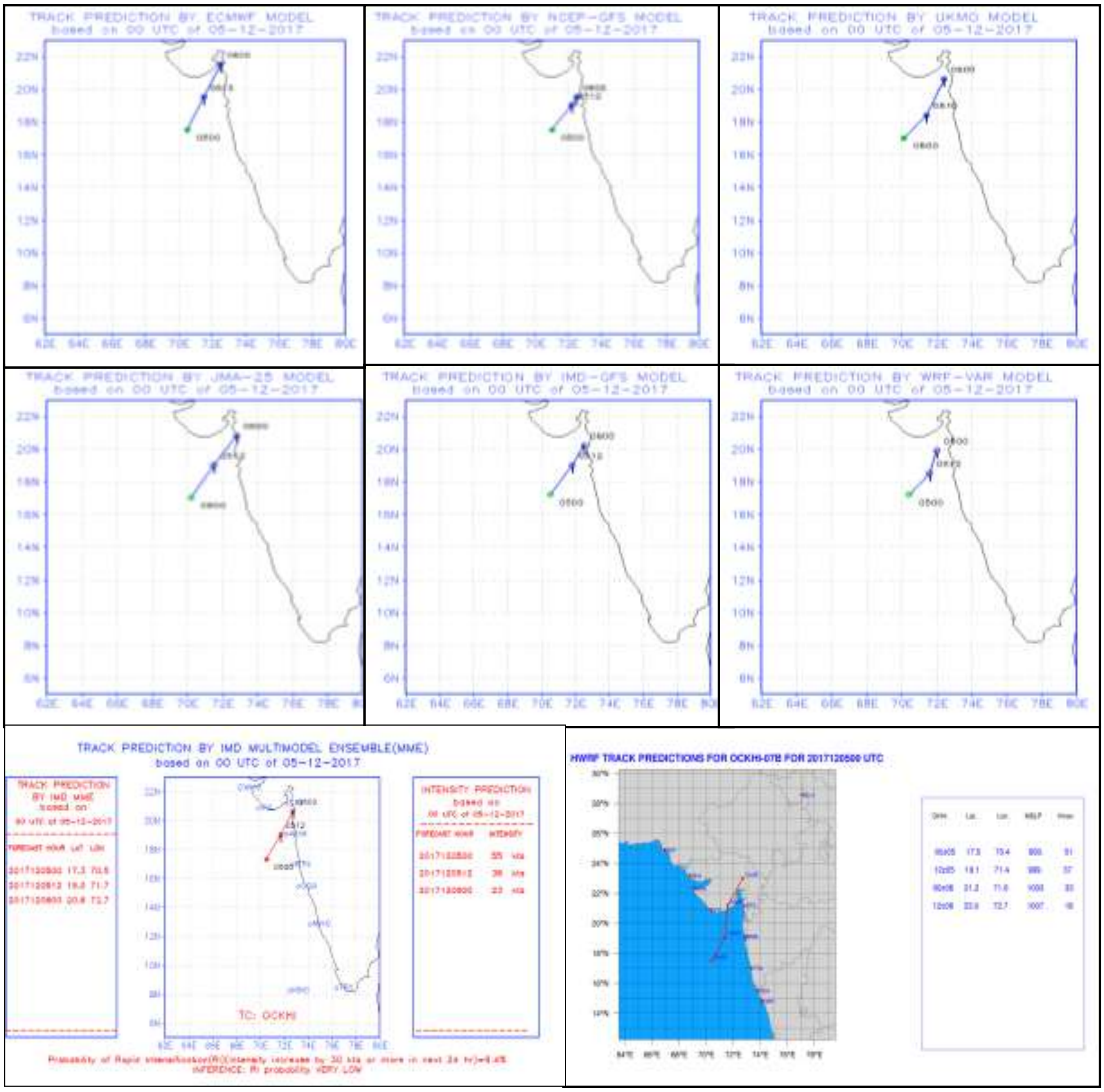


Fig. 3.15 (f): NWP model track forecast based on 0000 UTC of 3rd December

Hence to conclude all the models except WRF-VAR were indicating movement towards north Maharashtra and south Gujarat coast. Most of the models were indicating gradual weakening over eastcentral and adjoining northeast AS close to south Gujrat & North Maharashtra coasts. Most of the models indicated weakening around night of 5th December.

Composite forecast track based on various initial conditions by MME and observed track is presented in Fig.3.16. It is seen that MME could predict the northeastward recurvature and movement towards Gujarat coast and weakening of system over eastcentral AS from initial conditions of 0000 UTC & 1200 UTC of 1st December onwards. However it had westward bias in predicting the point of recurvature during initial days (30th Nov & 1st Dec).

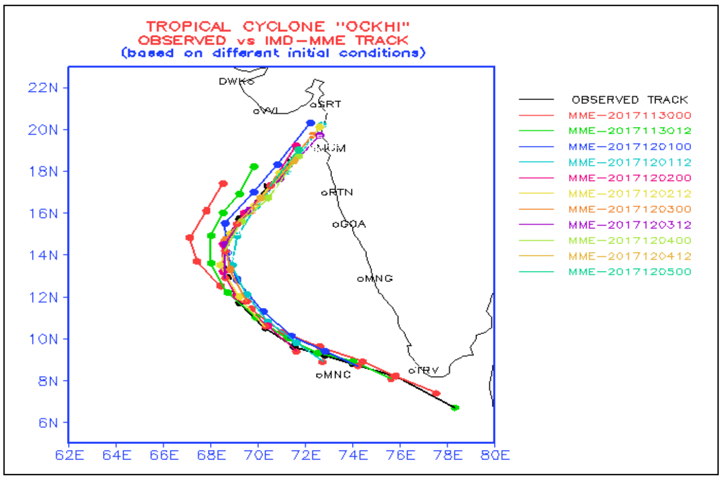


Fig. 3.16: Observed track and forecast tracks by MME based on initial conditions of 0000 & 1200 UTC during 30th November to 05th December

3.4.3.2. Track Prediction by Ensemble Prediction System:

The probabilistic and deterministic track forecast by UK Meteorological Office (UKMO) & European Centre for Medium Range Weather Forecasts (ECMWF) and consolidated forecast by these centres based on initial conditions of 0000 UTC of 1st December are presented in Fig. 3.17 (a).

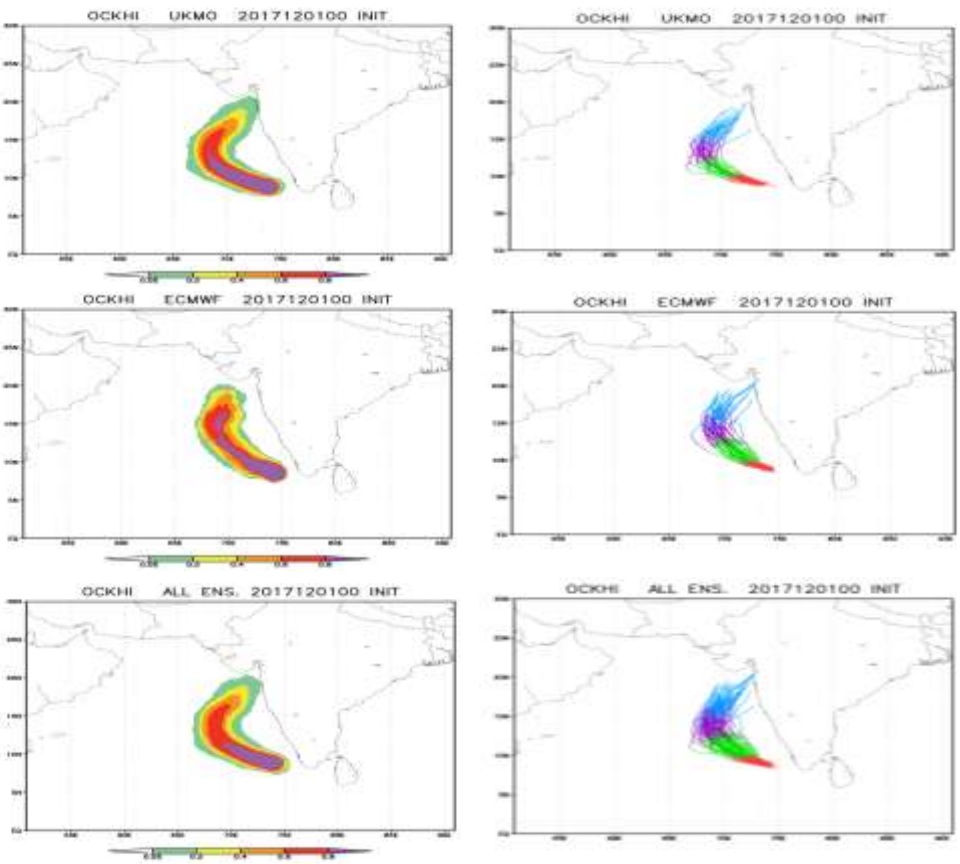


Fig. 3.17(a) : EPS track and strike probability forecast based on 0000 UTC of 1st December

Based on initial conditions of 0000 UTC of 1st December, all EPS models predicted initial west-northwestwards movement and north-northeastwards recurvature thereafter with weakening over eastcentral AS.

The probabilistic and deterministic track forecast by ECMWF based on initial conditions of 1200 UTC of 1st December are presented in Fig. 3.17(b). 60-80 % members indicated north-northwestwards movement of system, followed by north-northeastwards recurvature with dissipation over eastcentral AS. Based on initial conditions of 0000 UTC of 2nd, (Fig. 3.17c) all members were unanimous about track, however 5-20% members indicated weakening over eastcentral AS off south Maharashtra coast or north Gujarat coast.

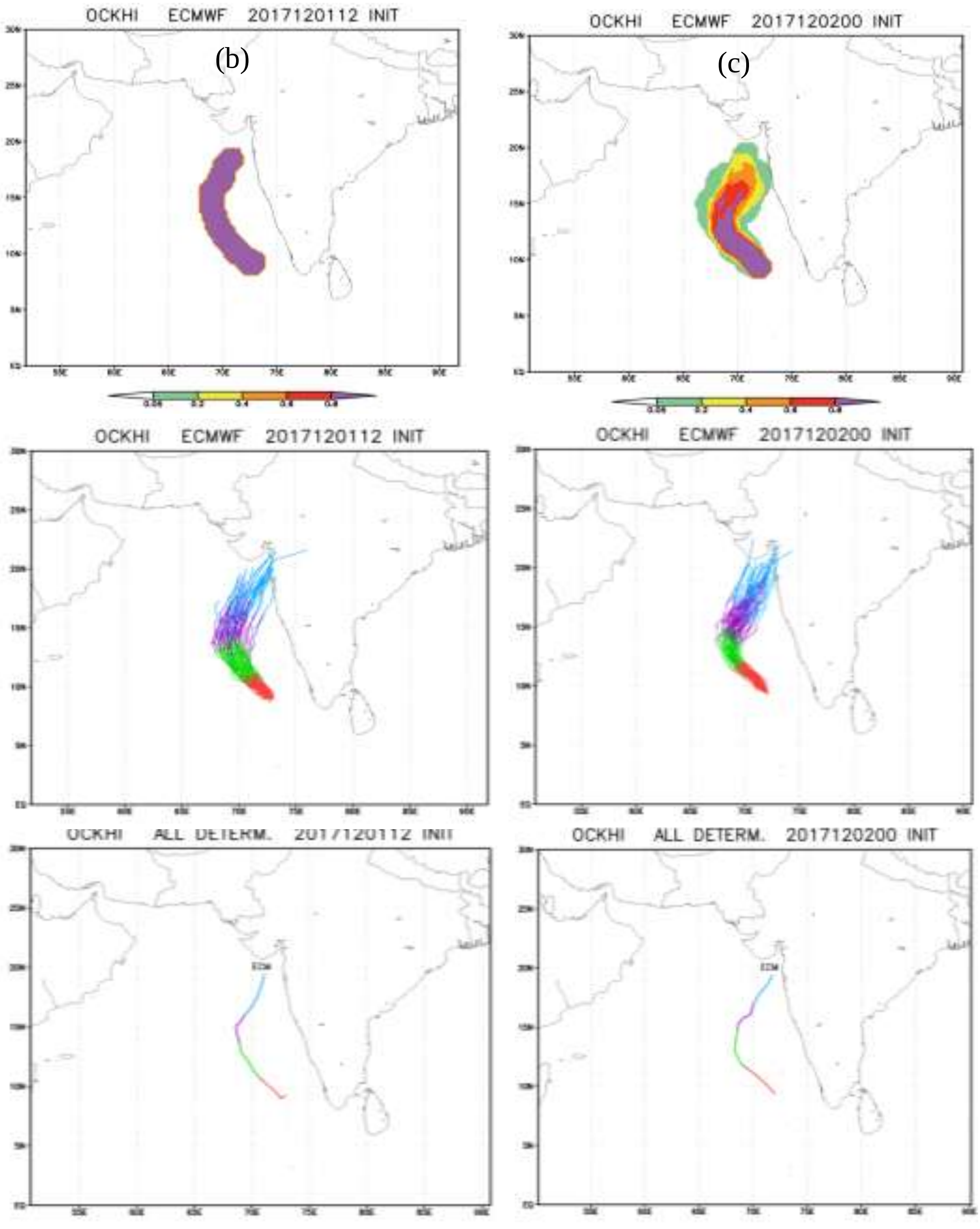


Fig.3.17 (b-c) : EPS track and strike probability forecast based on 1200 UTC of 1st December and 0000 UTC of 2nd December

3.4.3.3. Track forecast by NCMRWF Models

(a) NCMRWF Unified Model

The track forecast by NCMRWF Unified Model (NCUM) based on initial conditions of 0000/1200 UTC during 29th November to 5th December is presented in Fig. From 30th onwards, the model predicted initial west-northwestward movement with northeastwards recurvature towards south Gujarat-north Maharashtra coast. On 29th & 30th, it indicated dissipation over sea. The forecast based on initial conditions of 1st, 2nd & 5th December indicated movement towards south Gujarat & north Maharashtra coast (Fig. 3.17 (d).

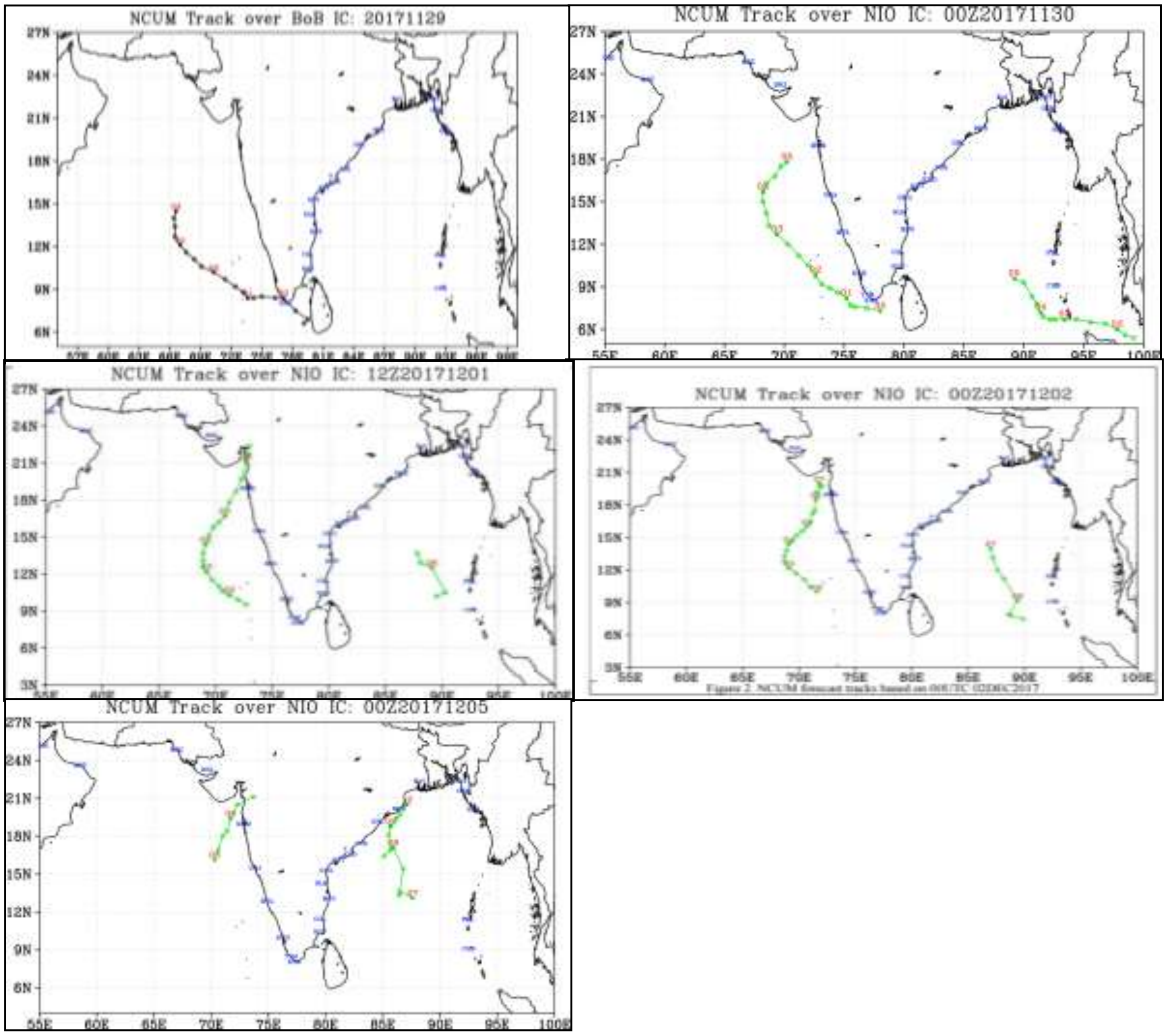


Fig. 3.17 (d): Track forecast by NCUM Models

(b) Met Office Global & Regional Ensemble Prediction System (MOGREPS)

The MOGREPS forecast tracks based on 0000 UTC of 29th predicted that the system will cross the Indian coast near Kanyakumari and emerge in Arabian Sea. The system would track northwestwards (>80% probability) and then there was some probability (40-60%) that the system would recurve and track towards Gujarat (Fig. 3.17 (e))..

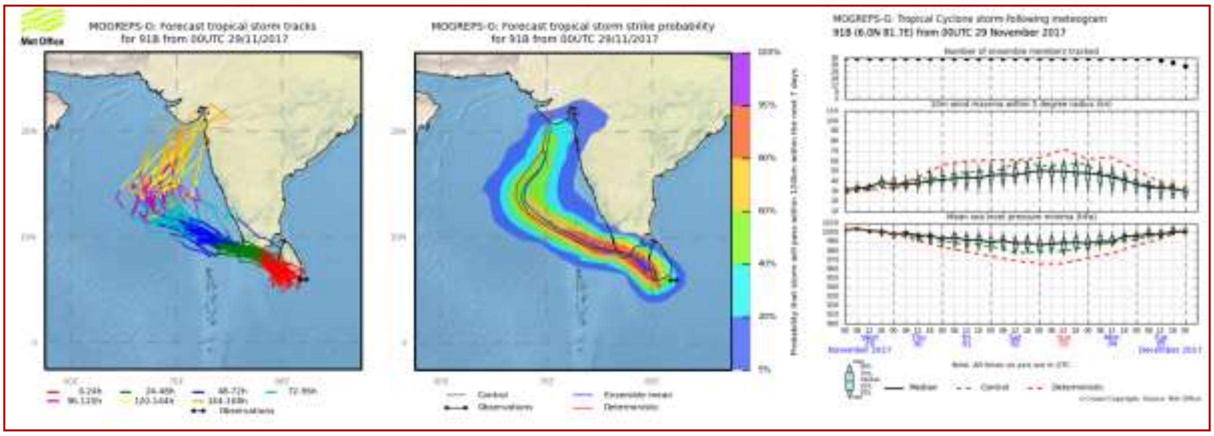


Fig. 3.17 (e): Track Prediction by MOGREPS models based on 0000 UTC of 29th November

The MOGREPS forecast tracks based on 0000 UTC of 2nd November predicted that TC Ockhi will move northeastwards (>80% probability), will recurve northeastwards (>80% probability) and cross the Indian coast near Gujarat Maharashtra border (Fig. 3.17 (f)).

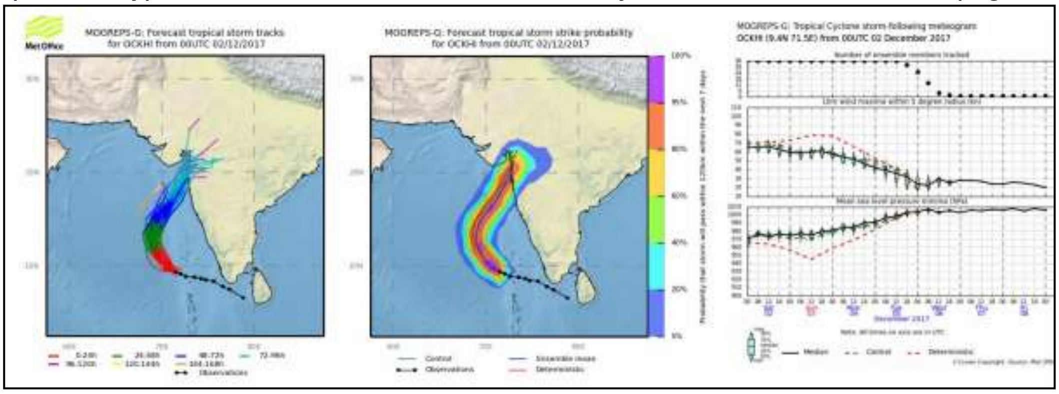


Fig. 3.17 (f): Track Prediction by MOGREPS models based on 0000 UTC of 2nd December

As per the MOGREPS forecast tracks based on 0000 UTC of 5th December, the system would track northeastwards (>80% probability) towards Maharashtra coast (Fig. 3.17 (g)).

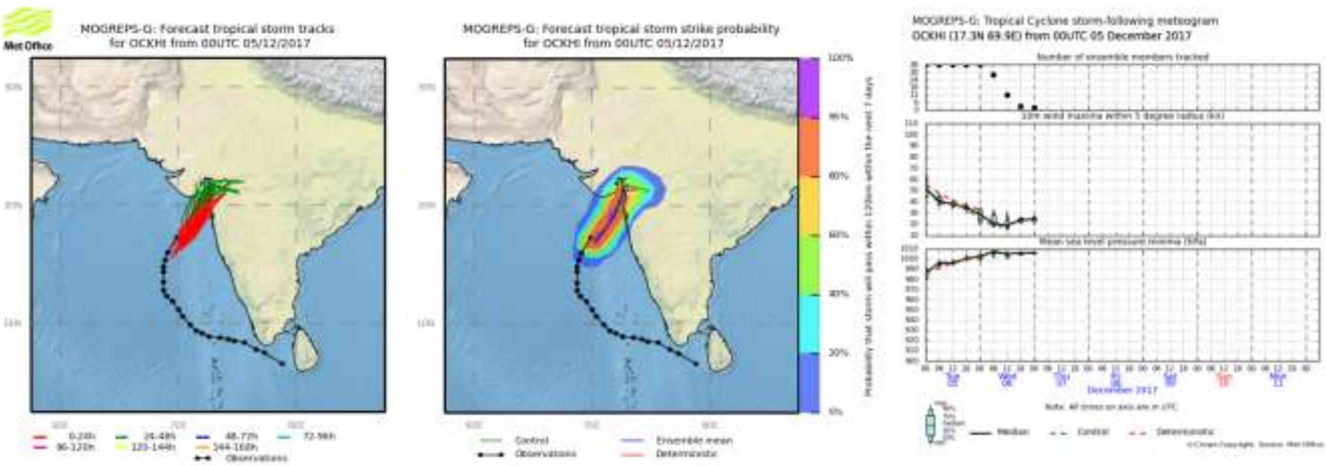


Fig. 3.17 (g): Track Prediction by MOGREPS models based on 0000 UTC of 5th December

3.4.4. Track forecast errors by various NWP Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in Table 3.14. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 3.15 (a-b). From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of MME were the least for 12, 24 and 36 hours lead period. It was lowest in case of for 48 to 96 hrs and NEPS and NCUM for 108 and 120 hrs respectively.

Table 3.14. Average track forecast errors (Direct Position Error (DPE)) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	51(11)	68(10)	98(9)	117(8)	123(7)	145(6)	211(5)	218(4)	190(3)	407(2)
IMD-WRF	59(11)	115(10)	166(9)	226(8)	271(7)	278(6)	-	-	-	-
JMA	70(11)	70(10)	85(9)	103(8)	148(7)	215(6)	304(5)	-	-	-
NCEP-GFS	60(11)	65(10)	75(9)	110(8)	91(7)	104(6)	131(5)	203(4)	259(3)	301(2)
UKMO	42(11)	63(10)	76(9)	122(8)	146(7)	173(6)	187(5)	191(4)	203(3)	294(2)
ECMWF	58(11)	69(10)	64(9)	62(8)	86(7)	100(6)	90(5)	139(4)	201(3)	329(2)
IMD-HWRF	58(21)	99(20)	130(18)	180(16)	234(14)	251(12)	279(10)	251(8)	-	-
IMD-MME	29(11)	44(10)	58(9)	86(8)	100(7)	112(6)	118(5)	147(4)	169(3)	187(2)
NCUM	82 (13)	122(12)	129(11)	121(10)	144(9)	180(8)	155(7)	155(6)	178(5)	169(3)
NEPS	90(7)	134(6)	178(6)	217(5)	211(5)	208(4)	187(4)	157(3)	148(3)	

( ): Number of forecasts verified;   -: No forecast issued

Table 3.15 (a). Average cross-track forecast errors (CTE) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	32	33	40	54	72	106	164	203	171	366
IMD-WRF	28	49	87	138	177	216	-	-	-	-
JMA	32	24	54	81	117	165	234	-	-	-
NCEP-GFS	33	23	28	51	38	53	96	179	233	279
UKMO	19	32	43	66	76	101	113	112	87	114
ECMWF	43	37	58	51	62	55	48	77	146	315
IMD-HWRF	99	150	191	221	278	282	276	279	-	-
IMD-MME	20	24	40	52	58	59	52	86	112	161
NCUM	54	65	59	68	74	84	77	84	130	154
NEPS	63	75	100	123	144	145	147	102	94	

Table 3.15 (b). Average along-track forecast errors (ATE) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	30	54	84	99	92	86	125	78	76	178
IMD-WRF	47	97	110	140	156	144	-	-	-	-
JMA	54	57	50	58	87	133	184	-	-	-
NCEP-GFS	39	57	66	87	73	76	67	85	106	100
UKMO	34	50	58	93	110	128	138	154	176	257
ECMWF	30	53	19	28	51	76	67	109	117	92
IMD-HWRF	35	46	48	80	92	132	158	84	-	-
IMD-MME	14	34	38	64	73	86	89	117	112	83
NCUM	51	112	108	91	103	138	119	116	111	105
NEPS	54	65	59	68	74	84	77	84	130	154

Above tables show that DPE was largely contributed by CTE for 12-36 hrs, 108 to 120 hrs and ATE by 48-96 hrs for most of models & MME except HWRF. ATE was less than CTE for all lead times in case of HWRF.

3.4.5. Intensity forecast error

The intensity forecast errors of IMD-SCIP model and HWRF model are shown in Table 3.16. The errors by IMD-HWRF were less as compared to IMD-SCIP upto 36 hours lead period and beyond that errors in intensity forecast by SCI{P model were less.

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 →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-SCIP (AAE)	8.3 (11)	11.8 (10)	13.1 (9)	13.3 (8)	12.4 (7)	9.7 (6)	10.4 (5)	15.3 (4)	13.7 (3)	7.5 (2)
HWRF (AAE)	7.2 (21)	9.2 (20)	7.8 (18)	16.8(16)	13.0 (14)	11.3 (12)	12.9 (10)	8.3 (8)		
IMD-SCIP (RMSE)	10.0	13.7	15.0	16.7	14.7	11.2	12.2	17.9	14.8	9.9
HWRF (RMSE)	9.3	10.7	10.2	19.8	17.6	14.4	15.8	11.6		

The figure in parenthesis indicates the No. of observations verified.

Intensity forecast skill by IMD-HWRF is presented in Table 3.17.

Table-3.17 Intensity forecast Skill by IMD-HWRF Model

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr
Skill in AAE	1.3 (21)	31.5 (20)	67.2 (18)	51.5 (16)	71.9 (14)	83.2 (12)	84.2 (10)	90.4 (8)
Skill in RMSE	12 (21)	32.2 (20)	62.0 (18)	51.2 (16)	68.3 (14)	81.5 (12)	84.3 (10)	88.6 (8)

The figure in parenthesis indicates the No. of observations verified.

The operational intensity versus predicted intensity by SCIP model and HWRF model are presented in Fig. 3.18. IMD SCIP all along underestimated the intensity of the system. HWRF could pick up the intensity upto 36 hours lead period and beyond 96 hours lead period. For period between 48 hours to 90 hours, there was large error in intensity prediction.

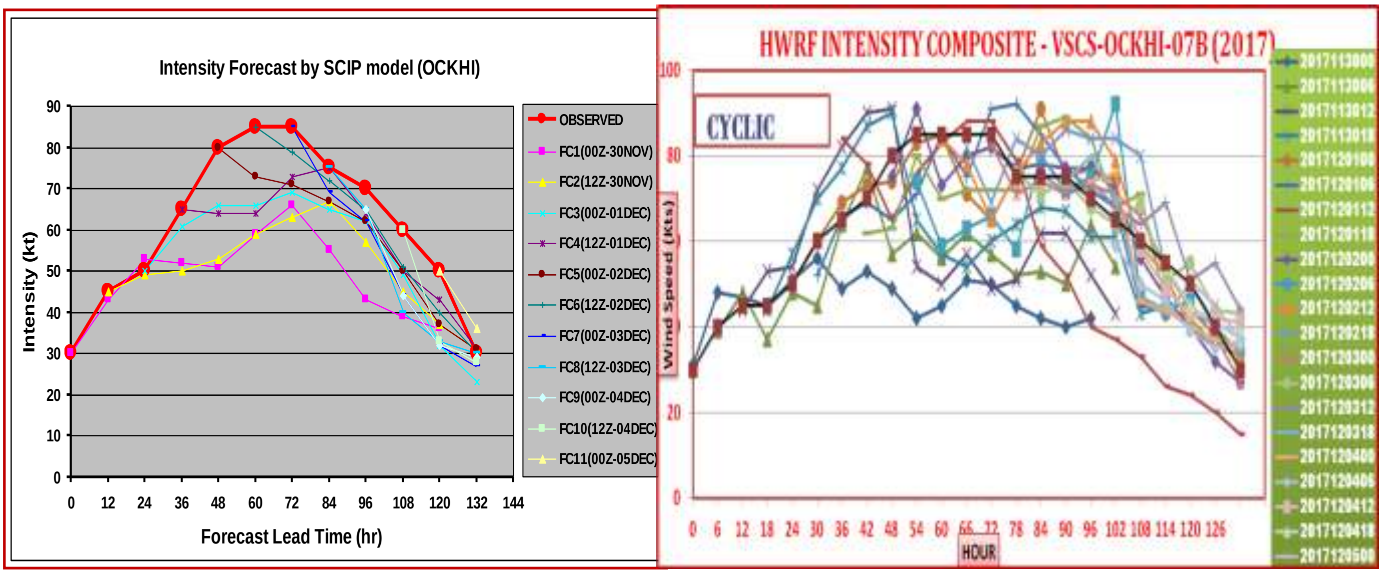


Fig. 3.18. Operational Intensity vs predicted intensity by SCIP Model and HWRF model

3.4.6. Heavy rainfall forecast by models

3.4.6.1. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in Fig. 3.19. HWRF predicted heavy rainfall over Tamil Nadu, Kerala and Karnataka on 30th November. On 1st, it predicted light to moderate rainfall over Tamil Nadu and Kerala. From 2nd onwards, it predicted light to moderate rainfall over Goa, Maharashtra and Gujarat. The error in rainfall prediction was mainly due to track forecast error of the model.

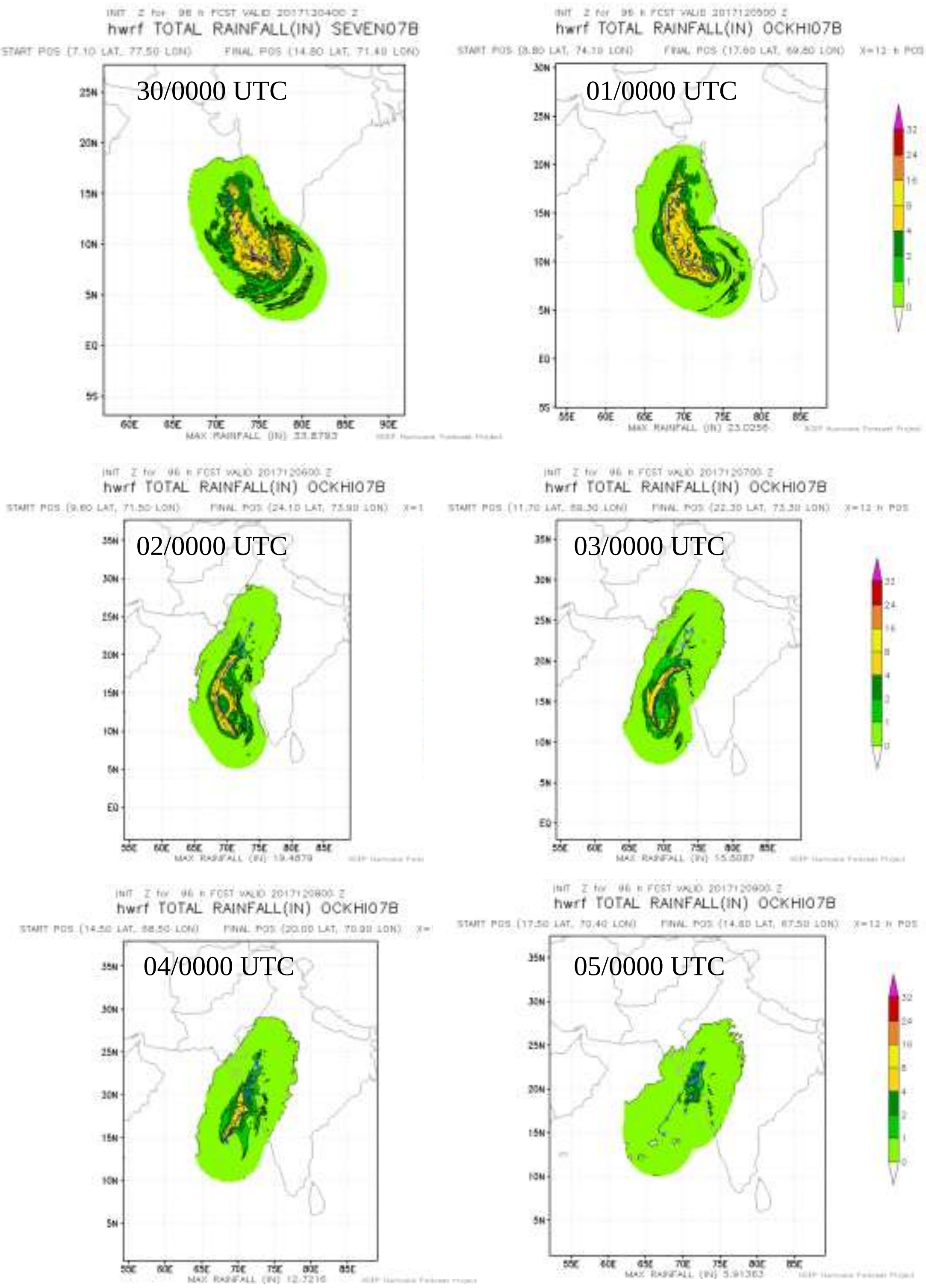


Fig.3.19: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 30th November to 5th December, 2017.

3.4.6.2. Heavy rainfall forecast by IMD GFS model

Rainfall forecast upto 120 hours by IMD GFS model based on 0000 UTC observations of 29th November to 5th December is presented in Fig. 3.20.

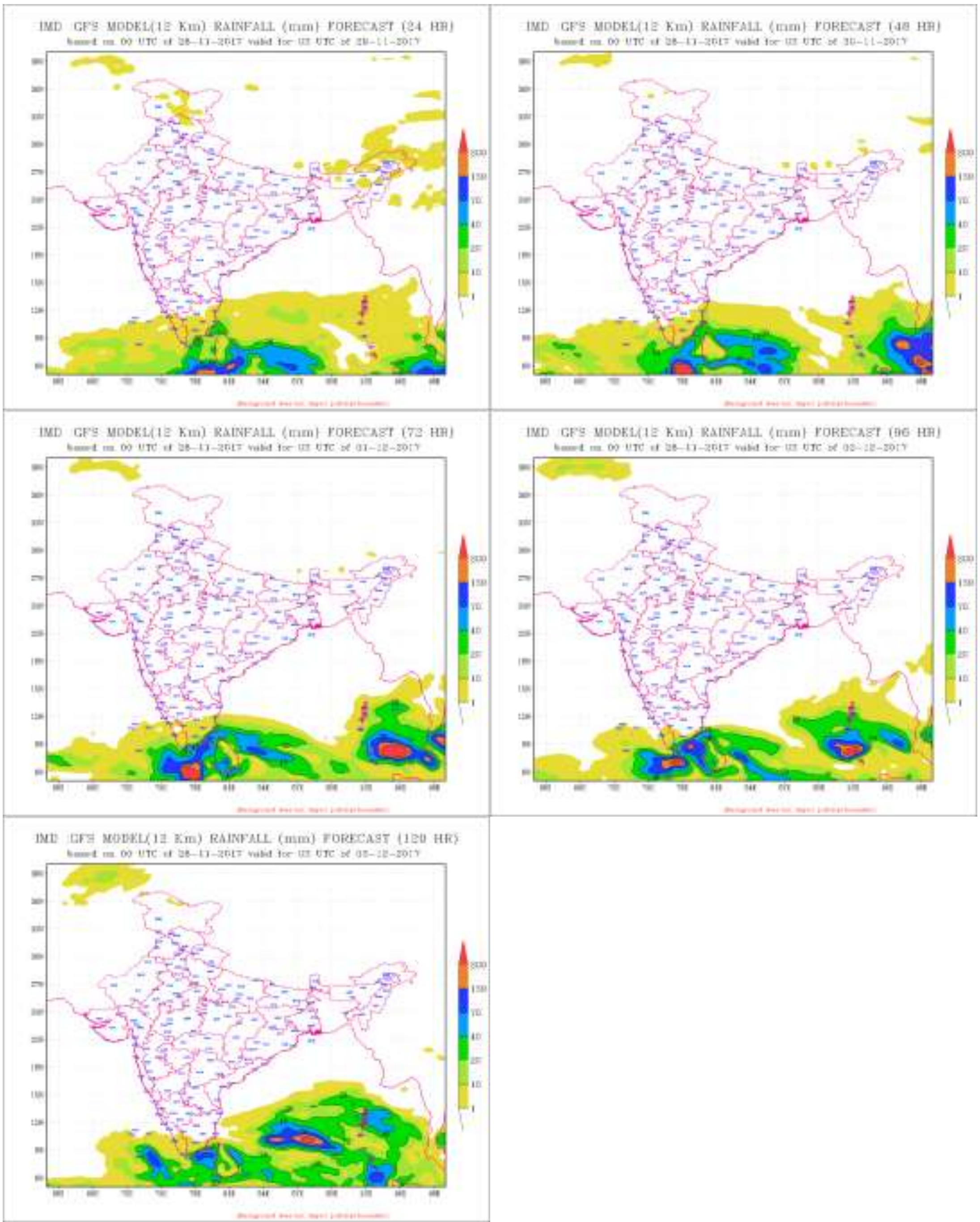


Fig 3.20 (a) IMD : GFS MODEL Rainfall forecast based on 000UTC of 28th November 2017

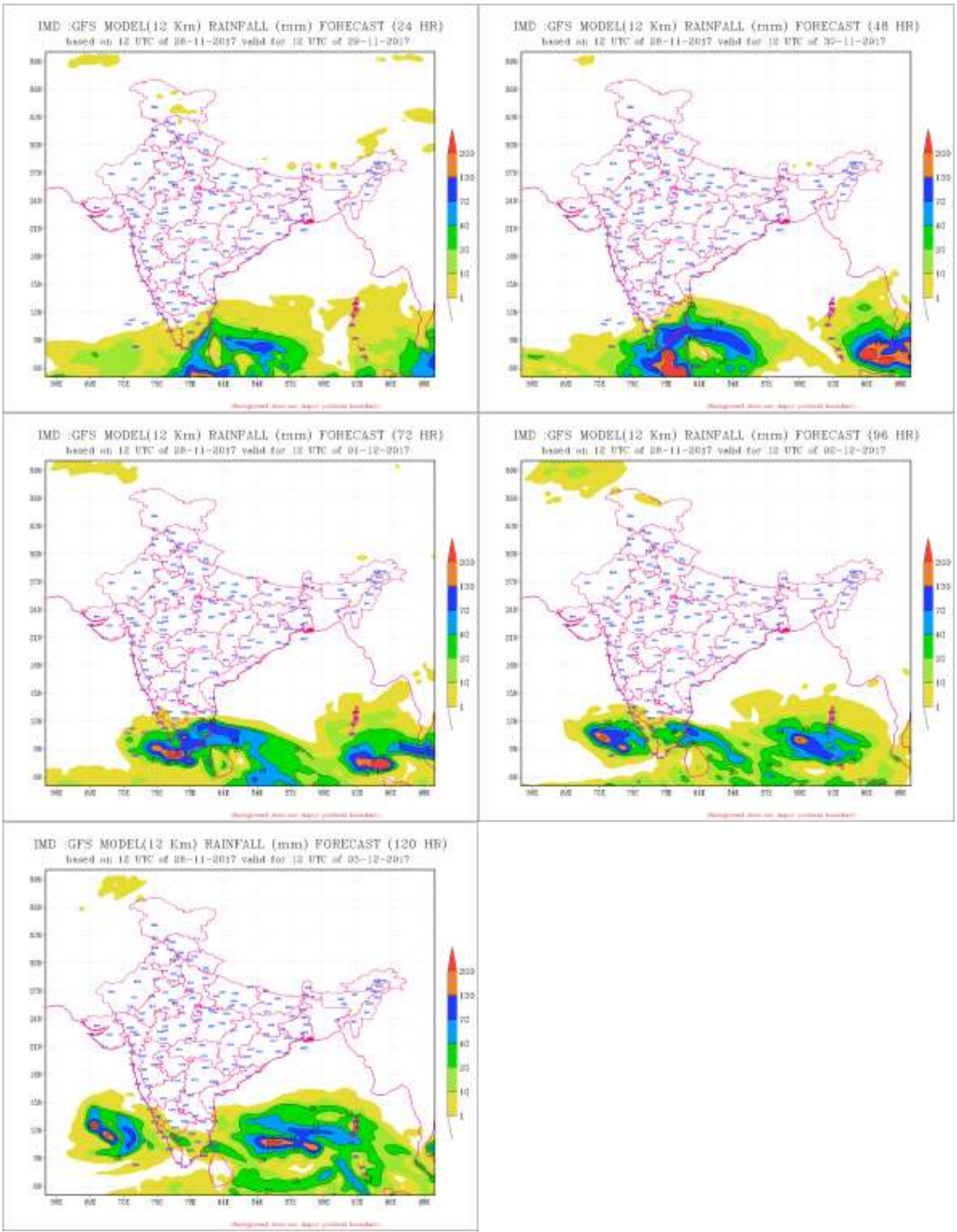


Fig. 3.20 (b) IMD : GFS MODEL Rainfall forecast based on 1200UTC of 28th November 2017

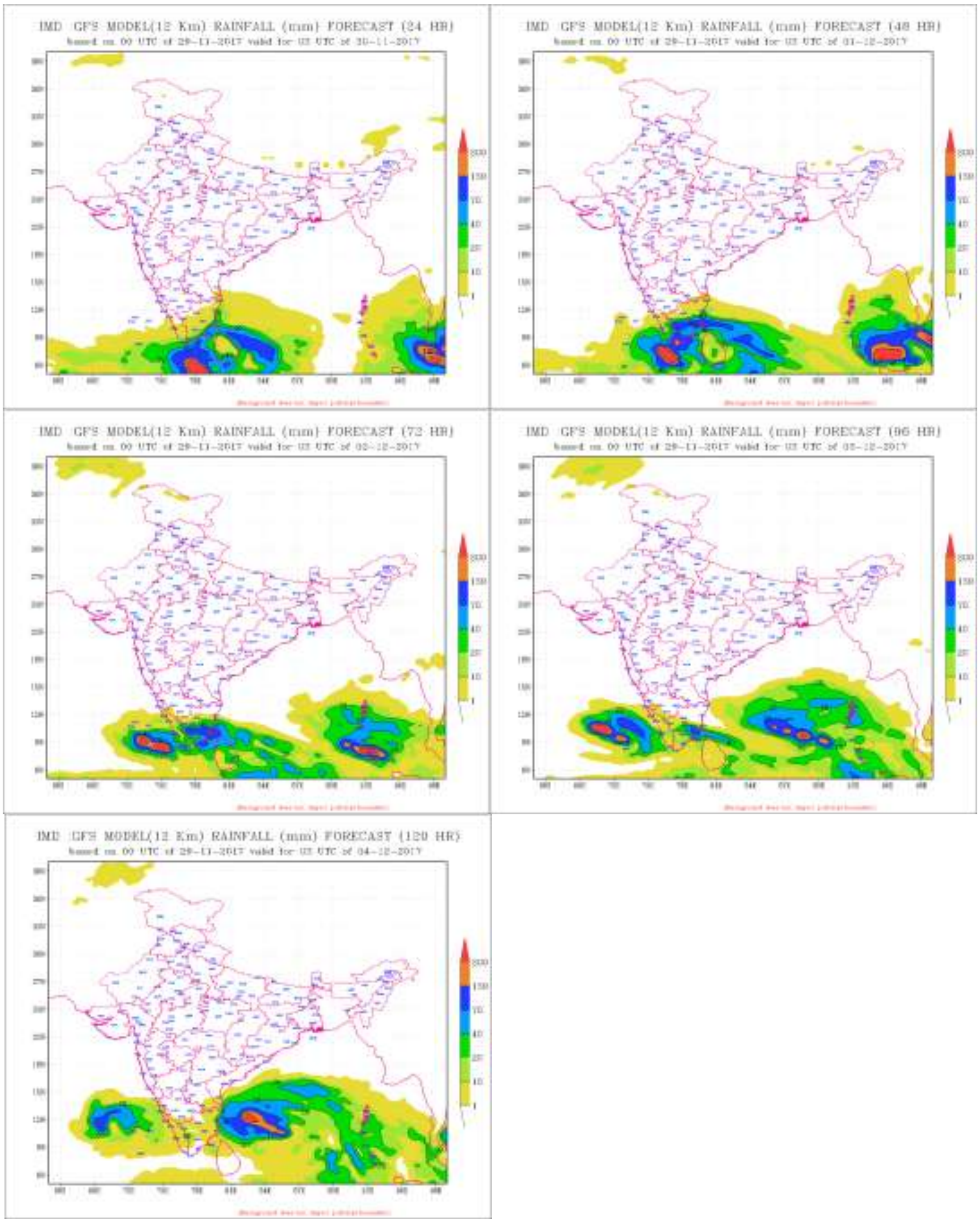


Fig. 3.20 (c) IMD GFS MODEL Rainfall forecast based on 0000UTC of 29th November c17

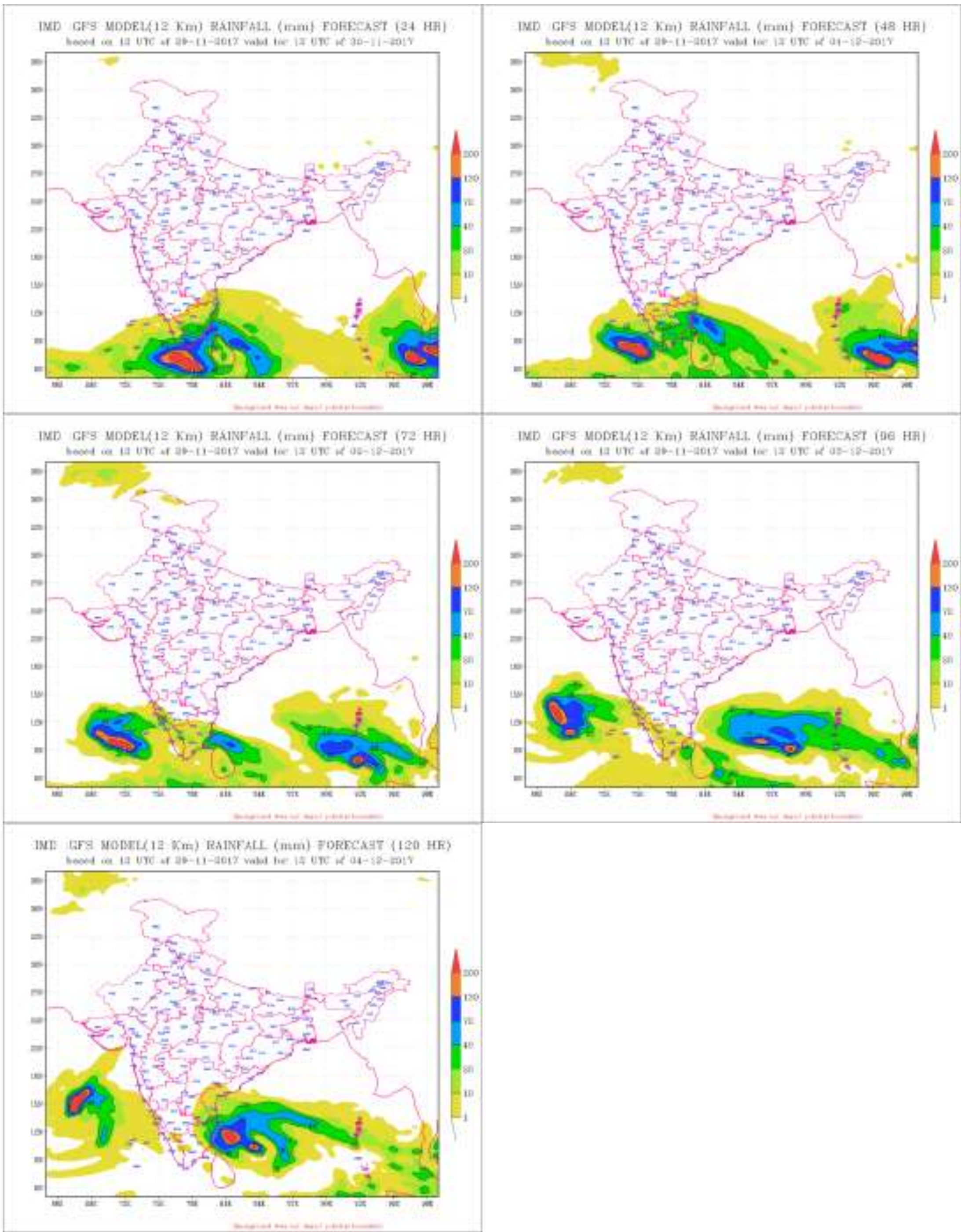


Fig. 3.20 (d) IMD : GFS MODEL Rainfall forecast based on 1200UTC of 29th November 2017

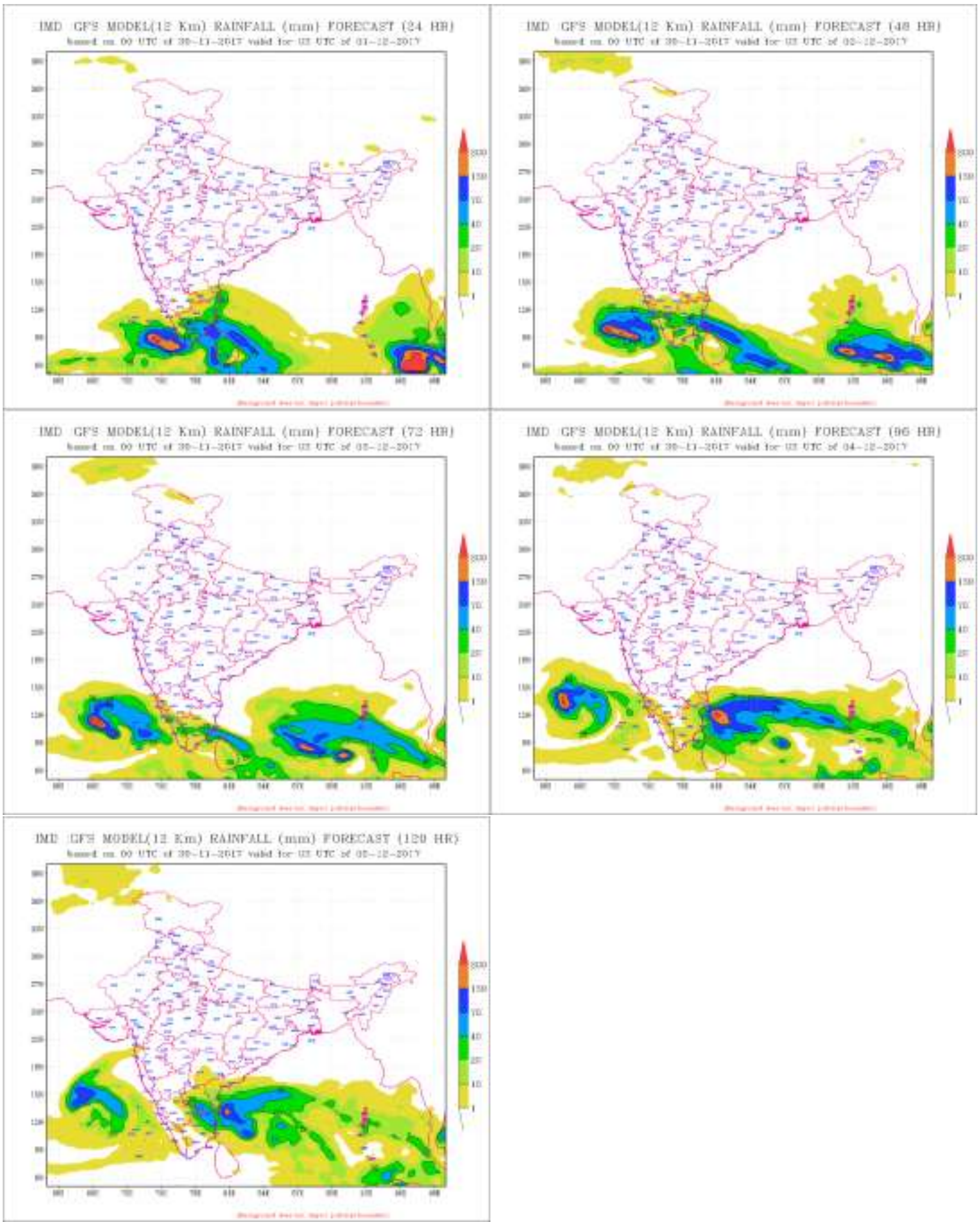


Fig. 3.20 (e) IMD : GFS MODEL Rainfall forecast based on 0000UTC of 30th November 2017

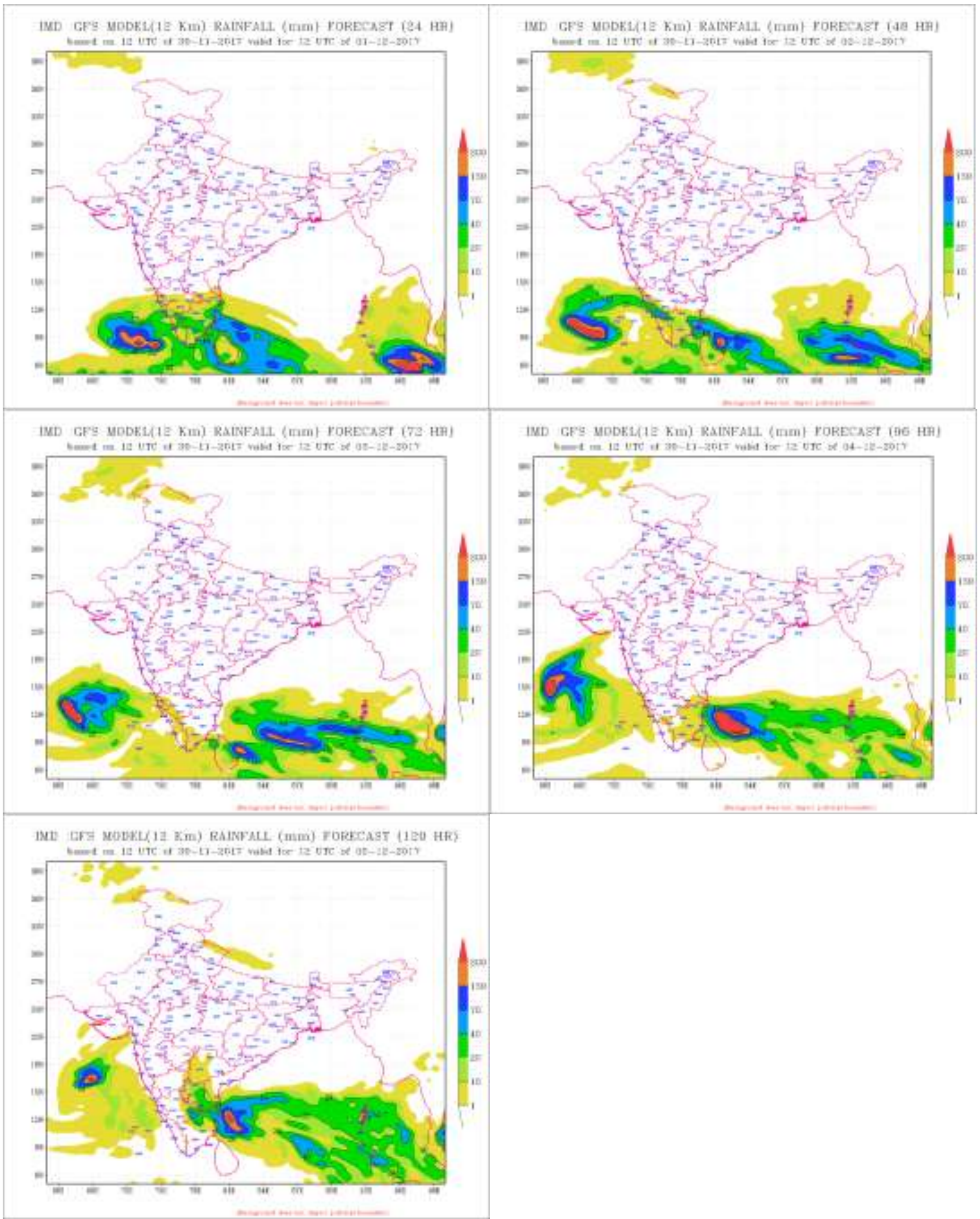


Fig. 3.20 (f) IMD : GFS MODEL Rainfall forecast based on 1200UTC of 30th November 2017

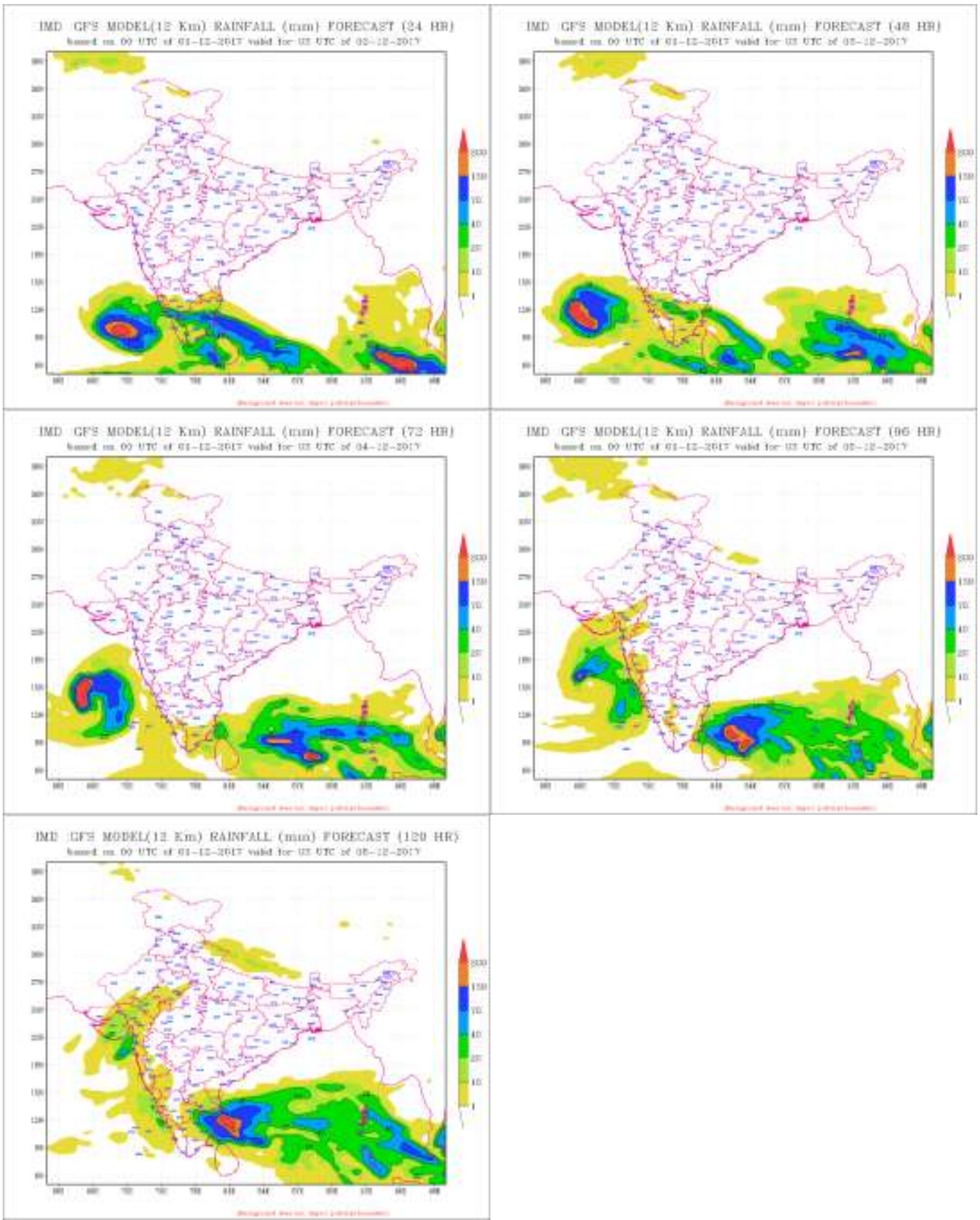


Fig. 3.20 (g): IMD GFS MODEL Rainfall forecast based on 0000UTC of 1st December 2017

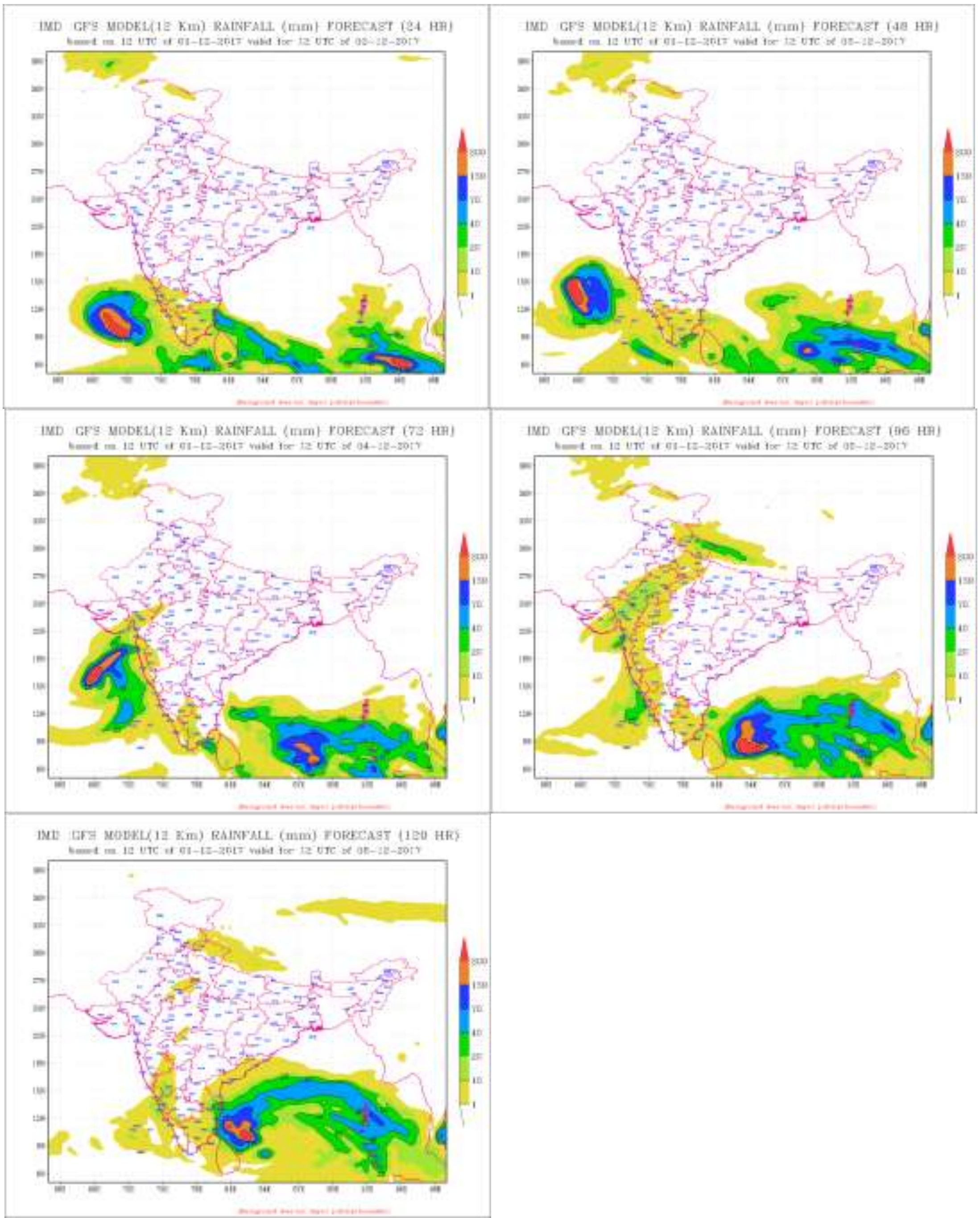


Fig. 3.20 (h): IMD GFS MODEL Rainfall forecast based on 1200UTC of 1st December 2017

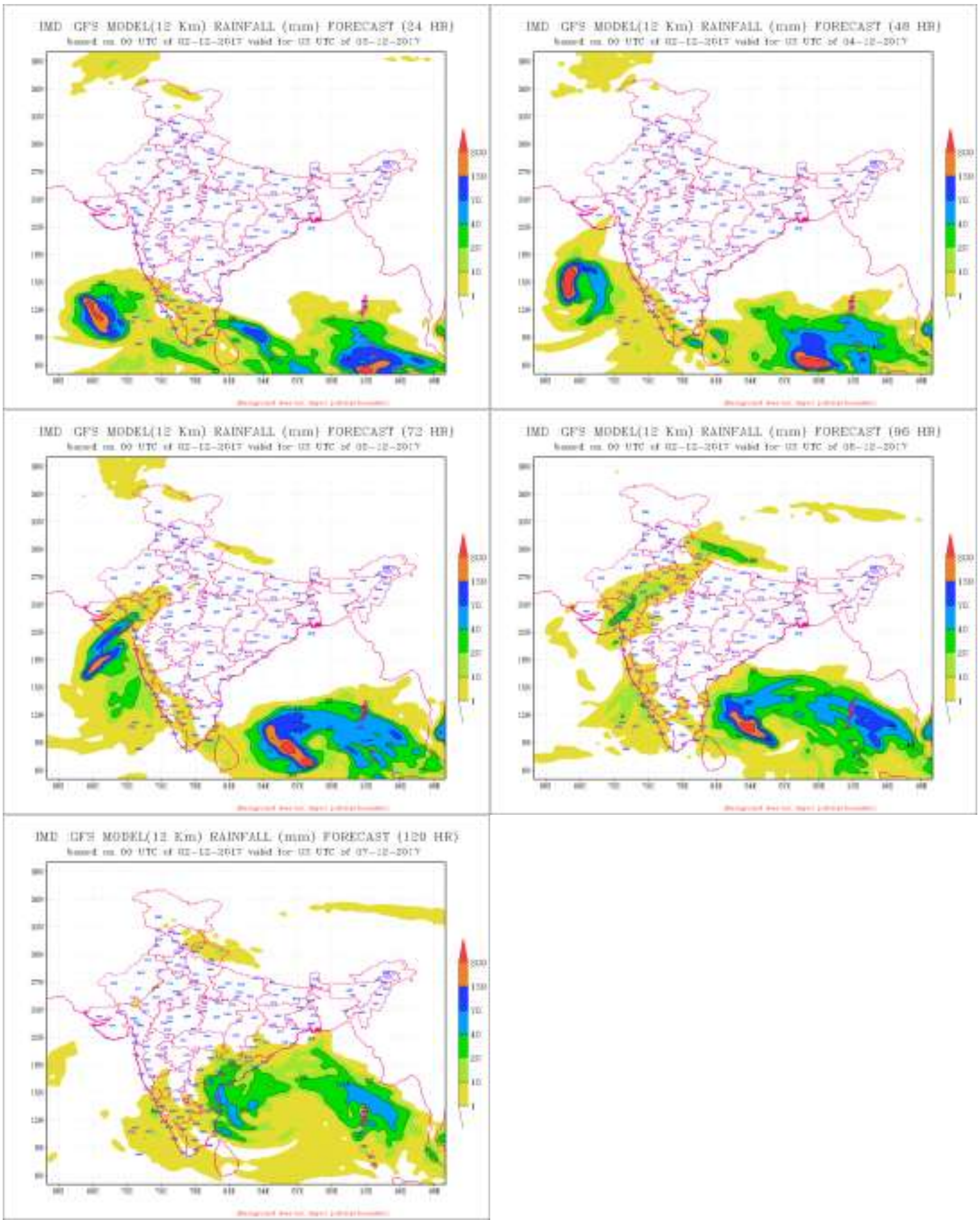


Fig. 3.20 (i) IMD GFS MODEL Rainfall forecast based on 0000UTC of 2nd December 2017

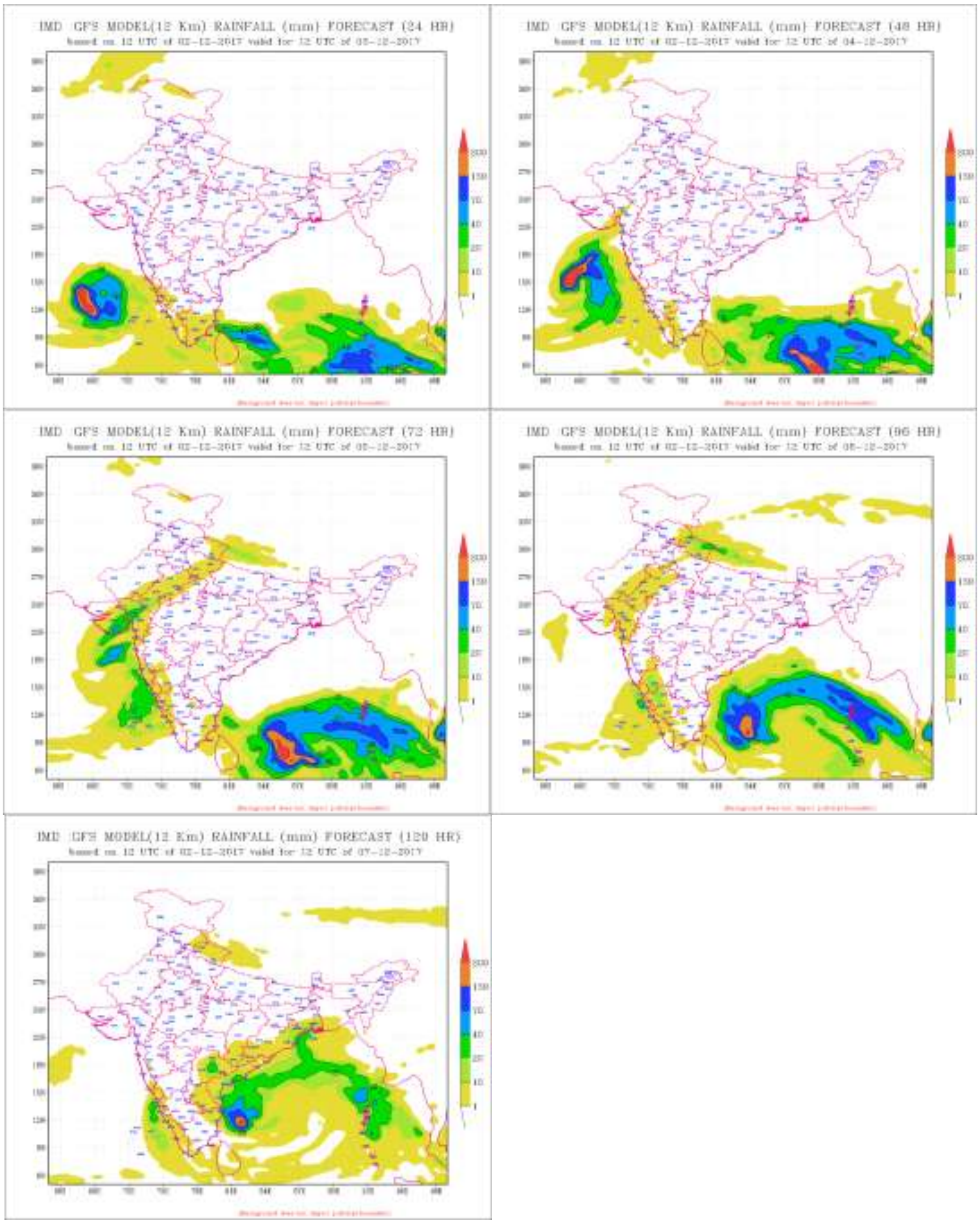


Fig. 3.20 (j): IMD GFS MODEL Rainfall forecast based on 1200UTC of 2nd December 2017

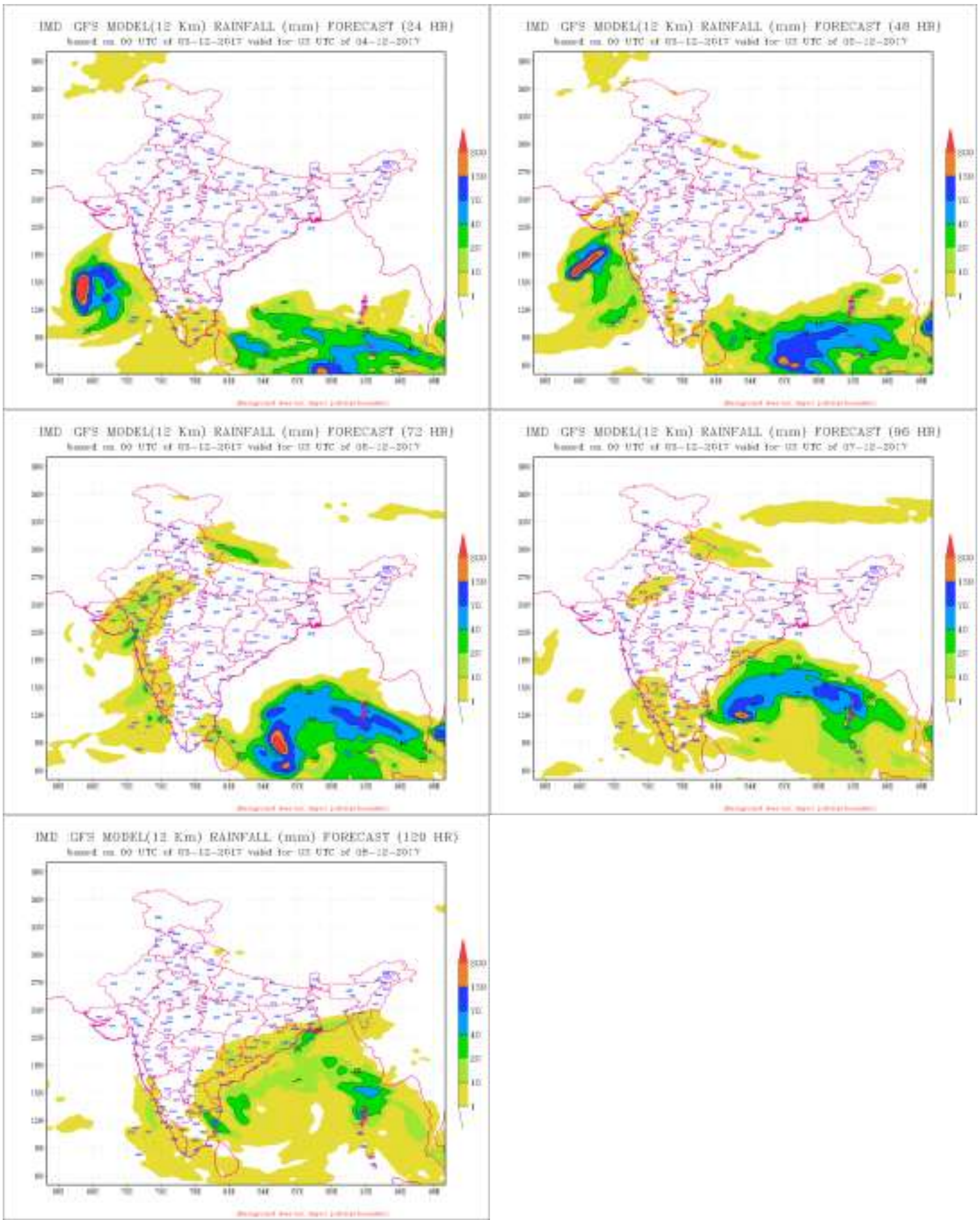


Fig. 3.20 (k) IMD GFS MODEL Rainfall forecast based on 0000UTC of 3rd December 2017

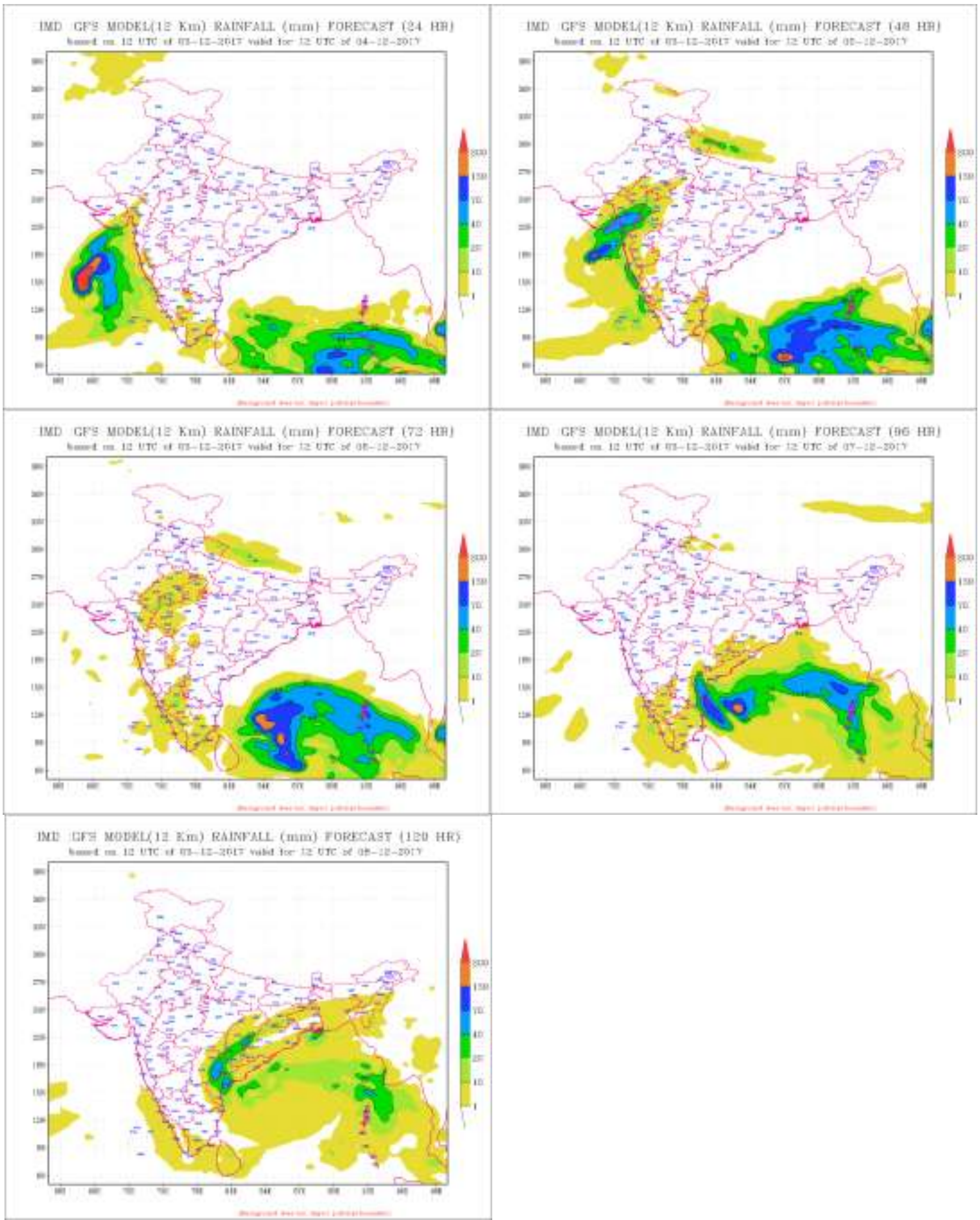


Fig. 3.20 (l): IMD GFS MODEL Rainfall forecast based on 1200UTC of 3rd December 2017

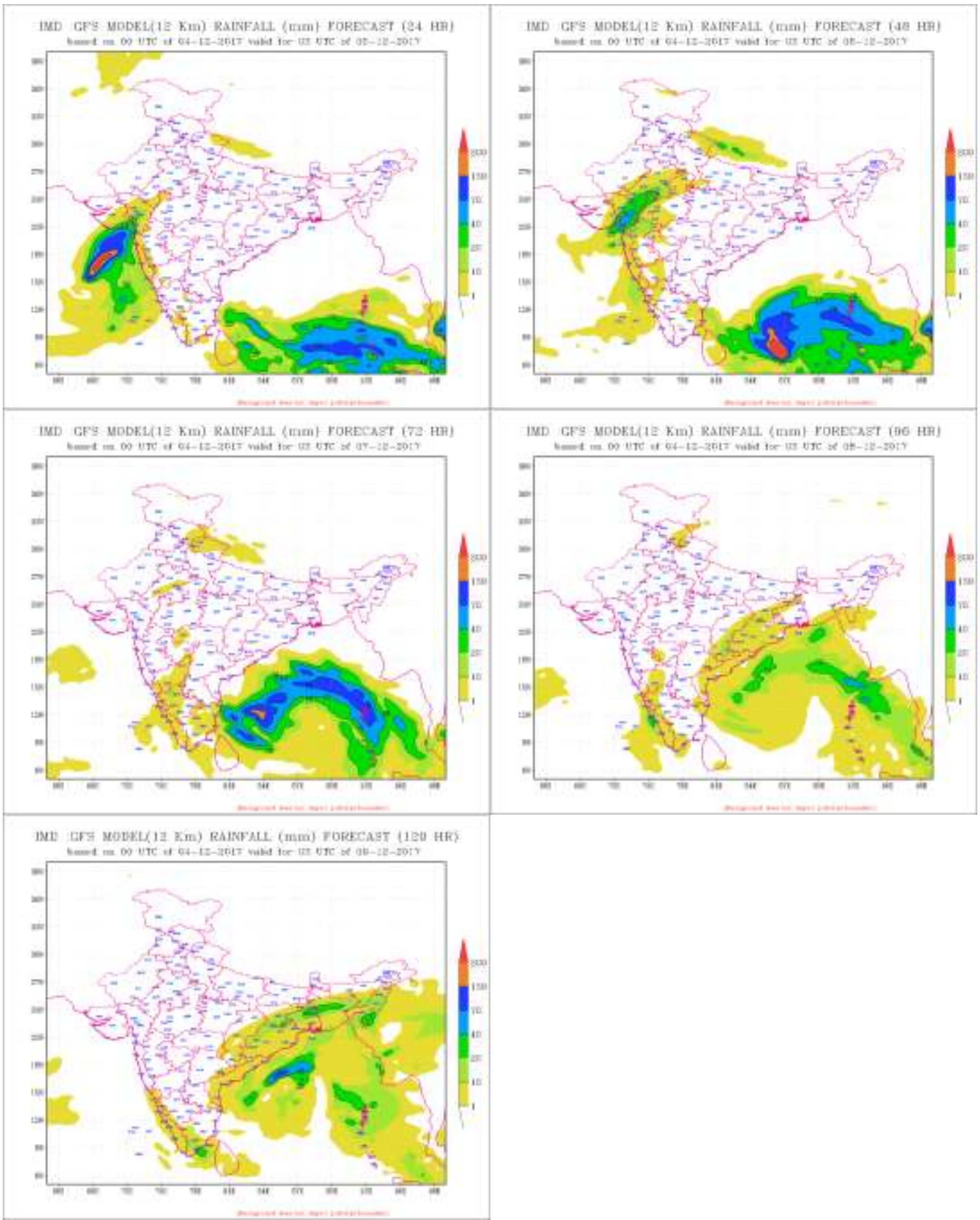


Fig. 3.20 (m): IMD GFS MODEL Rainfall forecast based on 0000UTC of 4th December 2017

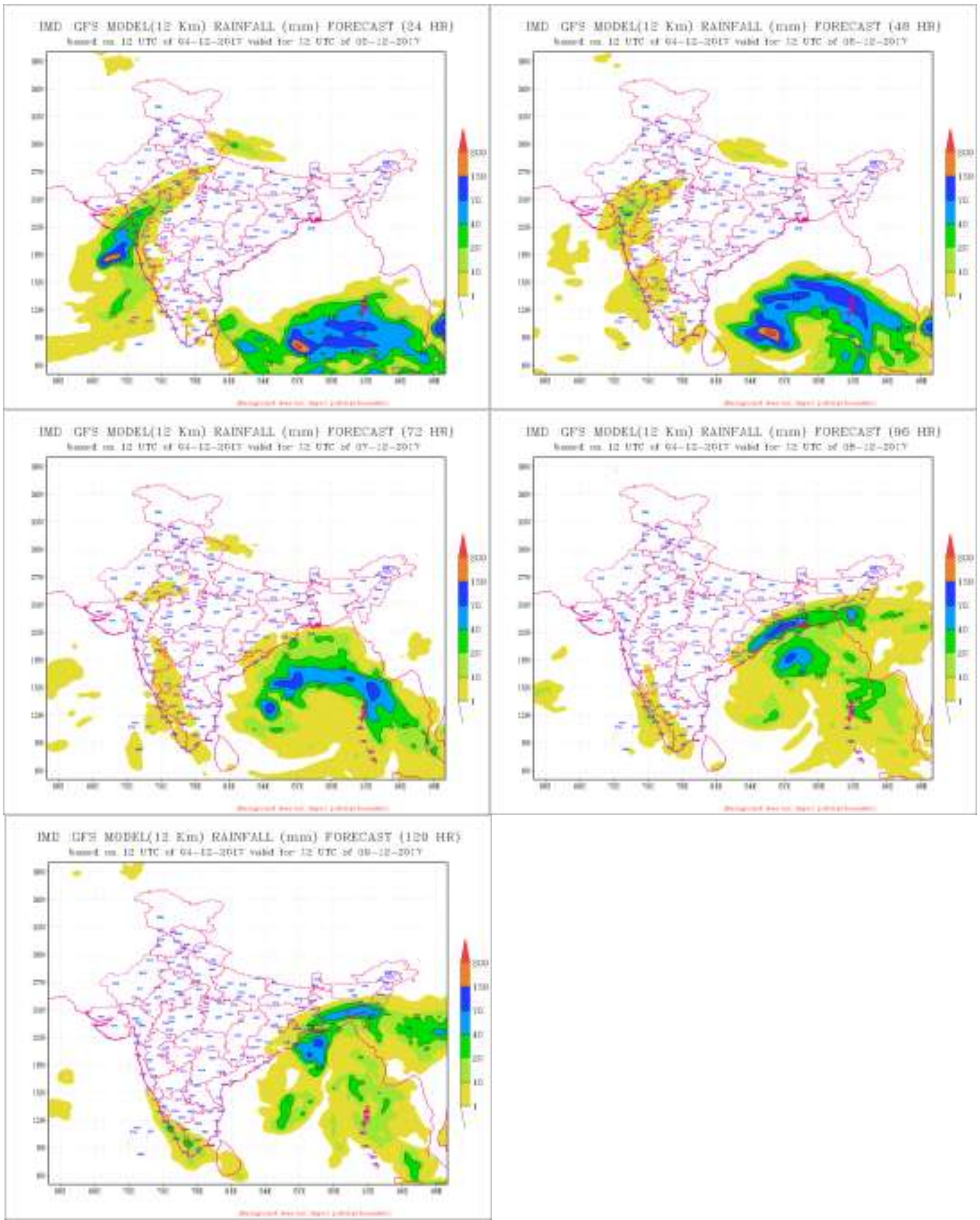


Fig. 3.20 (n) IMD GFS MODEL Rainfall forecast based on 1200UTC of 4th December 2017

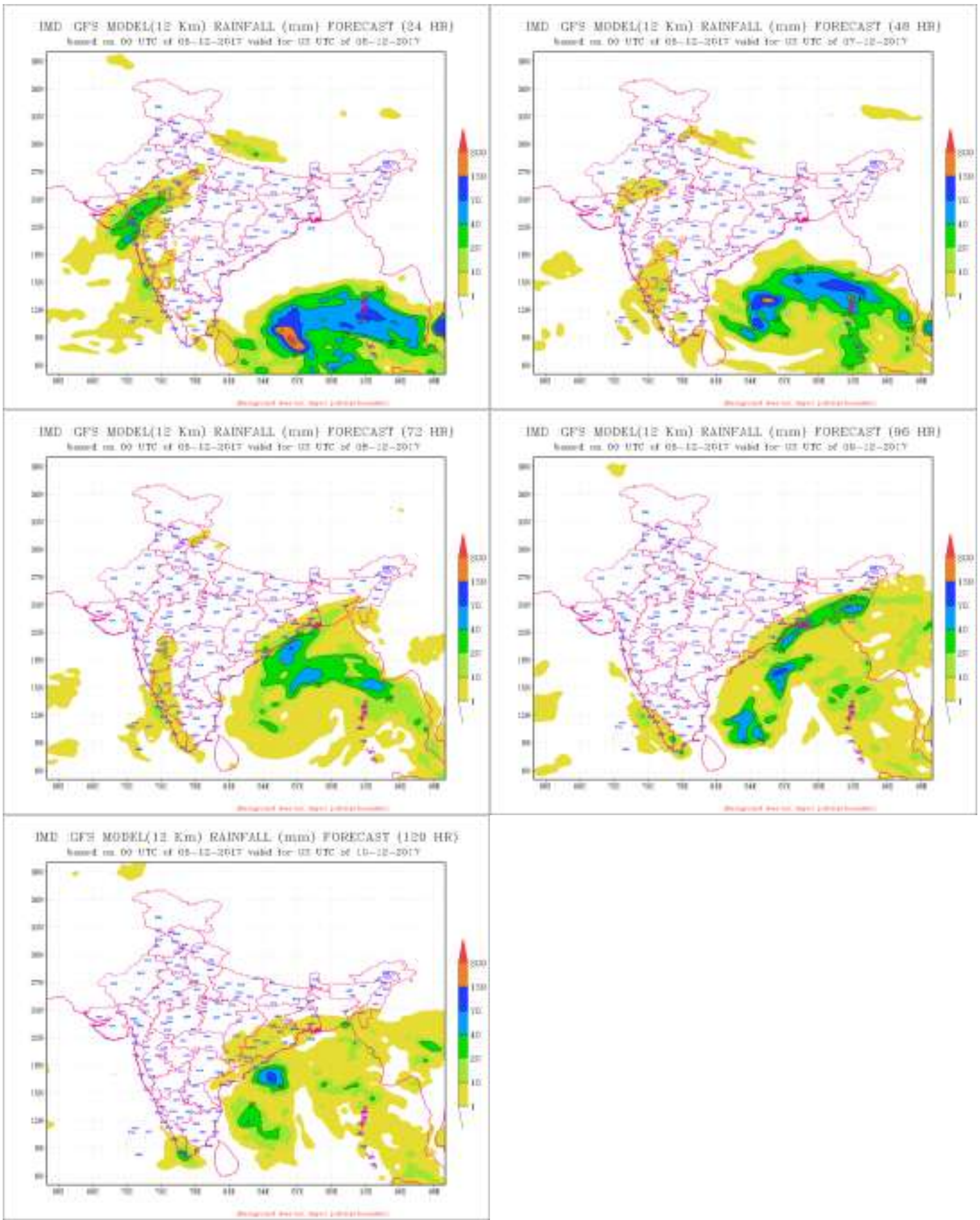


Fig. 3.20 (o): IMD GFS MODEL Rainfall forecast based on 0000UTC of 5th December 2017

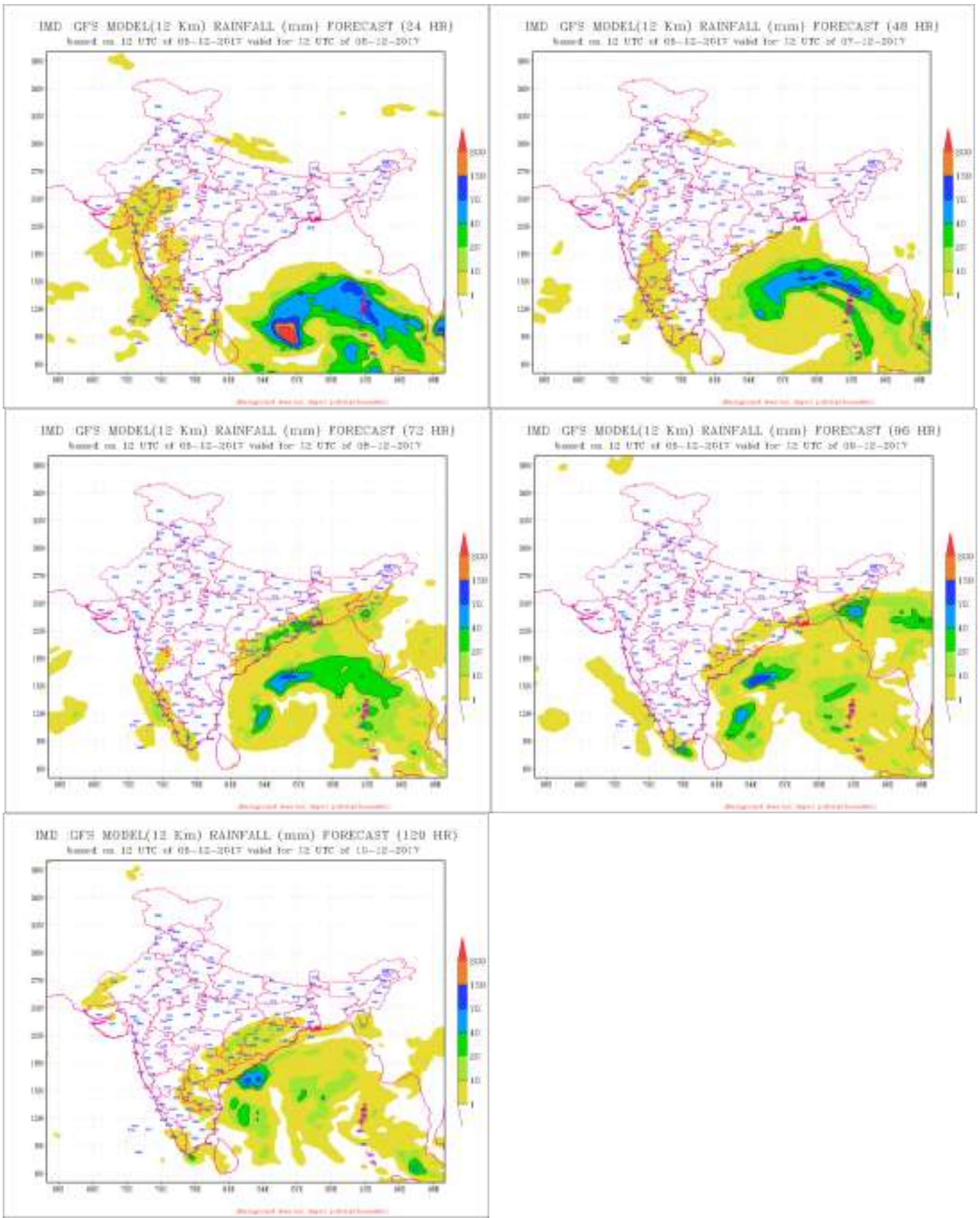


Fig. 3.20 (p): IMD GFS MODEL Rainfall forecast based on 1200UTC of 5th December 2017

3.4.6.3. Heavy rainfall forecast by IMD WRF model

Rainfall forecast by IMD WRF based on 0000 & 1200 UTC during 28th -30th November is presented in Fig. 3.21.

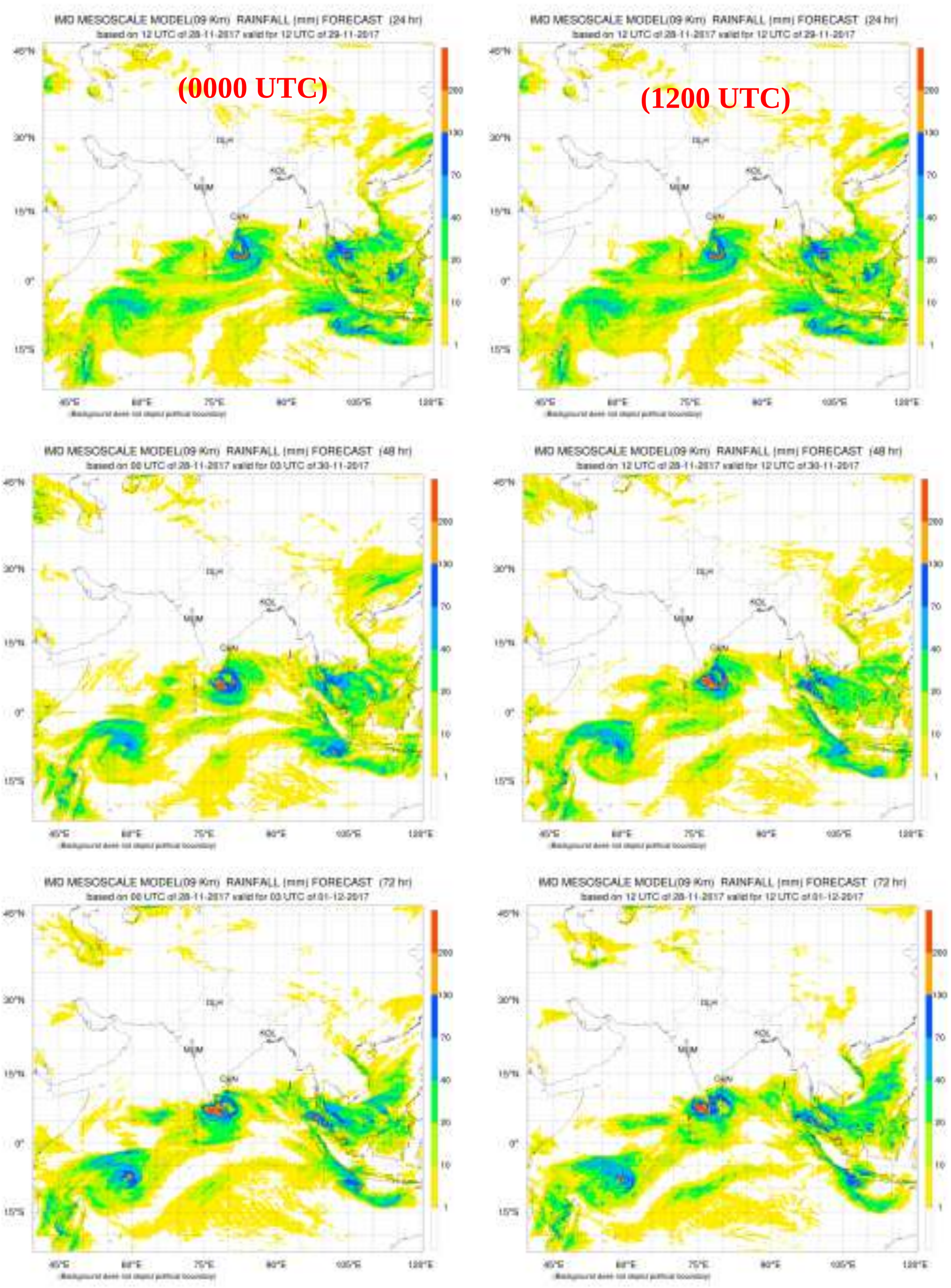


Fig. 3.21 (a) IMD WRF MODEL Rainfall forecast based on 0000UTC and 1200UTC of 28th November 2017

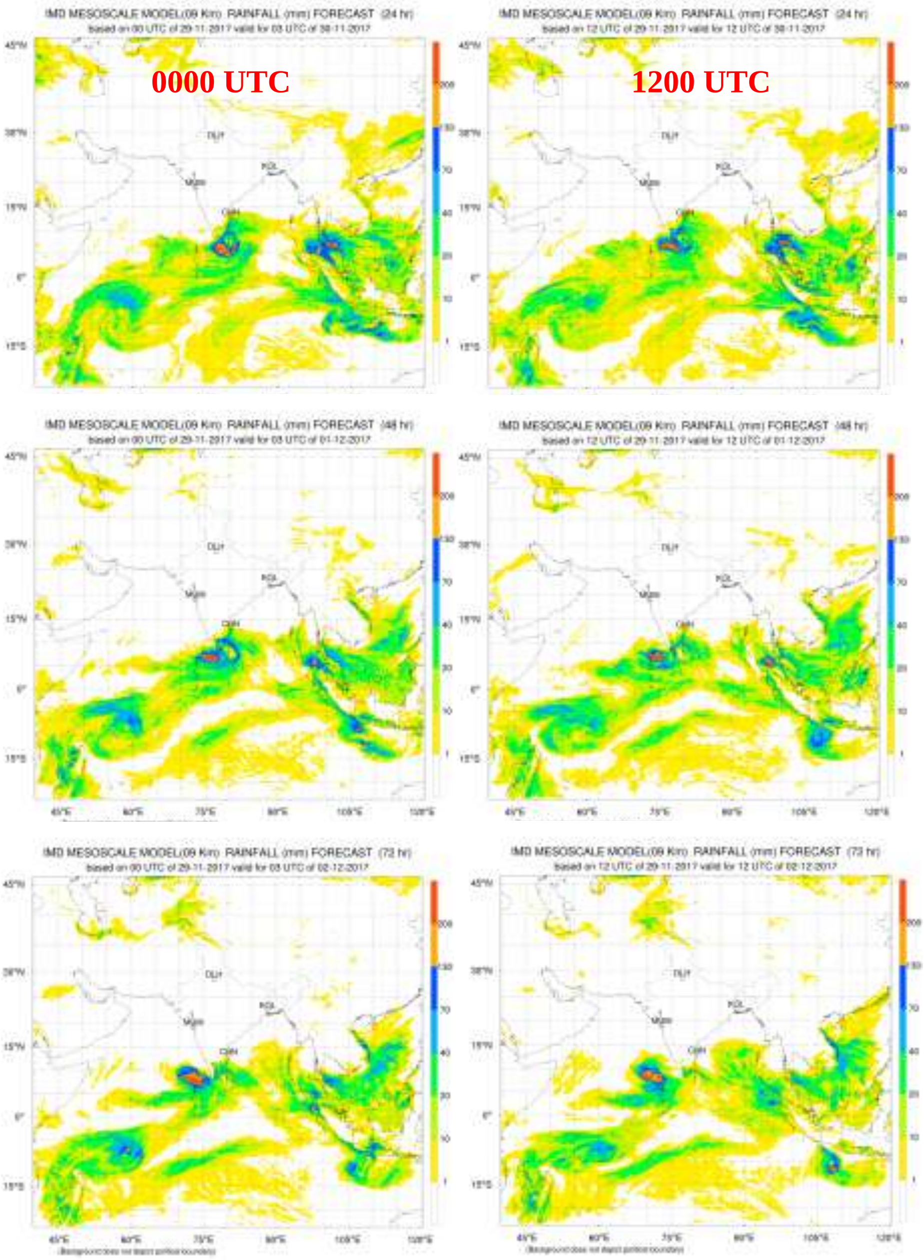


Fig. 3.21 (b) IMD WRF MODEL Rainfall forecast based on 0000UTC and 1200UTC of 29h November 2017

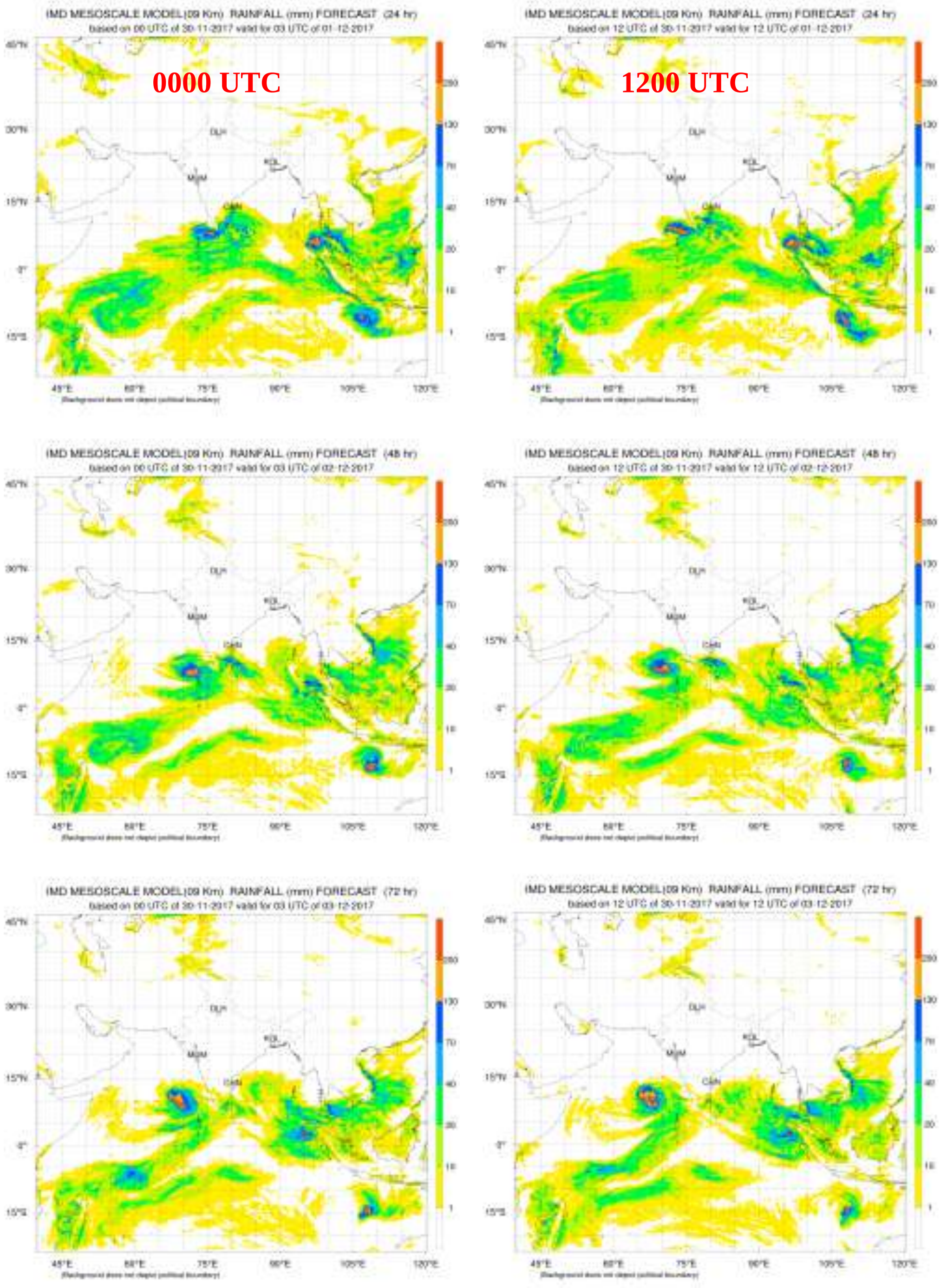


Fig. 3.21 (c): IMD WRF MODEL Rainfall forecast based on 0000UTC and 1200UTC of 30th November 2017

3.4.7. Storm surge forecast

IMD predicted storm surge forecast based on guidance from Indian National Centre for Ocean Information Services (INCOIS) Advance Circulation (ADCIRC) model and Indian Institute of Delhi. First warning of storm surge of height about 1.0 m above astronomical tides likely to inundate low lying areas of Lakshadweep Islands was issued on 1700 hrs IST of 30th.

3.5. Forecast skill of Genesis Potential Parameter (GPP), average track and intensity forecast errors for cyclonic storms over the north Indian Ocean during 2017

3.5.1. Forecast Skill of Genesis potential parameter (GPP) during 2017

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, 2.0) 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 2017 and during 2008-17 Fig. 3.22.

Fig. 3.22.(a) depicts the verification of the GPP forecasts for all cases during 2017. It can be seen from the figure that the POD of the GPP was 1.00, the FAR was 0.22, CSI was 0.78, ETS was 0.37, BIAS was 1.28 and PC was 0.82 for 154 forecast events during 2017. 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 2008-2017 is depicted in the Fig. 3.22.(a) below.

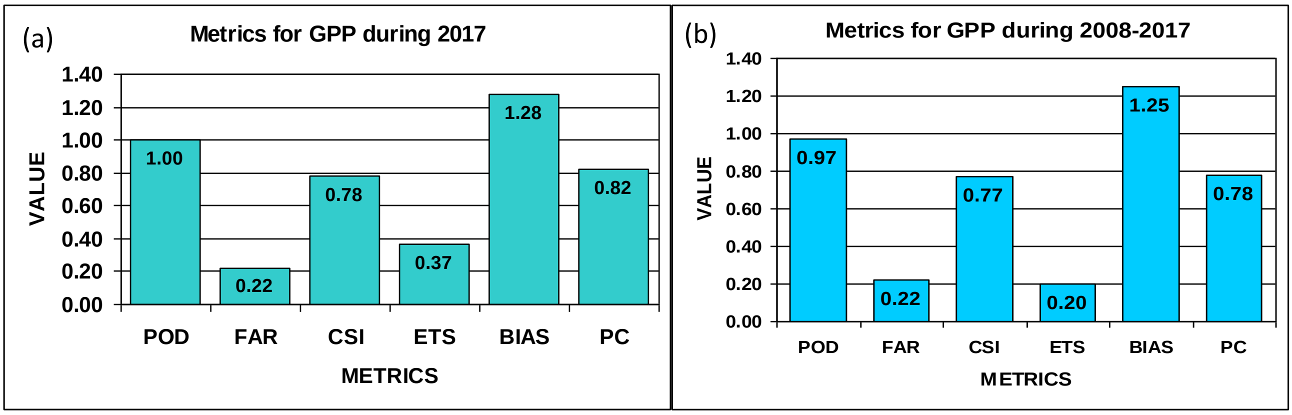


Fig. 3.22. POD, FAR, CSI, ETS, BIAS and PC for all genesis forecasts of GPP during (a) 2017 and (b) 2008-2017

3.5.2. Mean track forecast error (km) – 2017

The annual average track forecast errors (Direct position error (DPE)) of various models during the year 2017 are shown in Table 3.18 (Fig. 3.23). The 24 hr track forecast errors is less than 100 km for all models except WRF, 48 hr track forecast errors is less than 100 km for ECMWF and MME and more than 150 for WRF and IMDHWRF, 72hr track forecast errors is less than 150 km for all models except JMA, UKMO, WRF and IMDHWRF, 96hr track forecast errors is less than 150 km for MME and ECMWF, 120hr track forecast errors is less than 200 km for MME. Track forecast error of HWRF model ranged from 50 km at 12h to 307 km at 84h. Consensus track forecast error of MME ranged from 37 km at 12h to 187 km at 120h. Year wise MME track forecast error (km) during 2009-2017 is shown in Fig 3.24(a) below. Mean MME track forecast error (km) during 2009-2017 (84h to 120h for the period 2013-2017) is presented in the Fig 3.24(b).

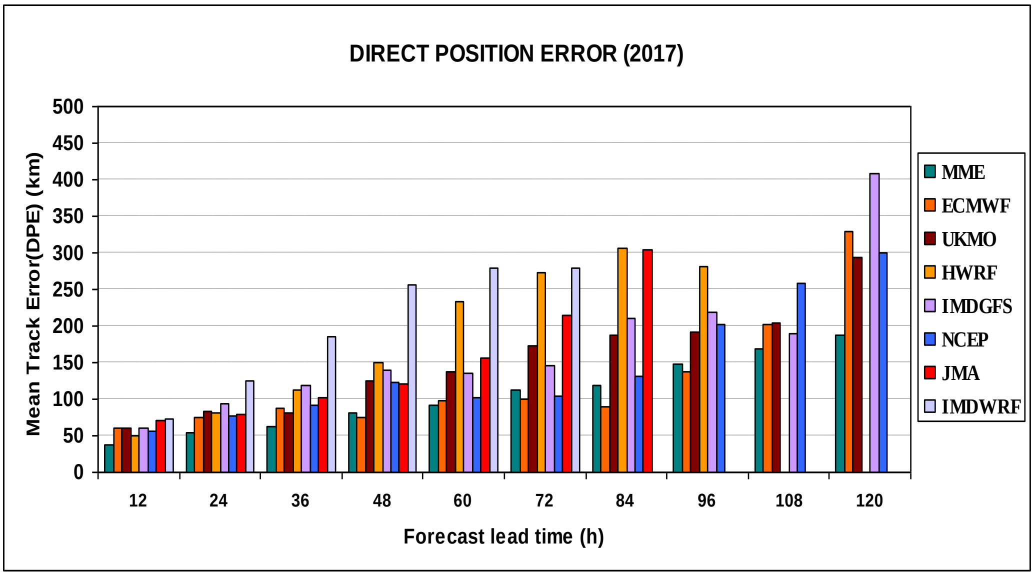


Fig. 3.23. Mean track forecast error (km) during 2017

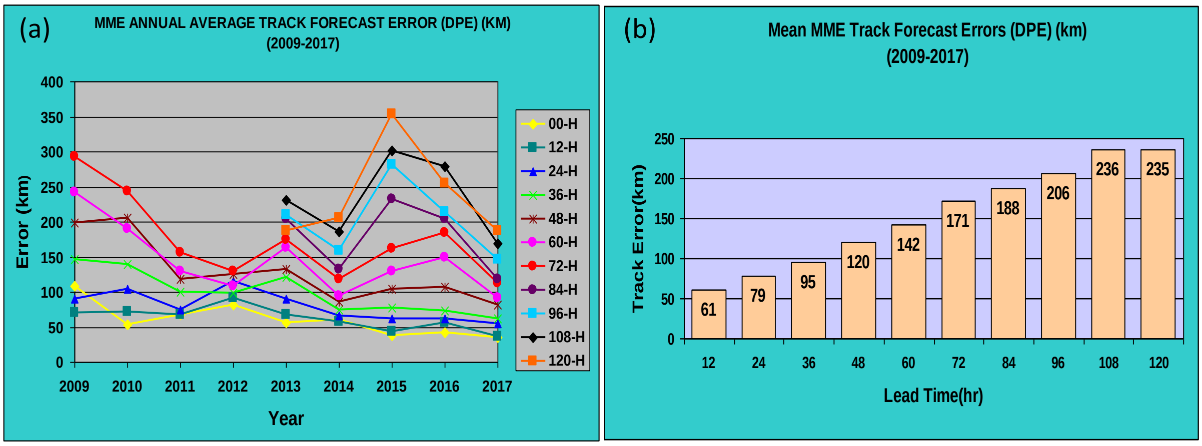


Fig. 3.24 (a): Year wise MME track forecast error (km) during 2009-2017 and (b) Mean MME track forecast error (km) during 2009-2017 (84h to 120h for the period 2013-2017)

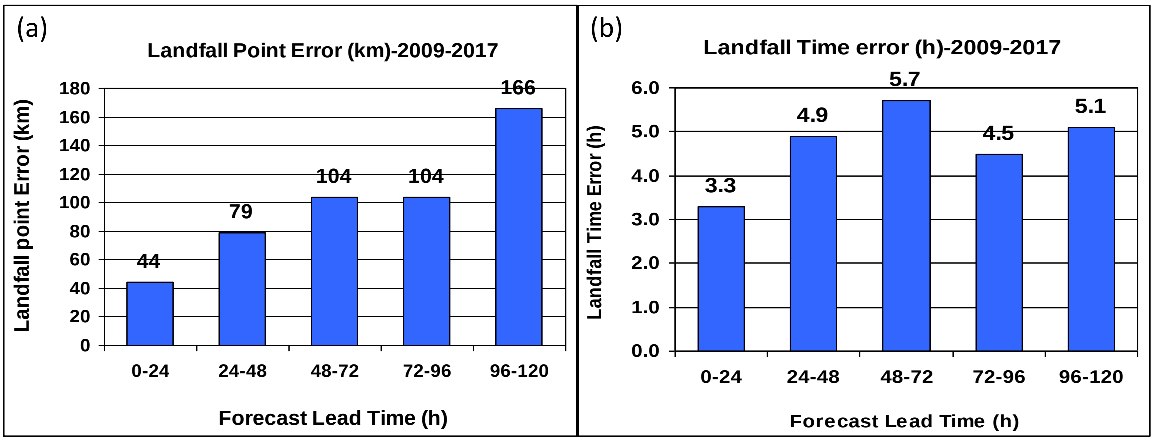


Fig. 3.25: Mean forecast error in (a) landfall point (km) and (b) landfall time (hrs) during 2009-2017

Table-3.18: Annual average track forecast errors (DPE) of various models for the year 2017 (Number of forecast verified given in the parentheses)

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
IMD-GFS	61(18)	94(17)	119(14)	139(11)	136(8)	145(6)	211(5)	218(4)	190(3)	407(2)
IMD-WRF	72(18)	125(17)	185(14)	257(11)	279(8)	278(6)	-	-	-	-
JMA	71(18)	79(17)	103(14)	122(11)	156(8)	215(6)	304(5)	-	-	-
NCEP	57(18)	78(17)	91(14)	123(11)	102(8)	104(6)	131(5)	203(4)	259(3)	301(2)
UKMO	61(18)	83(17)	82(14)	125(11)	138(8)	173(6)	187(5)	191(4)	203(3)	294(2)
ECMWF	60(18)	75(17)	88(14)	75(11)	98(8)	100(6)	90(5)	139(4)	201(3)	329(2)
IMD-HWRF	50(34)	81(30)	113(26)	151(21)	234(16)	272(12)	307(10)	282(8)	-	-
IMD-MME	37(18)	55(17)	62(14)	81(11)	91(8)	112(6)	118(5)	147(4)	169(3)	187(2)

3.5.3 Mean Intensity forecast error (kt) -2017

I. SCIP model -2017

The annual average intensity forecast errors of SCIP model are shown in Table 3.19. The absolute average error(AAE) is 10.1 kts at 24hr, 13.3 kts at 48hr, 9.7 kts at 72hr, 15.3 kts at 96hr and 7.5 at 120 kts for all the cyclonic storms over the North Indian Seas during the year 2017.

Table-3.19: The annual average intensity forecast errors (kt) of SCIP for all the systems during 2017 (Number of forecast verified given in the parentheses)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-SCIP (AAE)	6.7(18)	10.1(15)	11.2(12)	13.3(9)	12.4(7)	9.7(6)	10.4(5)	15.3(4)	13.7(3)	7.5(2)
IMD-SCIP (RMSE)	8.4	12.1	13.4	16.5	14.7	11.2	12.2	17.9	14.8	9.9

Year wise and mean intensity forecast error (kt) by SCIP model during 2008-2017 for 12h to 72h forecasts are presented in Fig. 3.26 and Fig. 3.27 below.

II. HWRF model -2017

The annual average intensity forecast errors (kt) of HWRF model for the systems during 2017 are shown in Table 3.20.

Table-3.20 Average Absolute Error (kt) of INTENSITY of IMD-HWRF Model-2017 (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
AAE	7.7(34)	9.8(30)	8.3(26)	16.4(21)	12.1(16)	11.3(12)	12.9(10)	8.3(8)
RMSE	9.7	11.3	10.1	18.9	16.1	14.4	15.8	11.6

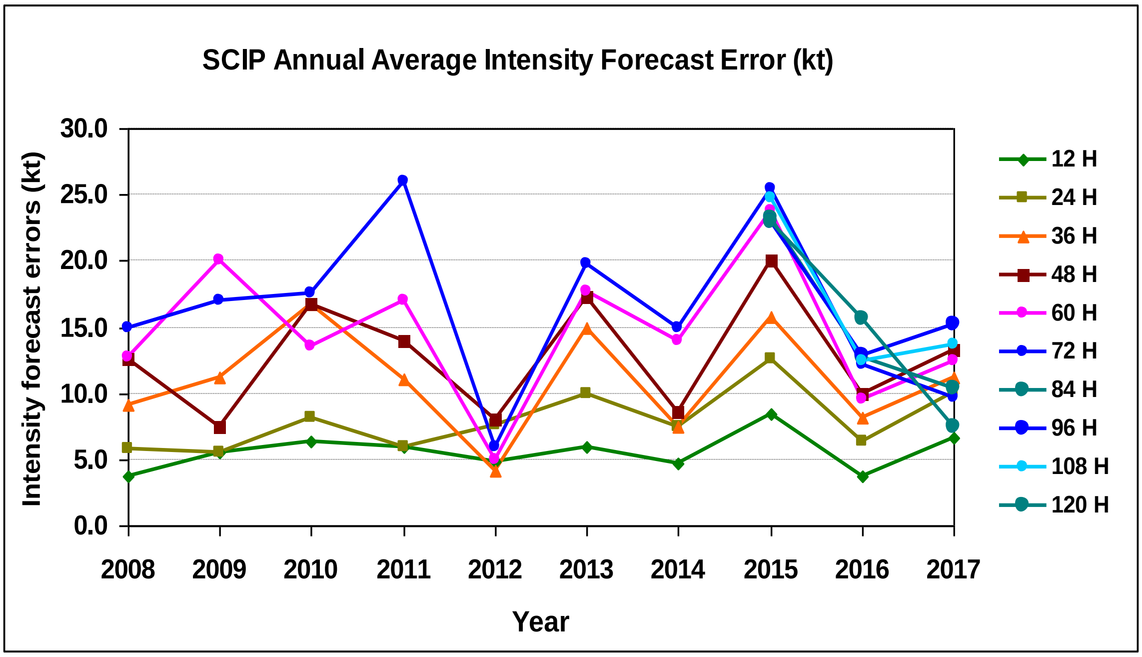


Fig. 3.26: Year wise intensity forecast error (kt) by SCIP model during 2008-2017 for 12h to 120 h forecasts

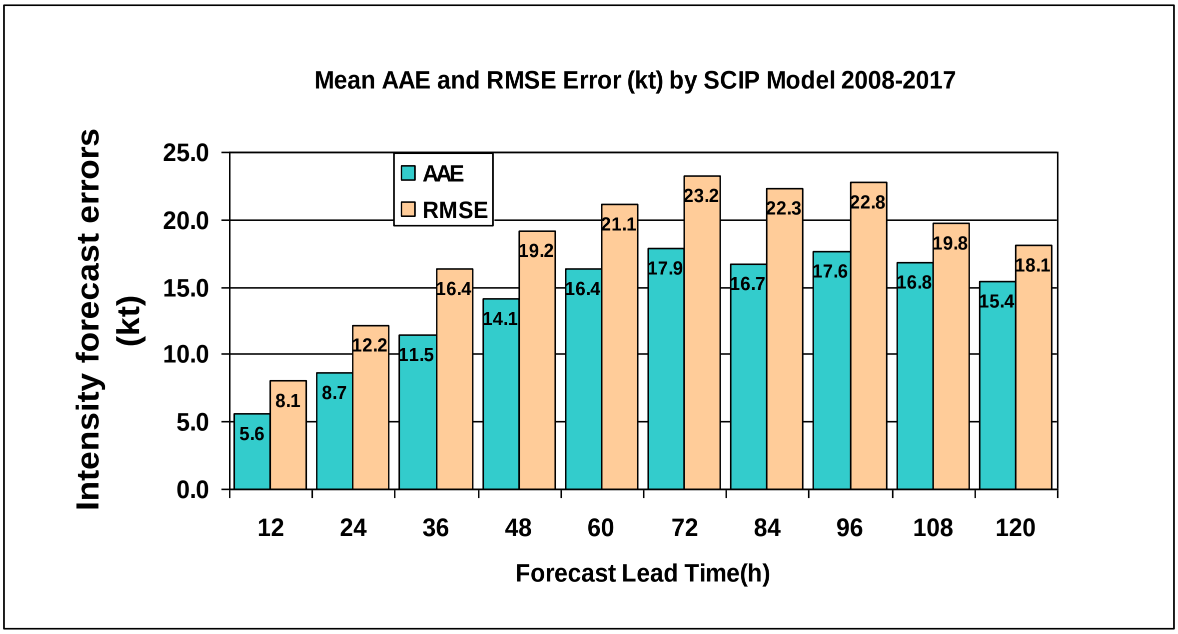


Fig. 3.27: Mean Intensity forecast error (kt) of SCIP model during 2008-2017

CHAPTER-IV

PERFORMANCE OF RSMC, NEW DELHI IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2016

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 2017. 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, Maldives and Yemen during cyclone period. As tropical cyclone advisory centre (TCAC), it also issued tropical cyclone advisories with effect from the stage of deep depression for international civil aviation purpose as per the requirement of international civil aviation organization (ICAO) 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 2017 are analysed and discussed in sec.4.3.

4.2 Bulletins issued by IMD

The following are the statistics of bulletins issued by IMD in association with the cyclonic disturbances during 2017

Bulletins issued during ‘Maarutha'		
Bulletins for national disaster management agencies	:	15
Bulletin for WMO/ESCAP Panel counties		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	16
Tropical cyclone advisory for international civil aviation	:	07
Bulletins issued during ‘Mora’		
Bulletins for national disaster management agencies	:	23
Bulletin for WMO/ESCAP Panel counties		

(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	22
Tropical cyclone advisory for international civil aviation	:	10
Bulletins issued during 'Ockhi'		
Bulletins for national disaster management agencies	:	54
Bulletin for WMO/ESCAP Panel counties		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	52
Tropical cyclone advisory for international civil aviation	:	23
Bulletins issued for all cyclones during 2017		
Bulletins for national disaster management agencies	:	92
RSMC bulletin for WMO/ESCAP Panel member countries		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	90
TCAC bulletin for international civil aviation	:	40
***Bulletins issued for all cyclonic disturbances (depression and above) during 2018**		
Bulletins for national disaster management agencies	:	161
RSMC bulletin for WMO/ESCAP Panel member countries		
(Special Tropical Weather Outlook and Tropical Cyclone Advisory)	:	119
TCAC bulletin for international civil aviation	:	40

The number of bulletins issued during 2009-2017 for all cyclones over the NIO is shown in Fig.4.1 for comparison.

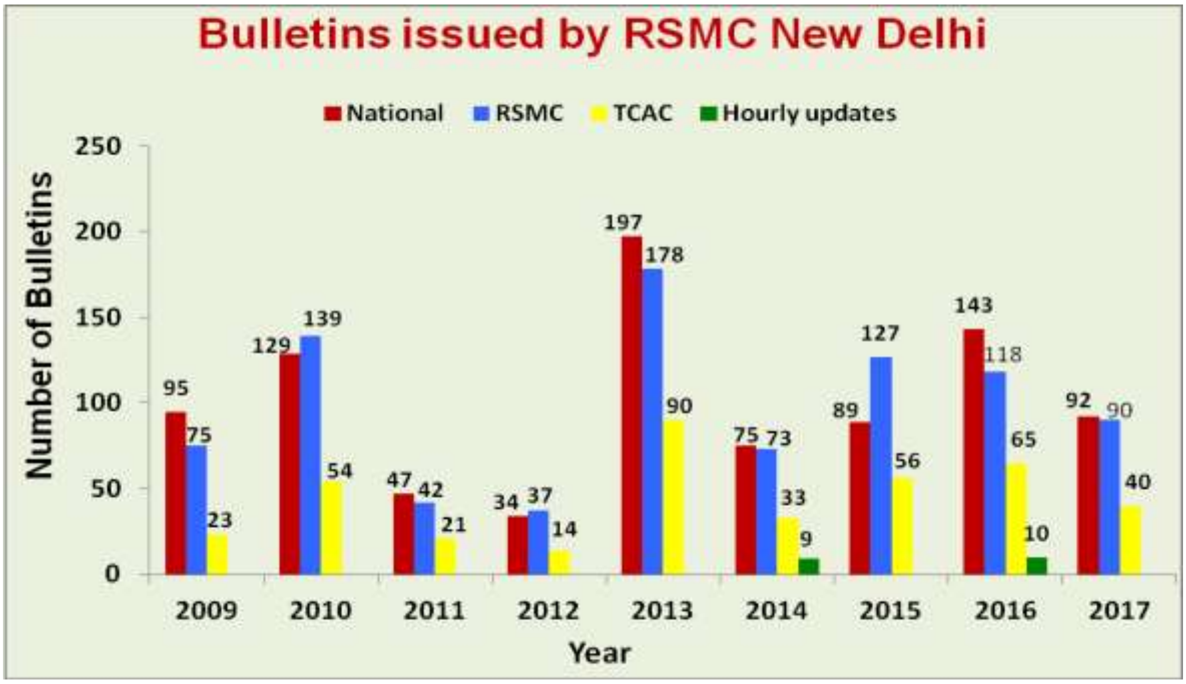


Fig 4.1: Total Number of bulletins issued by RSMC, New Delhi for all cyclones during 2009-2017

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 the three cyclones during 2017 is described in following sections:

4.3.1 Cyclonic storm (CS) Maarutha (17-21 May 2016)

4.3.1.1. Genesis Forecast:

i. The first information regarding formation of a low pressure area over southeast & adjoining eastcentral Bay of Bengal around 14th April was issued in the morning of 12th April and low pressure area developed over southeast BOB and neighbourhood in the evening of 13th (about 36 hrs in advance of formation of low pressure area).

ii. The first information regarding formation of depression over southeast BOB on 15th April was issued by IMD on 13th morning and depression formed over southeast BOB in the morning of 15th (48 hours in advance of formation of depression).

4.3.1.2. Operational landfall forecast error and skill

i. In it's first bulletin based on 0000 UTC of 15th April, RSMC New Delhi indicated the nearly northeastward movement of system towards Myanmar coast (42 hours prior to landfall).

ii. The first bulletin indicating movement of cyclone north-northeastwards and landfall over Myanmar coast between Sittwe and Sandoway (Thandwe), Myanmar by forenoon of 17th April was given on 0300 UTC of 15th (39 hours prior to landfall).

iii. The first bulletin indicating landfall near Sandoway (Thandwe), Myanmar around midnight of 16th April was given on 0000 UTC of 17th and system crossed Myanmar coast near Sandoway (Thandwe) between 1800 and 1900 UTC of 17th (18 hours prior to landfall).

iv. There was almost zero error in landfall point forecast issued 12 hrs before landfall and about 41 km and 60 km respectively in the forecast issued 24 and 36 hrs before landfall.

The operational landfall forecast errors and skill are presented in Table 4.1. The landfall point error (LPE) has been about 3, 41 and 60 km against long period average (LPA) based on 2012-16 of 27, 36 and 57 km for 12, 24 and 36 hours lead period respectively. For 12 hour lead period, the landfall point error was almost zero. The landfall time error (LTE) has been 2.0, 0.5 and 6.5 hours against the LPA of 2.4, 4.2 and 4.3 hours for 12, 24 and 36 hours lead period respectively.

Table 4.1: Landfall Point and Time Error in association with CS Maarutha

Lead Period (hrs)	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Operational Error		LPA error (2012-16)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	16/0600	18.47/94.30	18.44/94.31	16/1630	16/1830	3	2.0	27.2	2.4
24	15/1800	18.79/94.17	18.44/94.31	16/1900	16/1830	41	0.5	35.8	4.2
36	15/0600	18.92/94.06	18.44/94.31	17/0100	16/1830	60	6.5	56.9	4.3

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

The landfall point and time could not be predicted beyond 36 hours as the life of the system from DD to landfall was about 33 hours.

4.3.1.3 Operational track forecast error and skill

The operational average track forecast errors and skills (compared to climatological and persistence (CLIPER) forecasts) are shown in Table 4.2. The track forecast errors for 12, 24 and 36 hours lead period have been 32, 33.5 and 110.5 km against the long period average (LPA) of 59.7, 97.2 and 119.4 km respectively. The track forecast errors have been significantly lower than the LPA for all lead periods. The skill in operational track forecast compared to CLIPER forecast has also been higher than long period average for all lead periods. The track forecast skill was about 56%, 82% and 59% for 12, 24 and 48 hrs lead period respectively, which are higher than the long period average (LPA) during 2012-16 for 12 and 24 hrs lead period.

Table 4.2: Average Track forecast error in association with CS Maarutha

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2012-16)	
				Track forecast error (km)	Skill (%)
12	5	32.0	56.0	59.7	43.7
24	3	33.5	82.3	97.2	53.6
36	1	110.5	59.3	119.4	63.4

4.3.1.4 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 4.3. The operational AE in intensity forecast has been significantly less than LPA as it was about 3.6, 2.3 and 15.1 knots against the LPA (2012-16) of 6.5, 10.7 and 13.8 knots respectively for 12, 24 and 36 hrs lead period. Similarly, operational RMSE in intensity forecast has been about 5.0, 2.4 and 15.1 knots against LPA of 9.0, 14.4 and 18.5 knots for 12, 24 and 36 hours lead period respectively.

Table 4.3: Average Intensity forecast error in association with CS Maarutha

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2012-16)	
		AE	RMSE	AE	RMSE	AE	RMSE
12	5	3.6	5.0	60.4	53.5	6.5	9.0
24	3	2.3	2.4	87.2	90.1	10.7	14.4
36	1	15.1	15.1	39.5	39.5	13.8	18.5

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average

4.3.1.5. Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 4.4-4.6. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 4.4: Verification of Heavy Rainfall Forecast

Date & Time	**Heavy rainfall warning issued**	**24-hour Heavy rainfall realised ending at 0300 UTC of date**
15.04.2017 0300 UTC	Rainfall at most places with heavy rainfall at isolated places very likely to occur over Andaman Islands during next 24 hrs and isolated heavy rainfalls during subsequent 24 hours.	Andaman & Nicobar Islands: Maya Bandar-4, Port Blair-2
16.04.2017 0300 UTC	Light to moderate (upto 3 cm) rainfall at many places very likely to occur over Andaman Islands during next 12 hrs.	Andaman & Nicobar Islands:: Long Island-5, Hut Bay-4, Port Blair-4, Maya Bandar-4, IAF Carnicobar-2

Table 4.5 (a): Verification of Gale Wind Forecast

Date/ Time(IST)	**Sqall/ Gale wind Forecast**	**Recorded wind speed (knots)**
15.04.2017 0300 UTC	Squally winds speed reaching 50-60 kmph gusting to 70 kmph would prevail over Andaman Islands and adjoining Sea areas during next 48 hours.	40-50 kmph
16.04.2017 0300 UTC	Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail over Andaman Islands and adjoining Sea areas during next 12 hours.	

Table 4.5 (b): Gale Wind Frecast verfication at the time of landfall over Myanmar:

S.No.	**Lead Period**	**Forecast Wind**	**Estimated Wind**	**Error(Estimated-Forecast)**
1.	**12**	**35 kts**	**40 kts**	**+5 kts**
2.	**24**	**43 kts**	**40 kts**	**-3 kts**
3.	**36**	**38 kts**	**40 kts**	**+2 kts**

Sandoway reported maximum sustained wind (MSW) of 35 knots at the time of landfall.

Table 4.6: Verification of Storm Surge Forecast issued by IMD

Forecast Storm surge above astronomical tide and area to be affected	**Actual Storm Surge**
0300 UTC of 16 April The storm surge of about one meter height above the astronomical tide is very likely to inundate the low lying areas of Myanmar coast near landfall point at the time of landfall. 1200 UTC of 16 April The storm surge of about one to two meter height above the astronomical tide is very likely to inundate the low lying areas of Myanmar coast near landfall point at the time of landfall.	Not reported

4.3.2. Severe Cyclonic Storm ‘Mora’ over the Bay of Bengal (28-31 May 2017)

4.3.2.1 Operational Genesis forecast

(i) The first information regarding formation of a low pressure area over southeast & adjoining central Bay of Bengal was issued in the morning of 25th May.

(ii) The first information regarding formation of depression over southeast BOB during next 48 hours (i.e. 28th May) was issued on 26th May and depression formed over southeast BOB in the morning of 28th (48 hours in advance of formation of depression).

4.3.2.2. Operational landfall forecast error and skill

The operational landfall forecast errors and skill are presented in Table 12. The landfall point error (LPE) has been about 35, 59 and 00 km against long period average (2012-16) of 36.3, 56.3 and 60.6 km respectively for 12, 24 and 36 hrs lead period of forecast and landfall time forecast error was almost nil for all the above forecast times.

Observed track alongwith forecast tracks based on different lead periods is presented in **Fig.4.2**. It indicates that for all lead periods, the operational forecast of track was highly consistent and was along the observed track. An example of forecast track along with cone of uncertainty and quadrant wind distribution around the centre of cyclone issued on 0000 UTC of 11th December and observed track is presented in **Fig.4.3**.

. **Table 4.6: Landfall Point and Time Error in association with SCS Mora**

Lead Period (hrs)	Base Time (UTC)	Landfall Point (^{0}N/^{0}E)		Landfall Time (UTC)		Operational Error		LPA error (2012-16)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	29/1500	22.3/91.8	22.0/91.9	30/0430	30/0430	35	0.0	36.5	2.5
24	29/0300	22.5/91.7	22.0/91.9	30/0500	30/0430	59	0.5	56.3	4.2
36	28/1500	22.3/91.8	22.0/91.9	30/0400	30/0430	00	0.5	60.6	4.7
48	28/0300	22.5/91.7	22.0/91.9	30/0900	30/0430	59	4.5	93.5	4.7

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
Forecast is verified upto 48 hrs only due to short life period of the cyclone

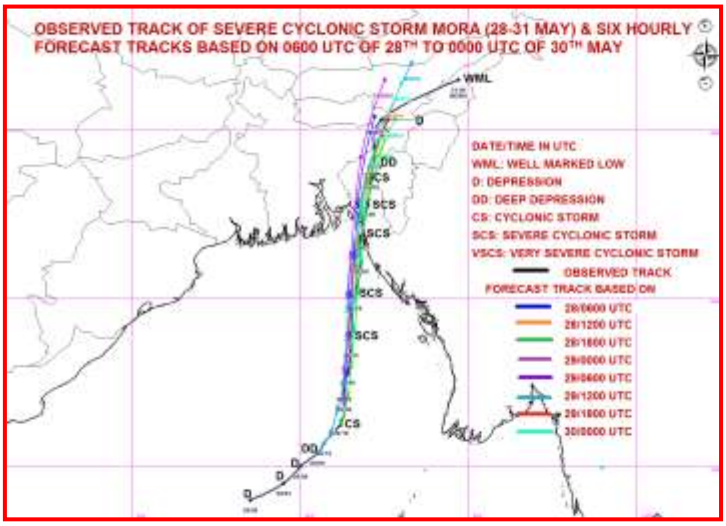


Fig.4.2: Observed and forecast tracks of SCS, MORA

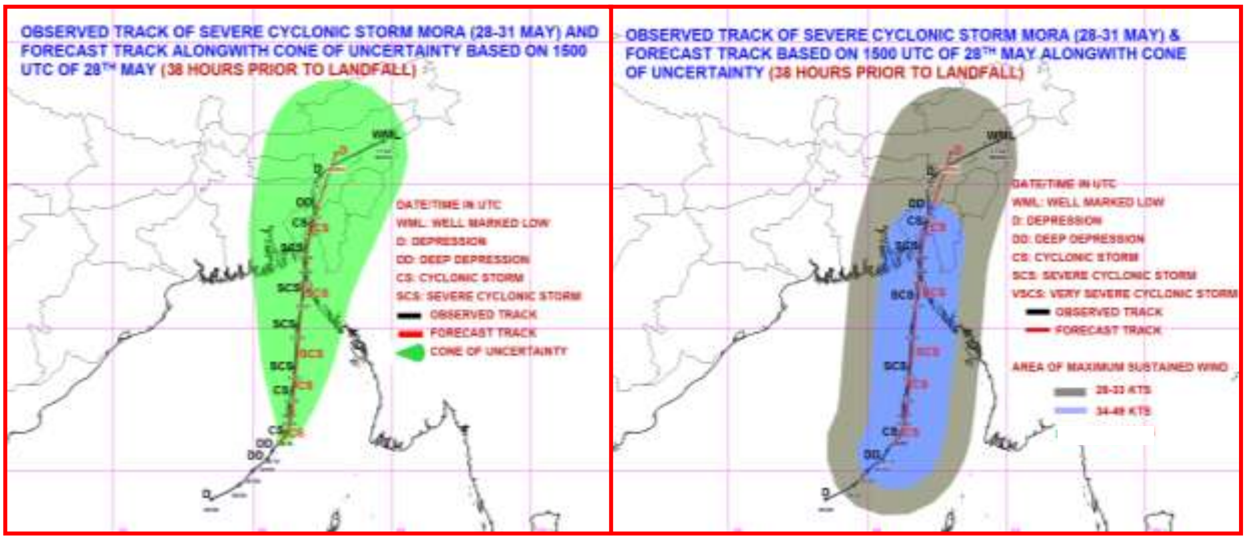


Fig.4.3: Observed track of SCS Mora (28-31 May, 2017) and forecast track based on 1500 UTC of 18th May alongwith (a) Cone of uncertainty and (b) Quadrant wind distribution

4.3.2.3 Operational track forecast error and skill

The operational average track forecast errors and skills (compared to climatological and persistence (CLIPER) forecasts) are shown in Table 13. The track forecast error for 12, 24 and 48 hrs lead period were 27, 22 and 73 km respectively against the last five years (2012-2016) average (LPA) track forecast error of 60, 97 and 149 km. The track forecast skill was about 64%, 87% and 86% for 12, 24 and 48 hrs lead period respectively against the last five years (2012-2016) average track forecast skill of 44%, 54% and 67% (Table 4.7). It may be mentioned here that for all lead periods, the errors were significantly less as compared to LPA and skills were exceptionally better.

Table 4.7: Average Track forecast error in association with SCS Mora

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2012-16)	
				Track forecast error (km)	Skill (%)
12	8	27.2	63.6	59.7	43.7
24	6	22.5	86.7	97.2	53.6
36	4	34.3	88.2	119.4	63.4
48	2	73.5	86.0	149.1	67.2

N: No. of observations verified, LPA: Long Period Average (2012-16)
Forecast verified upto 48 hours due to short life period of system.

4.3.2.4 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 4.8. The operational AE in intensity forecast has been significantly less than LPA as it was about 2.1, 3.0 and 3.4 knots against LPA of 6.5, 10.7 and 13.8 knots for 12, 24 and 48 hours lead period. Similarly, operational RMSE in intensity forecast has been about 2.3, 3.6 and 3.8 knots against LPA of 9.0, 14.4 and 20.8 knots for 12, 24 and 48 hours lead period respectively. The skill in intensity forecast with reference to AE is about 83.4%, 84.8% and 93.3% for 12, 24 and 48 hours lead period.

Table 4.8: Average Intensity forecast error in association with SCS Mora

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2012-16)	
		AE	RMSE	AE	RMSE	AE	RMSE
12	8	2.1	2.3	83.4	88.1	6.5	9.0
24	6	3.0	3.6	84.8	87.4	10.7	14.4
36	4	10.8	12.5	64.0	64.7	13.8	18.5
48	2	3.4	3.8	93.3	92.9	15.5	20.8

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2012-16). Forecast verified upto 48 hours due to short life period of system.

4.3.2.5. Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 4.9-4.11. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 4.9: Verification of Heavy Rainfall Forecast

<table>
<tr><th>Date/Time (UTC) of issue</th><th>Heavy rainfall warning for the date</th><th>Realised 24-hour heavy rainfall ending at 0300 UTC of date</th></tr>
<tr><td>28.05.2017
0300</td><td>30th May 2017: Heavy to very heavy rainfall at isolated places over south Assam, Meghalaya, Tripura and Mizoram; and heavy rainfall at isolated places over Arunachal Pradesh and Nagaland.
31st May 2017: Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall over Assam & Meghalaya. Heavy to very heavy rainfall at isolated places over Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.</td><td rowspan="2"><u>31.05.2017</u>
Arunachal Pradesh: Pasighat AERO and Basar-8 each
Assam & Meghalaya: Halflong and B P Ghat-11 each, Lumding-10, Shillong C.S.O.-9, Lakhipur-8 and Karimganj, Chauldhowaghat, Matijuri, Barpathar, Jia Bharali N T Xing and N.Lakhimpur/Lilabari-7 each
Nagaland, Manipur, Mizoram & Tripura: Lunglei and Serchip (Hydro)-10 each and Kohima-7.</td></tr>
<tr><td>29.05.2017
0300</td><td>29th May 2017: Heavy rainfall at isolated places to commence over Tripura and Mizoram from today evening, the 29th May, 2017.
30th May 2017: Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall over Assam & Meghalaya. Heavy to very heavy rainfall at isolated places over Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.
31st May 2017: Heavy to very heavy rainfall at isolated places over Assam & Meghalaya, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.</td></tr>
</table>

30.05.2017 0300	**30th May 2017**: Heavy to very heavy rainfall at a few places and isolated extremely heavy rainfall over Assam & Meghalaya. Heavy to very heavy rainfall at isolated places over Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh. **31st May 2017**: Heavy to very heavy rainfall at isolated places over Assam & Meghalaya, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh.	**<u>01.06.2017</u>** **Arunachal Pradesh:** Roing-11 **Assam & Meghalaya:** Karimganj-9, A P Ghat-8, Mawsynram, Cherrapunji (RKM), Cherrapunji & Silchar-7 each **Manipur, Mizoram & Tripura:** Agartala AERO-13 Kailashahar AERO-10
31.05.2017 0000	Heavy to very heavy rainfall at isolated places very likely over south and eastern Assam, eastern Meghalaya, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh during next 24 hours.	

Table 4.10. Verification of Gale Wind Forecast

Date/ Time(UTC)	**Squally wind Forecast**	**Recorded wind speed**
28.05.2017 0300	Squally winds speed reaching 40-50 kmph gusting to 60 kmph would prevail along & off Andaman Islands and adjoining Sea areas during next 48 hours. Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail over South Assam, Meghalaya, Mizoram, Manipur and Tripura on 30th May and along & off West Bengal coast on 29th & 30th.	Aizawl/ Lengpui : 35 knots on 30th May 2017
29.05.2017 0300	-do-	
30.05.2017 0300	Squally winds speed reaching 60-70 kmph gusting to 80 kmph would prevail over Mizoram and Tripura during next 24 hours. Squally winds speed reaching 45-55 kmph gusting to 65 kmph would prevail over South Assam, Meghalaya & Manipur and along & off West Bengal coast during next 24 hours.	

Table 4.11: Verification of Storm Surge Forecast issued by IMD

Date/ Time(UTC)	**Storm Surge Forecast**	**Recorded storm surge**
29.05.2017 0300 (21 hours in advance)	The storm surge of height of about 1 to 1.5 meter above astronomical tides is likely to inundate over low lying areas of Bangladesh coast between Sitakund and Uttar Jaldi at the time of landfall.	Not received

4.3.3 Very Severe Cyclonic Storm "Ockhi" over Bay of Bengal (29 Nov–06 Dec 2017)

4.3.3.1 Operational Genesis forecast

- The first information regarding formation of depression during next 48-72 hours (i.e. 29th onwards) was issued on 28th November in the Tropical Weather Outlook issued at 1200 hours IST. The system developed into a depression in the forenoon of 29th.
- In the first bulletin based on 1150 IST of 29th Nov, IMD, New Delhi indicated the west-northwestward movement of system and its emergence into Comorin area by 30th. It was also mentioned that the system would intensify further. The system emerged into Comorin Area during night of 29th and intensified into Deep Depression in the early hrs (0230 IST) of 30th and into Cyclonic Storm in the forenoon (0830 IST) of 30th Nov. 2017.

4.3.3.2. Operational track forecast error and skill

- The west northwestward movement towards Lakshadweep was predicted in the first bulletin itself issued at 0830 hrs IST of 29th Nov.
- The observed and forecast track with cone of uncertainty issued for (a) Kerala, Tamil Nadu, Lakshadweep and (b) Gujarat coast are shown in **Fig.4.4 and 4.5.**
- The track forecast error for 12, 24, 48 and 72 hrs lead period were 52.4, 77.2, 111.9 and 189.6 km respectively, which is significantly less than the average track forecast errors of 59.7, 97.2, 149.1 and 202.8 km during last five years (2012-16). The track forecast skill was about 45%, 61%, 76% and 69% for 12, 24, 48 and 72 hrs lead period respectively, which are higher than the long period average (LPA) during 2012-16 for 12 and 24 hrs lead period (**Fig.4.6**).

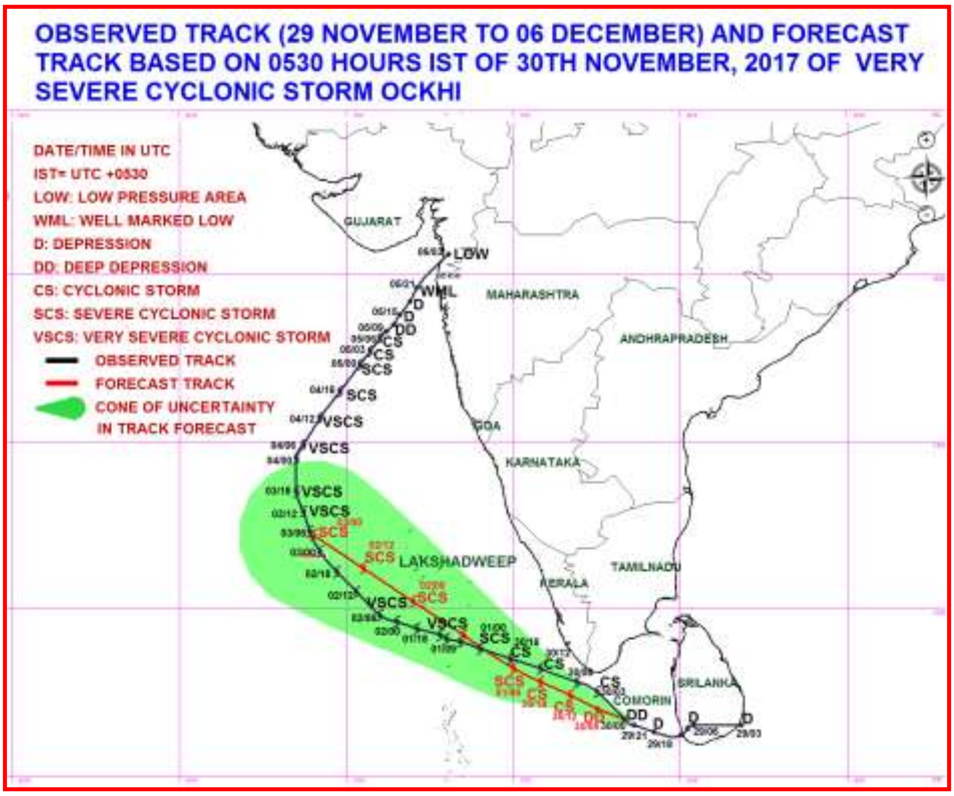


Fig.4.4: Observed and forecast track with cone of uncertainty issued for Kerala, Tamil Nadu, Lakshadweep

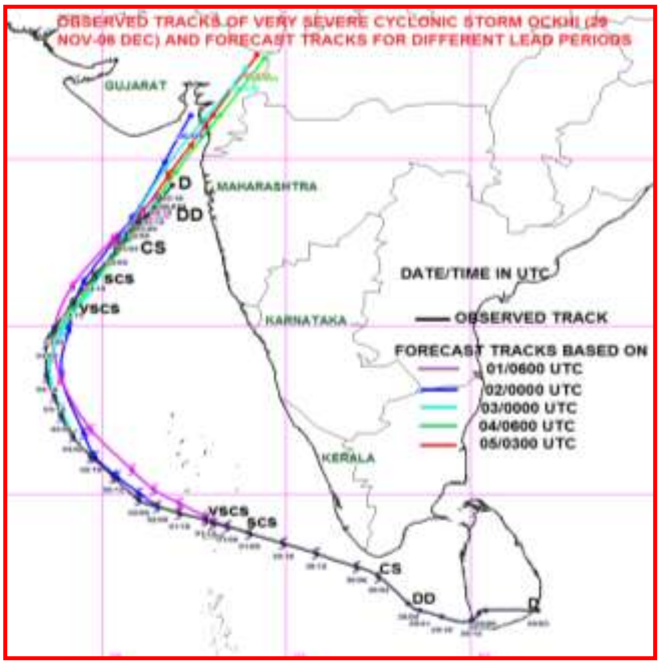


Fig.4.5: Typical graphical products displaying observed and forecast track for movement towards Gujarat coast

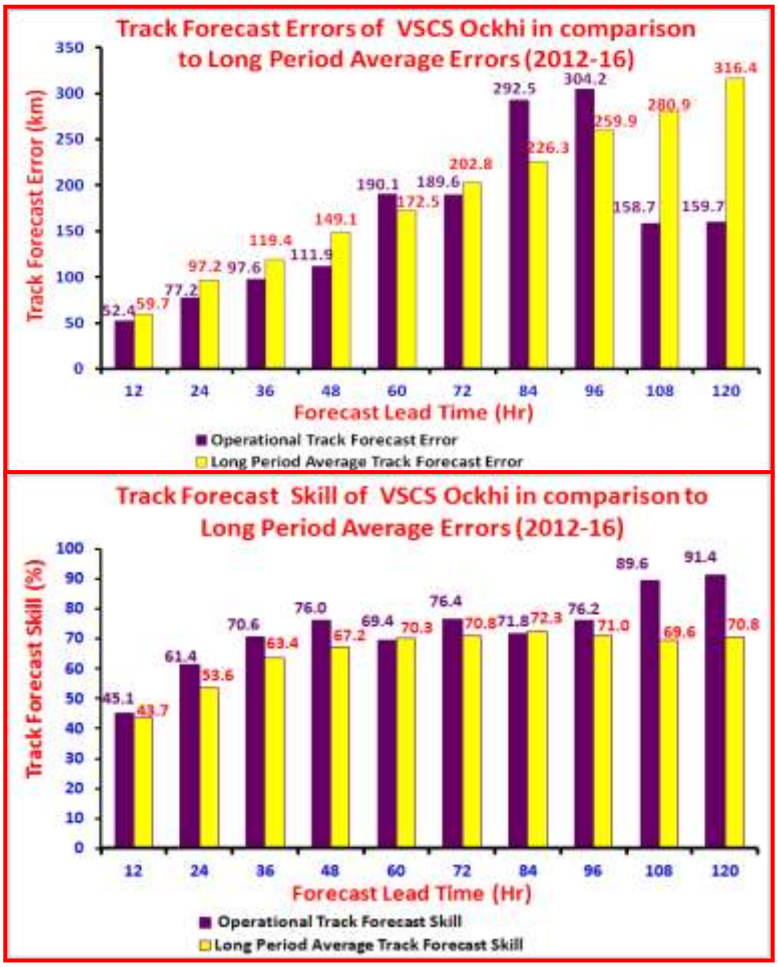


Fig.4.6: Track Forecast Errors and Skill of VSCS Ockhi

4.3.3.3: Operational Intensity forecast error and skill

- First wind warning for 45-55 kmph gusting to 65 kmph for south Kerala, south Karnataka and Lakshadweep was first issued at 1150 hrs IST of 29th November.
- It was increased gradually with expected intensification of the system
- Thiruvananthapuram recorded 62 kmph in gustiness at 1300 IST of 30th Nov. The threshold wind speed of 45 kmph was recorded over Thiruvananthapuram from 1230 IST of 30th Nov. Onwards **(Fig.4.7).**
- Maximum wind 120-130 kmph gusting to 145 kmph prevailed over northern parts of Lakshadweep
- First wind warning for 40-50 kmph gusting to 60 kmph for south Gujarat and north Maharashtra coast on 5th Dec. was first issued at 1700 hrs IST and 1930 hrs IST of 2nd Dec. The actual wind along these coasts has been 30-40 kmph.
- The absolute intensity (wind) forecast error for 12, 24, 48 and 72 hrs lead period were 5.4, 7.0, 13.5 and 16.4 knots against the LPA of 6.5, 10.7, 15.5 and 16.3 knots respectively. The skill in absolute intensity (wind) forecast for 12, 24, 48 and 72 hrs lead period was 26.6, 48.4, 61.0 and 75.7% against the LPA of 18.2, 35.2, 55.7 and 66.8% respectively. (**Fig.4.8**).

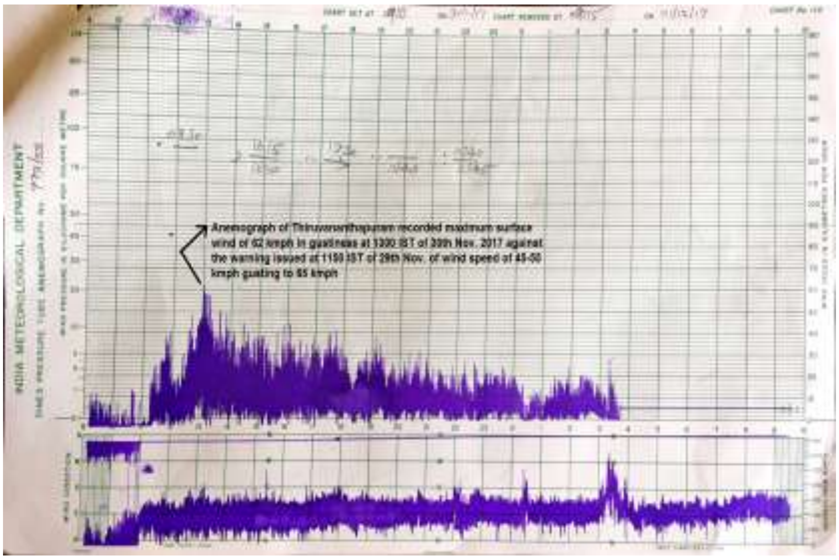


Fig.4.7: Anemograph record of 30th November over Thiruvananthapuram.

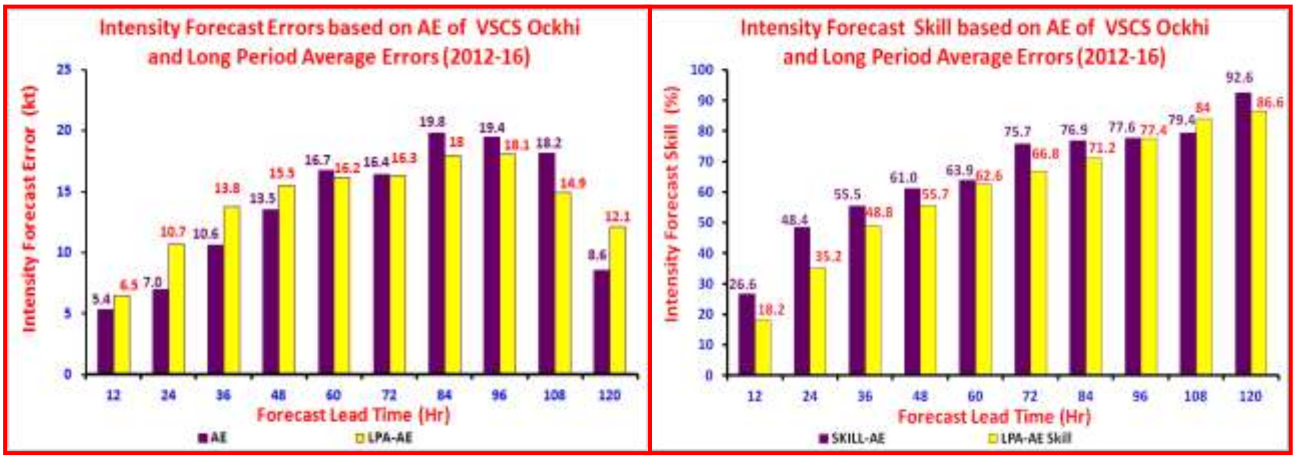


Fig. 4.8: Absolute Error (AE) of intensity forecast and skill of IMD for VSCS Ockhi

4.3.3.4: Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD at 0300 UTC during 30^{th} November to 6^{th} December are presented in Table 4.12-4.14. It is found that all the three types of adverse weather were predicted accurately and well in advance.

- Heavy rainfall warning for south Kerala, south Tamil Nadu and Lakshadweep was first issued at around noon of 28^{th} November for occurrence during next 72 hours.
- Heavy rainfall warning for south coastal Gujarat was first issued at 1700 hrs IST of 2^{nd} December for occurrence on 5^{th} December.
- Heavy rainfall warning for north coastal Maharashtra was first issued at 1330 hrs IST of 2^{nd} December for occurrence from 4^{th} night during subsequent 48 hours.
- It caused isolated heavy rainfall over south Tamil Nadu on 28^{th} and 29^{th} and scattered heavy to very heavy rainfall and isolated extremely heavy rainfall over south Tamil Nadu on 30^{th} Nov. and 1^{st} & 2^{nd} Dec. It caused isolated heavy rainfall over south Kerala on 29^{th} Nov. and 1^{st} Dec. and heavy to very heavy rainfall on 30^{th} Nov. It caused heavy to very heavy rainfall over Lakshadweep on 01^{st} and 2^{nd} Dec. There was heavy rainfall over north coastal Maharashtra and adjoining south coastal Gujarat on 5^{th} Dec.

Table – 4.12 Verification of Heavy Rainfall Forecast

<table>
<tr><th>Date/Time of issue (base time (hours IST)</th><th>Heavy rainfall warning for the date</th><th>Realised 24-hour heavy rainfall ending at 0300 UTC of date</th></tr>
<tr><td>29.11.2017
1150 (0830)</td><td>• Heavy to very heavy rainfall at isolated places is very likely over south Tamil Nadu during next 48 hours.
• Heavy rainfall at isolated places during next 24 hours and isolated heavy to very heavy rainfall during subsequent 24 hours over south Kerala.
• Heavy to very heavy rainfall at isolated places is very likely over Lakshadweep islands on 1st and 2nd December.</td><td rowspan="2"><u>27 November 2017</u>

Tamil Nadu & Puducherry: Rameswaram-14, Chembarabakkam-12, Chembarambakkam ARG-11, Chennai & Sirkali-10 each, Kancheepuram-9, Vedaranyam-8, Poonamalle ARG, Kolapakkam ARG, Chidambaram, Poonamallee, Anaikaranchatram, Kollid and Anna University-7 each.
South Interior Karnataka:-Imangala ARG-100
Kerala:-Kollam RLY-7

<u>28 November 2017</u>
Kerala:-Piravam-7

<u>29 November 2017</u>
Tamilnadu & Puducherry:-Nannilam-7

<u>30 November 2017</u>
Tamil Nadu & Puducherry: Vallam, Thuckalay and Pondicherry-7 each
Kerala: Aryankavu-15</td></tr>
<tr><td>30.11.2017
1200 (0830)</td><td>• Heavy to very heavy rainfall at isolated places very likely over south Tamil Nadu & south Kerala during next 24 hours and isolated heavy falls over interior Tamil Nadu and Kerala during subsequent 24 hours.
• Heavy to very heavy rainfall at a few places and isolated extremely heavy falls very likely over Lakshadweep area during next 48 hours.</td></tr>
</table>

<table>
<tr>
<td>01.12.2017
1130 (0830)</td>
<td>• Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (>20 cm) very likely over Lakshadweep area during next 24 hours and isolated heavy to very heavy falls during subsequent 24 hours.
• Heavy rainfall at isolated places very likely over Kerala during next 24 hours.</td>
<td rowspan="4"><u>1 December 2017</u>
Tamil Nadu & Puducherry: Papanasam (District: Tirunelveli)-45, Manimutharu-38, Mylaudy-19, Thenkasi-17, Thuckalay, Pechiparai, Gudalur & Bhoothapandy-16 each, Watrap-15, Maniyachi, Eraniel & Colachel-14 each, Nagercoil, Kodaikanal & Coonoor PTO-13 each, Kuzhithurai, Srivilliputhur, Satankulam, Shencottah, Ayikudi, Coonoor, Samayapuram & Srivaikuntam-12 each, Ottapadiram, Tiruchendur & Kovilpatti AWS-11 each, Tuticorin, Ambasamudram, Uttamapalayam & Kanyakumari-10 each, Radhapuram, Polur, Kovilpatti, Madavaram AWS, Sankarankoil & Sattur-9 each, Arani, Sivaganga, Sivagiri, Uthiramerur, Rajapalayam, Anna University, Grand Anaicut, Uthagamandalam, Chembarabakkam & DGP Office-8 each and Musiri, Vadipatti, K.Paramathi, Karur, Vilathikulam, Anna UTY ARG, Lalgudi, Ambur, Padalur, Panchapatti, Mayanur, Thamaraipakkam, K Bridge, Cholavaram, Nanguneri, Periyakulam, Kalugumalai & Chennai(N)-7 each
Kerala: Aryankavu-26, Myladumpara AGRI-12, Varkala & Punalur-9 each and Trivandrum AERO &, Neyyattinkara-8 each
Lakshadweep: Minicoy-19.

<u>2 December 2017</u>
Tamil Nadu & Puducherry: Sathanur Dam-23, Sirkali-19, Chidambaram & Anaikaranchatram (Kollid)-18 each, Chidambaram AWS-17, Virudachalam & Chengam-15 each, Gingee-14, Mylam AWS & K.M.Koil-14 each, Tirukoilur, Vilupuram, Coonoor PTO & Karaikal-13 each, Cuddalore, Sethiathope & Tiruvannamalai-12 each, Pondicherry-11, Mayanur, Paramathivelur & Polur-10 each, Parangipettai, Kallakurichi, Kodavasal, Nagapattinam, Vanur, Mayiladuthurai, Sankarapuram,& Eraniel, Jayamkondam, Rayakottah, Neyveli AWS, Kuzhithurai, Ariyalur & Tindivanam-9 each, Tiruvaiyaru, Tozhudur, Srimushnam, Valangaiman, Tiruvarur, Ulundurpet, Papanasam (District: Thanjavur) &, Kothagiri-8 each and Harur,</td>
</tr>
<tr>
<td>02.12.2017
1130 (0830)</td>
<td>• Heavy to very heavy rainfall at a few places and isolated extremely heavy falls (>20 cm) very likely over north Lakshadweep Islands during next 24 hours and isolated heavy to very heavy falls during subsequent 24 hours. Isolated heavy to very rainfall is very likely over south Lakshadweep Islands during next 24 hours.
• Heavy rainfall at isolated places very likely over Kerala during next 24 hours.</td>
</tr>
<tr>
<td>03.12.2017
1130 (0830)</td>
<td>• Heavy rainfall at isolated places is very likely over south Gujarat on 05th December.</td>
</tr>
<tr>
<td>04.12.2017
1200 (0830)</td>
<td>• Gujarat: Light to moderate rainfall is very likely at a few places over Saurashtra and south Gujarat region on 4th December. Light to moderate rainfall at most places with heavy rainfall at isolated places is very likely over Saurashtra and south Gujarat region on 05th December and light to moderate rainfall over Gujarat region at many places on 6th December (upto around noon).
• Maharashtra: Light to moderate rainfall is very likely at a few places over north Konkan including Mumbai on 4th December. Light to moderate rainfall at most places with isolated heavy rainfall is also likely over north Konkan on 5th December.</td>
</tr>
</table>

05.12.2017 1150 (0830)	• Gujarat: Light to moderate rainfall at most places with heavy rainfall at isolated places is very likely over Saurashtra and south Gujarat region till the morning of 6th December, 2017 (Valsad, Surat, Navsari, Bharuch, Dang, Tapi, Amreli, Gir- Somnath, Bhavnagar, Diu, Daman, Dadra, and Nagar Haveli districts) and light to moderate rainfall over Gujarat region at many places during subsequent 12 hours. • Maharashtra: Light to moderate rainfall at most places with isolated heavy rainfall is also likely over north Konkan till the morning of 6th December, 2017 (Palghar, Thane, Raigarh, Greater Mumbai, Dhule, Nandurbar, Nashik, Jalgaon, Ahmednagar and Pune districts).	Panruti, Needamangalam, Thuckalay, Uthangarai, Nagercoil, Arani & Attur-7 each. **Kerala:** Trivandrum AERO-8 and Perinthalamanna & Angadipuram-7 each **Lakshadweep:** Minicoy-14 **<u>3 December 2017</u>** **Tamil Nadu & Puducherry:** Tiruvarur-14, Pandavaiyar Head & Kodavasal-13 each, Valangaiman & Nannilam-12 each, Nagapattinam-11, Needamangalam, Kumbakonam, & Karaikal-9 each, Thiruthuraipoondi, Aduthurai AWS & Tiruvadanai-8 each and Thiruvidaimaruthur-7 **<u>6 December 2017</u>** **Konkan & Goa:** Dahanu-10, Talasari & Colaba-8 each and Palghar AGRI-7 **Gujarat Region:** Umergam & Vapi-9 each and Pardi, Waghai, Vansda & Gandevi ARG-7 each
06.12.2017 1150 (0830)	• Heavy rainfall very likely over Nicobar Islands and rainfall at many places over Andaman Islands during next 2 days • Rainfall at many places very likely over north Andhra Pradesh and south Odisha during 7th to 9th December, 2017 with isolated heavy falls on 8th and 9th.	

Table 4.13. Verification of Gale Wind Forecast

Date/Time of issue (base time) (hours IST)	Gale wind Forecast	Recorded wind speed
29.11.2017 1150 (0830)	• Squally winds reaching 45-55 kmph gusting to 65 kmph is very likely along and off South Tamil Nadu and South Kerala during next 48 hours and over Lakshadweep Islands and adjoining sea areas on 01st and 02nd December.	Thiruvananthapuram recorded 62 kmph in gustiness at 1300 IST of 30th Nov.
30.11.2017 1200 (0830)	• Gale wind speed reaching 65-75 kmph gusting to 85 kmph very likely along & off South Kerala during next 48 hours and along & off south Tamilnadu during next 24 hours. • Squally winds speed reaching 55-65 kmph gusting to 75 kmph very likely along & around Lakshadweep Islands during next 12 hours and increase thereafter with wind speeds becoming 80-90 kmph gusting to 100 kmph from tonight, the 30th November 2017.	

01.12.2017 1130 (0830)	• Gale winds speed reaching 110-120 kmph gusting to 130 kmph very likely over & around Lakshadweep Islands during next 24 hours and gradual decrease thereafter. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely along & off Kerala during next 24 hours and along & off Karnataka coast during next 24 hours.
02.12.2017 1130 (0830)	• Gale winds speed reaching 100-110 kmph gusting to 120 kmph very likely over & around north Lakshadweep Islands during next 24 hours and gradual decrease thereafter. Gale winds speed reaching 70-80 kmph gusting to 90 kmph very likely south Lakshadweep Islands during next 12 hours and gradual decrease thereafter. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely along & off Kerala coast during next 24 hours and along & off Karnataka coast during next 48 hours.
03.12.2017 1130 (0830)	• Squally winds speed reaching 50-60 kmph gusting to 70 kmph very likely over & around north Lakshadweep Islands during next 12 hours and gradual decrease thereafter. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely along & off north Maharashtra and South Gujarat coasts from 4th night to 6th December 2017 morning.
04.12.2017 1200 (0830)	• Squally wind speed reaching 50-60 kmph gusting to 70 kmph very likely along & off north Maharashtra and South Gujarat coasts from today, the 4th night to 6th December 2017 morning.
05.12.2017 1150 (0830)	• Squally wind speed reaching 50-60 kmph gusting to 70 kmph very likely along & off north Maharashtra and South Gujarat coasts during next 24 hours.
06.12.2017 1150 (0830)	• Squally winds speed reaching 40-50 kmph gusting to 60 kmph very likely over and around Nicobar Islands during next 24 hours and decrease thereafter. • Squally winds speed reaching 40-50 kmph gusting to 60 kmph very likely to prevail along and off Andhra Pradesh and south Odisha coasts from 7th evening to 9th December morning and decrease thereafter.

Table 4.14: Verification of Storm Surge Forecast issued by IMD

First warning of storm surge of height about 1.0 m above astronomical tides likely to inundate low lying areas of Lakshadweep Islands was issued on 1700 hrs IST of 30th.

Date/Time of issue (base time) (hours IST)	Storm Surge Forecast	Recorded storm surge
29.11.2017 1150 (0830)	NIL	
30.11.2017 1200 (0830)	NIL	

01.12.2017 1130 (0830)	Storm surge of about 1 meter above astronomical tides very likely to inundate low lying areas of Lakshadweep Islands.	
02.12.2017 1130 (0830)	Storm surge of about 1 meter above astronomical tides very likely to inundate low lying areas of north Lakshadweep Islands during next 24 hrs and storm surge of about 0.5 metre above astronomical tides very likely to inundate low lying areas of south Lakshadweep Islands during next 12 hrs.	
03.12.2017 1130 (0830)	NIL	
04.12.2017 1200 (0830)	NIL	
05.12.2017 1150 (0830)	NIL	
06.12.2017 1150 (0830)	NIL	

4.4 Annual Performance of 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 errors in 2017 have been 61 km, 108 km and 190 km, respectively for 24, 48 and 72hrs against the past five year average error of 97, 149 and 183 km based on data of 2012-2016. The errors have been significantly lower during this year as compared to long period average (LPA) (2012-16). The track forecast skills compared to climatology and persistence forecast have been 68%, 77% and 76% respectively for the 24, 48 and 72 hrs lead period which is much higher than long period average of 2012-2016 (54%, 67% & 69% respectively). The annual average track forecast errors and skill during 2017 are presented in Fig. 4.9 (a-b). For the lead period of 84 and 96 hours, the operational track forecast errors during 2017 were more as compared to LPA mainly because it represents the case of cyclone Ockhi only. Other two cyclones viz. Maarutha and Mora were short lived. Cyclone Ockhi had a recurving track. As per the study by Mohapatra etal, 2013, the average errors in case of recurving tracks are higher as compared to straight moving tracks.

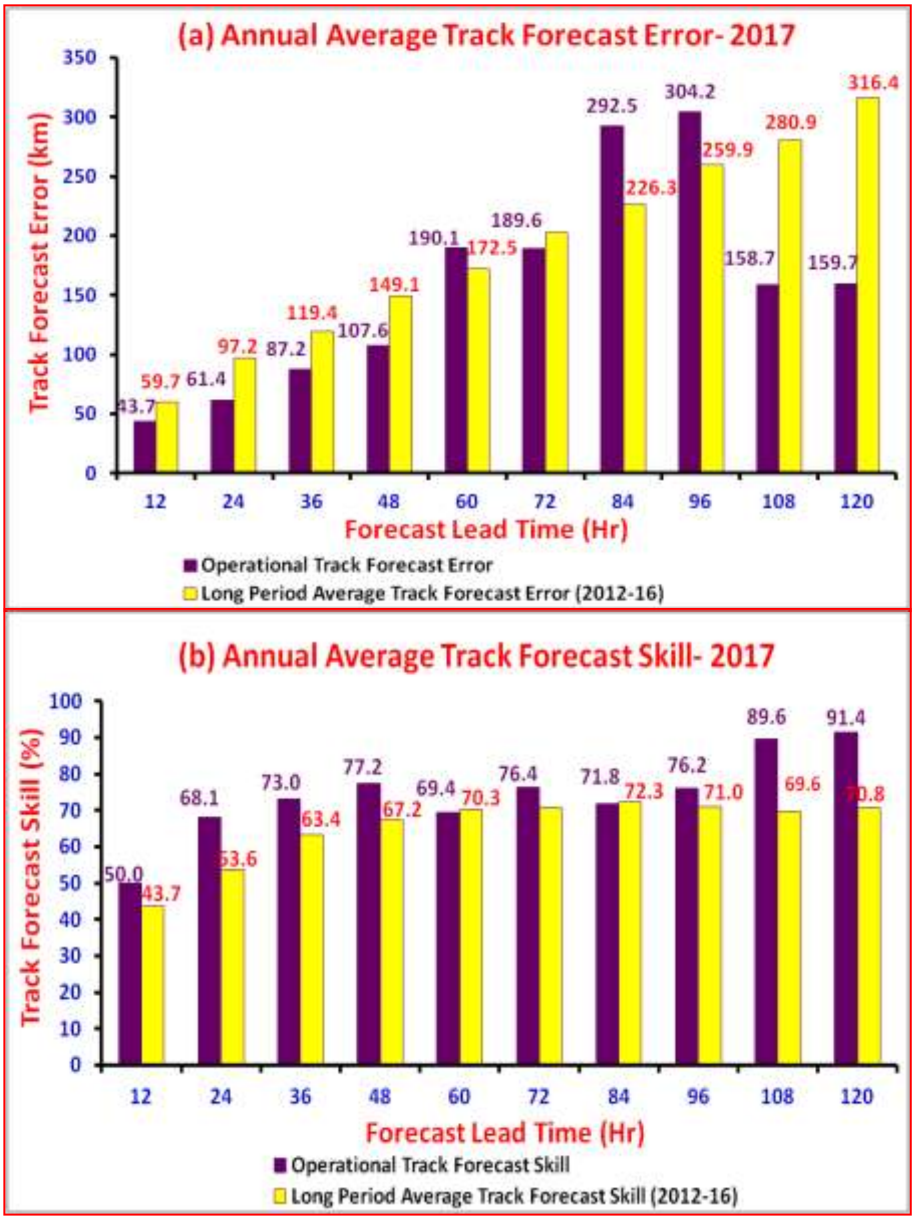


Fig.4.9. Annual average (a) track forecast error (km) and (b) track forecast skill against the climatology and persistence forecast as compared to that during 2012-2016

4.4.2 Landfall Forecast

The annual average landfall forecast errors for the year 2017 have been 19 km, 50 km and 59 km for 12, 24 and 48 hrs lead period during 2017 against the average of past five years of 37 km, 56 km and 94 km during 2012-2016. The landfall time forecast errors have been 1, 0.5 and 3.5 hrs for 12, 24 and 48 hrs lead period during 2017 against the average of past five years of 2.5, 4.2 and 4.7 hrs during 2012-2016. The annual average landfall point and time forecast errors are presented in Fig. 4.10 (a-b). The landfall forecast errors have been verified upto a lead period of 48 hours as the landfalling cyclones Mora and Maarutha during 2017 had a shorter life period and cyclone Ockhi weakened over sea.

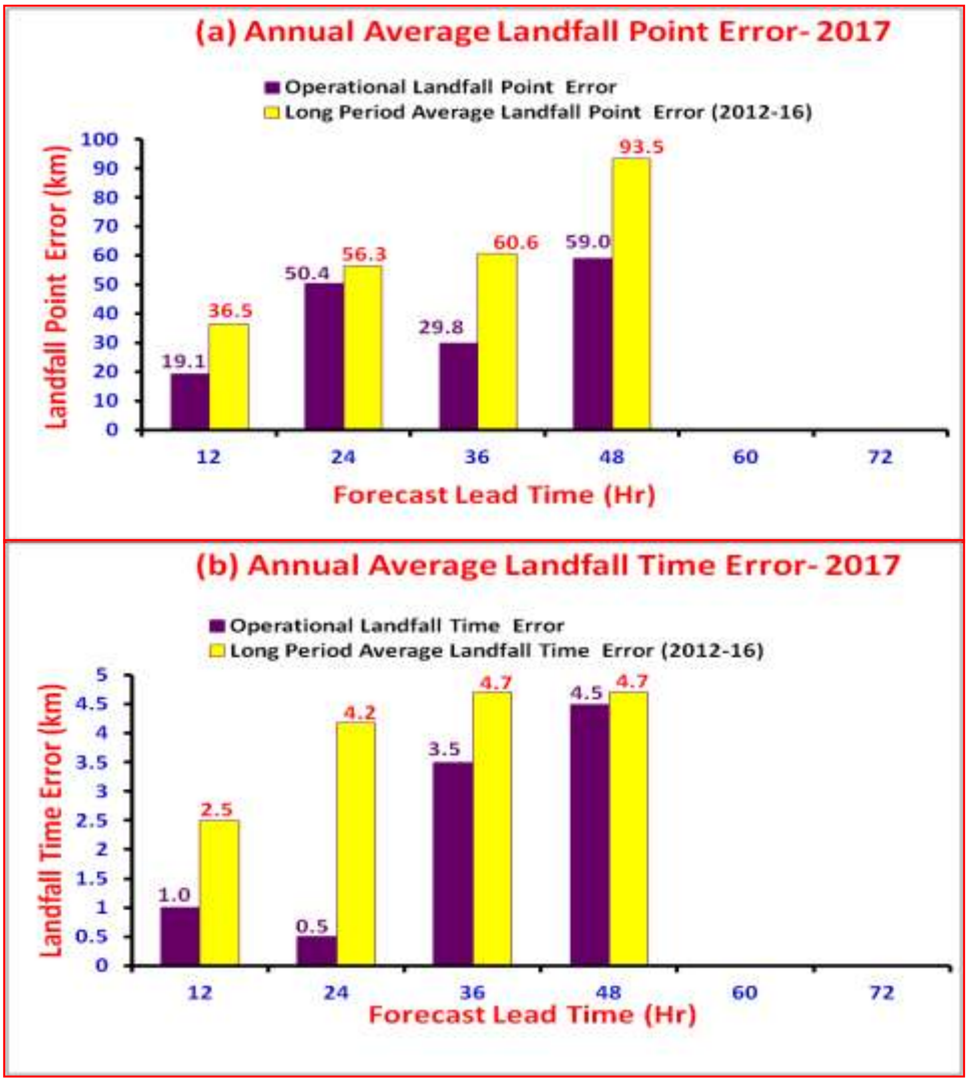


Fig.4.10. Annual average (a) landfall point forecast error (km) and (b) landfall time forecast skill against the climatology and persistence forecast as compared to that during 2012-2016

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 absolute error (AE) in intensity forecast error (Fig.4.11 a-b) has been 5.7 knots, 12.4 knots and 16.4 knots respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 10.7, 15.5 and 16.3 knots. The skill in terms of AE compared to persistence forecast was 63%, 66% and 76% as compared to long period average (2012-16) of 35, 56 and 67 for 24, 48 and 72 hours lead period.

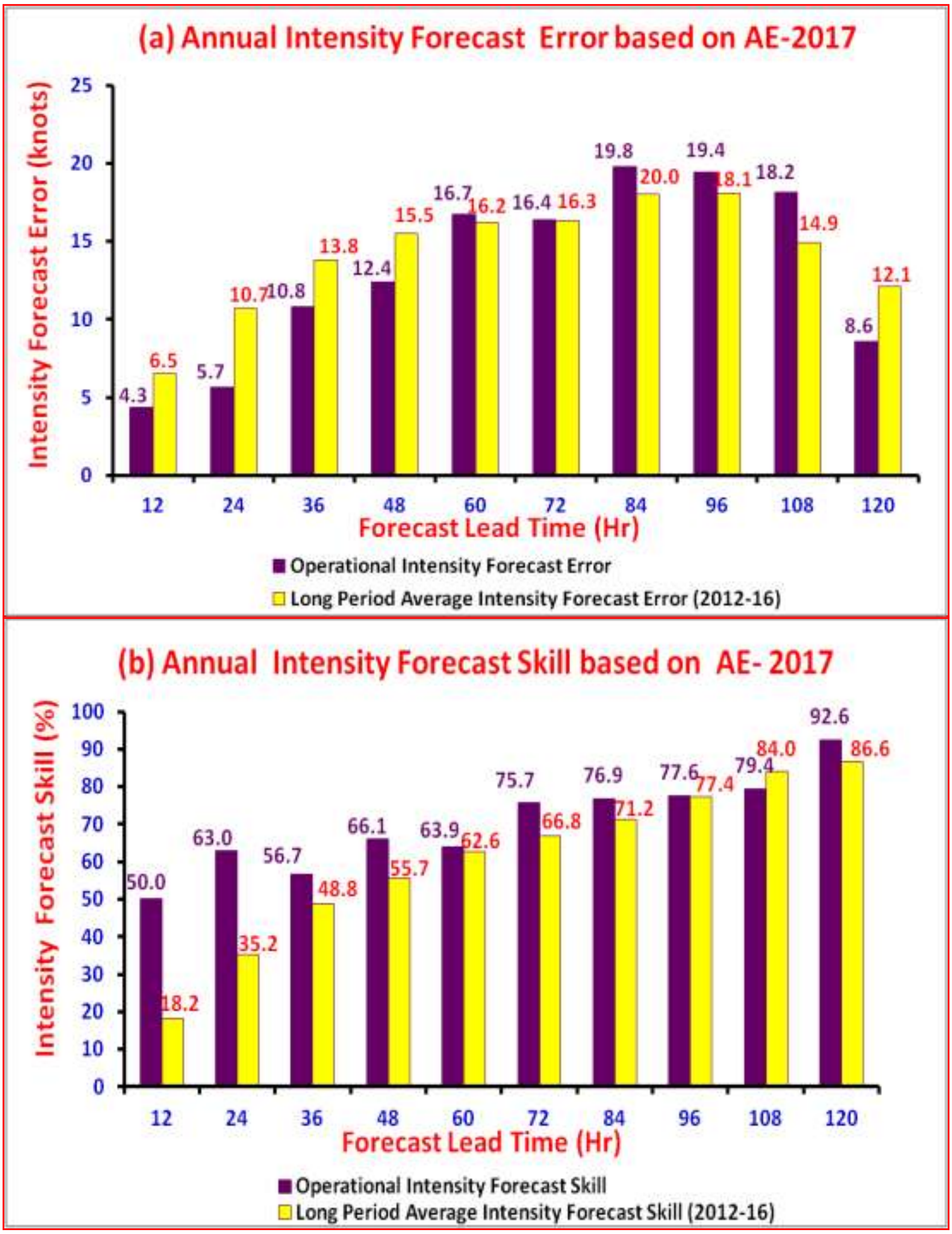


Fig.4.11. Annual average (a) absolute error (AE) in kts and (b) skill in % during 2017 as compared to that during 2012-2016

The annual average root mean square error (RMSE) in intensity forecast error (Fig.4.12 a-b) has been 7.6 knots, 14.8 knots and 12.6 knots respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 14.4, 20.8 and 21.1 knots. The skill in terms of RMSE compared to persistence forecast was 62%, 65% and 84% as compared to long period average (2012-16) of 39, 60 and 72 for 24, 48 and 72 hours lead period.

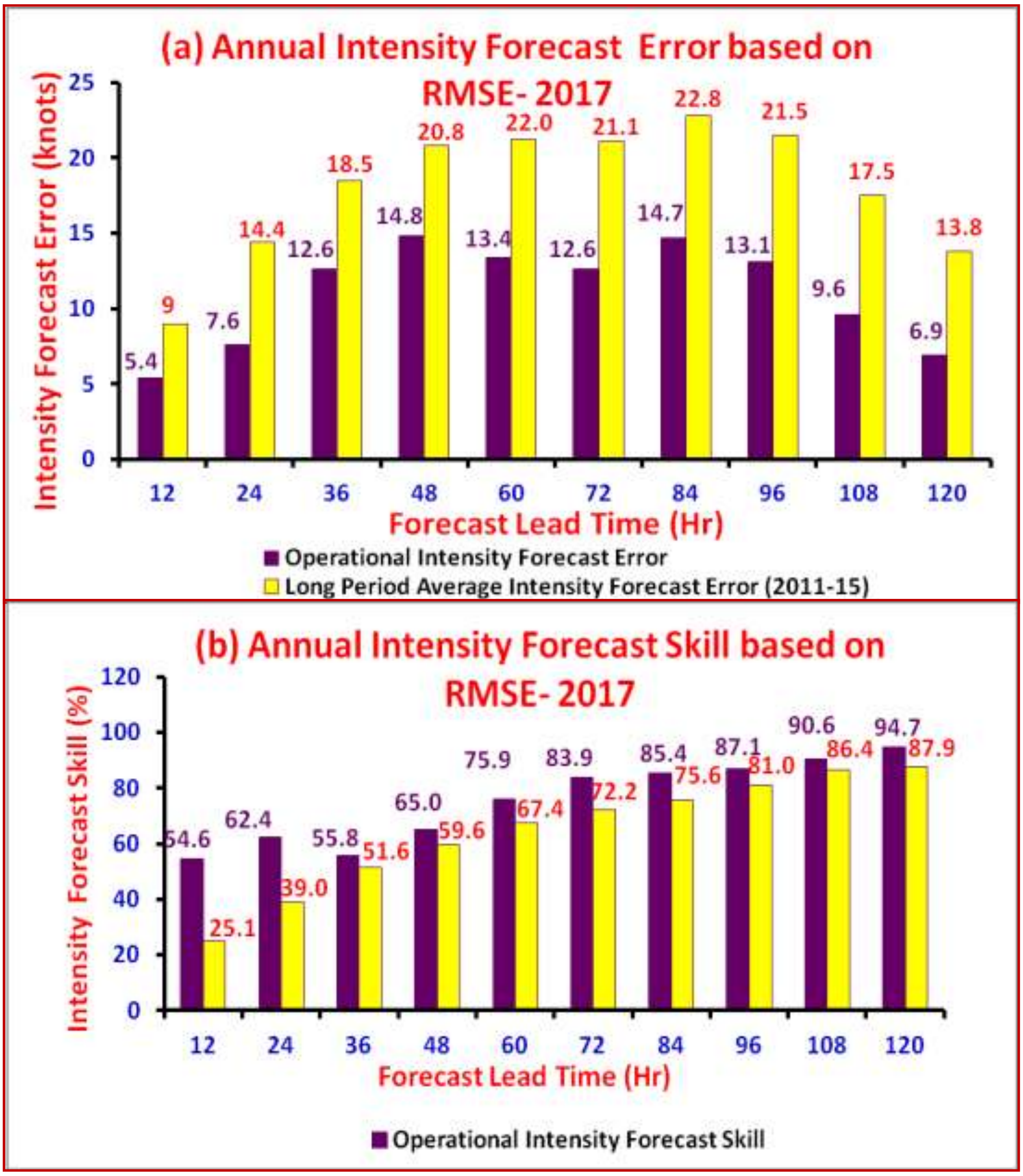


Fig.4.12. Annual average (a) root mean square error (RMSE) in kts and (b) skill in % during 2017 as compared to that during 2012-2016

4.5 Forecast accuracy in recent five years as compared to previous five years

4.5.1 Landfall Forecast Error

Significant improvement in landfall forecast errors have been observed during 2013-17 compared to that during 2008-12 due to implementation of modernisation programme in IMD in 2009. The landfall point error during 2013-17 has been 42.3 and 94.8 km against 90.8 and 95.8 km during 2008-12 (Fig.4.13 a) for 24 & 48 hours lead period. Thus, 53% and 1% improvement in landfall point error was observed during 2013-17 compared to 2008-12 for 24 and 48 hours lead period. Landfall time (Fig.4.13 b) and has been 3.6 and 5.4 hrs against 5.5 and 7.3 hrs during 2008-12 for 24 & 48 hrs lead period respectively with an improvement of 35% and 26%. The landfall forecast error for 60 and 72 hrs during 2013-17 could not be compared with that during 2008-12, as 72 hr forecast was introduced in December 2009 and hence the average for 2008-12 is not available.

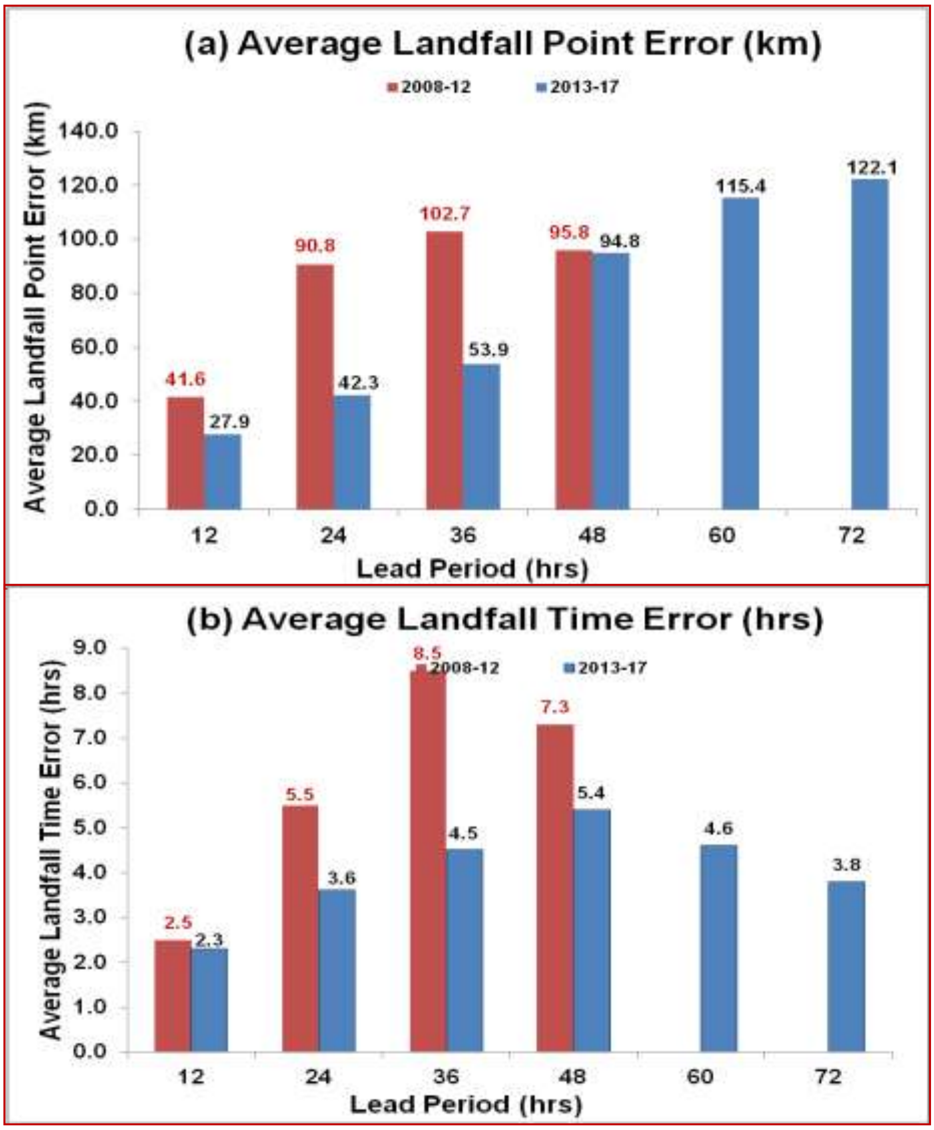
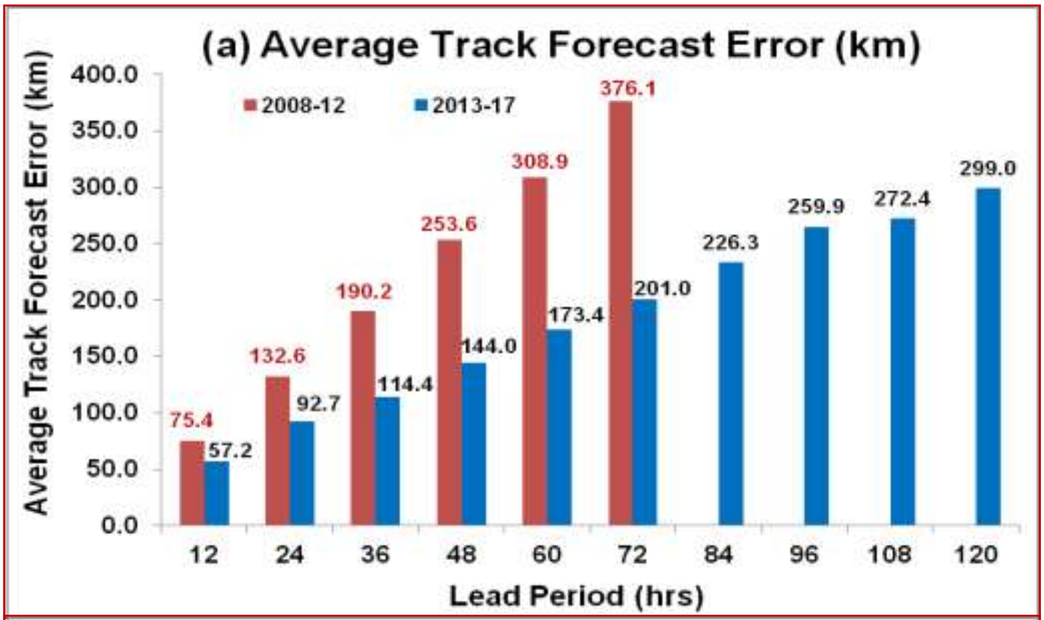


Fig.4.13 Average landfall (a) point forecast error (km) and (b) time forecast error (hrs) during 2013-17 as compared to that during 2008-12

4.5.2 Track forecast error and skill

The track forecast errors during 2013-17 have been 93, 144, 201 km against 133, 254, 376 km during 2008-12 for 24, 48 and 72 hrs lead period respectively (Fig.4.14 a). The period during 2013-17 registered a decrease in track forecast error by 30, 43 & 47% as compared to 2008-12 for 24, 48 and 72 hours lead period respectively. Similarly skill also improved significantly during 2013-17 (Fig.4.14 b) and has been 55, 68 & 72 % during 2013-17 against 35, 42 & 50% during 2008-12 for 24, 48 and 72 hrs lead period respectively.



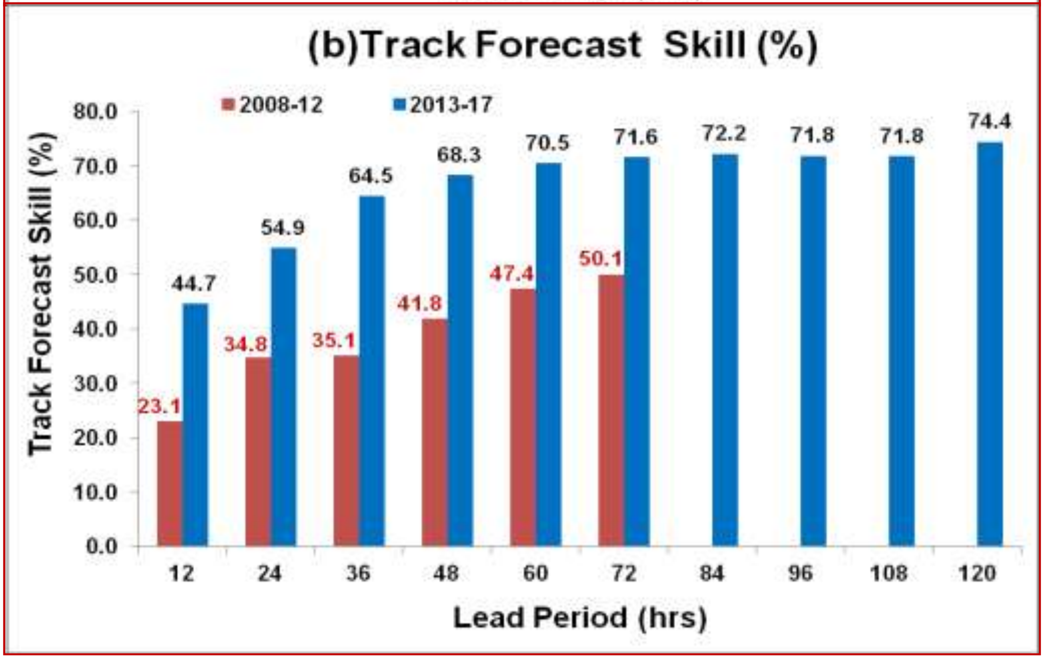


Fig.4.14. Average track forecast (a) error (km) and (b) skill (%) during 2007-11 and 2012-16

4.5.3 Intensity forecast error and skill

Comparative analysis of intensity forecast errors and skill based on absolute error (AE) & root mean square error (RMSE) relative to persistence error is shown in Fig.4.15 (a-b). The intensity forecast errors based on AE during 2013-17 has been 10.4, 15.5 & 15.7 knots against 9.7, 13.4 & 18.8 knots during 2008-12 for 24, 48 and 72 hrs lead period respectively. The intensity forecast errors based on RMSE during 2013-17 has been 14.0, 20.6 & 20.7 knots against 15.2, 18.7 & 22.3 knots during 2008-12 for 24, 48 and 72 hrs lead period respectively.

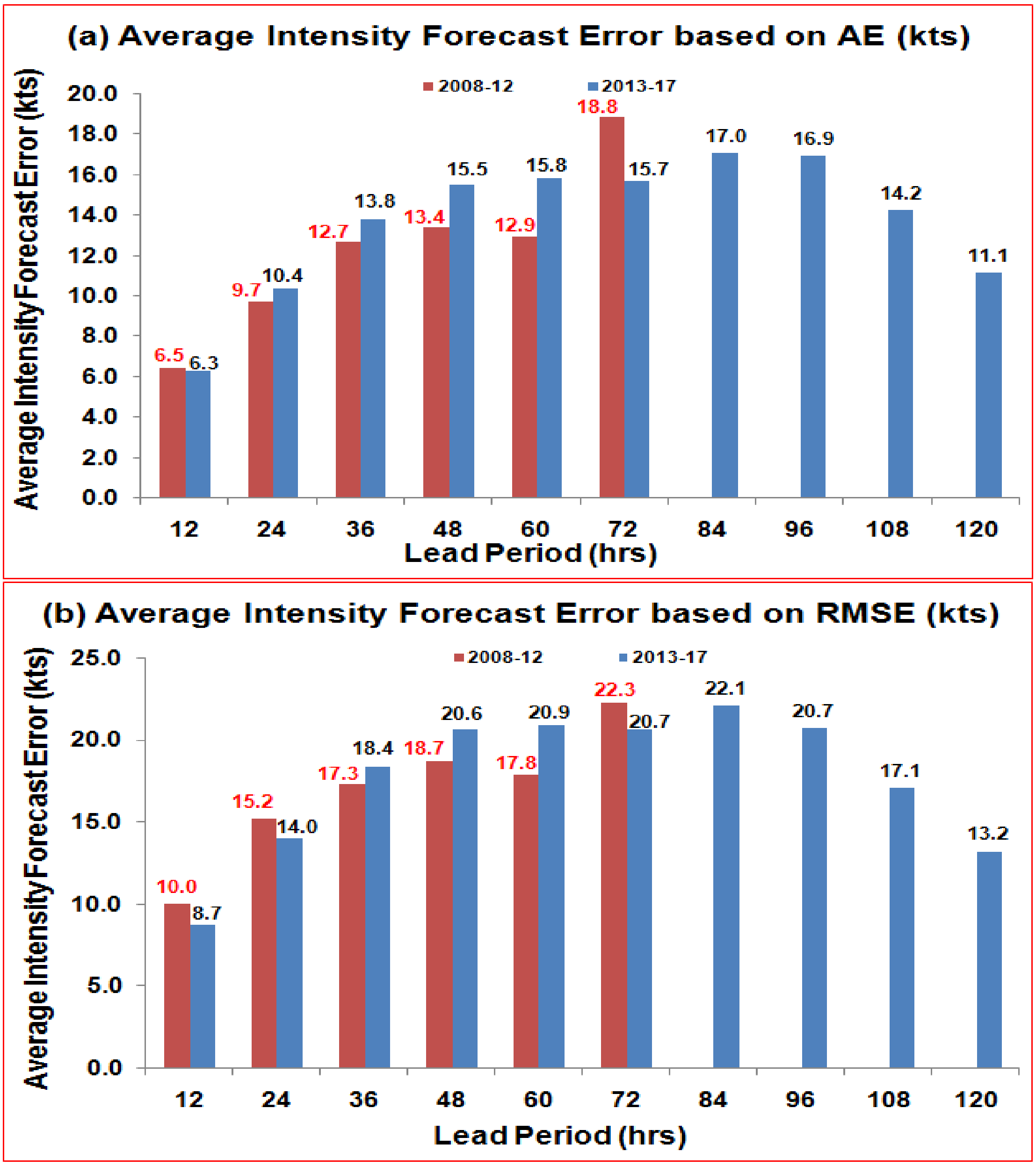
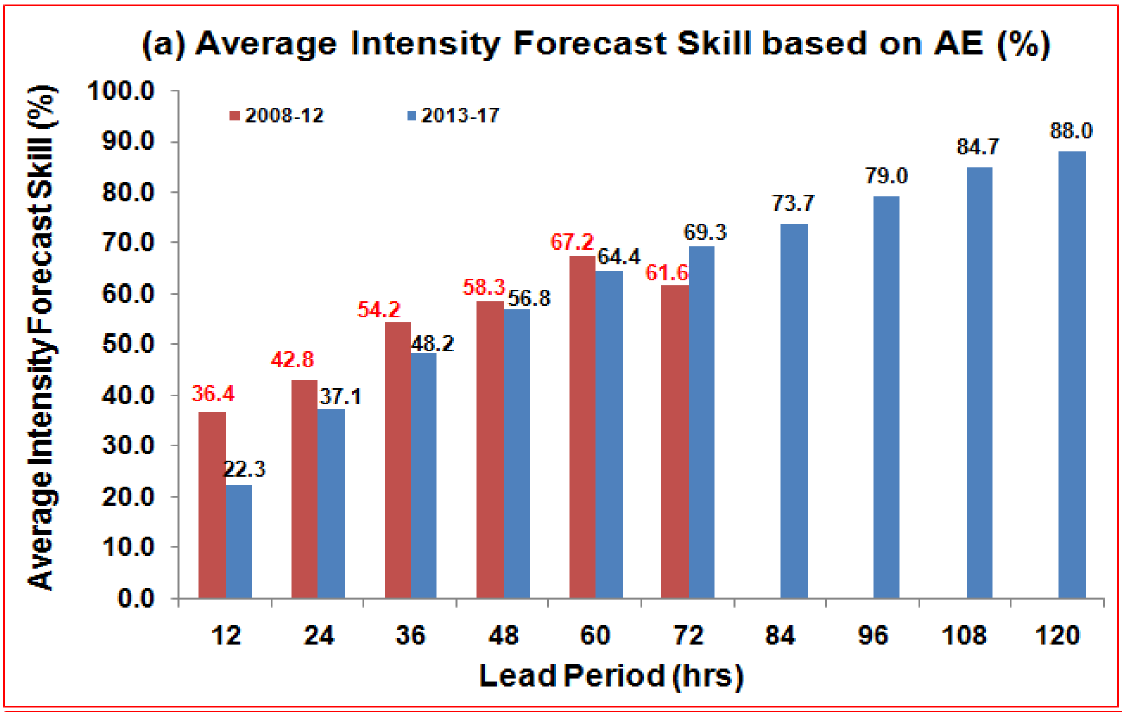


Fig.4.15. Average intensity forecast errors (kts) based on (a) AE and (b) RMSE compared to persistence during 2008-12 and 2013-17

Skill in Intensity forecast error based on AE has been 37.1, 56.8 and 69.3% during 2013-17 against 42.8, 58.3 and 61.6% during 2008-12 for 24, 48 and 72 hr lead period (Fig.4.16 a). Skill in Intensity forecast error based on RMSE has been 37.5, 60.0 and 73.1% during 2013-17 against 40.2, 61.9 and 73.8% during 2008-12 for 24, 48 and 72 hr lead period(Fig.4.16 b).



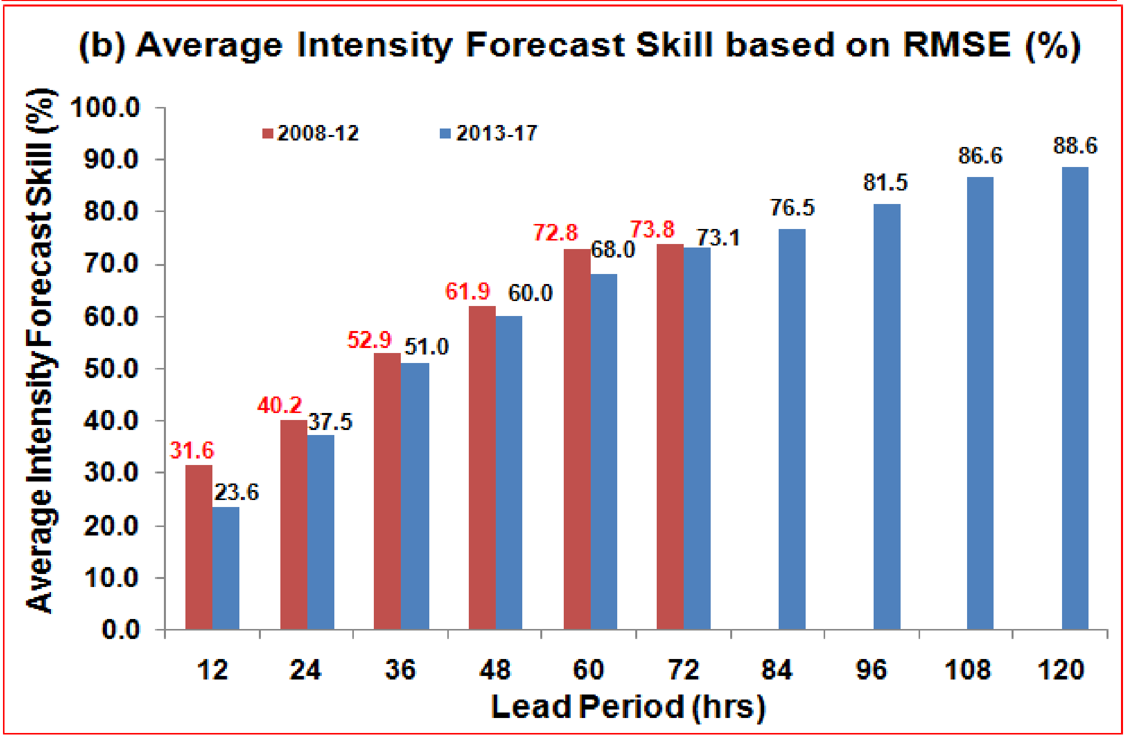


Fig.4.16. Average intensity forecast skill (%) based on (a) AE and (b) RMSE compared to persistence during 2008-12 and 2013-17

4.6 Five year moving averages of errors and skill

It can be seen from Fig.4.17-4.18 that there has been continuous improvement in forecast accuracy with decrease in landfall and track forecast errors 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. 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. However, the rate of improvement in intensity forecast over the years has been marginal as can be seen from Fig.4.19-4.20.

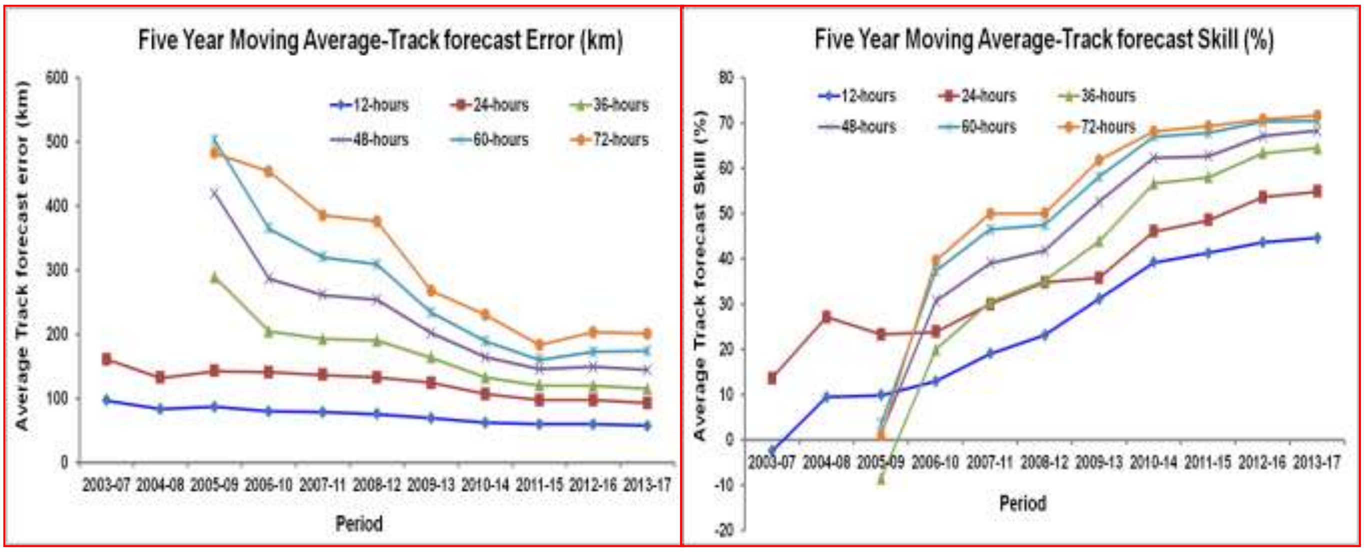


Fig. 4.17: Five Year Moving Average (a) Track Forecast Error (km) and (b) Track Forecast Skill (%) of RSMC, New Delhi over North Indian Ocean

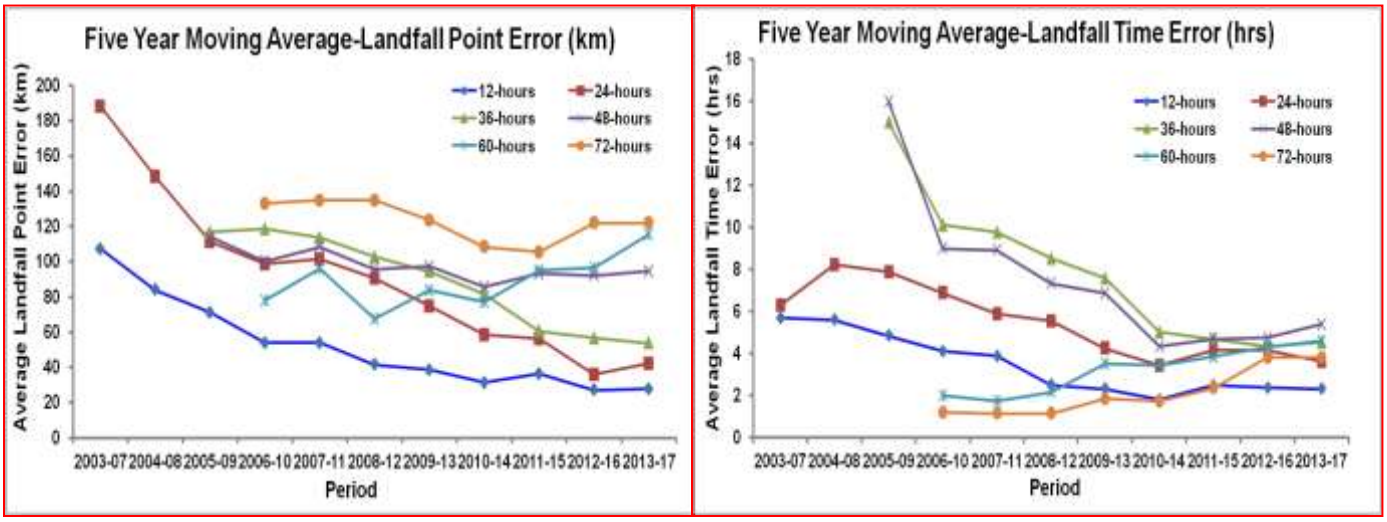


Fig. 4.18: Five Year Moving Average (a) Landfall Point Forecast Error (km) and (b) Landfall Time Forecast Error (hrs) of RSMC, New Delhi over North Indian Ocean

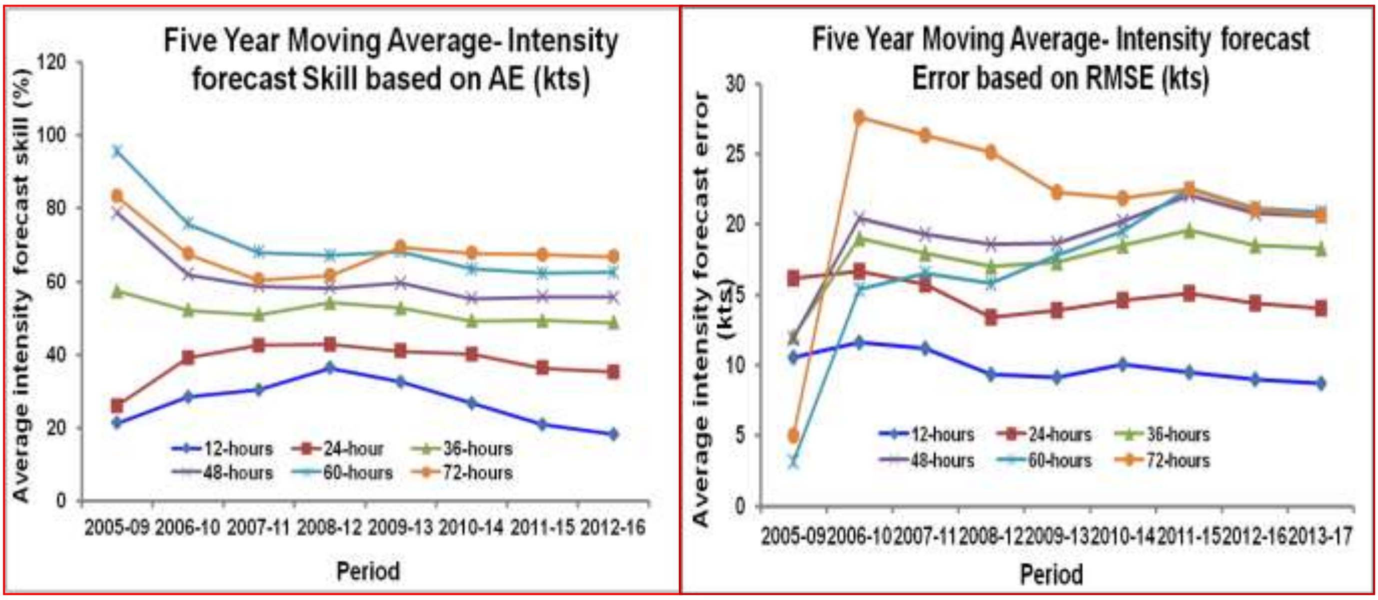


Fig. 4.19: Five Year Moving Average Intensity Forecast Error based on (a) AE and (b) RMSE of RSMC, New Delhi over North Indian Ocean

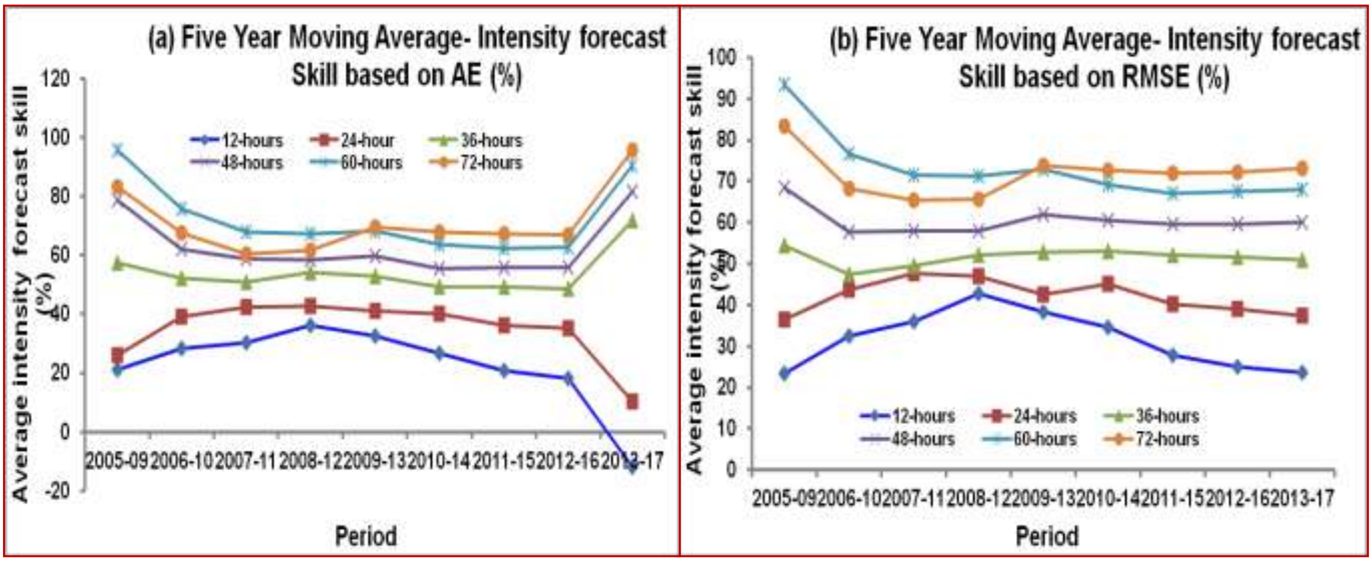


Fig. 4.20: Five Year Moving Average Intensity Forecast Skill (%) based on (a) AE and (b) RSMC of RSMC, New Delhi over North Indian Ocean

Table 4.17: Homogeneous comparison of Official Landfall Forecast Errors over north Indian Ocean in 2017 with Averages for 2012-16 and 2006-16.

Parameter	**Forecast Period (hr)**					
	12	**24**	**36**	**48**	**60**	**72**
2017						
Mean OFCL Landfall Point Error (km)	19.1	50.4	29.8	59.0		
Mean OFCL Landfall Time Error (hr)	1.0	0.5	3.5	4.5		
No. of cases	2	2	2	2		
2012-16						
Mean OFCL Landfall Point Error (km)	27.2	35.9	56.9	92.3	96.4	122.1
Mean OFCL Landfall Time Error (hr)	2.4	4.2	4.3	4.8	4.3	3.8
No. of cases	12	12	12	11	11	7
2007-16						
Mean OFCL Landfall Point Error (km)	41.6	72.6	75.5	88.1	81.4	116.6
Mean OFCL Landfall Time Error (hr)	3.1	4.9	6.2	5.7	2.7	2.5
No. of cases	32	30	22	19	15	11
2017 OFCL Landfall Point Error relative to 2012-16 mean (%)	-29.7	-40.6	-47.6	-36.0	-	-
2017 OFCL Landfall Time Error relative to 2012-16 mean (%)	-67.9	-28.1	-34.0	-91.5	-	-

OFCL: Official. The landfall forecast was issued upto 24 hrs till 2008 and 72 hrs from 2009 onwards, during 2017 forecast upto 48 hrs has been verified as the landfalling cyclones (Mora & Maarutha) were short lived

Table 4.18: Homogeneous comparison of OFCL & CLIPER Track Forecast Errors over NIO in 2017 with Averages for 2012-16 and 2007-16

Parameter	**Forecast Period (hr)**									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2017 Mean OFCL Forecast Error (km)	43.7	61.4	87.2	107.6	190.1	189.6	292.5	304.2	158.7	159.7
2017 Mean CLIPER Error (km)	87.5	192.5	322.5	472.9	620.5	802.6	1306.1	1275.8	1519.1	1860.4
2017 Mean OFCL Skill wrt CLIPER (%)	50.0	68.1	73.0	77.2	69.4	76.4	71.8	76.2	89.6	91.4
2017 No. of cases	35	29	23	18	14	12	10	8	3	3
2012-16 Mean OFCL Forecast Error (km)	59.7	97.2	119.4	149.1	172.4	202.8	226.3	259.9	280.9	30.5.3
2012-16 Mean CLIPER Error (km)	106.0	209.4	326.4	453.9	580.9	694.6	816.6	897.6	922.6	1082.3
2012-16 Mean OFCL Skill wrt CLIPER (%)	43.7	53.6	63.4	67.2	70.3	70.8	72.3	71.0	69.6	70.8
2012-16 No. of cases	283	251	212	180	148	117	85	62	40	24
2007-16 Mean OFCL Forecast Error (km)	66.4	110.8	137.6	173.9	203.3	238.2	226.3	259.9	280.9	30.5.3
2007-16 Mean CLIPER Error (km)	102.6	204.4	314.1	448.4	584.6	709.3	816.6	897.6	922.6	1082.3
2007-16 Mean OFCL Skill wrt CLIPER (%)	35.3	45.8	56.2	61.2	65.2	66.4	72.3	71.0	69.6	70.8
2007-16 No. of cases	443	384	282	231	187	145	85	62	40	24

Parameter	Forecast Period (hr)									
	12	24	36	48	60	72	84	96	108	120
2017 OFCL error relative to 2012-16 mean (%)	-26.8	-36.8	-27.0	-27.8	10.2	-6.5	29.2	17.0	-43.5	-49.5
2017 CLIPER error relative to 2012-16 mean (%)	-17.5	-8.1	-1.2	4.2	6.8	15.5	26.9	42.1	64.7	71.9

The track forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards
OFCL: Official

Table 4.19: Homogeneous comparison of OFCL & Persistence Intensity Forecast Errors based on Absolute Error over NIO in 2017 with Averages of 2012-16 and 2007-16

Parameter	Forecast Period (hr)									
	12	24	36	48	60	72	84	96	108	120
2017 Mean OFCL Forecast Error (kts)	4.3	5.7	10.8	12.4	9.0	8.2	9.0	7.8	5.0	3.7
2017 Mean Persistence Error (kts)	8.7	15.3	25.0	36.5	46.4	67.5	85.5	86.9	88.3	115.0
2017 Mean OFCL Skill wrt Persistence (%)	50.6	62.7	56.8	66.0	80.6	87.9	89.5	91.0	94.3	96.8
2017 No. of cases	35	29	23	18	14	12	10	8	3	3
2012-16 Mean OFCL Forecast Error (kts)	6.5	10.7	13.8	15.5	16.2	16.3	18.0	18.1	14.9	12.2
2012-16 Mean Persistence Error (kts)	8.0	16.6	26.9	35.1	43.3	48.9	62.3	79.9	93.5	89.8
2012-16 Mean OFCL Skill wrt Persistence (%)	18.2	35.2	48.8	55.7	62.6	67.0	71.2	77.4	84.1	85.6
2012-16 No. of cases	283	251	215	179	148	116	85	62	40	24
2007-16 Mean OFCL Forecast Error (kts)	6.9	11.0	13.7	15.2	15.7	16.9	18.0	18.1	14.9	12.2
2007-16 Mean Persistence Error(kts)	9.1	17.8	27.1	34.8	43.1	49.3	62.3	79.9	93.5	89.8
2007-16 Mean OFCL Skill wrt Persistence (%)	23.6	38.0	49.3	56.4	63.7	65.6	71.2	77.4	84.1	85.6
2007-16 No. of cases	442	383	287	233	186	143	85	62	40	24
2017 OFCL error relative to 2012-16 mean (%)	-34.2	-46.9	-21.7	-20.2	-44.5	-49.5	-49.9	-56.8	-66.5	-69.3
2017 Persistence error relative to 2012-16 mean (%)	8.9	-7.7	-7.1	4.0	7.2	37.9	37.2	8.8	-5.6	28.0

The intensity forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards
OFCL: Official

Table 4.20: Homogeneous comparison of OFCL & Persistence Intensity Forecast Errors based on Root Mean Square Error over NIO in 2017 with Averages of 2012-16 & 2007-16

Parameter	**Forecast Period (hr)**									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2017 Mean OFCL Forecast Error (km)	5.4	7.6	12.6	14.8	13.4	12.6	14.7	13.1	9.6	6.9
2017 Mean Persistence Error (km)	11.9	20.2	28.5	42.3	55.6	78.2	100.8	101.9	102.5	129.9
2017 Mean OFCL Skill wrt Persistence (%)	54.6	62.4	55.8	65.0	75.9	83.9	85.4	87.1	90.6	94.7
2017 No. of cases	35	29	23	18	14	12	10	8	3	3
2012-16 Mean OFCL Forecast Error (km)	8.9	14.4	18.5	20.8	21.2	21.1	22.8	21.5	17.5	13.8
2012-16 Mean Persistence Error (km)	12.0	23.6	38.3	51.6	65.0	75.7	93.2	113.2	128.8	114.1
2012-16 Mean OFCL Skill wrt Persistence (%)	25.1	39.0	51.6	59.6	67.4	72.2	75.6	80.9	86.4	87.9
2012-16 No. of cases	283	252	215	179	148	116	85	62	40	24
2007-16 Mean OFCL Forecast Error (km)	9.8	14.9	18.4	20.5	20.3	22.2	22.8	21.5	17.5	13.8
2007-16 Mean Persistence Error (km)	14.2	26.0	37.6	50.3	63.7	75.8	93.2	113.2	128.8	114.1
2007-16 Mean OFCL Skill wrt Persistence (%)	30.8	42.8	51.1	59.3	68.1	70.7	75.6	80.9	86.4	87.9
2007-16 No. of cases	442	383	287	233	186	143	85	62	40	24
2017 OFCL error relative to 2012-16 mean (%)	-40.0	-47.1	-32.0	-28.9	-36.7	-40.3	-35.4	-39.2	-45.2	-50.1
2017 Persistence error relative to 2012-16 mean (%)	-0.9	-14.3	-25.5	-17.9	-14.5	3.2	8.1	-10.0	-20.4	13.9

The intensity forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards

OFCL: Official

Damage due to gale winds over Kanyakumari

Damage over Lakshadweep

Damage over Kerala

Damaged over Minicoy

DAMAGE DUE TO VERY SEVERE CYCLONIC STORM 'OCKHI'