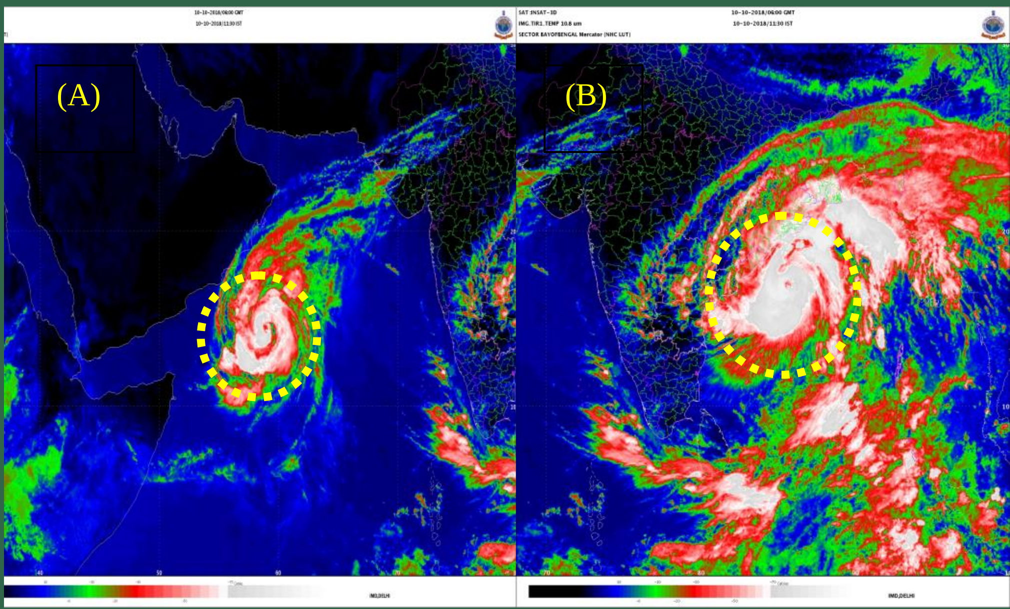
World Meteorological Organisation

Government of India
Ministry of Earth Sciences
India Meteorological Department

No. ESSO/IMD/CWD Report No-01 (2019)/09

REPORT ON CYCLONIC DISTURBANCES OVER NORTH INDIAN OCEAN DURING 2018



SATELLITE IMAGERY BASED ON 0600 UTC OF 10TH OCTOBER OF VERY SEVERE CYCLONIC STORMS, (A) "LUBAN" AND (B) "TITLI"

RSMC-TROPICAL CYCLONES, NEW DELHI

JULY 2019

WMO

INDIA METEOROLOGICAL DEPARTMENT

RSMC- TROPICAL CYCLONES, NEW DELHI

JULY 2019

INDIA METEOROLOGICAL DEPARTMENT

DOCUMENT CONTROL SHEET
Ministry of Earth Sciences (MoES)
Earth System Science Organisation

1.	ESSO Report Number	No. ESSO/IMD/CWD Report-01(2019)/09
2.	Title of The Report	Report on cyclonic disturbances over the north Indian Ocean during 2018
3.	Authors	RSMC-Tropical Cyclones, New Delhi
4.	Originating Unit	RSMC-Tropical Cyclones, New Delhi
5.	Type of Document	Technical Report
6.	No. of Pages and figures	420/369
7.	No. of references	0
8.	Key words	Cyclogenesis, intensity, track, landfall, NWP model, forecast verification
9.	Security classification	Open
10.	Distribution	Open
11.	Date of Publication	JULY 2019
12.	Funding Agency	India Meteorological Department
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 2018. 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, Iran, Maldives, Myanmar, Pakistan, Qatar, Saudi Arabia, Sultanate of Oman, Sri Lanka, Thailand, United Arab Emirates 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 40^0E and 100^0E and includes the member countries of WMO/ESCAP Panel on Tropical Cyclones viz, Bangladesh, India, Iran, Maldives, Myanmar, Oman, Pakistan, Saudi Arabia, Sri Lanka, Qatar, Thailand, United Arab Emirates and Yemen as shown in Fig. 1.1.

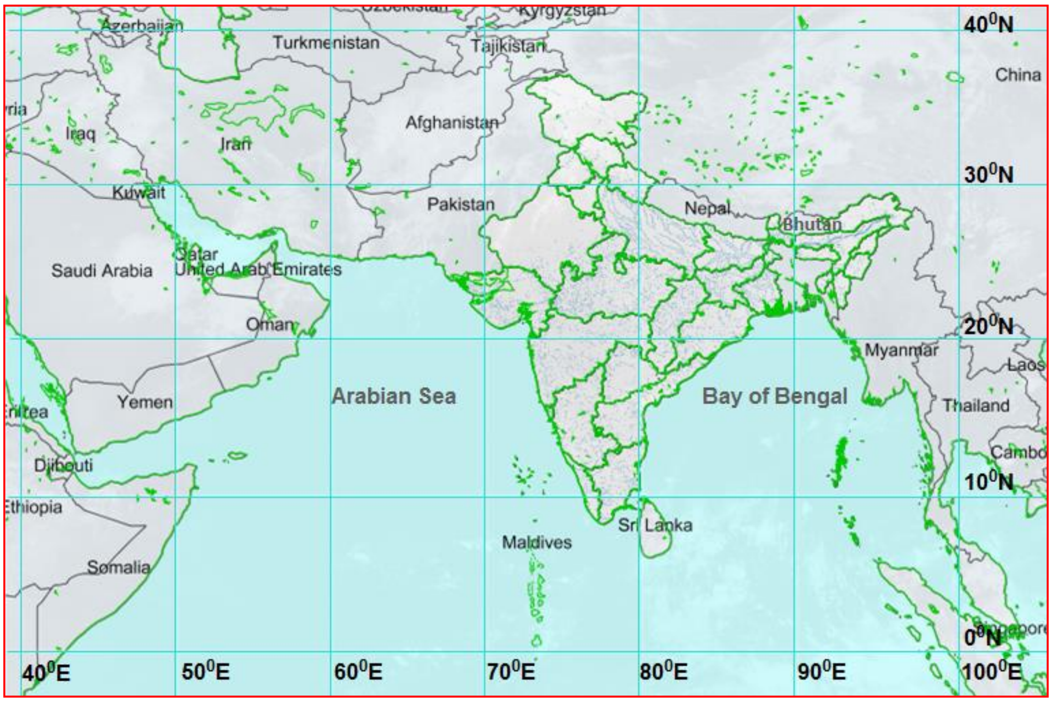


Fig. 1.1 Area of responsibility of RSMC- Tropical Cyclone, New Delhi

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, 56 names have been utilized till the end of year 2018.

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 560 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.

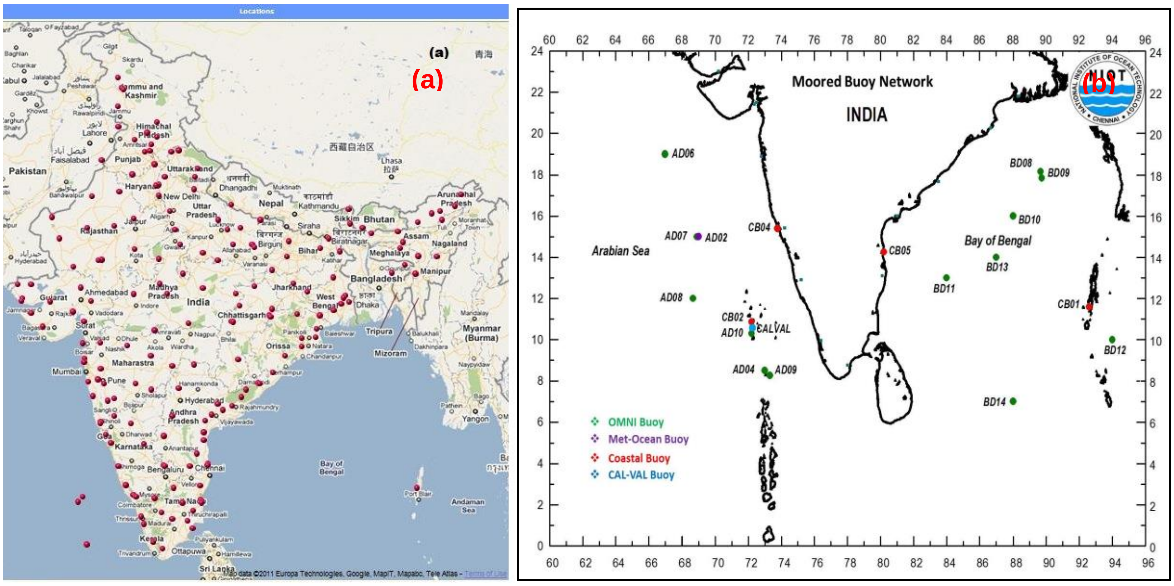


Fig.1.2. (a) The surface Observatory Network of IMD (b) Buoy network of NIOT

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. 26 AWS are installed by ISRO. 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. In addition 20 nos of High Wind speed recorders are installed for continuous monitoring of High wind speeds along east & west coast of India.

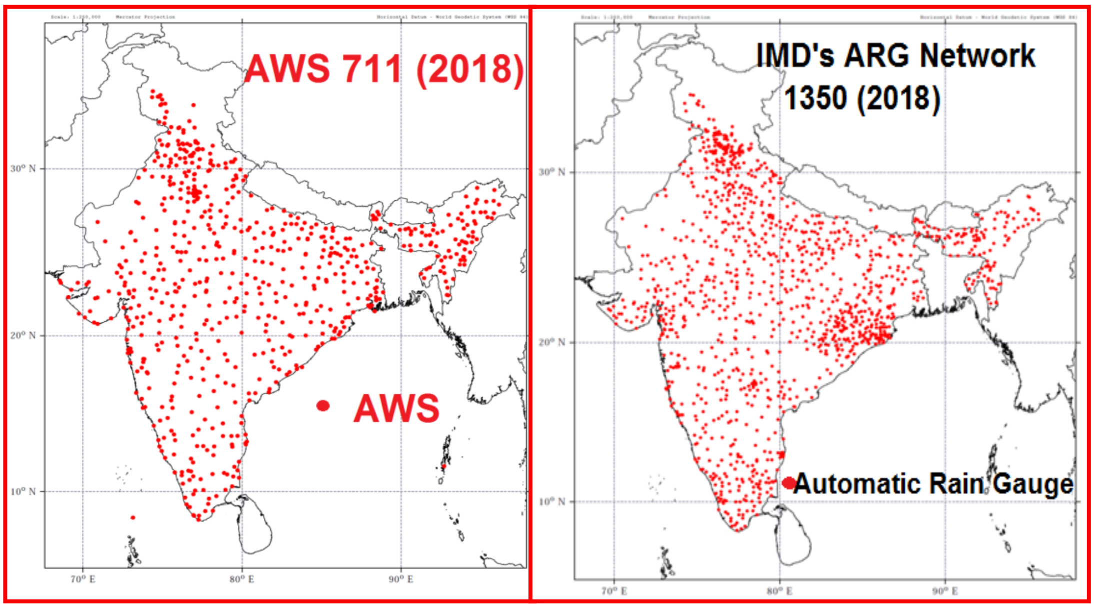


Fig. 1.3 (a) Network of 711 AWS and (b) 1350 ARGs.

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, six 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

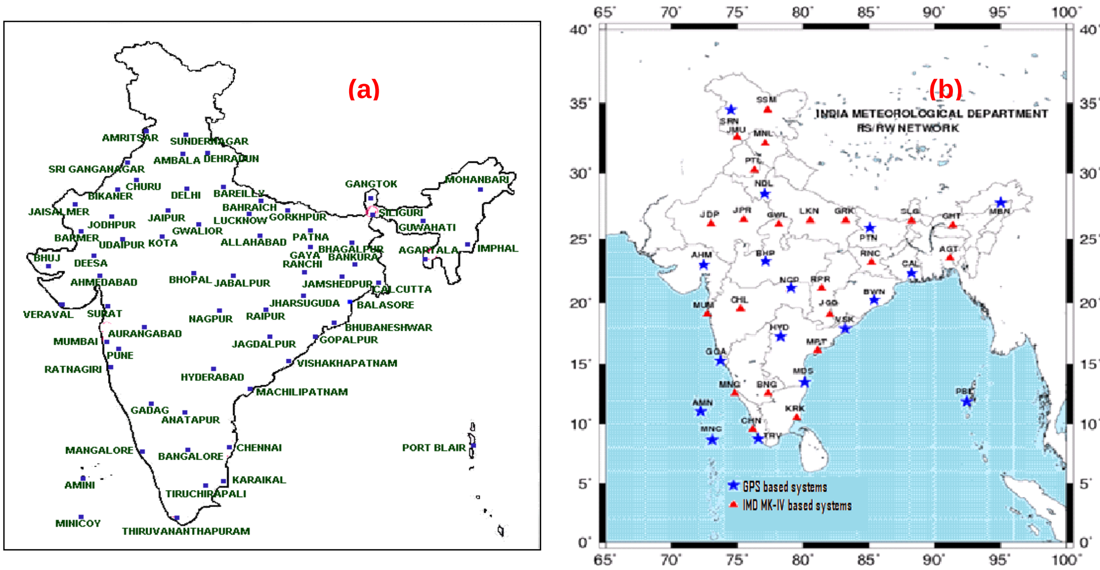


Fig.1.4 (a) Network of Pilot Balloon Observatories (PBO) and (b) Network of Radiosonde/ Radio wind observatories

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. The PBOs at New Delhi, Mumbai and Lucknow have been upgraded with GPS based PBO.

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 four Doppler weather radars (DWRs) presently spreading across the country. It includes twenty one S-band, two sites with C-band Polarimetric DWRs and one in X-band. Two indigenously manufactured S-band polarimetric DWRs have been installed at Kochi and Gopalpur. IMD also utilizes the DWR installed by ISRO at Thiruvananthapuram, Cherrapunji and Sriharikota.

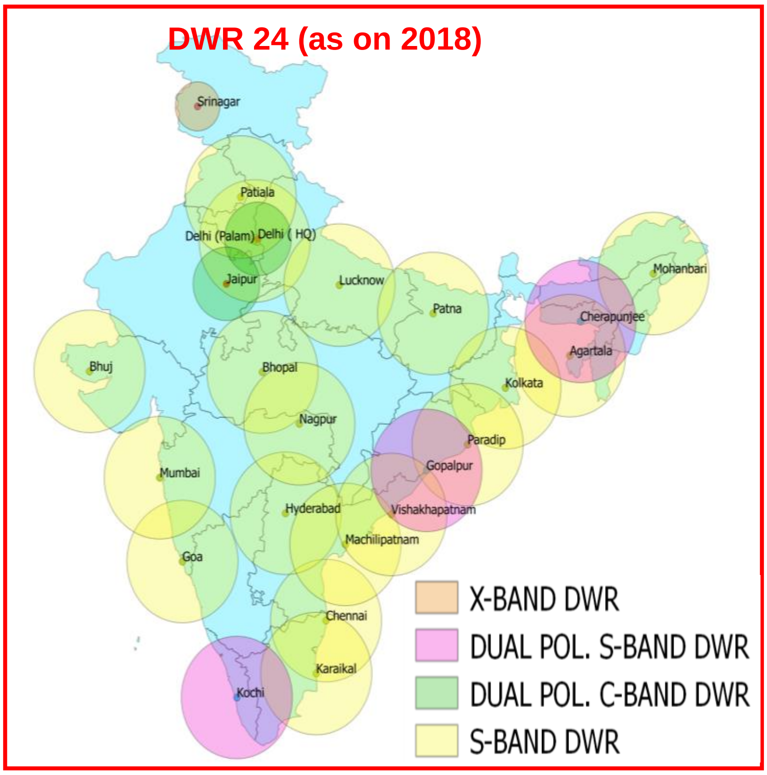


Fig. 1.5 Network of Radar

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.

Radars of IMD are being used for detection of rainfall, hail storm, dust storms, thunder storms and tracking of cyclonic storms. 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. A national Radar data centre has been established at IMD, New Delhi for archival and retrieval of radar data.

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. It is proposed to install 10 X-band radars in the northwest India including Jammu & Kashmir, Himachal Pradesh & Uttrakhand, 11 C-band radars in the plains of the country and 14 X-band radars in the northeastern states. 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.

Real-time Analysis of Product and Information Dissemination (RAPID) is a visualization tool developed jointly by IMD & ISRO for monitoring and analysis of satellite imageries and products of INSAT 3D and INSAT 3D(R). A satellite based nowcast tool for its prediction is also available in RAPID. As RAPID is a geo-reference platform, it provides real time information on genesis, growth and decay alongwith its location and other geo-physical parameters to help forecasters to provide more objective nowcast. This tool is available in IMD website at the link: http://www.rapid.imd.gov.in/

With the Web Archival System developed at IMD, INSAT-3D and INSAT 3DR 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.

1.3.5. Lightning monitoring:

The occurrence of lightning in India is being monitored with the help of lightning detectors established by Ministry of Earth Sciences and Indian Air Force. Currently, there are 203 No. of lightning detectors in the country (46 Indian Institute of Tropical Meteorology and 157 Indian Air Force). The area of lightning during preceding 10 min., 20 min. and 30 min. are superimposed with satellite and radar imageries. It help in proper monitoring of thunderstorm and lightning activities and nowcasting of such events.

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.

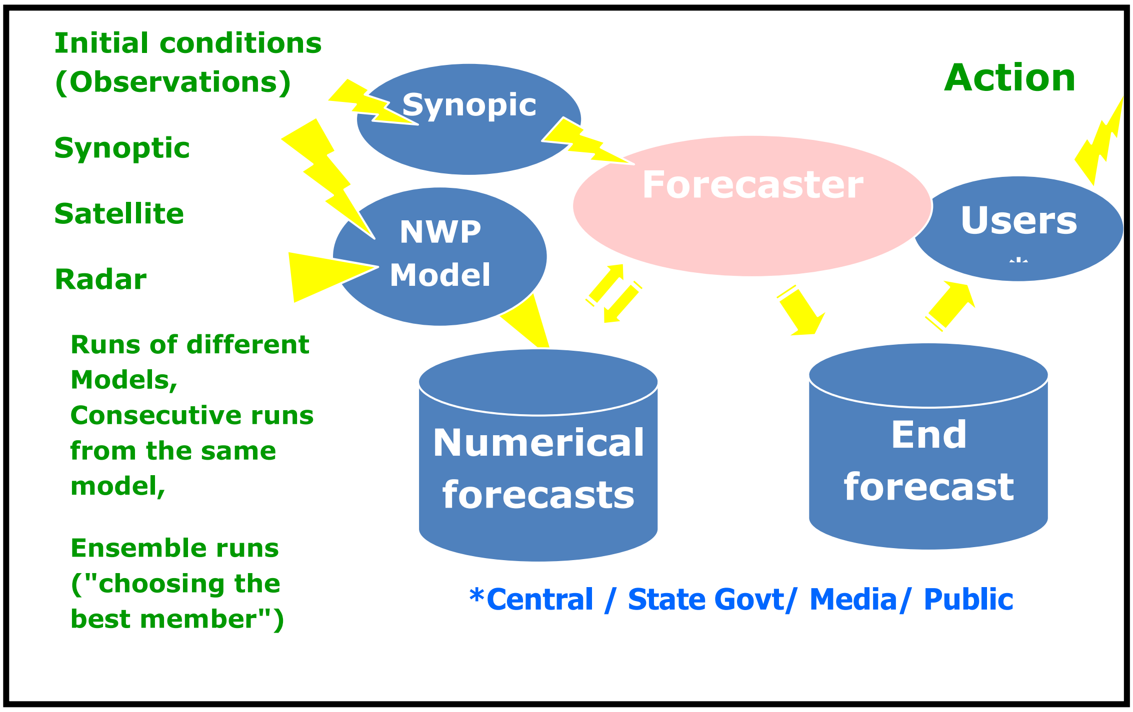


Fig.1.6. Strategy adopted for cyclone analysis and forecasting

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 upto 120 hrs
- Depiction of uncertainty in track forecast
- Preparation of quadrant wind radii forecast upto 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, INSAT-3D and INSAT-3D (R) 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 2018

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, the joint collaborative work within TC-project of IMD under the MOU between MOES-NOAA, has upgraded operational coupled Hurricane-WRF model for Tropical Cyclone forecast over North Indian Ocean. The HWRF model coupled with POM-TC model has been made operational in the year 2017 and first coupled run of HWRF-POM has been carried out during OCKHI cyclone over NIO. The HWRF-POM coupled configuration was operational in cyclic mode for all the system in the year 2018 viz Sagar,. Mekunu, Luban, Titli, Gaja, Phethai and Pabuk.The HWRF model is now operational in coupled mode with both POM and HYCOM ocean models.

The HWRF version H217 which was operational at EMC, NCEP USA has been ported on the MHIR HPCS with horizontal resolution of 18 km for parent domain and 6km & 2 km for intermediate and innermost nested domains following the center of cyclonic storm. The model is running with 61 vertical levels with parent domain, intermediate and innermost domain covering area of 80^ox80^o, 24^ox24^o and 7^ox7^o respectively. The model also has state of the art features specially modified for tropical cyclone forecasting. The special feature includes vortex initialization and correction, GSI based regional data assimilation, coupler for two way coupling between atmosphere and ocean components of coupled HWRF model and physics options fine-tuned for tropical cyclone prediction. The ocean model provides the SST field to the atmospheric component through coupler during the model integration to update the effect of mixing, cooling as well as advection effect on SST field, whereas the atmospheric component provides the heat fluxes, wind stress, precipitation and surface pressure fields to the ocean model through coupler. The coupled HWRF model uses GFDL vortex tracker and diagnostic software to provide the graphic and text information on track, intensity as well as structure of tropical cyclones for real time operational requirements. The HWRF physics scheme upgrades include updated Scale-Aware Simplified Arakawa-Schubert (SASAS) scheme, Ferrier-Aligo microphysics, GFS Hybrid-EDMF PBL, partial cloudiness for RRTMG scheme, and surface-exchange coefficients in the surface layer.

Within coupled framework of HWRF modeling system, the POM is initialized based on the climatological data whereas the HYCOM is initialized based on the ocean fields from RTOFS(Real-Time Ocean Forecast System) of INCOIS, Hyderabad. The atmospheric component of HWRF is initialized based on the analysis and forecast from IMD-GFS(T1534L64) and associated GDAS analysis. The HWRF model uses 3D-EnVAR-GSI as its data assimilation component. The coupled HWRF model is run every 6 hours on real time basis in cyclic mode based on 00, 06, 12, 18 UTC initial conditions to provide track and intensity forecast along with surface wind, rain swaths and other diagnostic products for up to 126 hours.

The INCOIS-IMD joint team successfully carried out a thorough study and several experiments with HWRF-HYCOM coupled model using INCOIS HYCOM input fields for the ―PHETHAI" cyclonic system during February, 2019 before its operational implementation. The first operational forecasts from HWRF-HYCOM (INCOIS inputs) Cyclic Coupled runs in real-time were provided recently during the FANI cyclonic system (ESCS) over Bay of Bengal. The coupled HWRF system with both ocean models viz, POM-TC and HYCOM was operational simultaneously and model guidance products were provided from both the configurations. Recently the output ATCF files from both HWRF-POM-TC and HWRF-HYCOM runs were also shared with EMC, NOAA/NCEP (USA counterpart within the collaborative program) and the tracks from these were made available along with tracks from other NWP tropical cyclone modelling centres on the EMC website.

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. Global Ensemble Forecast System

The Ministry of Earth Sciences (MoES) has commissioned two very high resolution (12 km grid scale) state-of-the-art global Ensemble Prediction Systems (EPS) for generating operational 10-days probabilistic forecasts of weather. The EPS involves the generation of multiple forecasts using slightly varying initial conditions. The forecast products from these two prediction systems are available at the following links (http://nwp.imd.gov.in/gefspro.php) and (http://www.ncmrwf.gov.in/product_main.php). The frameworks of the new EPSs are among the best weather prediction systems in the world at present. Very few forecasting centres in the world use this high resolution for short-medium range probabilistic weather forecasts.

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 (ENKF) 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. Extended Range Outlook

IMD started issuing Extended Range Outlook for cyclogenesis during next two weeks every Thursday from 22nd April, 2018. It contains information about large scale features over the region, model guidance on probable cyclogenesis from various global/regional models, probability of cyclogenesis as LOW (0-33%), MODERATE (34-67%) and HIGH (68-100%) alongwith verification of forecast issued during last two weeks. The product is available on RSMC website at http://www.rsmcnewdelhi.imd.gov.in/images/bulletin/eroc.pdf

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), day 3 (48 – 72 hrs), day 4 (72-96 hrs) and day 5 (96-120 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 %. It is based on the consensus developed from various NWP and dynamical statistical guidance coupled with guidance from observations and analyses. This forecast has been introduced since 1st June 2014 upto 72 hrs lead period. The lead period of cyclogenesis forecast has been extended to 120 hrs since 22nd April, 2018.

1.6.2 Special Tropical Weather Outlook

The Special Tropical Weather Outlook is issued at +03 hours based on observations of 0000, 0300, 0600, 1200 & 1800 UTC observations when a tropical depression forms over NIO. 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 72 hrs in case of depression and upto 120 hrs in case of a deep depression. It also includes the description of sea condition. It also includes discussion on various diagnostic and prognostic parameters. The 72 and 120 hours track and intensity forecasts are being issued from the stage of depression and deep depression respectively since 2009 and 2018. 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 well marked low pressure area. IMD has initiated to give the quantitative forecast of track & intensity from depression stage for lead period of +12, +24, +48, +72 hours since April 2018. 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.imd.gov.in and 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.imd.gov.in** and **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. IMD has initiated to issue the fishermen warning for entire BoB and AS since April, 2018. Further a graphics based fishermen warning is being generated for entire BoB and AS since 26th April 2019.

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 and RSMC website. These are also posted on social networking sites like facebook, tweeter and whatsapp.

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. The cone of uncertainty has been further revised with effect from 2019 based on the average error of 2014-18.

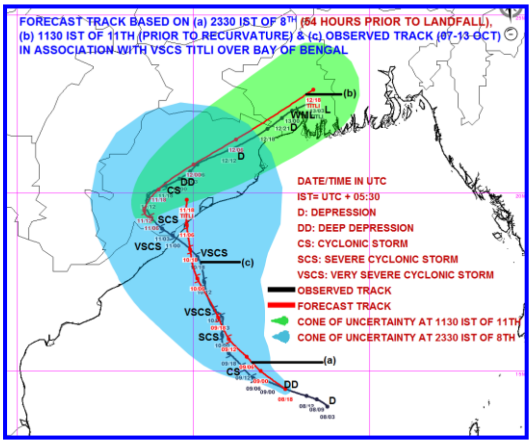


Fig.1.7. A typical example of observed and forecast track along with cone of uncertainty of VSCS Titli

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.

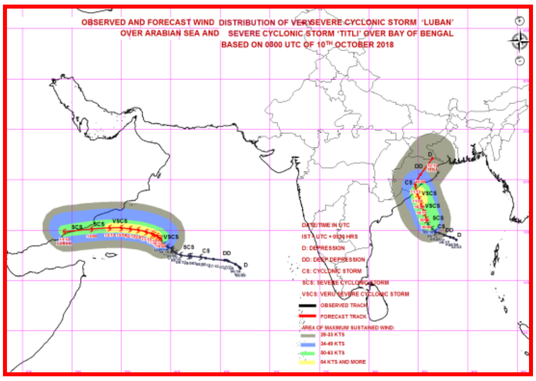


Fig.1.8. A typical graphical presentation of cyclone wind forecast during VSCS Titli and Luban

1.6.10 Hourly Update

On the day of landfall IMD issues hourly updates on the landfalling cyclone over the Indian coast since October, 2014. It contains information about the centre, it‘s distance & direction from the station, landfall point and time, current maximum sustained wind speed (MSW), MSW at the time of landfall. These bulletins are available at http://www.rsmcnewdelhi.imd.gov.in/images/bulletin/hourly.pdf on the day of landfall.

1.6.11 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.

In addition, 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.

IMD is also working in collaboration with ISRO for disseminating the SMS to fishermen in deep seas through GAMES and NAVIK systems. IMD has also established new cyclone warning centre at Thiruvananthapuram w.e.f. October, 2018 to improve dissemination of warnings and advisories for the states of Kerala, Karnataka and Lakshadweep Islands.

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 2018, due to development of cyclonic storm ―Phethai" over northeast BoB in the month of December, the FDP campaign was extended upto 18th December 2018. Like previous years (2008-2018), 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 19 days during the field phase 2018 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-2018 will be available in RSMC, New Delhi website (www.rsmcnewdelhi.gov.in).

CHAPTER-II

CYCLONIC ACTIVITIES OVER NORTH INDIAN OCEAN DURING 2018

There were 14 cyclonic disturbances (CDs) i.e. depressions and cyclones over the north Indian Ocean (NIO) & adjoining land regions during 2018 against the long period average (LPA) of 12 disturbances per year based on satellite era during 1961-2017. Out of 14 CDs, 7 intensified into tropical cyclones against the normal frequency of 4.5 cyclones per year over north Indian Ocean (NIO) during satellite era (1961-2017). Last such development of seven cyclones in a year occurred in 1985 (33 years before). It included including 2 cyclonic storms (CS), 1 severe cyclonic storm, 3 very severe cyclonic storms (VSCS) and 1 extremely severe cyclonic storm (ESCS).

Arabian Sea was more active with 3 cyclones against an average of 1 per year. In May, back to back cyclones Sagar and Mekunu formed over Arabian Sea within a week. Last such development of two cyclones over Arabian Sea in quick succession occurred in 2015 (Chapala and Megh). The cyclonic storm, Sagar was the first cyclone to cross the coast to the west of 45 deg East and travelling upto Ethiopia across Gulf of Aden and western Somalia. The cyclone, Mekunu was an extremely severe cyclonic storm, which crossed Oman coast. It was the most intense cyclone which crossed Oman coast during satellite era. It had maximum sustained wind speed of 95 knots at landfall over Oman coast.

Over the Bay of Bengal, the Cyclonic Storm, Daye developed in monsoon season (in the month of September). The last cyclone in September formed in 2005. During October, two very severe cyclonic storms, Luban and Titli formed over Arabian Sea and Bay of Bengal simultaneously. Such activity of simultaneous occurrence of two severe cyclonic storms over the Bay of Bengal and Arabian Sea was last observed in November 1977. The cyclone Titli had northeastward recurvature across Odisha after landfall over north Andhra Pradesh and adjoining south Odisha coasts as a very severe cyclonic storm with maximum sustained wind speed of 80 knots. The very severe cyclonic storm, Luban had multiple recurvature and weakening before landfall over Yemen coast. It crossed Yemen and adjoining Oman coast as a cyclonic storm with wind maximum sustained wind speed of 40 knots. In November very severe cyclonic storm Gaja with an anticlockwise recurving track, southwestward recurving track after the loop and with one of the longest tracks with a life period of about 10 days developed over Bay of Bengal and dissipated over Arabian Sea. The last such recurving track over the Bay of Bengal occurred in 1996. It had rapid intensification before landfall reaching upto 70 knots at the time of landfall over Tamil Nadu and Puducherry coasts. The Cyclonic storm Phethai developed in December with a recurving track. It recurved during and after the landfall over Andhra Pradesh coast and moved along the coast causing two landfalls over Andhra Pradesh coast (near south of Yanam at 0900 UTC followed by another landfall near Tuni at 1430 UTC of the same day, i.e. 17th Dec. 2018).

Thus the year 2018 witnessed cyclones all types of unusual characteristics like northeastward and southwestward recurving tracks, looping tracks, cyclogenesis in very quick succession, simultaneous development of two severe cyclones, rapid intensification before landfall and weakening before landfall. These cyclones are:

- *Cyclonic storm, Sagar over Arabian Sea (16-21 May)*
- *Extremely Severe Cyclonic storm, Mekunu over Arabian Sea (21-27 May)*

- *Cyclonic storm, Daye over eastcentral Bay of Bengal and adjoining Myanmar (19-22 September)*
- *Very Severe Cyclonic storm, Luban over eastcentral Arabian Sea (06-14 October)*
- *Very Severe Cyclonic storm, Titli over eastcentral Bay of Bengal (08-13 October)*
- *Very Severe Cyclonic storm, Gaja over eastcentral Bay of Bengal (10-19 November)*
- *Severe Cyclonic storm, Phethai over Southeast Bay of Bengal (13-18 December)*

- The Cyclonic Storm (CS) **Sagar** originated from a low pressure area which formed over southwest Arabian Sea in the morning (0300 UTC) of 14th May. It became a well marked low pressure area in the early morning (0000 UTC) of 15th over the same region. Under favourable environmental conditions, it concentrated into a Depression (D) over Gulf of Aden in the evening (1200 UTC) of 16th May. Moving west-northwestwards it intensified into a deep depression (DD) in the early morning (0000 UTC) and further into a cyclonic storm (CS) **"Sagar**" in the morning (0300 UTC) of 17th May 2018 over Gulf of Aden. Thereafter, it moved west-southwestwards and crossed Somalia coast near latitude 10.65^0N and longitude 44.0 ^{0}E as a cyclonic storm with maximum sustained wind speed (MSW) of 70-80 kmph gusting to 90 kmph between 1330 and 1430 IST of 19th May. Moving further west-southwestwards, it weakened into a DD in the mid night (1800 UTC) of 19th, D in the early morning (0000 UTC) of 20th and well marked low pressure area (WML) over Ethiopia and adjoining Somalia in the morning (0300 UTC) of 20th.

  - Extremely Severe Cyclonic Storm (ESCS) **Mekunu** originated from a low pressure area which formed over southeast Arabian Sea (AS) in the morning (0300 UTC) of 20th May. It became a well marked low pressure area over southwest & adjoining southeast AS in the early morning (0000 UTC) of 21st May. Under favourable environmental conditions, it concentrated into a Depression (D) over southwest AS in the evening (1200 UTC) of 21st May. Moving west-northwestwards it intensified into a deep depression (DD) in the morning (0300 UTC) of 22nd May. It then moved north-northwestwards and intensified into a cyclonic storm (CS) **"Mekunu**" in the evening (1200 UTC) of same day over southwest AS. It further continued to move north-northwestwards, intensified into a Severe Cyclonic Storm (SCS) in the morning (0300 UTC) and into a Very Severe Cyclonic Storm (VSCS) in the afternoon (0900 UTC) of 23rd May over Westcentral AS. Moving further north-northwestwards, it intensified into an Extremely Severe Cyclonic Storm (ESCS) in the morning (0300 UTC) of 25th and crossed south Oman coast near 16.85^0N/53.75^0E around midnight (between 1830-1930 UTC) of 25th May as an ESCS with an estimated wind speed of 170-180 kmph gusting to 200 kmph. It moved north-northwestwards and weakened into a VSCS over Oman in the early hours of 26th May (2100 UTC of 25th May). Continuing to move north-northwestwards, it weakened into an SCS in the early morning (0000 UTC), into a CS in the afternoon (0900 UTC) and into a DD around midnight (1800 UTC) of 26th May. It further weakened into a D in the early morning (0000 UTC) and into a well marked low pressure area over Saudi Arabia and adjoining Oman & Yemen in the morning (0300 UTC) of 27th May.

  - Cyclonic Storm (CS) **Daye** originated from a low pressure area (LPA) which formed over eastcentral Bay of Bengal (BoB) and adjoining Myanmar in the afternoon (0900 UTC) of 18th September. It lay as a well marked low pressure area (WML) over the same region in the morning (0300 UTC) of 19th September. Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the night (1500 UTC) of 19th September. Moving nearly west-northwestwards, it intensified into a deep depression (DD) over westcentral BoB in the morning (0300 UTC) of 20th September and further into a cyclonic storm (CS) **"Daye"** in the same night (1500 UTC). It crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a cyclonic storm with a wind speed of 60-70 kmph gusting to 80 kmph during 1900-2000 UTC of 20th September. It continued to move west-northwestwards, weakened into a DD in the early morning (0000 UTC) of 21st , into a D in the same evening (1200 UTC) and into a WML over west Madhya Pradesh and adjoining east Rajasthan in the evening (1200 UTC) of 22nd September. It lay as a WML over southeast Rajasthan in the morning (0300 UTC) of 23rd. It lay over north Rajasthan and adjoining southwest Uttar Pradesh & south Haryana in the early morning (0000 UTC) of 24th and lay as an LPA over south Haryana and neighbourhood on 24th morning. It became less marked on 25th morning.

- Very Severe Cyclonic Storm (VSCS) **Luban** originated from a low pressure area (LPA) which formed over southeast Arabian Sea (AS) and neighbourhood in the morning (0830 IST/0300 UTC) of 5th October. It lay as a well marked low pressure area (WML) over southeast and adjoining eastcentral AS in the morning (0530 IST/0000UTC) of 6th October. Under favourable environmental conditions, it concentrated into a Depression (D) over southeast and adjoining eastcentral AS in the afternoon (1430 IST/0900 UTC) of 6th October. Moving west-northwestwards, it intensified into a deep depression (DD) over the same region in the afternoon (1430 IST/0900 UTC) of 7th October. It further intensified into a cyclonic storm (CS) **"Luban"** in the early morning (0530 IST/0000 UTC) of 8th October over westcentral and adjoining south & eastcentral AS. Moving further west-northwestwards it intensified, into a severe cyclonic storm (SCS) in the afternoon (1430 IST/0900 UTC) of 9th over westcentral AS. It then moved northwestwards and further intensified into a very severe cyclonic storm (VSCS) in the early morning (0530 IST/0000 UTC) of 10th over westcentral AS. It attained it"s peak intensity of 75 kts around noon (1130 IST/0600 UTC) of 10th.It maintained it"s peak intensity till early morning(0530 IST/0000 UTC) of 11th. Thereafter, it experienced unfavourable environment like colder sea and dry & cold air advection from Arabian Peninsula and hence, it started weakening. It weakened into an SCS in the morning (0830 IST/0300 UTC) of 12th and into a CS in the same midnight (2330 IST/1800 UTC). It crossed Yemen and adjoining south Oman coasts near 15.8^{0}N and 52.2^{0}E during 1100-1130 hrs IST (0530 to 0600 UTC) of 14th as a CS with the wind speed of 70-80 gusting to 90 kmph. After landfall, it weakened quickly into a DD in the afternoon (1430 IST/0900 UTC) of 14th, into a D in the same midnight (2330 hrs IST/1800 UTC) and into a WML over Yemen and adjoining Saudi Arabia in the morning (0830 IST/0300 UTC of 15th)**.**

- Very Severe Cyclonic Storm (VSCS) Titli originated from a low pressure area (LPA) which formed over southeast Bay of Bengal (BoB) and adjoining north Andaman Sea in the morning (0830 IST) of 7th October. It lay as a well marked low pressure area (WML) over the same region in the same evening (1730 IST). Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the morning (0830 IST) of 8th October. Moving nearly west-northwestwards, it intensified into a deep depression (DD) over eastcentral BoB in the mid-night (2330 IST) of 8th October and further into a cyclonic storm (CS) **"Titli**" around noon (1130 IST) of 9th October. It then moved northwestwards and intensified, into a severe cyclonic storm (SCS) in the early hours (0230 IST) of 10th. It then moved north-northwestwards and further intensified into a very severe cyclonic storm (VSCS) around noon (1130 IST) of 10th. It crossed north Andhra Pradesh and south Odisha coasts near Palasa (18.8^{0}N/84.5^{0}E) to the southwest of Gopalpur during 0430-0530 IST of 11th as a VSCS with the wind speed of 140-150 gusting to 165 kmph. Moving further west-northwestwards, it weakened into an SCS around noon (1130 IST) of 11th and a CS in the same evening (1730 IST). Under the influence of southwesterly winds at middle and upper tropospheric levels, the system recurved northeastwards from 11th evening. It weakened into a DD over south Odisha in the mid-night (2330 IST) of 11th. It further weakened into a D in the afternoon (1430 IST) of 12th, into a WML over Gangetic West Bengal and adjoining Bangladesh & north BoB in the early hours (0530 IST) of 13th and into an LPA over the same region in the morning (0830 IST) of 13th.

- Very Severe Cyclonic Storm (VSCS) Gaja originated from a low pressure area (LPA) which formed over Gulf of Thailand and adjoining Malay Peninsula in the morning (0830 IST) of 8th November**.** It lay as a well marked low pressure area (WML) over north Andaman Sea and neighbourhood in the evening (1730 IST) of 9th November. Under favourable environmental conditions, it concentrated into a Depression (D) over southeast BoB in the morning (0830 IST) of 10th November. Moving west-northwestwards, it intensified into a deep depression (DD) over southeast & adjoining central BoB in the same evening (1730 IST). Moving further west-northwestwards, it intensified into cyclonic storm (CS) "Gaja" over eastcentral and adjoining westcentral & southeast BoB in the early morning (0530 IST) of 11th November, 2018. It then moved nearly westwards till early morning (0530 IST) of 12th. Thereafter it recurved south-southwestwards and followed an anticlockwise looping track till 13th morning. It then moved west-southwestwards and intensified, into a severe cyclonic storm (SCS) over southwest BoB in the morning (0830 IST) of 15th November and into a very severe cyclonic storm in the same night (2030 IST). Moving further west-southwestwards it crossed Tamilnadu & Puducherry coast between Nagapattinam and Vedaranniyam near latitude 10.45˚N and longitude 79.8°E with wind speed of 130 kmph gusting to 145 kmph during 0030 to 0230 hours IST of 16th November. Thereafter, it moved nearly westwards, and weakened rapidly into an SCS in the early morning (0530 IST), a CS in the morning (0830 IST) and into a DD over interior Tamil Nadu in the forenoon (1130 IST) of 16th November. It then moved west-southwestwards and weakened into a D in the same evening (1730 IST) over central Kerala. Moving nearly westwards, it emerged into southeast Arabian Sea (AS) in the same midnight (2330 IST). Moving nearly westwards, it intensified into a DD over southeast AS in the early morning (0530 IST) of 17th November. Thereafter, it moved nearly west-northwestwards and crossed Lakshadweep Islands in the 17th afternoon (1400-1700 hrs IST) as a deep depression. It continued to move west-northwestwards and weakened into a D over southeast AS around noon (1130 IST) of 19th & into a WML over southwest & adjoining southeast AS in the same midnight (2330 IST). It lay as a low pressure area over southwest Arabian Sea on 21st and became less marked over the same region on 22nd.

- The Severe Cyclonic Storm (SCS) **Phethai** originated from a low pressure area (LPA) which formed over Equatorial Indian Ocean and adjoining central parts of south Bay of Bengal (BoB) in the evening (1730 IST) of 9th December. It lay as a well marked low pressure area (WML) over central parts of south BoB and adjoining EIO in the morning (0830 IST) of 11th December. Under favourable environmental conditions, it concentrated into a Depression (D) over southeast BoB in the early morning (0530 IST) of 13th December. Moving north-northwestwards, it intensified into a deep depression (DD) over southeast BoB in the same mid-night (2330 IST) of 13th December. It intensified into a cyclonic storm (CS) **"Phethai**" (Pronounced as Pay-ti) in the evening (1730 IST) of 15th December and into a severe cyclonic storm (SCS) in the afternoon of 16th December. It maintained its intensity of SCS till early morning (0530 IST) of 17th December and weakened into a CS in the same morning (0830 IST). Continuing to move north-northwestwards and then northwards it crossed Andhra Pradesh coast near 16.550N and 82.250E (close to south of Yanam and 40 km south of Kakinada) during 17th afternoon (1330-1430 IST) as a cyclonic storm with maximum sustained wind speed of 75-85 kmph gusting to 95 kmph. After landfall, it moved north-northeastwards and weakened rapidly into a deep depression over westcentral BoB off Kakinada coast in the evening (1730 IST) of 17th December. Continuing to move north-northeastwards, it crossed again Andhra Pradesh coast close to Tuni during 1930-2030 IST and weakened into a depression over coastal Andhra Pradesh during same midnight (2330 IST). It further weakened into a WML over northwest and adjoining westcentral BoB & coastal Odisha in the early morning (0530 IST) and into a low pressure area over northwest BoB and adjoining Odisha in the morning (0830 IST) of 18th December.

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 2018:

1.	Depression over Southeast Arabian sea and adjoining equatorial Indian Ocean (13-15 March)
2.	Cyclonic storm SAGAR over Arabian Sea (16-21 May)
3.	Extremely Severe Cyclonic Storm MEKUNU over Arabian Sea **(** 21-27 May)
4.	Deep Depression over northeast Bay of Bengal (29-30 May)
5.	Depression over northeast Bay of Bengal and adjoining Bangladesh (10-11 June)
6.	Deep Depression over northwest Bay of Bengal (21-23 July)
7.	Depression over northwest Bay of Bengal and neighbourhood (07-08 August)
8.	Depression over coastal Odisha (15-17 August)
9.	Deep Depression over Bay of Bengal (06-07 September)
10.	Cyclonic storm, DAYE over eastcentral Bay of Bengal and adjoining Myanmar (19-22 September)
11.	Very Severe Cyclonic Storm LUBAN over eastcentral Arabian Sea (06-14 October)
12.	Very Severe Cyclonic Storm TITLI over eastcentral Bay of Bengal (08-13 October)
13.	Very Severe Cyclonic Storm GAJA over eastcentral Bay of Bengal (10-19 November)
14.	Severe Cyclonic Storm PHETHAI over southeast Bay of Bengal (13-18 December)

Table 2.2 Some Characteristic features of cyclonic disturbances formed over north Indian Ocean and adjoining region during 2018

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	Depression over Southeast Arabian sea and adjoining equatorial Indian Ocean (13-15 March)	13th March 2018, 0300 UTC over southeast Arabian Sea near (5.0N/76.0E)	Weakened into a Well-marked low pressure area over Lakshadweep and adjoining southeast Arabian Sea	1006 hPa at 0300 UTC 13th March 2018 near (5.0/76.0)	25 knots at 0300 UTC on 13th March 2018 near (5.0/76.0)	T 1.5
2	Cyclonic storm SAGAR over Arabian Sea (16-21 May)	16th May 2018, 1200 UTC over Gulf of Aden near (13.0N/50.0E)	Crossed Somalia coast near latitude 10.65^0N/44.0^0E between 0800-0900 UTC	994 hPa at 0300 UTC 18th May 2018 near (12.2/46.3)	45knots at 0000 UTC of 18th May 2018	T 3.0
3	Extremely Severe Cyclonic Storm MEKUNU over Arabian Sea (21-27 May)	21th May 2018, 1200 UTC over southwest Arabian Sea (8.5N/58.5E)	Crossed south Oman coast near Latitude 16.85^0 N and longitude 53.75^0 E during 1830 UTC and 1930UTC of 25th May 2018.	960 hPa at 1200 UTC 25th May 2018 near (16.4/54.1)	95 knots at 1200 UTC of 25th May 2018	T 5.0
4	Deep Depression over northeast Bay of Bengal (29-30 May)	29th May 2018,0600 UTC over eastcentral and adjoining northeast Bay of Bengal near (18.5°N/92.2°)	Weakened into a well-marked low pressure area over Myanmar at 06 UTC of 30th May 2018.	992 hPa at 0000 UTC 29th May, 2018 near (19.2/93.0)	30 knots at 1800 UTC 29th May, 2018	T2.0
5	Depression over northeast Bay of Bengal and	10th June, 2018, 0600 UTC over northeast BoB and adjoining	Weakened into a well marked low pressure area over Bangladesh	988 hPa at 1200 UTC 10thJune 2018 near	25 knots at 0600 UTC 10thJune 2018	T 1.5

	adjoining Bangladesh (10-11 June)	Bangladesh (22.3N/91.5E)	and neighbourhood.	(22.7/91.4)		
6	Deep Depression over northwest Bay of Bengal (21-23 July)	21th July 2018, 0300 UTC over over northwest BoB near (21.0N/88.0E)	Depression Weakened into a Well Marked Low Pressure Area over northwest Jharkhand and neighbourhood at 0300 UTC	989 hPa at 0300 UTC on 21th July 2018 near (21.4/87.7)	25 knots at 0300 UTC on 21th July 2018	T 1.5
7	Depression over northwest Bay of Bengal and neighbourhood (07-08 August)	7th July 2018 at 0900 UTC over northwest BoB near (21.5N/87.5E)	Weakened into a well-marked low pressure area over north Chattisgarh & neighborhood at 0300 UTC	992 hPa at 0900 UTC on 07th Aug 2018. (21.5/87.5)	25 knots at 0900 UTC on 07th Aug 2018.	T1.5
8	Depression over coastal Odisha (15-17 August)	15th Aug 2018, 0300 UTC over coastal Odisha (20.0N/86.0E)	Weakened into a well-marked low pressure area over southwest Madhya Pradesh and adjoining Gujarat & north Madhya Maharashtra	993 hPa at 0300 UTC 15th Aug, 2018 near (20.0/86.0)	25 knots at 0300 UTC 15th Aug, 2018	-
9	Deep Depression over Bay of Bengal (06-07 September)	06th Sept. 2018, 0000 UTC over northwest BoB and adjoining West Bengal Bangladesh coasts near (21.8N/88.0E)	Crossed West Bengal coast close to Digha between during 0430-0530 UTC.	990 hPa at 0300 UTC 06th Sept 2018 near (21.8/87.9)	30 knots at 0300 UTC 06th Sept 2018	T 2.0
10	Cyclonic storm, DAYE over eastcentral Bay of Bengal and adjoining Myanmar (19-22 September)	19th September 2018,0300 UTC over eastcentral BoB near (17.2N/89.0E)	Crossed south Odisha and adjoining north Andhra Pradesh coasts close to Gopalpur near 19.27^0N/84.92^0E between 1900-2000 UTC of 20th Sept. 2018	992 hPa at 0000 UTC 20th Sept. 2018.near (18.7/85.6)	35 knots at 1500 UTC 20th Sept 2018.	T 2.5

11	Very Severe Cyclonic Storm LUBAN over eastcentral Arabian Sea (06-14 Oct.)	06th October 2018,0900 UTC Over southeast and adjoining eastcentral AS near (11.2N/67.0E)	Crossed Yemen and adjoining Oman coasts near 15.8^{0}N and 52.2^{0}E during 0530 to 0600 UTC	978 hPa at 0600 UTC 10th Oct. 2018.near (14.2/58.9)	75 knots at 0600 UTC 10th Oct. 2018.near (14.2/58.9)	T4.5
12	Very Severe Cyclonic Storm TITLI over eastcentral Bay of Bengal (08-13 Oct.)	08th October 2018,0300 UTC Over eastcentral BoB near (14.0N/88.8E)	Crossed north Andhra Pradesh and south Odisha coasts near 18.8^{0}N/ 84.5^{0}E during 2300 UTC of 10th and -0000 UTC of 11th	972 hPa at 1200 UTC 10th Oct. 2018.near (17.5/85.3)	80 knots at 1200 UTC 10th Oct. 2018.near (17.5/85.3)	T 4.5
13	Very Severe Cyclonic Storm Gaja over eastcentral Bay of Bengal (10-19 November)	10th November 2018,0300 UTC Over southeast BoB (11.7/92.5)	Crossed Tamil Nadu and Puducherry coasts between Nagapattinam & Vedaranniyam near 10.45^{0}N and 79.8^{0}E during 1900 to 2100 UTC	976 hPa at 1800 UTC 15th Nov. 2018.near (10.5/80.3)	70 knots at 1800 UTC 15th Nov. 2018.near (10.5/80.3)	T 4.0
14	Severe Cyclonic Storm "Phethai" over southeast Bay of Bengal (13-18 Dec.)	13th December 2018,0000 UTC Over southeast BoB (6.5/88.7)	Crossed Andhra Pradesh coast near 16.55^{0}N and 82.25^{0}E 25 km south of Yanam and 40 km south of Kakinada during 0800 to 0900 UTC	992 hPa at 1200 UTC 16th Nov. 2018.near (13.3/83.0)	55 knots at 1200 UTC 16th Nov. 2018.near (13.3/83.0)	T 3.5

Table 2.3 Statistical data relating to cyclonic disturbances over the north Indian Ocean during 2018

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

S N	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.	D			↔			↔		↔ ↔				
2.	DD					↔		↔		↔			
3.	CS					↔				↔			
4.	SCS												↔
5.	VSCS										↔ ↔	↔	
6.	ESCS					↔							

↔ Peak intensity of the system, LD: Land Depression

B) Life time of cyclonic disturbances during 2018 at different stages of intensity

S.No.	Type	Life Time in (Days)
1	D	14 days 21 hours
2.	DD	09 days 18 hours
3.	CS	13 days 09 hours
4.	SCS	03 day 18 hours
5.	VSCS	05 days 9 hours
6.	ESCS	00 days 21 hours
	Total Life Time in(Days)	48 days 0 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	14	9	7	6	5	2	1	-	-	-

D) Basin-wise distribution of cyclonic distribution

Basin	Number of cyclonic disturbances
Bay of Bengal	9
Arabian Sea	4
Land depression	1

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								8
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**
2018	BOB	2	3	1	2	1	0	0	**9**
	ARB	1	0	0	0	1	2	0	**4**
	Land	1	0	0	0	0	0	0	**1**
	Total								**14**

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

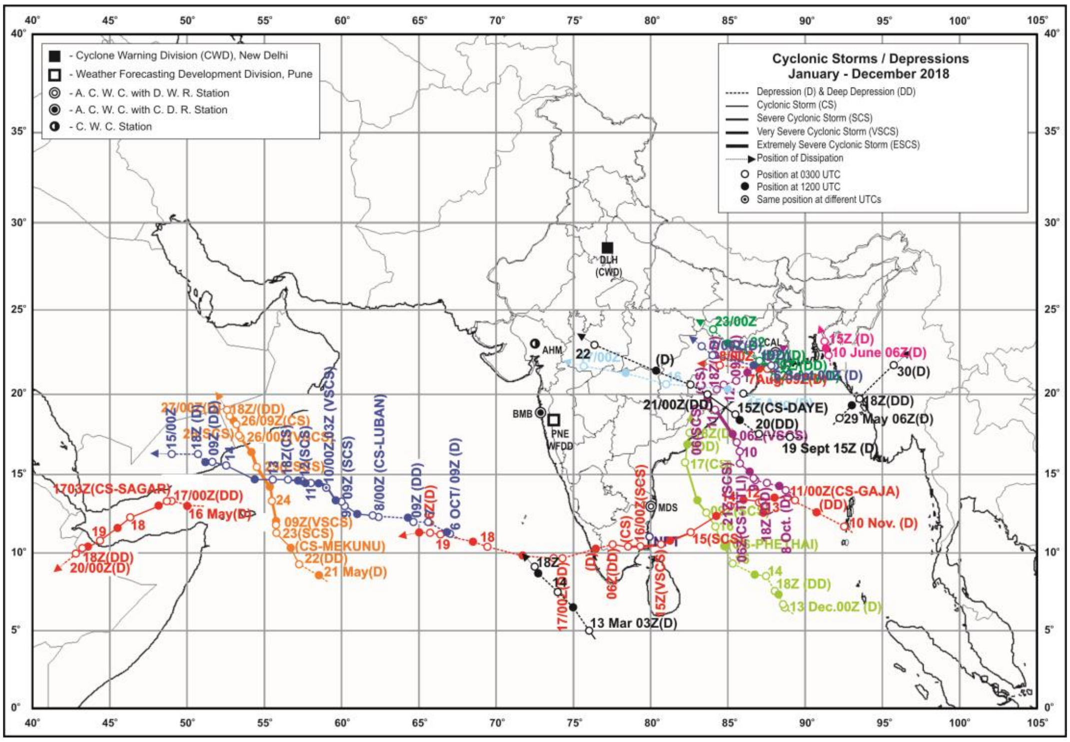


Fig. 2.1.: Tracks of cyclonic disturbances over north Indian Ocean and adjoining land region during 2018

Table 2.5 Average translational speed of Tropical cyclones over the NIO during 2018

TC Name	Basin	Period	Average Translational Speed		
			6 Hr	12 Hr	24 Hr
SAGAR	AS	16-21 April	10.5	10.6	10.8
MEKUNU	AS	21-27 May	10.5	10.4	10.4
DAYE	BOB	19–22 September	25.8	26.2	26.7
LUBAN	AS	06-14 October	10.5	10.4	10.4
TITLI	BOB	08-13 October	12.7	12.1	11.3
GAJA	BOB	10-19 November	10.5	10.4	10.4
PHETHAI	BOB	13-18 December	13.4	13.5	13.4
Average Translational Speed During 2018			13.4	13.4	13.3

Table 2.6 Velocity Flux of Tropical cyclones over the NIO during 2018

TC Name	**Velocity Flux (10^2 kt)**	**Accumulated Cyclone Energy (10^4 kt^2)**	**Power Dissipation Index (10^6 kt^3)**
Sagar	4.55	1.9	0.8
Mekunu	11.6	8.4	6.5
Daye	0.35	0.12	0.04
Luban	14.1	8.11	4.92
Titli	6.25	3.85	2.55
Gaja	9.4	4.35	2.1
Phethai	3.6	1.67	0.79
TOTAL	49.85	28.4	17.7

2.1. Depression over southeast Arabian Sea and adjoining equatorial Indian Ocean (13-15 March, 2018)

2.1.1. Introduction

A low pressure area formed over equatorial Indian Ocean and adjoining southwest Bay of Bengal (BoB) and south Sri Lanka coast on 10th March. It lay as a well-marked low pressure (WML) area near Maldives-Comorin area on 12th March and later concentrated into a depression in the morning of 13th March over southeast Arabian Sea and adjoining equatorial Indian Ocean. It initially moved northwestwards and later north-northwestwards and weakened into well marked low pressure area over Lakshadweep and adjoining southeast Arabian Sea (AS) in the early morning of 15th March (0530 hours IST), a low pressure area over Lakshadweep Area and adjoining southeast AS on 16th and less marked on 17th March. Its genesis, movement and associated adverse weather could be predicted well by IMD. The salient features of the system were as follows:

(i) The system had a straight moving track.

(ii) The life period of the system was 45 hours.

(iii) It caused heavy to very heavy rainfall at isolated places in south Tamil Nadu and Kerala on 14th, heavy at isolated places over Kerala and Lakshadweep on 16th and Tamilnadu & interior Karnataka on 17th.

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 Sri Lanka.

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

2.1.2. Brief life history

A trough of low developed at mean sea level lay over Equatorial Indian Ocean and adjoining southeast BoB and Nicobar Islands on 7th March, 2018. It lay over Equatorial Indian Ocean and adjoining southeast BoB on 08th March 2018 and over Equatorial Indian Ocean and adjoining central parts of south BoB on 09th. It lay as a low pressure area over southwest BoB off Sri Lanka- south Tamilnadu coasts with the associated cyclonic circulation extending up to mid tropospheric levels on 10th. It lay over Equatorial Indian Ocean & adjoining southwest BoB & south Sri Lanka coast with associated cyclonic circulation extending up to mid tropospheric levels on 11th. Considering the environmental conditions at 0300 UTC of 11th, the sea surface temperature (SST) was 29-30˚C, Ocean Thermal Energy (OTE) was about 50 KJ/cm^2 over Comorin area and more than 100 KJ/cm^2 over many parts of Lakshadweep area and adjoining southeast AS. Low level convergence & upper level divergence were $10x10^{-5}$ s^{-1} & $20x10^{-5}$ s^{-1} respectively, both to the southern parts of low pressure area adjacent to equator. Vorticity is $50x10^{-6}$ s^{-1} over the same region. Vertical wind shear was low to moderate over the region and low over Lakshadweep area and adjoining southeast AS. Upper tropospheric ridge lay along latitude 10.0^{0}N near long. 80^{0}E. It was favouring poleward outflow and hence increasing the upper level divergence. The upper and lower level winds indicate that the system will move initially west-northwestwards and then west-northwestwards across Comorin area and emerge into lakshadweep area and adjoining southeast As during next 72 hrs. All these features indicated that the low pressure area will experience further favourable environmental parameters.

It lay as a WML over Equatorial Indian Ocean and adjoining south Sri Lanka and Maldives- Comorin area, with associated cyclonic circulation extending upto mid tropospheric levels on 12th. Favourable environmental features continued. Similar thermal features continued. Low level convergence was 10x10-5 s^{-1} in the southwest sector of the system. The upper level divergence increased during past 24 hours and was about 30x10-5 s^{-1} in the southeast sector of the system. The vorticity increased during past 24 hours & was about 60-70 $x10^{-6}$ s^{-1} over the same region. Vorticity field was extending upto mid tropospheric level and was oriented southwest to northeast. Vertical wind shear was low to moderate over the region and low over lakshadweep area & adjoining southeast AS. Upper tropospheric ridge lay along latitude 10.0^0N near long. 80^0E. It was favouring poleward outflow and hence increasing the upper level divergence. The total precipitable water (TPW) vapour imageries indicated warm air advection from southeast sector. The upper and lower level winds indicated that the system will move initially west-northwestwards and then northwestwards. Under these favourable conditions the system intensified into a WML over Equatorial Indian Ocean and adjoining south Sri Lanka and Maldives- Comorin area on 12^{th}.

At 0300 UTC of 13th, similar thermal conditions prevailed. The upper level divergence increased during past 24 hours and was about $30x10^{-5}$ s^{-1} in the southeast sector of the system. The vorticity increased and was about 100 $x10^{-6}$ s^{-1} over the same region extending upto mid-tropospheric level. Vertical wind shear was low to moderate over the region and low over Lakshadweep area and adjoining southeast AS. There was no change in shear tendency during past 24 hours over the region. Upper tropospheric ridge lay along latitude 10.0^0N near long. 80^0E. It was favouring poleward outflow. Under these conditions, the system intensified into a depression over southeast Arabian Sea and adjoining equatorial Indian Ocean at 0300 UTC of 13th. However, TPW imageries indicated reduction in the supply of moisture from southeast sector and increase in incursion of cold air to the outer periphery from southwest sector.

At 0300 UTC of 14th, the system lay over southeast AS. Similar thermal conditions prevailed over the region. The low level convergence was about $15x10^{-5}$ s^{-1} around the system center. The upper level divergence decreased and was about $20x10^{-5}$ s^{-1} around system center. The vorticity was about 100 $x10^{-6}$ s^{-1} over the region. Vertical wind shear was low to moderate (10-15 kts) over the region. Upper tropospheric ridge lay along latitude 11.0^0N near longitude 80.0^0E in association with anti-cyclonic circulation over southwest and adjoining westcentral BoB. It was favouring poleward outflow. The upper and lower levelwinds indicated that the system will move northwestwards. TPW imageries indicated reduction in warm air advection and cold air was reaching southwest periphery of the system. Under these conditions, the system maintained it"s intensity and moved northwestawards.

At 0000 UTC of 15^{th} moving northwestwards, the system weakened into a WML over Lakshadweep and adjoining southeast Arabian Sea. The low level convergence was about $10x10^{-5}$ s^{-1} around the system center. The upper level divergence was about $10x10^{-5}$ s^{-1} around system center. The vorticity was about 80 $x10^{-6}$ s^{-1} over the same region. Vertical wind shear was low to moderate (5-15 kts) over the region. Upper tropospheric ridge continued at similar position. The upper and lower level winds indicated that the system will move north-northwestwards. TPW imageries indicated reduction in warm air advection and cold air reached southwest periphery of the system.

The best track parameters of the system are presented in Table 2.1.1. The track of the depression is presented in Fig.2.1.1. The typical satellite imageries are presented in Fig. 2.2.2.

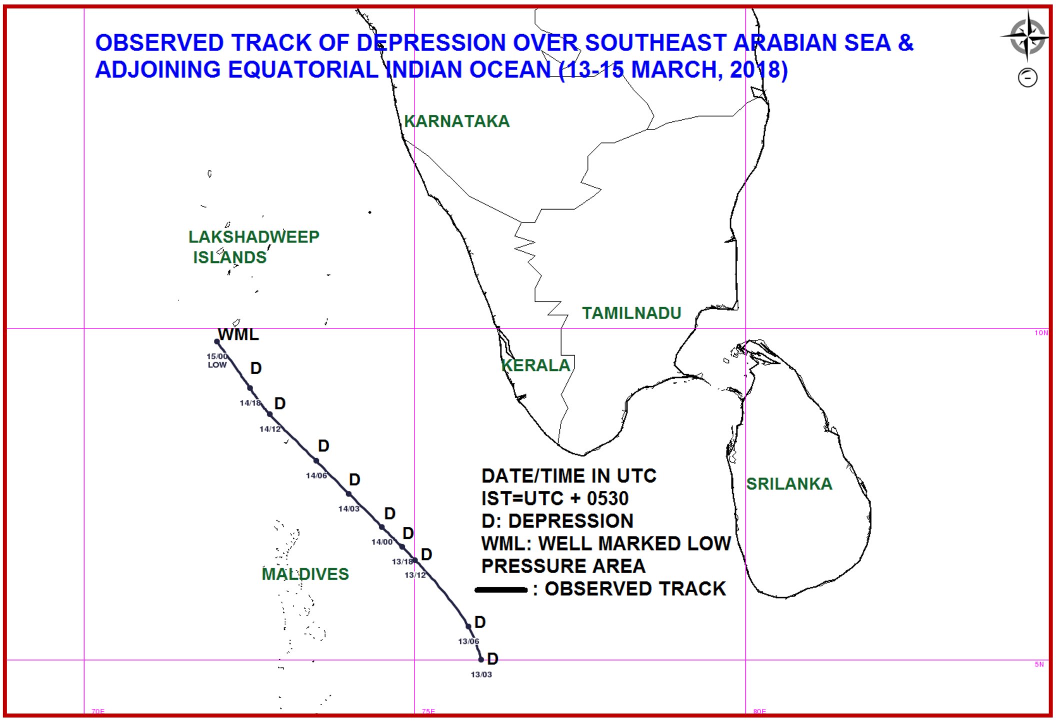


Fig.2.1.1. Observed track of Depression over southeast Arabian Sea and adjoining equatorial Indian Ocean (13-15 March, 2018)

Table 2.1.1: Best track positions and other parameters of the Depression over southeast Arabian Sea and adjoining equatorial Indian Ocean during 13-15 March, 2018

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
13/03/2018	0300	05.0/76.00	1.0	1006	25	3	D
	0600	05.5/75.80	1.5	1006	25	3	D
	1200	06.5/75.00	1.5	1006	25	3	D
	1800	06.7/74.80	1.5	1006	25	3	D
14/03/2018	0000	07.0/74.50	1.5	1006	25	3	D
	0300	07.5/74.00	1.5	1006	25	3	D
	0600	08.0/73.50	1.5	1006	25	3	D
	1200	08.7/72.80	1.5	1006	25	3	D
	1800	09.1/72.50	1.5	1006	25	3	D
15/03/2018	0000	Weakened into a Well-marked low pressure area over Lakshadweep and adjoining southeast Arabian Sea					

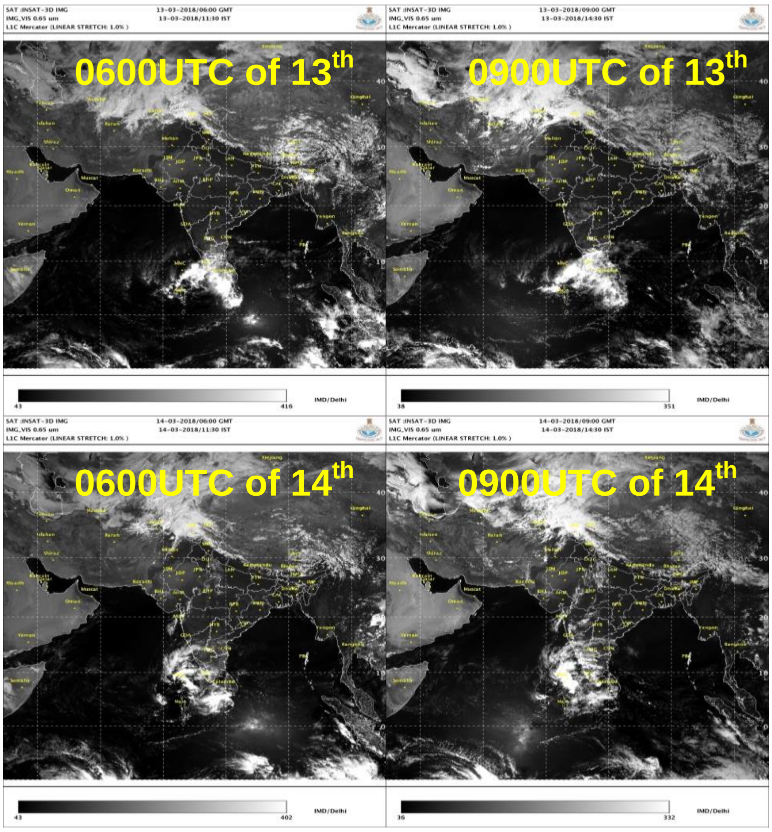


Fig. 2.1.2(i): INSAT-3D visible imageries during Depression (13-15 March, 2018)

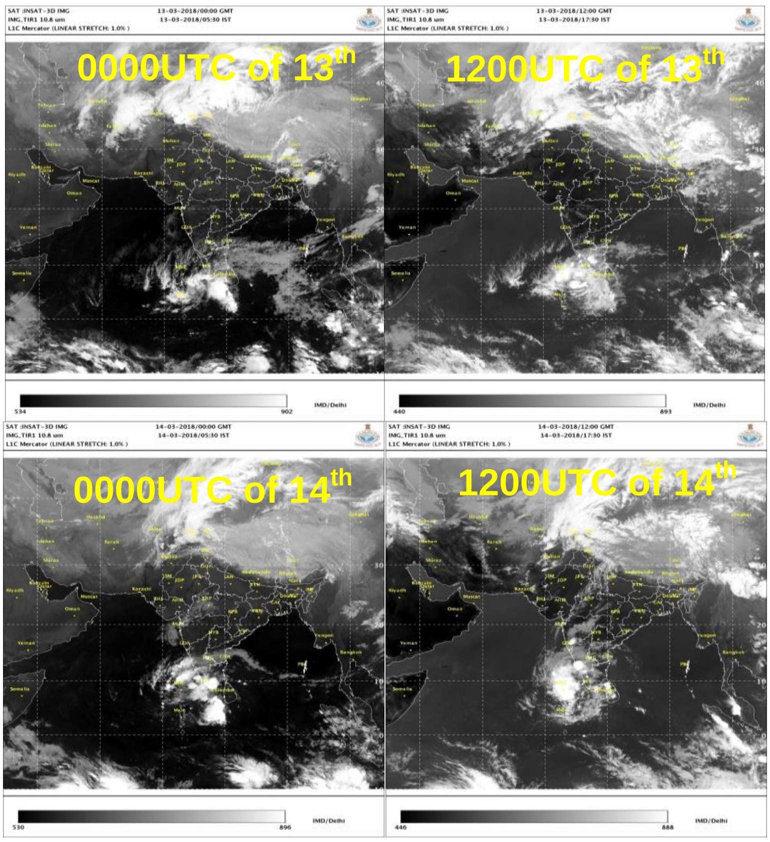


Fig. 2.1.2(ii): INSAT-3D IR imageries during Depression (13-15 March, 2018)

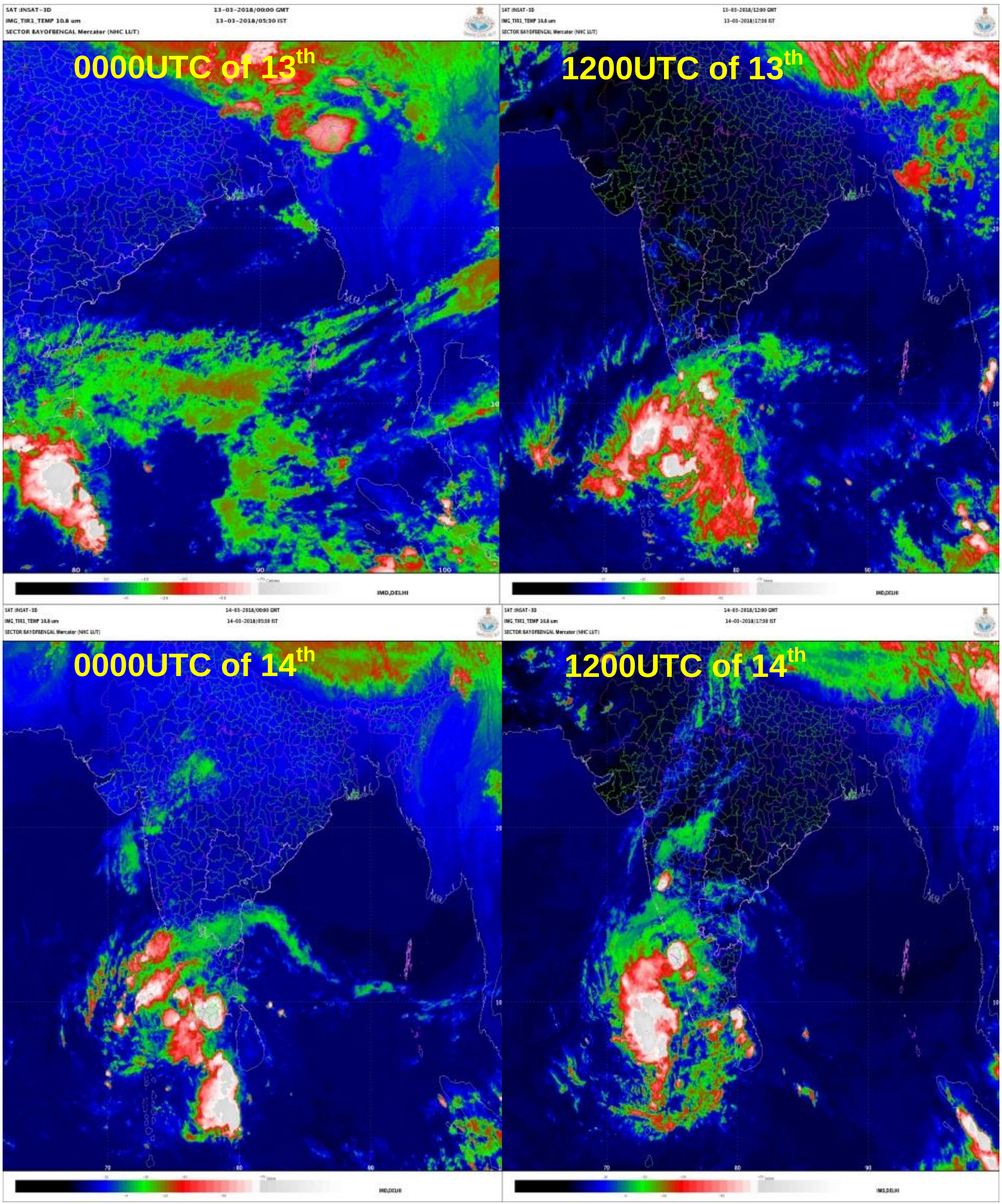


Fig. 2.1.2(iii): INSAT-3D enhanced coloured imageries during Depression (13-15 March, 2018)

2.1.3. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig.2.1.3. GFS (T1534) could simulate the genesis of the system and the presence of upper tropospheric ridge on 13th. The charts based on 13th and 14th also indicated northwestward movement of system with no intensification.

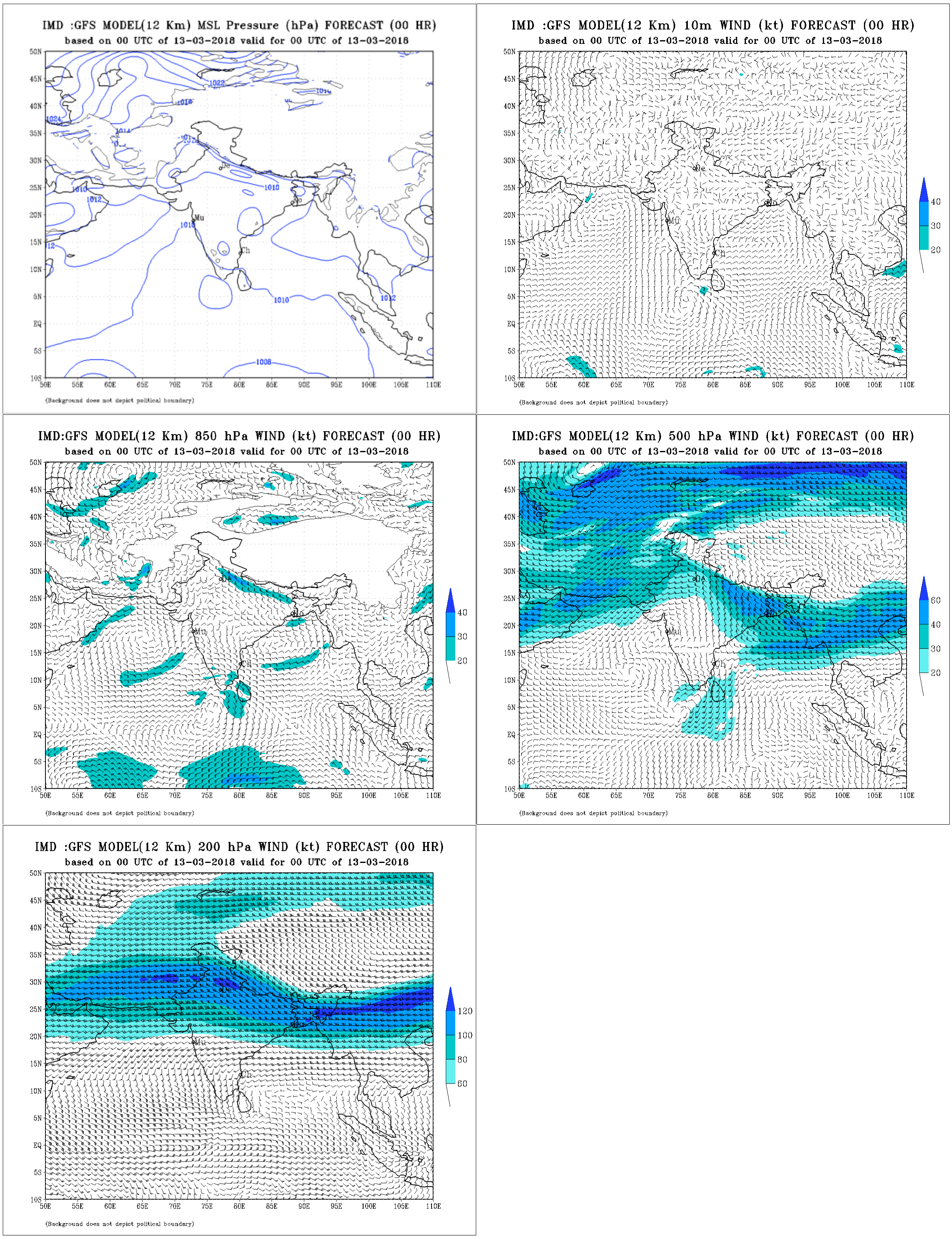


Fig. 2.1.3 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th March

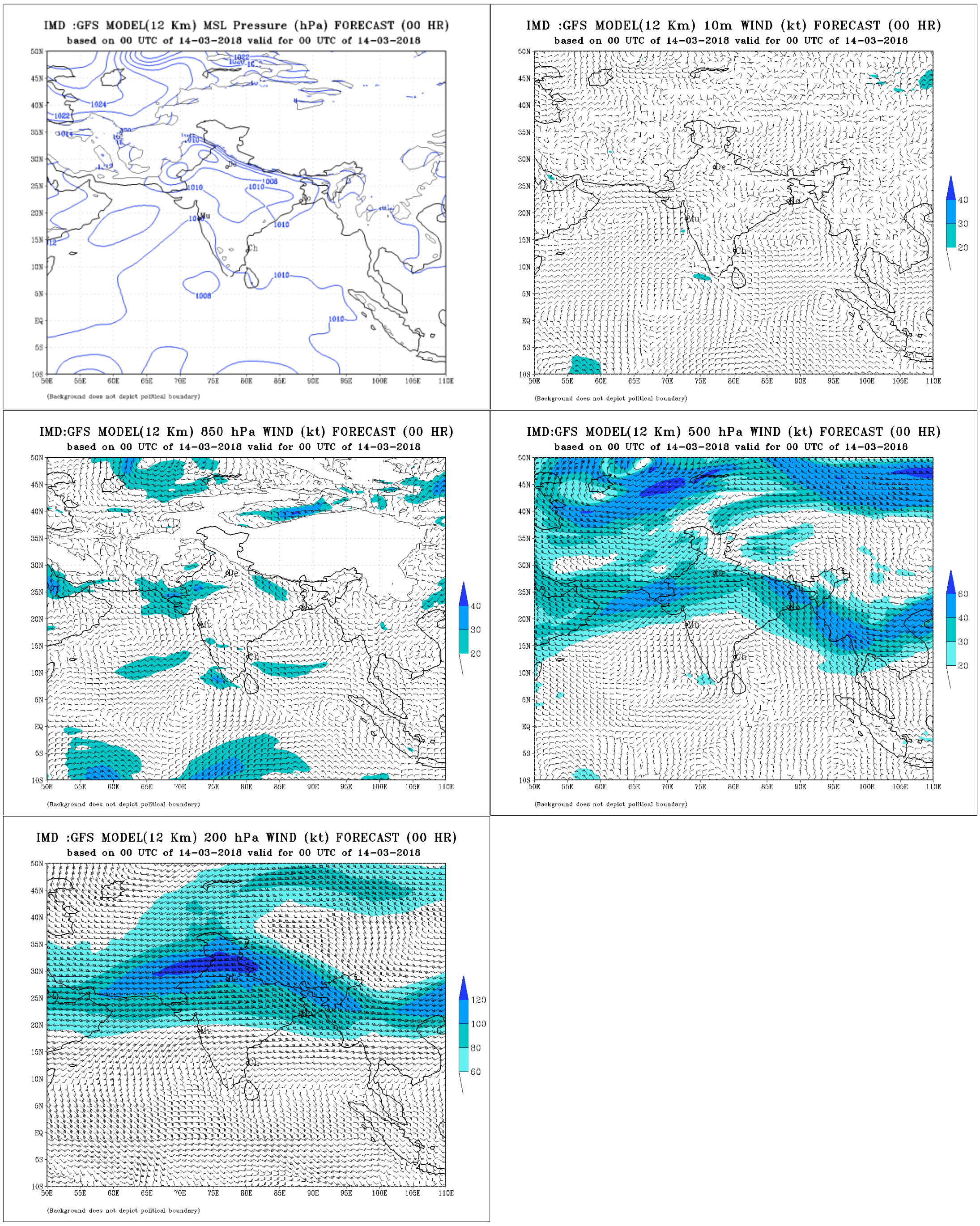


Fig. 2.1.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th March

2.1.4. Realized Weather:

2.1.4.1 Rainfall:

Realised weather:

Under the influence of depression, heavy to very heavy rainfall occurred at isolated places in south Tamil Nadu and Kerala on 14th while heavy rainfall occurred at isolated places over Kerala and Lakshadweep on 16th and in Tamilnadu and interior Karnataka on 17th.

The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig. 2.1.4.

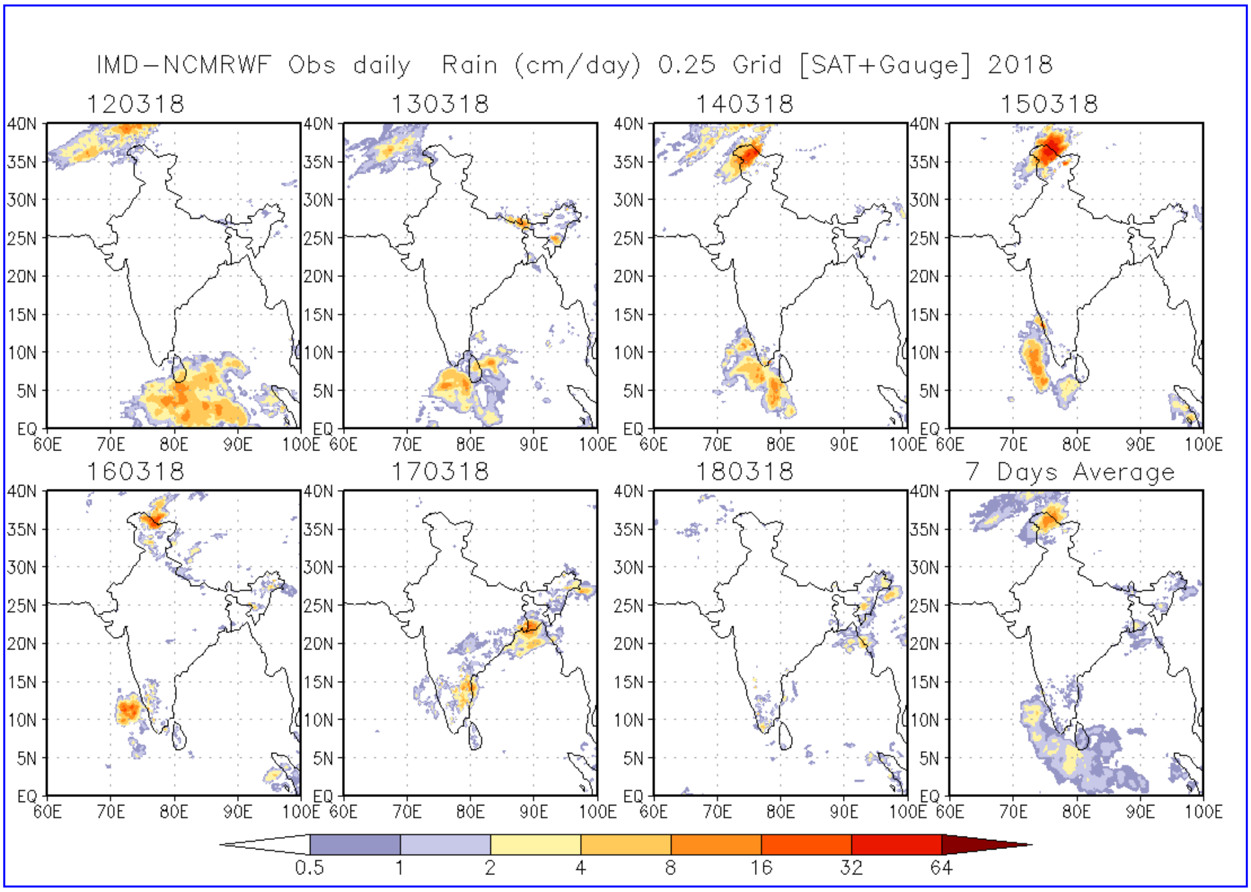


Fig. 2.1.4: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 13-15 March 2018

The 24 hour cumulative rainfall (≥ 7 cm) ending at 0830 hours IST of date during 14^{th}-17^{th} March is presented below:

<u>14th March</u>

Tamilnadu & Puducherry: Tuticorin-20, Papanasam (Tirunelveli)-19, Shencottah-10, Srivaikuntam & Thenkasi-9 each, Tiruchendur-8 and Manimutharu & Ambasamudram-7 each

Kerala: Aryankavu-12

<u>16th March</u>

Kerala: Vyttiri-9

Lakshadweep: Agathi-11.

<u>17th March</u>

Tamilnadu & Puducherry: Tirupattur-8, Omalur-7

North Interior Karnataka: Haveri -7

South Interior Karnataka: Chintamani -10

2.2. Cyclonic Storm "Sagar" over Arabian Sea (16 – 21 May 2018)

2.2.1. Introduction

The Cyclonic Storm (CS) Sagar originated from a low pressure area which formed over southwest Arabian Sea in the morning (0300 UTC) of 14th May. It became a well marked low pressure area in the early morning (0000 UTC) of 15th over the same region. Under favourable environmental conditions, it concentrated into a Depression (D) over Gulf of Aden in the evening (1200 UTC) of 16th May. Moving west-northwestwards it intensified into a deep depression (DD) in the early morning (0000 UTC) and further into a cyclonic storm (CS) **"Sagar**" in the morning (0300 UTC) of 17th May 2018 over Gulf of Aden. Thereafter, it moved west-southwestwards and crossed Somalia coast near latitude 10.65^{0}N and longitude 44.0 ^{0}E as a cyclonic storm with maximum sustained wind speed (MSW) of 70-80 kmph gusting to 90 kmph between 1330 and 1430 IST of 19th May. Moving further west-southwestwards, it weakened into a DD in the mid night (1800 UTC) of 19th, D in the early morning (0000 UTC) of 20th and well marked low pressure area (WML) over Ethiopia and adjoining Somalia in the morning (0300 UTC) of 20th. The salient features of the system are as follows:

- The CS, Sagar was the first cyclone to cross coast to the west of longitude 45^{0}E during satellite era (since 1965).
- Last cyclone developing and passing through Gulf of Aden was cyclone Bandu (19-23 May, 2010, MSW-40 kts) which dissipated over Gulf of Aden without making landfall.
- It had an anticlockwise and west southwestward recurving track.
- The peak maximum sustained surface wind speed (MSW) of the cyclone was 80-90 kmph gusting to 100 kmph (45 knots) during 0000 UTC of 18th to 0300 UTC of 19th May.
- The lowest estimated central pressure was 994 hPa (from 0000 UTC of 18th to 0300 UTC of 19th May).
- The life period of cyclone was 87 hours (3 days & 15 hours) against long period average (LPA) (1990-2013) of 3.7 days for cyclonic storm over Arabian Sea.
- The track length of the cyclone was 766 km.
- The 12 hour average translational speed of the cyclone was 10.6 kmph against LPA (1990-2013) of 13.6 kmph over AS.

The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 4.55 X10^{2} knots, 1.9 X 10^{4} knots^{2} and 0.8 X10^{6} knots^{3} respectively against LPA (1990-2013) of 1.89 X10^{2} knots, 1.4 X 10^{4} knots^{2} and 1.2 X10^{6} knots^{3} during pre-monsoon season for AS.

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 CS, 'SAGAR'

The cyclone was monitored & predicted continuously since its inception by India Meteorological Department (IMD). The observed track of the cyclone over Arabian Sea during 16-20 May is shown in **Fig. 2.2.1**. The best track parameters of the systems are presented in **Table 2.2.1.**

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it"s genesis as low pressure area over AS from 11th May onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations and available ships & buoy observations in the region. Various national and international numerical weather prediction 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 including Yemen, Oman and Somalia, National & State Disaster Management Agencies, general public and media since inception of the system over AS.

2.2.3. Brief life history

2.2.3.1. Genesis

The Cyclonic Storm (CS) Sagar originated from a low pressure area which formed over southwest Arabian Sea in the morning (0300 UTC) of 14th May. It became a well marked low pressure area in the early morning (0000 UTC) of 15th over the same region. On 16th may 2018, considering the environmental parameters, the sea surface temperature (SST) was 30-32^{0}C over the system area. The tropical cyclone heat potential is about 80-100 kJ/cm^2 over the region of the low pressure system and it was less than 50kJ/cm^2 over the Gulf of Aden. There was a maxima of $10x10^{-5}$ s^{-1} in low level convergence to the southwest of the system centre. The upper level divergence was about $20x10^{-5}$ s^{-1} to the north of system centre. The vorticity at 850 hpa level was about $100x10^{-6}$ s^{-1} around the system centre and was extending upto 500 hpa level. Vertical wind shear was low to moderate (10-15 kts) around the system centre and over Gulf of Aden. It increased towards Yemen and Oman coasts. Upper tropospheric ridge lay along latitude 18.0^{0}N near longitude 50^{0}E. It favoured poleward outflow and hence increase in the upper level divergence. The Madden Julian Oscillation (MJO) index lay over phase 1 with amplitude greater than 1. The middle and upper level winds indicated the system to move initially west-northwestwards across Gulf of Aden during next 24 hrs. Under these favourable environmental conditions, it concentrated into a Depression (D) over Gulf of Aden in the evening (1200 UTC) of 16th May.

2.2.3.2. Intensification and Movement

The similar environmental conditions like SST and Ocean thermal energy continued on 17th May. The low level convergence increased and there was a maxima of $30x10^{-5}$ s^{-1} at 0000 UTC of 17th May to the south of the system centre. The upper level divergence was about $20x10^{-5}$ s^{-1} over the system centre. The vorticity at 850 hpa level was about $100x10^{-6}$ s^{-1} around the system centre and was extending upto 500 hpa level. The vertical wind shear continued to be low to moderate (10-15 kts) around the system centre and over Gulf of Aden. It increased towards Yemen and Oman coasts. The upper tropospheric ridge lay along latitude 17.0^{0}N near longitude 50^{0}E. It favoured poleward outflow and hence increase in the upper level divergence. The MJO index continued to be in phase 1 with amplitude greater than 1. The middle and upper level winds indicate that the system would move initially westwards during next 12 hours and then west-southwestwards across Gulf of Aden during subsequent24 hrs.

Under these conditions, the depression moved west-northwestwards and intensified into a deep depression (DD) in the early morning (0000 UTC) and further into a cyclonic storm (CS) **"Sagar**" in the morning (0300 UTC) of 17th May 2018 over Gulf of Aden. Thereafter, it moved west-southwestwards maintaining maximum intensity of 45 knots (CS) till 0300 UTC of 19th May.

On 19th morning, the tropical cyclone heat potential is about 50kJ/cm^{2}over the region of the system. The lower level convergence decreased and was about 20 x10^{-5} s^{-1} to the south southeast of the system centre. The upper level divergence continued to be about 30 x10^{-5} s^{-1} around the system centre. The vorticity at 850 hpa level also continued to be about 100x10^{-6} s^{-1}to the south of the system centre. The vertical wind shear decreased and was low (05-10kts) around the system centre. It increased towards Yemen and Oman coasts. Upper tropospheric ridge ran along latitude 14.0^{0}N near longitude 45^{0}E. As the system moves west-southwestwards, it was coming closer to land surface and hence there was increased land interaction. The total precipitable water (TPW) imagery indicates relatively dry air condition in the periphery of the system in southern sector covering Somalia. However, system maintained intensity of CS due to favourable vertical wind shear, though it showed marginal decrease in intensity.

It crossed Somalia coast near latitude 10.65^{0}N and longitude 44.0 ^{0}E as a cyclonic storm with maximum sustained wind speed (MSW) of 70-80 kmph gusting to 90 kmph between 0800 and 0900 UTC of 19th May. Moving further west-southwestwards, it weakened into a DD in the mid night (1800 UTC) of 19th, D in the early morning (0000 UTC) of 20th and well marked low pressure area (WML) over Ethiopia and adjoining Somalia in the morning (0300 UTC) of 20th

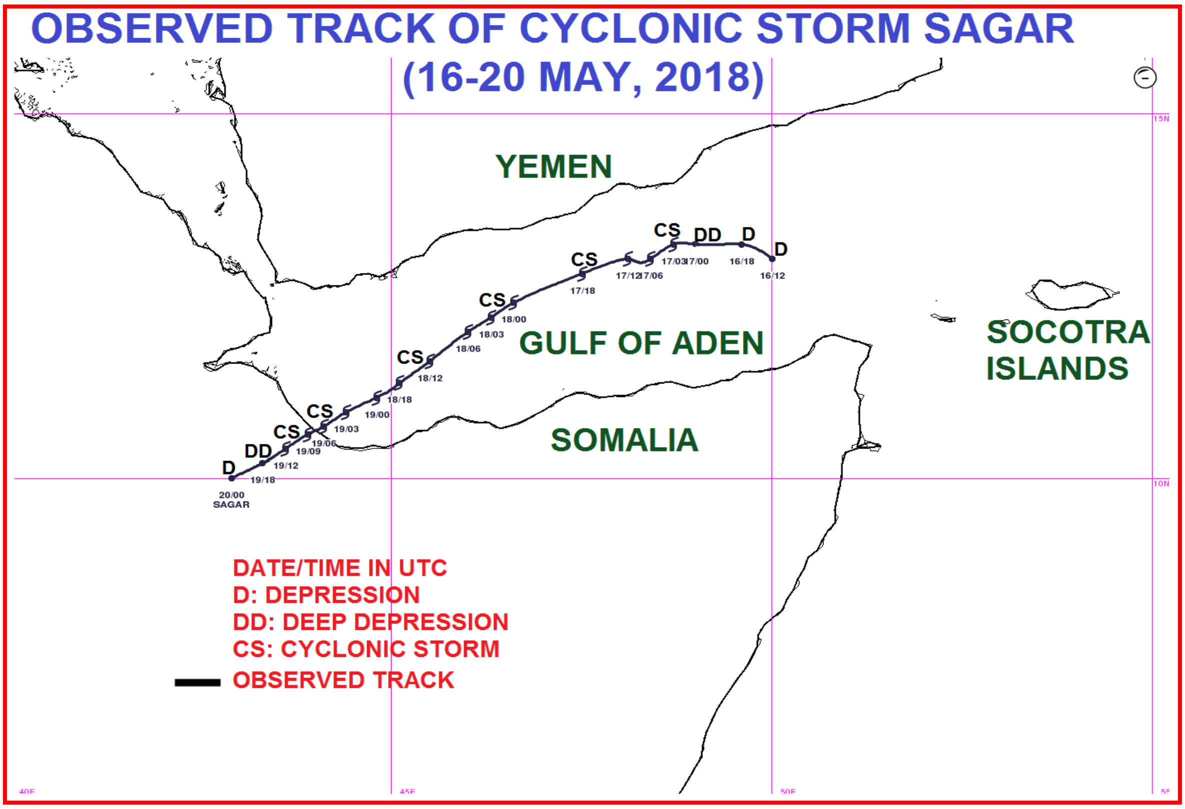


Fig.2.2.1 Observed track of CS Sagar (16- 20 May, 2018) over Arabian Sea

Table 2.2.1: Best track positions and other parameters of the Extremely Severe Cyclonic Storm, 'Sagar' over the Arabian Sea during 16 May-20 May, 2018

Date(DD/MM/YYYY)	Time (UTC)	Latitude (lat)	longitude (Long)	CI No [or "T. No"]	Estimated Central Pressure (hPa) [or "E.C.P"]	Maximum Sustained Surface	Pressure Drop (hPa)[or "delta P"]	Grade (text)
16/05/2018	1200	13.0	50.0	1.5	1001	25	3	D
	1800	13.2	49.6	1.5	1001	30	4	D
17/05/2018	0000	13.2	49.0	2.5	999	30	5	DD
	0300	13.2	48.7	2.5	997	35	7	CS
	0600	13.0	48.4	2.5	997	35	7	CS
	0900	13.0	48.3	2.5	997	35	7	CS
	1200	13.0	48.1	2.5	996	40	8	CS
	1500	13.0	47.8	2.5	996	40	8	CS
	1800	12.8	47.5	2.5	996	40	8	CS
	2100	12.7	47.2	2.5	996	40	8	CS
18/05/2018	0000	12.4	46.6	3.0	996	45	10	CS
	0300	12.2	46.3	3.0	994	45	10	CS
	0600	12.0	46.0	3.0	994	45	10	CS
	0900	11.8	45.6	3.0	994	45	10	CS
	1200	11.6	45.5	3.0	994	45	10	CS
	1500	11.4	45.3	3.0	994	45	10	CS
	1800	11.3	45.1	3.0	994	45	10	CS
	2100	11.2	45.0	3.0	994	45	10	CS
19/05/2018	0000	11.1	44.8	3.0	994	45	10	CS
	0300	10.9	44.4	3.0	994	45	10	CS
	0600	10.8	44.1	3.0	996	40	08	CS
	Crossed Somalia coast near latitude 10.65^0N/44.0^0E between 0800-0900 UTC							
	0900	10.6	43.9	-	998	40	08	CS
	1200	10.4	43.6	-	1000	35	7	CS
	1800	10.2	43.3	-	1001	30	5	DD
20/05/2018	0000	10.0	42.9	-	1003	25	3	D
	0300	Weakened into well marked low pressure area over Ethiopia						

The TPW imageries during 16-20 May, 2018 are presented in **Fig. 2.2.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system till 19th May, even when the system was located in Gulf of Aden. Thereafter, the system started interacting with land surfaces and moisture supply also reduced from southeast sector. However, it maintained the intensity due to low vertical wind shear over the region.

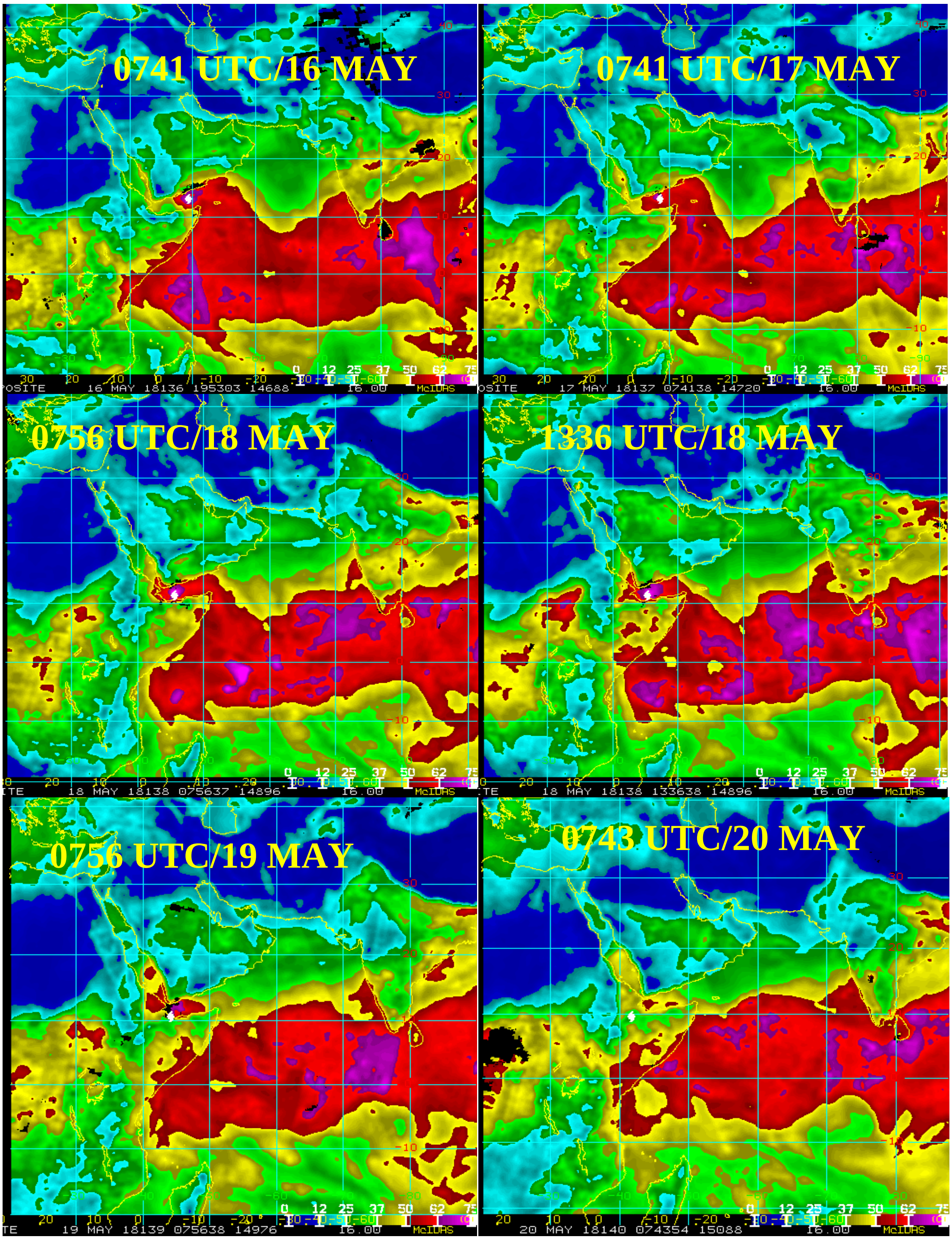


Fig. 2.2.2: Total Precipitable Water (TPW) imageries during 16-20 May, 2018

The wind speed in middle and deep layer around the system centre is presented in **Fig. 2.2.3**. The wind shear around the system between 200 & 850 hPa levels remained steady being about 10-20 knots. It was less than 10 knots at the time of genesis of the system, i.e. on 16th and early hrs of 17th May. It increased during the dissipation stage on 20th May. The direction of 200-850 hPa wind shear was southeasterly till 0600 UTC of 19th May and then it became northeasterly. It thus sheared the cloud mass to southwest sector of system from 19th May.

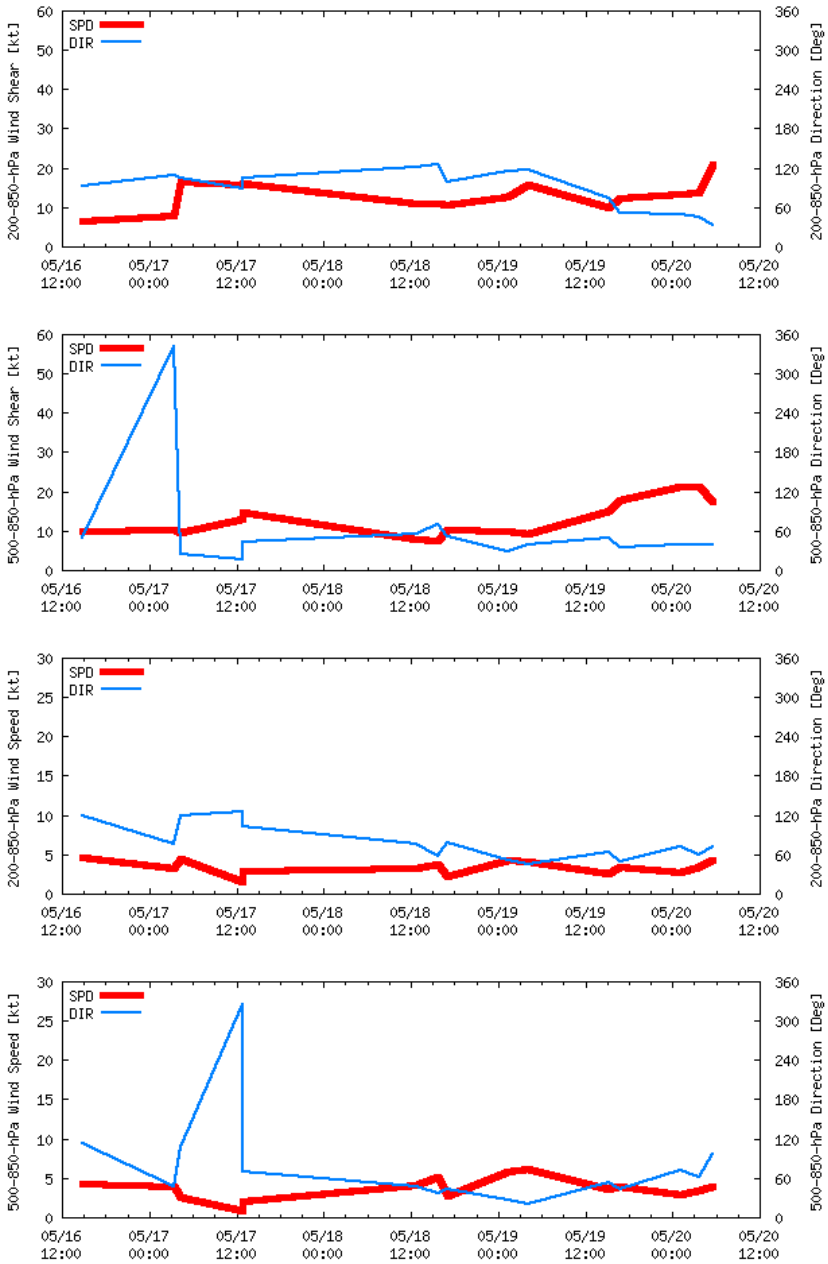


Fig.2.2.3 Wind shear and wind speed in the middle and deep layer around the system during 16th to 20th May 2018.

From **Fig. 2.2.3**, it indicates that from 16th May onwards, the mean deep layer winds between 200-850 hPa levels steered the system west–northwestwards till 17th and then southwestwards. The initial west-northwesterly movement of the system was in association with the upper tropospheric ridge lying to the north of the system centre in association with the anticyclonic circulation lying to the northeast of the system centre. Thereafter, it moved southwestwards till dissipation in association with the anti-cyclonic circulation lying to the northwest of the system centre

The twelve hourly movement of CS Sagar is presented in **Fig. 2.2.4**. The 12 hour average translational speed of the cyclone was about 10.6 kmph and hence was slow moving in nature. There was in general increasing trend in translational speed till 0000 UTC of 18th. Thereafter there was a decreasing trend.

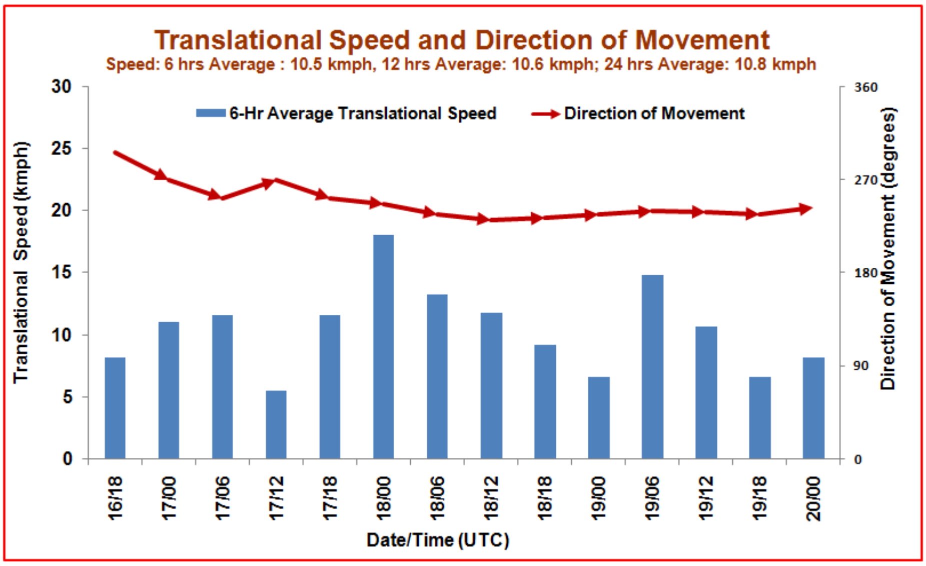


Fig.2.2.4 Twelve hourly average translational speed (kmph) and direction of movement in association with CS Sagar

2.2.4. 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 994 hPa during 0300 UTC of 18th to 0300 UTC of 19th. The estimated maximum sustained surface wind speed (MSW) was 45 knots during the same period. At the time of landfall, the ECP was 996 hPa and MSW was 40 knots (cyclonic storm). The ECP and Vmax graph indicate that the system intensified gradually till 0600 UTC of 18th, maintained its intensity till 0300 UTC of 19th and started weakening gradually.

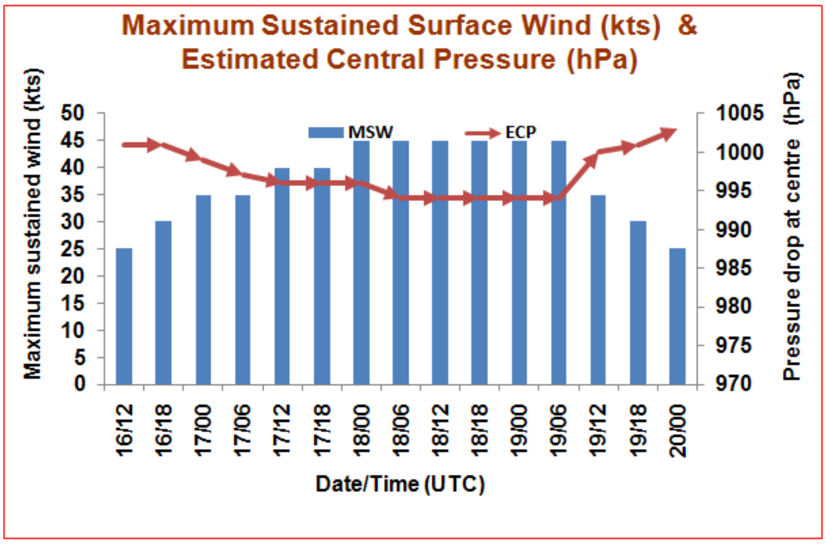


Fig.2.2.5. Lowest estimated central pressure and the maximum sustained wind speed

2.2.5. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 & MTSAT and microwave & high resolution images of polar orbiting satellites

DMSP, NOAA series, TRMM, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.2.6**.

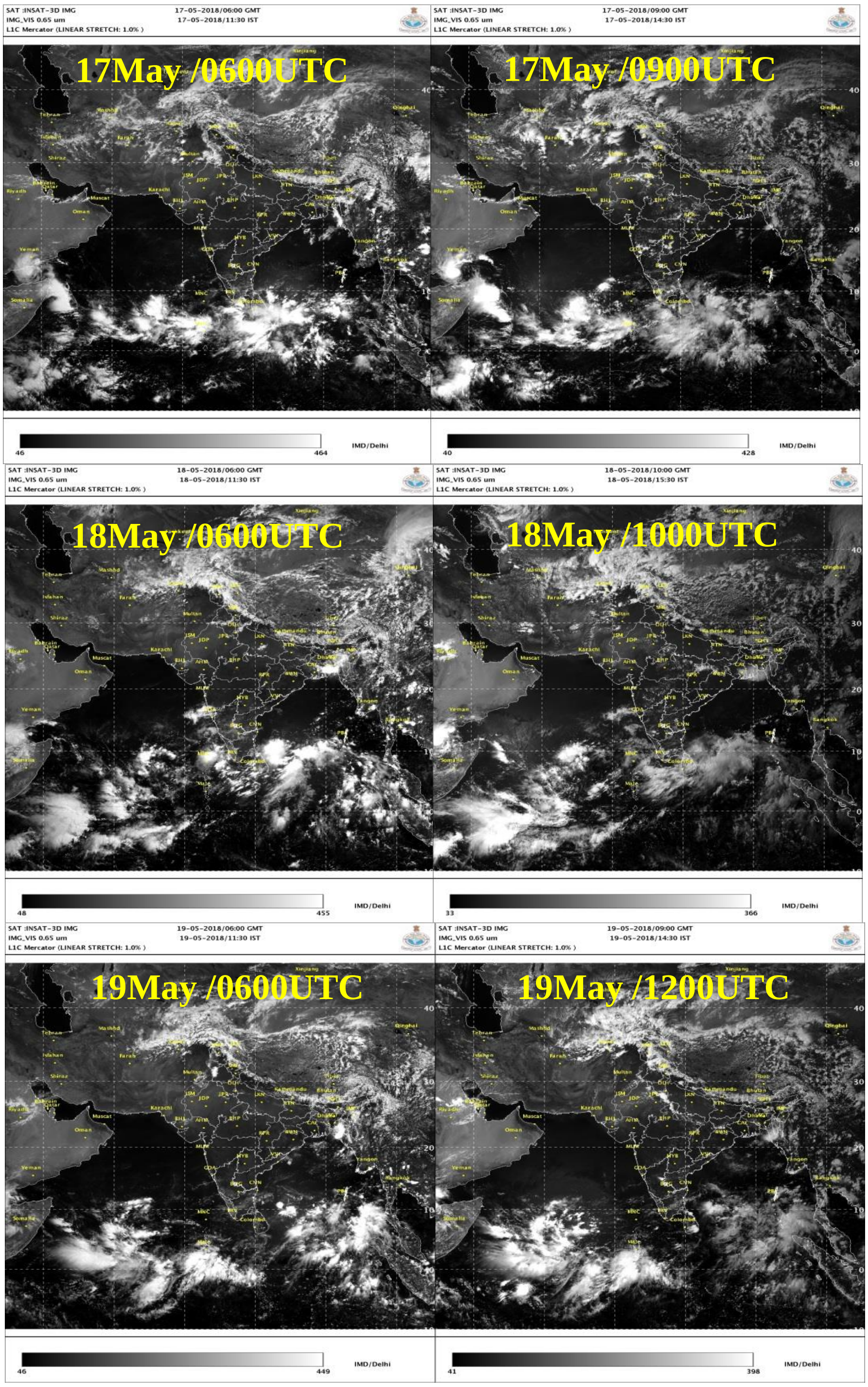


Fig. 2.2.6a: INSAT-3D visible imageries during life cycle CS SAGAR (16-21 May, 2018)

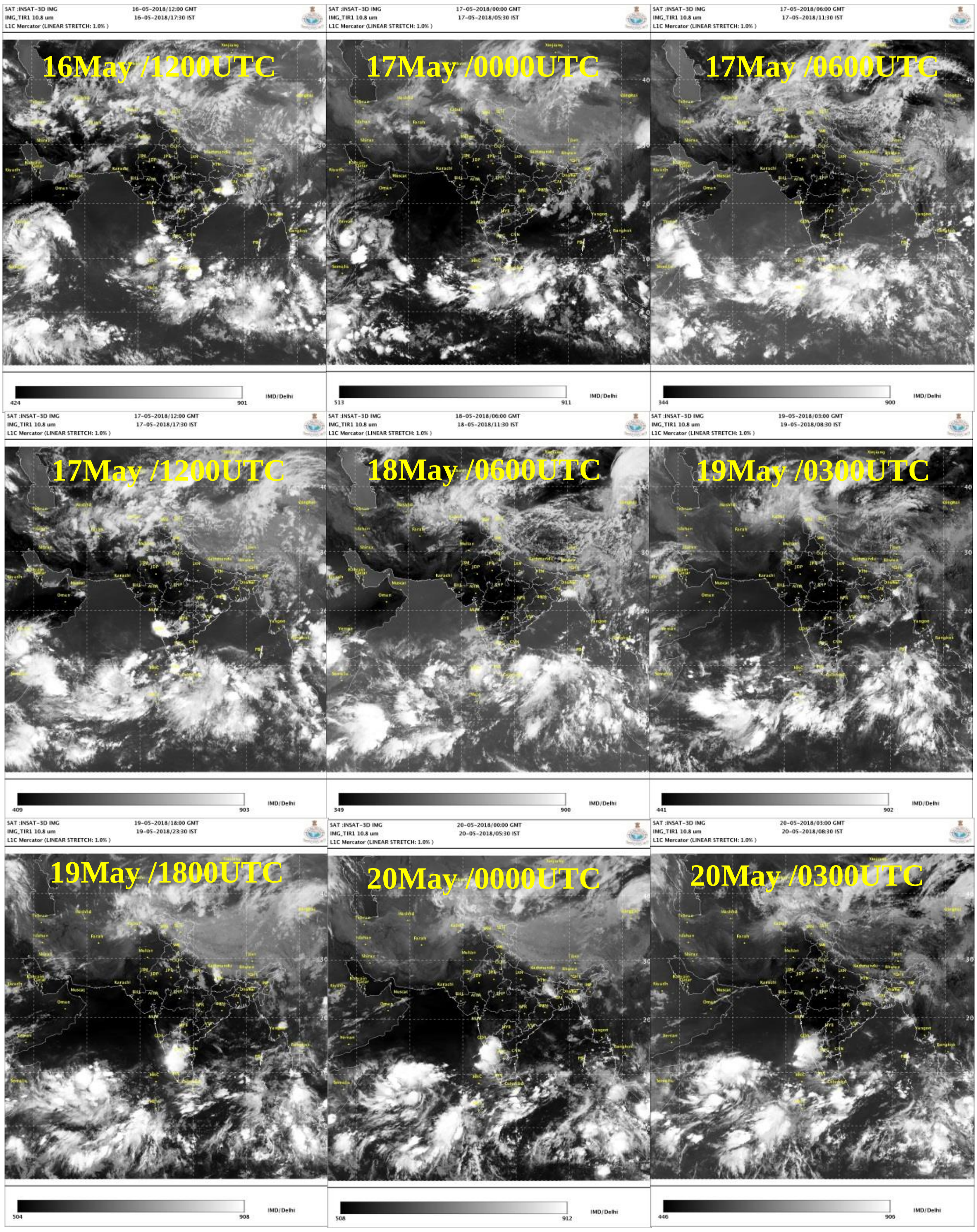


Fig. 2.2.6b: INSAT-3D IR imageries during life cycle of CS SAGAR (16-21 May, 2018)

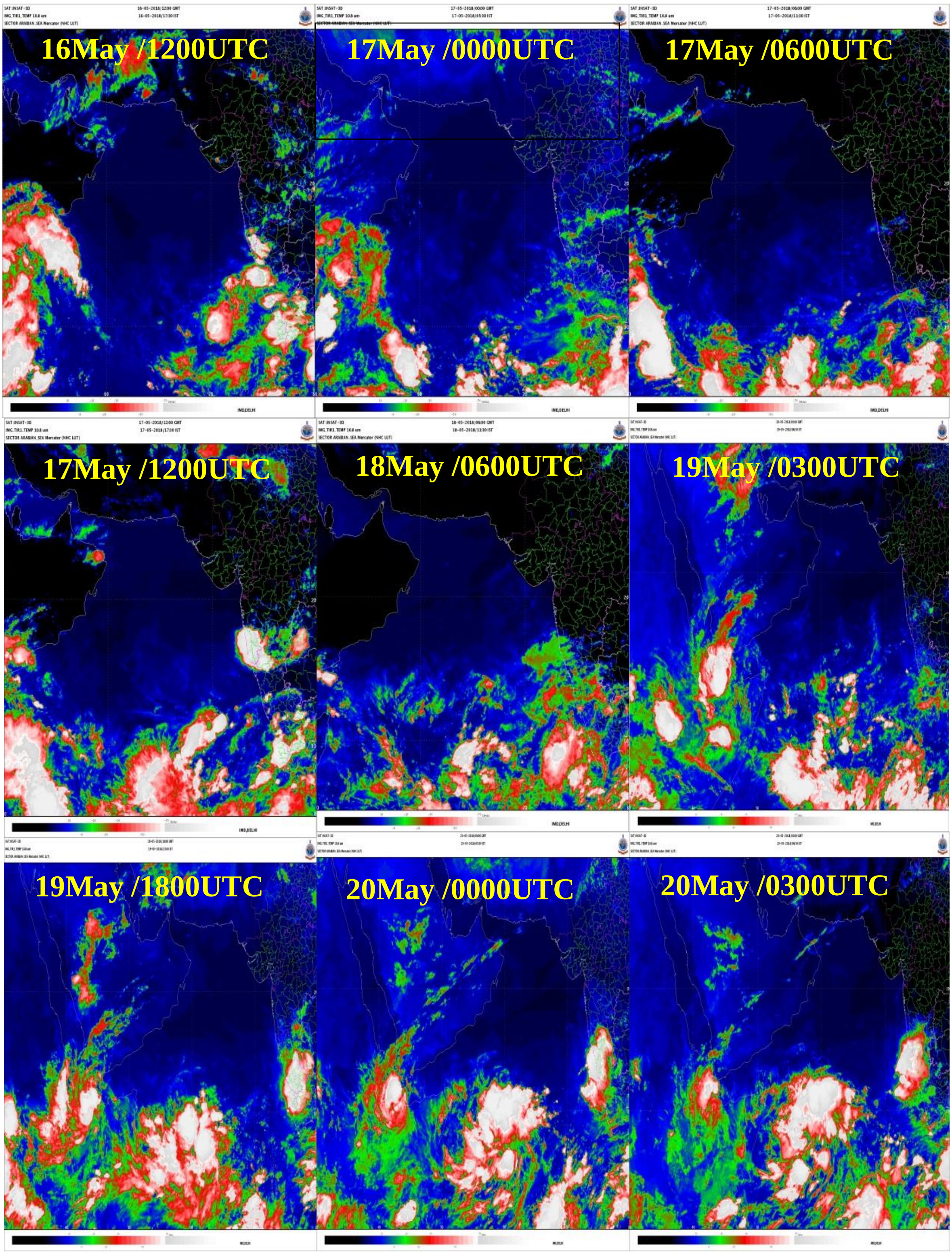


Fig. 2.2.6c: INSAT-3D enhanced colored imageries during life cycle of CS SAGAR (16-21 May, 2018)

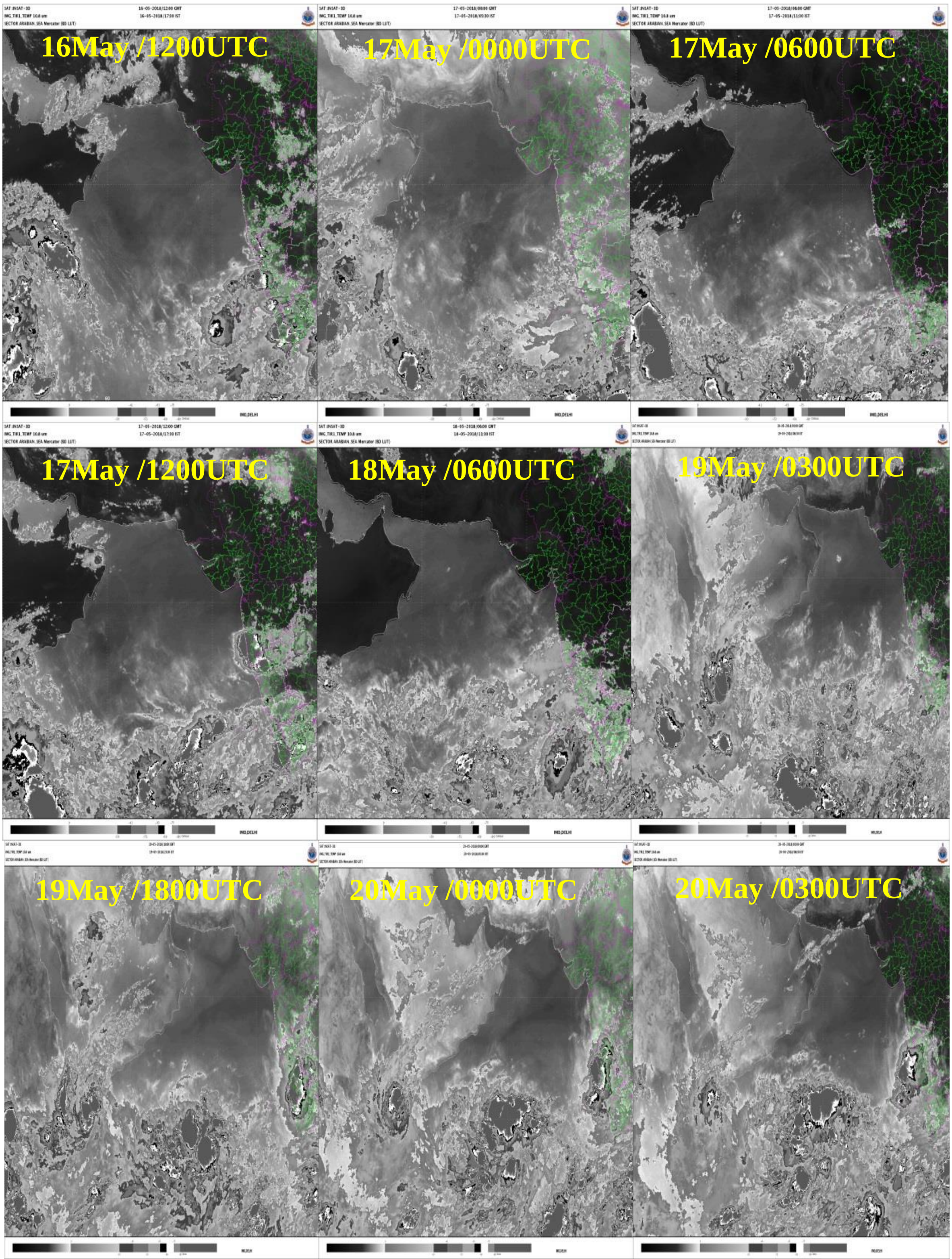


Fig. 2.2.6d: INSAT-3D cloud top brightness imageries during life cycle of CS SAGAR (16-21 May, 2018)

2.2.6. **Dynamical features**

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 16th-19th May are presented in Fig. 2.2.7. GFS (T1534). Based on 0000 UTC observations of 16th, the model predicted formation of extended low over southwest and adjoining westcentral Arabian and Gulf of Aden with associated cyclonic circulation extending upto 500 hPa level.

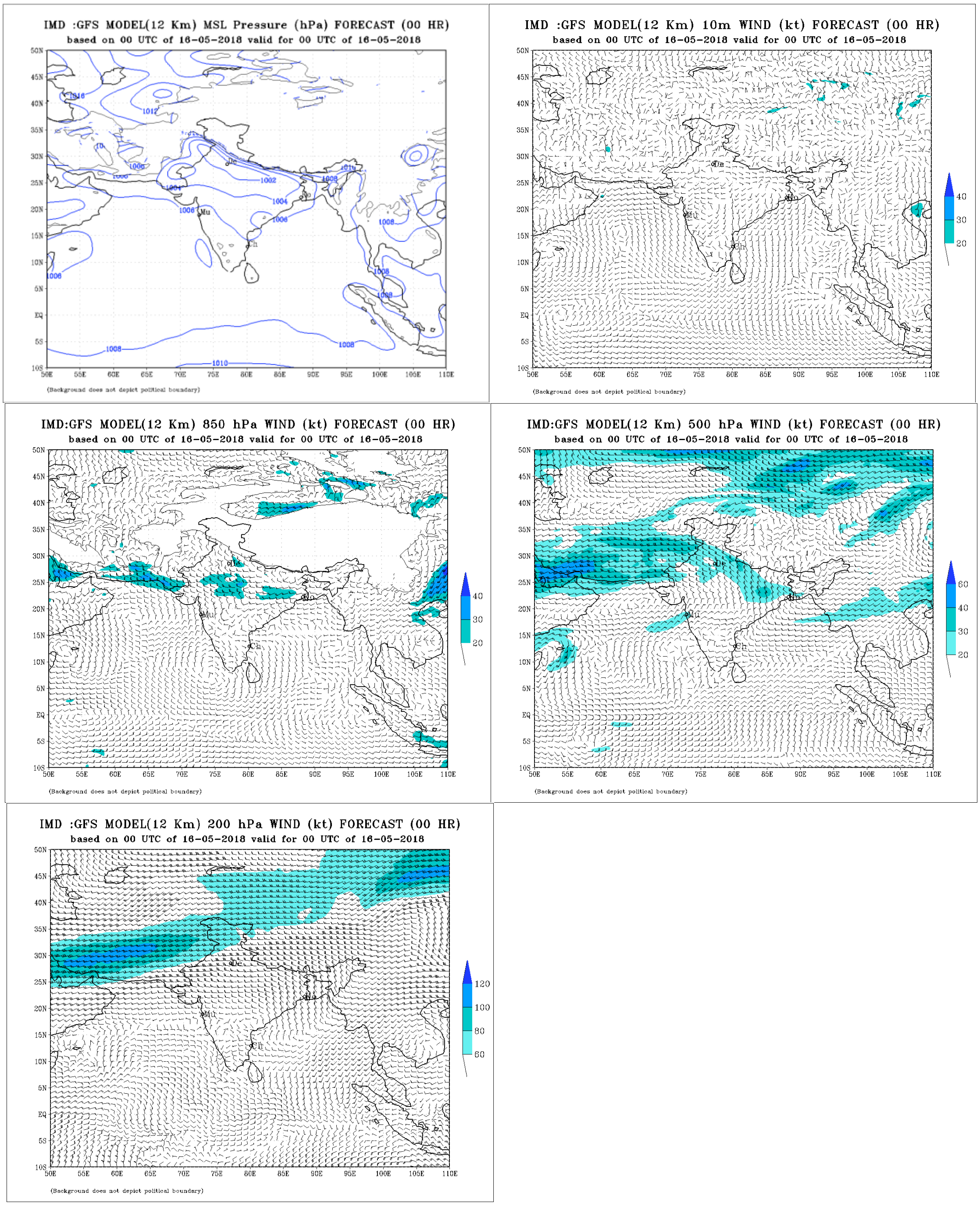


Fig. 2.2.7(a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th May

Analysis based on 0000 UTC of 16th to 19th May, indicates that the model highly underestimated the intensity of the system.

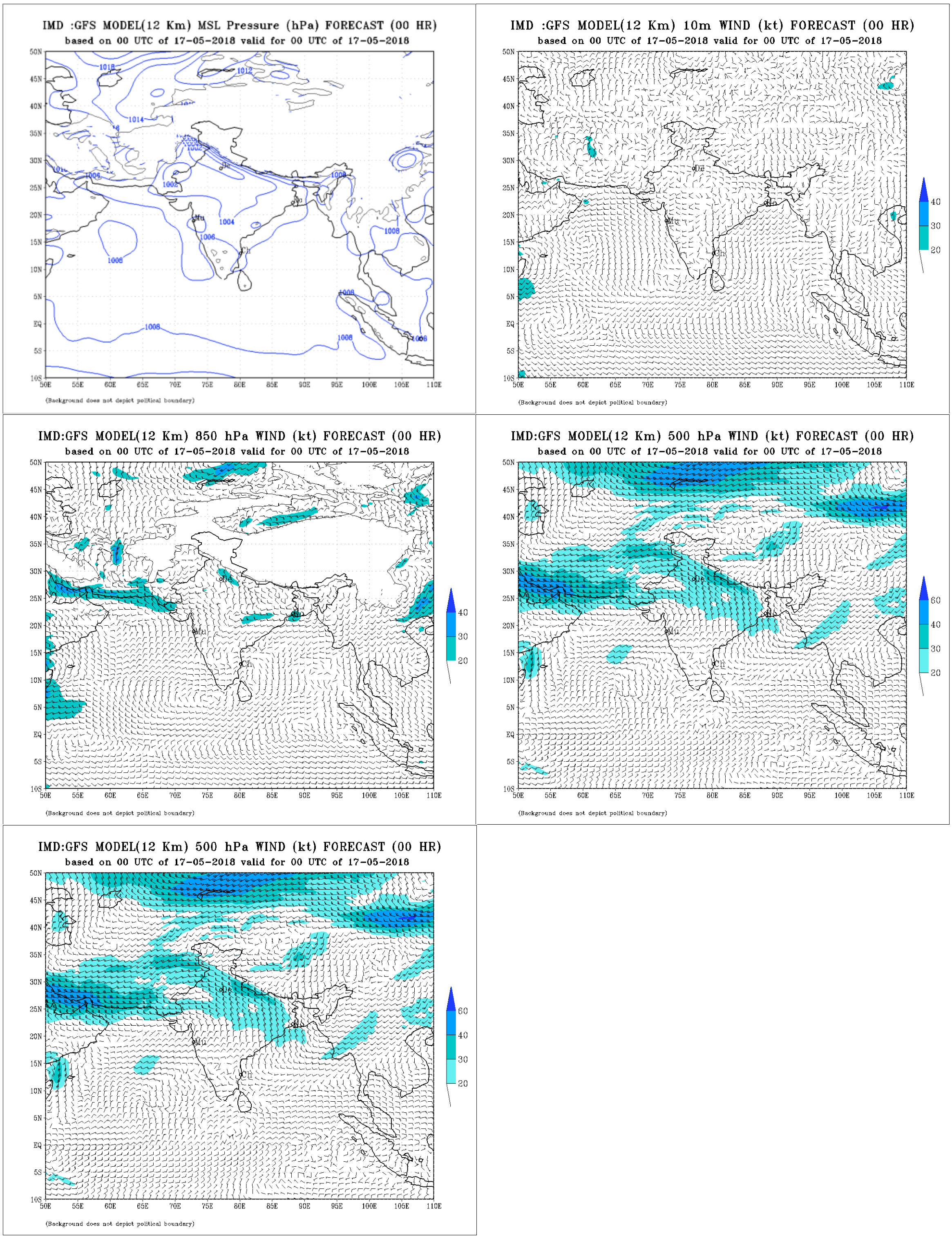


Fig. 2.2.7(b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th May

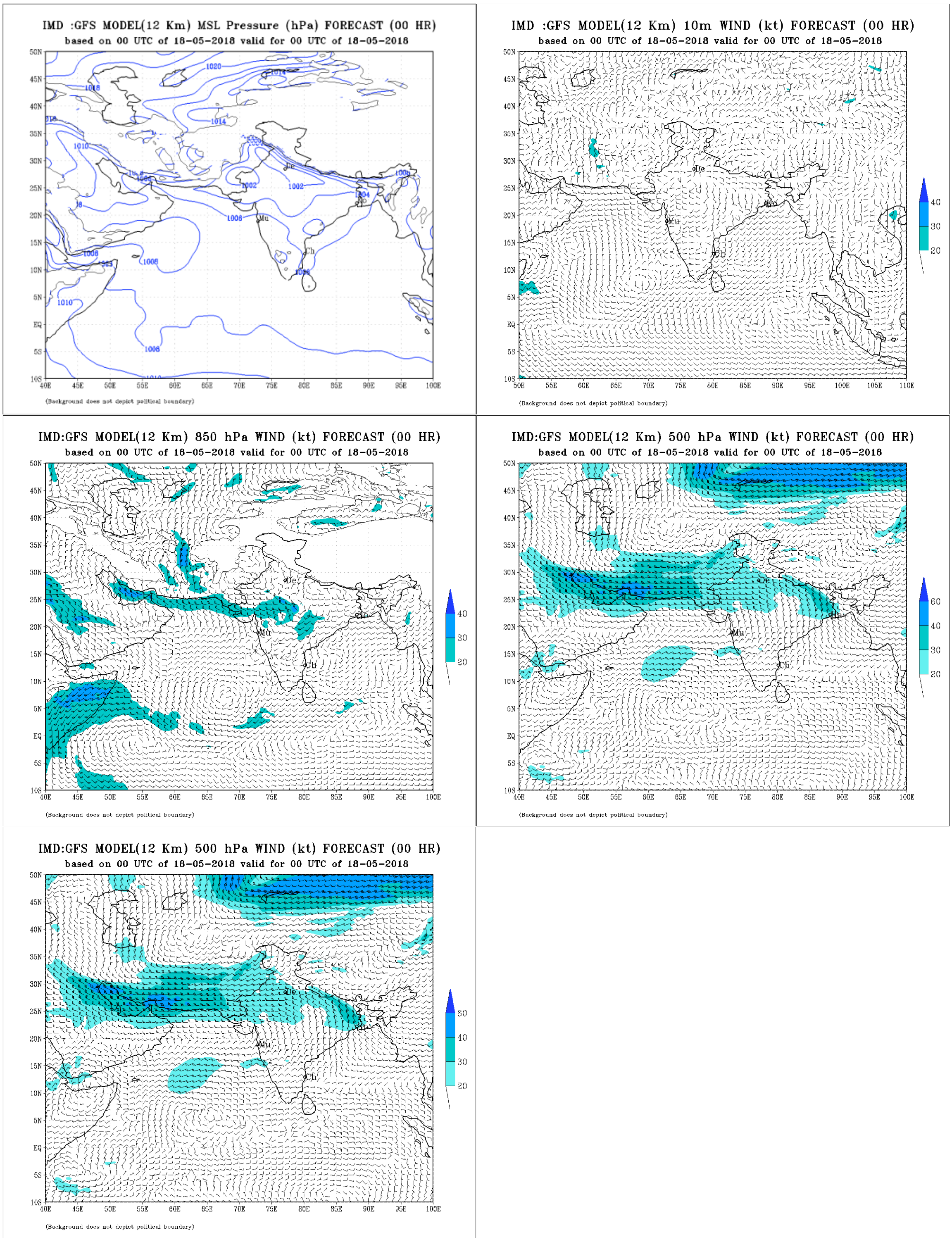


Fig. 2.2.7(c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th May

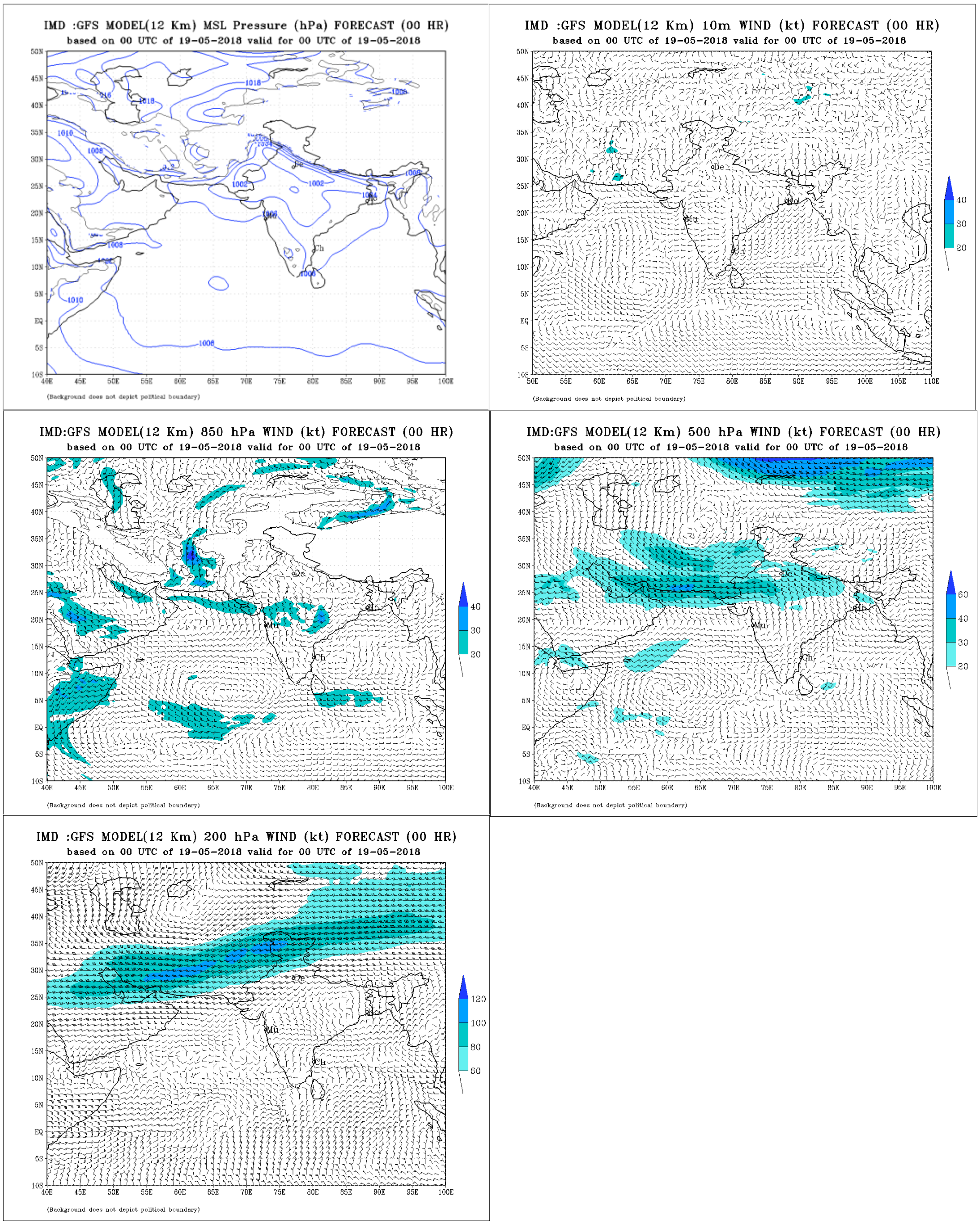


Fig. 2.2.7(d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th May

2.2.7. Realized Weather:

Rainfall associated with CS, Sagar based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 2.2.8**. It shows that the rainfall was maximum over Yemen coast on 16th and 17th and over north Somalia and Ethiopia on 18th and 19th May 2018.

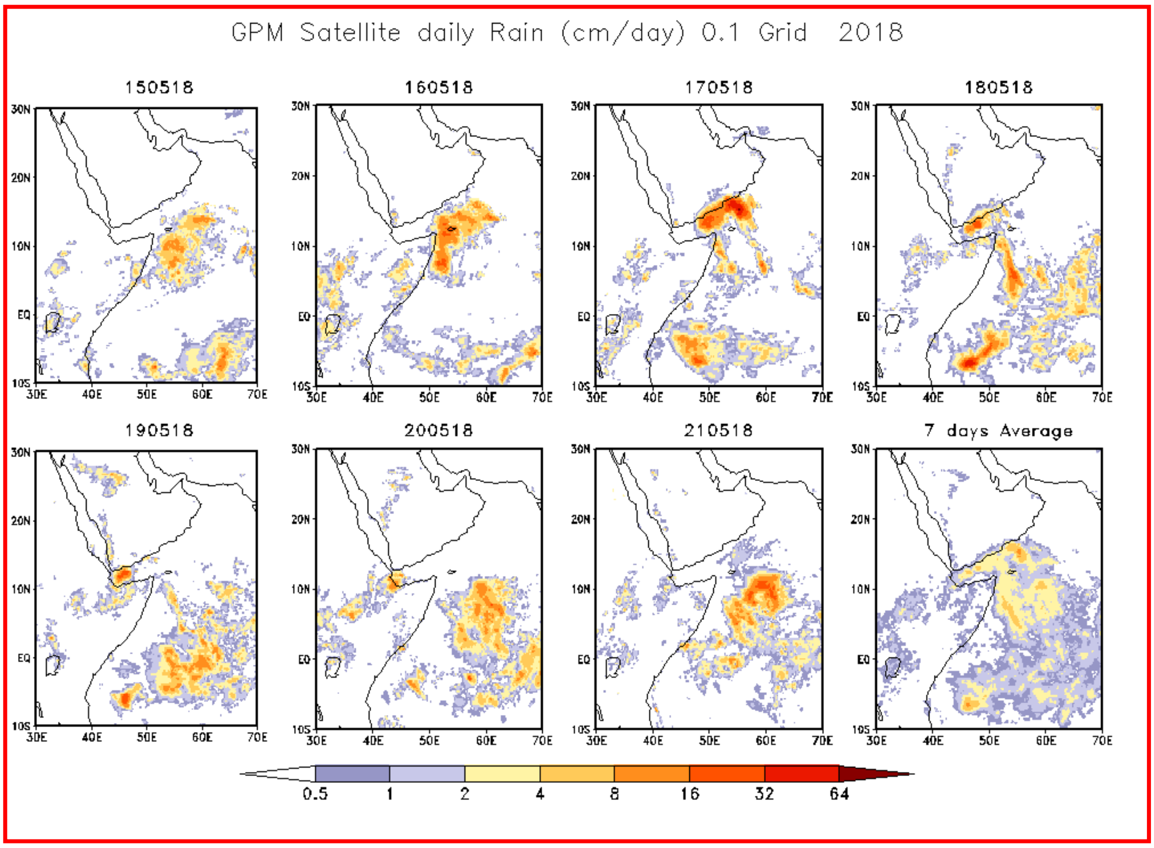


Fig.2.2.8: IMD-NCMRWF GPM merged gauge rainfall during 16th May– 21th May and 7 days average rainfall (cm/day)

2.2.8. Damage due to CS, Sagar

According to media report, along its rare trajectory through the Gulf of Aden, Cyclonic Storm Sagar caused rainfall in coastal Yemen, northern Somalia, Djibouti, and Ethiopia. The storm first affected Yemen's Socotra Island. Later, strong winds from Sagar damaged houses on Yemen's mainland. Heavy rainfall along the coast caused isolated flooding, which damaged roads and electric infrastructure.

In Djibouti, flooding damaged about 10,000 houses, with 2,000 of them severely damaged, which displaced 3,150 people. The rains flooded crops, streets, and buildings. Three people are reported to be killed.

In the Somalia Region of eastern Ethiopia, Sagar produced strong winds and heavy rainfall, resulting in flooding and landslides. Near the border of SNNPR and Oromia, a landslide killed 23 people. The storm damaged schools, health facilities, and houses, displacing 194,000 people. The village of Dambal was almost entirely washed away, affecting 150 households.

Beginning on May 17, Sagar caused heavy rainfall in northern Somalia and Somaliland, A total of 53 deaths were reported in Somalia as a result of the cyclone – 50 in Somaliland and 3 in Puntland. Typical damage photographs are presented in **Fig.2.2.9**.

Fig. 2.2.9(a). Flooding in eastern Africa due to CS, Sagar

Fig.2.2.9(b) Damage due to CS, Sagar (Source:Djib-Live)

2.3. Extremely Severe Cyclonic Storm, ‘MEKUNU’ over the Arabian Sea (21 – 27 May 2018)

2.3.1. Introduction

Extremely Severe Cyclonic Storm (ESCS) Mekunu originated from a low pressure area which formed over southeast Arabian Sea (AS) in the morning (0300 UTC) of 20th May. It became a well marked low pressure area over southwest & adjoining southeast AS in the early morning (0000 UTC) of 21st May.

Under favourable environmental conditions, it concentrated into a Depression (D) over southwest AS in the evening (1200 UTC) of 21st May. Moving west-northwestwards it intensified into a deep depression (DD) in the morning (0300 UTC) of 22nd May. It then moved north-northwestwards and intensified into a cyclonic storm (CS) **“Mekunu**” in the evening (1200 UTC) of same day over southwest AS. It further continued to move north-northwestwards, intensified into a Severe Cyclonic Storm (SCS) in the morning (0300 UTC) and into a Very Severe Cyclonic Storm (VSCS) in the afternoon (0900 UTC) of 23rd May over Westcentral AS. Moving further north-northwestwards, it intensified into an Extremely Severe Cyclonic Storm (ESCS) in the morning (0300 UTC) of 25th and crossed south Oman coast near 16.85^{0}N/53.75^{0}E around midnight (between 1830-1930 UTC) of 25th May as an ESCS with an estimated wind speed of 170-180 kmph gusting to 200 kmph. It moved north-northwestwards and weakened into a VSCS over Oman in the early hours of 26th May (2100 UTC of 25th May). Continuing to move north-northwestwards, it weakened into an SCS in the early morning (0000 UTC), into a CS in the afternoon (0900 UTC) and into a DD around midnight (1800 UTC) of 26th May. It further weakened into a D in the early morning (0000 UTC) and into a well marked low pressure area over Saudi Arabia and adjoining Oman & Yemen in the morning (0300 UTC) of 27th May.

The salient features of the system are as follows.

i. ESCS Mekunu was the second cyclonic storm over AS during the year 2018.
ii. Mekunu had a straight north-northwestward moving track.
iii. It formed (at 1200 UTC of 21st May) just 5 days after the formation of CS Sagar (at 1200 UTC of 16th May) over Arabian Sea. Such cylogenesis in quick succession within a week last occurred over AS in post-monsoon season of 2015 (ESCS Chapala followed by ESCS Megh).
iv. It attained its peak intensity on the day of landfall while lying close to coast.
v. It maintained the peak maximum sustained surface wind speed (MSW) of 170-180 kmph gusting to 200 kmph (95 knots) for 6 hours during 1200 UTC to 1800 UTC of 25th May.
vi. The lowest estimated central pressure was 960 hPa during 1200 UTC to 1800 UTC of 25th May.
vii. The life period of cyclone was 135 hours (5.6 days) against long period average (LPA) (1990-2013) of 6.6 days for very severe cyclonic storm over Arabian Sea in pre-monsoon season.
viii. The track length of the cyclone was 1385 km.
ix. The 12 hour average translational speed of the cyclone was 10.4 kmph against LPA (1990-2013) of 14.3 kmph over AS.
x. The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 11.6 X10^{2} knots, 8.4 X 10^{4} knots^{2} and 6.5 X10^{6} knots^{3} respectively against

LPA (1990-2013) of 1.89 X10^2 knots, 1.4 X 10^4 knots^2 and 1.2 X10^6 knots^3 during pre-monsoon season for AS.

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. The observed track of the system during 21st-27th May is presented in **Fig. 2.3.1**. Typical satellite imagery is presented in **Fig. 2.3.2**. The best track parameters of the system are presented in Table 2.3.1.

2.3.2. Monitoring of ESCS, 'MEKUNU'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it"s genesis as low pressure area over AS from 21st May onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations and available ships & buoy observations in the region. Various national and international numerical weather prediction (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 including Yemen, Oman and Somalia, National & State Disaster Management Agencies, general public and media since inception of the system over AS.

2.3.3. Brief life history

2.3.3.1. Genesis

Under the influence of a cyclonic circulation that developed over Lakshadweep and neighbourhood on 18th May, a low pressure area formed over southeast AS in the morning (0300 UTC) of 20th May. It lay as a well marked low pressure area over southwest & adjoining southeast AS in the early morning (0000 UTC) of 21st May.

At 0300 UTC of 21st May, the Madden Julian Oscillation (MJO) index lay over phase 2 with amplitude more than 1. The MJO phase was favouring cyclogenesis over the AS and its further intensification. The sea surface temperature (SST) was 29-31^{0}C over southwest and adjoining westcentral AS. The tropical cyclone heat potential (TCHP) was more than 100 KJ/cm^2 over the above region. The low level relative vorticity was about 100x10^{-6}sec^{-1} to the southwest of system centre. The lower level convergence was about 20 x10^{-5}sec^{-1} to the southwest of system centre. The upper level divergence was about 40 x10^{-5} sec^{-1} over the system centre. The vertical wind shear (VWS) was low to moderate (10-15 knots) over the system centre. VWS was also low to moderate over westcentral AS near Oman and Yemen coast. All these conditions indicated favourable environment for further intensification of the system.

At 1200 UTC of 21st, similar environmental features continued. The low level relative vorticity increased significantly and was about 150x10^{-6}sec^{-1} to the southwest of system centre. The lower level convergence was about 20 x10^{-5}sec^{-1} to the south and southwest of system centre. The upper level divergence was about 30 x10^{-5} sec^{-1} over the system centre. The vertical wind shear is low to moderate (10-15 knots) over the system. Hence the environmental conditions are favourable for further intensification of the system. Under these conditions the WML southwest & adjoining southeast AS concentrated into depression (**D**) at 1200 UTC over the same region.

2.3.3.2. Intensification and movement

At 0300 UTC of 22nd, the MJO was in Phase 2 with amplitude more than 1. The SST was 29-31^{0}C over southwest and adjoining westcentral AS. There was positive SST anomaly over westcentral AS. The TCHP was more than 60-80 KJ/cm^2 over the region. The low level relative vorticity increased significantly and was about 150x10^{-6}sec^{-1} to the south of system centre. The lower level convergence was about 20 x10^{-5}sec^{-1} to the southwest of system centre. The upper level divergence was about 30 x10^{-5} sec^{-1} to the west of the system centre. The vertical wind shear was low to moderate (05-15 knots) near the system centre. The total precipitable water (TPW) imagery indicated continous warm and moist air incursion into the core of the system. All these environmental conditions favoured the intensification of system into **DD** at 0300 UTC over southwest AS near latitude 9.2^{0}N and longitude 57.2^{0}E.

At 1200 UTC of 22nd, MJO was in Phase 2. Similar sea conditions prevailed. The low level relative vorticity increased significantly and was about 250x10^{-6}sec^{-1} over the system centre. The lower level convergence also increased and was about 50 x10^{-5}sec^{-1} around the system centre. The upper level divergence remained unchanged and was about 30 x10^{-5} sec^{-1} over the system area. The vertical wind shear was low to moderate (05-15 knots) near the system centre. The TPW imagery indicated continous warm and moist air incursion into the core of the system. All these conditions led to the intensification of system into **CS "Mekunu"** at 1200 over southwest AS near latitude 10.2^{0}N and longitude 56.8^{0}E.

At 0300 UTC of 23rd, MJO was in Phase 2 with amplitude greater than 1. The SST was 29-31^{0}C over southwest and adjoining westcentral AS. There was positive SST anomaly over westcentral AS. The tropical cyclone heat potential was about 80-100 KJ/cm^2 over the region. The low level relative vorticity was about 250x10^{-6}sec^{-1} close to east of the system centre. The lower level convergence decreased and was about 40 x10^{-5}sec^{-1} close to west of the system centre. The upper level divergence was about 30 x10^{-5} sec^{-1} close to west of the system centre. The TPW imagery indicated continuous warm and moist air incursion into the core of the system. Under these conditions, the system intensified into an **SCS** at 0300 UTC over southwest AS near latitude 11.2^{0}N and longitude 55.9^{0}E.

At 0900 UTC of 23rd, MJO was in Phase 2 with amplitude greater than 1. Similar sea conditions prevailed. The low level relative vorticity remained same and was about 250x10^{-6} sec^{-1} close to south of the system centre. The lower level convergence increased and was about 50 x10^{-5} sec^{-1} close to southwest of the system centre. The upper level divergence was about 40 x10^{-5} sec^{-1} close to west of the system centre. The vertical wind shear was moderate to high (15-25 knots) near the system centre. The TPW imagery indicated continuous warm and moist air incursion into the core of the system. The steering winds indicated that the system would move nearly northwards for next 12 to 24 hours and thereafter north-northwestwards towards south Oman–south east Yemen coasts under the influence of anticyclonic circulation at middle and upper troposhperic levels located to the northeast of the system centre. Under these conditions, the system intensified into a **VSCS** at 0900 UTC over southwest and adjoining westcentral AS near latitude 11.8^{0}N and longitude 55.9^{0}E.

At 0300 of 24th, the MJO was in Phase 2. The SST was 29-31^{0}C over southwest and adjoining westcentral AS. There was positive SST anomaly over westcentral AS. The tropical cyclone heat potential was about 80-100 KJ/cm^2 over the core region. However, it was relatively low along the predicted track. The low level relative vorticity was about 250x10^{-6} sec^{-1} to the south of system centre. The low level convergence increased and was about 60 x10^{-5} sec^{-1} to the southwest of the system centre. The upper level divergence was about 40 x10^{-5} sec^{-1} to the south of the system centre. The vertical wind shear was moderate to high (15-25 knots) near the system centre. The TPW imagery indicated continuous warm and moist air incursion into the core of the system. However, the rate of incursion showed decreasing trend. The environmental conditions predicted gradual intensification of the system during next 24 hours, as there was relatively lower tropical cyclone heat potential along the predicted track, moderate to high vertical wind shear and gradual decrease in rate of warm moist air incursion. An anticyclonic circulation at middle and upper troposhperic levels was located to the northeast of the system centre. Under it‟s influence, the system was expected to move nearly northwards for next 12 to 24 hours and thereafter north-northwestwards towards south Oman–south east Yemen coasts. Under these conditions, the system gradually intensified and lay over westcentral & adjoining southwest AS near latitude 13.3^0 N and longitude 55.4^0E as a **VSCS**.

At 0300 UTC of 25th, MJO was in Phase 2 with amplitude greater than 1. The SST was 30-31^0 C over westcentral AS with positive SST anomaly over the region. The TCHP was about 70-90 KJ/cm^2 to the left forward sector of the predicted track and around 60-70 KJ/cm^2 to the right of the predicted track. The low level relative vorticity increased and was about 300x10^{-6} sec^{-1} to the southeast of the system centre. The lower level convergence was about 60 x10^{-5} sec^{-1} to the south-southwest of the system centre. The upper level divergence was about 20 x10^{-5} sec^{-1} to the southwest of the system centre. The vertical wind shear was low to moderate (10-15 knots) over the system area. Under these conditions the system gradually intensified into **ESCS.** The upper level ridge ran along 20^0N and an anticyclonic circulation was located at middle and upper troposhperic level to the northeast of the system center.

The system was in the periphery of the anticyclone. The steering winds indicated that the system would move north-northwestwards towards south Oman–southeast Yemen coasts. Under these conditions the system moved north-northwestwards and lay over westcentral AS near latitude 15.4°N and longitude 54.5°E.

At 1200 UTC of 25th, similar sea conditions and MJO Phase continued. The low level vorticity decreased gradually and was about 300x10^{-6} sec^{-1} to the south of system centre. The lower level convergence decreased slightly and was about 50 x10^{-5} sec^{-1} to the south of the system centre. The upper level divergence increased and was about 30 x10^{-5} sec^{-1} to the south of the system centre. The vertical wind shear decreased and became low (5-10 knot) over the system area. Though there was decrease in warm moist air incursion into the core of system and decrease in lower level vorticity and convergence, the decreased wind shear and increased upper level divergence led to gradual intensification and the system reached it‟s **peak intensity of 95 knot**. Under the influence of anticyclonic circulation to the northeast of system centre, it moved north-northwestwards and lay over westcentral AS near latitude 16.4^0N and longitude 54.1^0E.

At 2100 UTC of 25th, similar sea conditions and MJO Phase continued. The low level relative vorticity was about 300x10^{-6} sec^{-1} to the southeast of the system centre. The lower level convergence was about 50 x10^{-5} sec^{-1} to the southeast of the system centre. The upper level divergence increased and about 40 x10^{-5} sec^{-1} to the southwest of the system centre. The vertical wind shear was low (5-10 knots) around system center. As a result, despite land interactions and decrease in warm & moist air incursion into the system, the strength of the system decreased gradually to 90 kt (ESCS) after landfall. As the system lay in the periphery of ridge at 20^0N and anticyclone to it‟s northeast, it moved northwestwards and lay over Oman near latitude 17.1^0N and longitude 53.5^0E at 2100 UTC of 25th.

Under the influence of anticyclonic circulation at middle and upper troposhperic level lying to the northeast of the system centre, it moved northwestwards after landfall. As the vertical wind shear was low (5-10 kt), the rate of weakening was restricted and the system gradually weakened over Oman into a **VSCS** at 0000 UTC of 26th near 17.2^{0}N and longitude 53.5^{0}E, into an **SCS** at 0300 UTC near 17.4^{0}N and longitude 53.2^{0}E, into a **CS** at 0900 UTC near 18.1^{0}N and longitude 53.1^{0}E, into a **DD** at 1800 UTC near 18.6^{0}N and longitude 52.8^{0}E, **D** at 0000 UTC of 27th near 19.0^{0}N and longitude 52.6^{0}E and **WML** at 0300 UTC over Saudi Arabia and adjoining areas of Oman & Yemen.

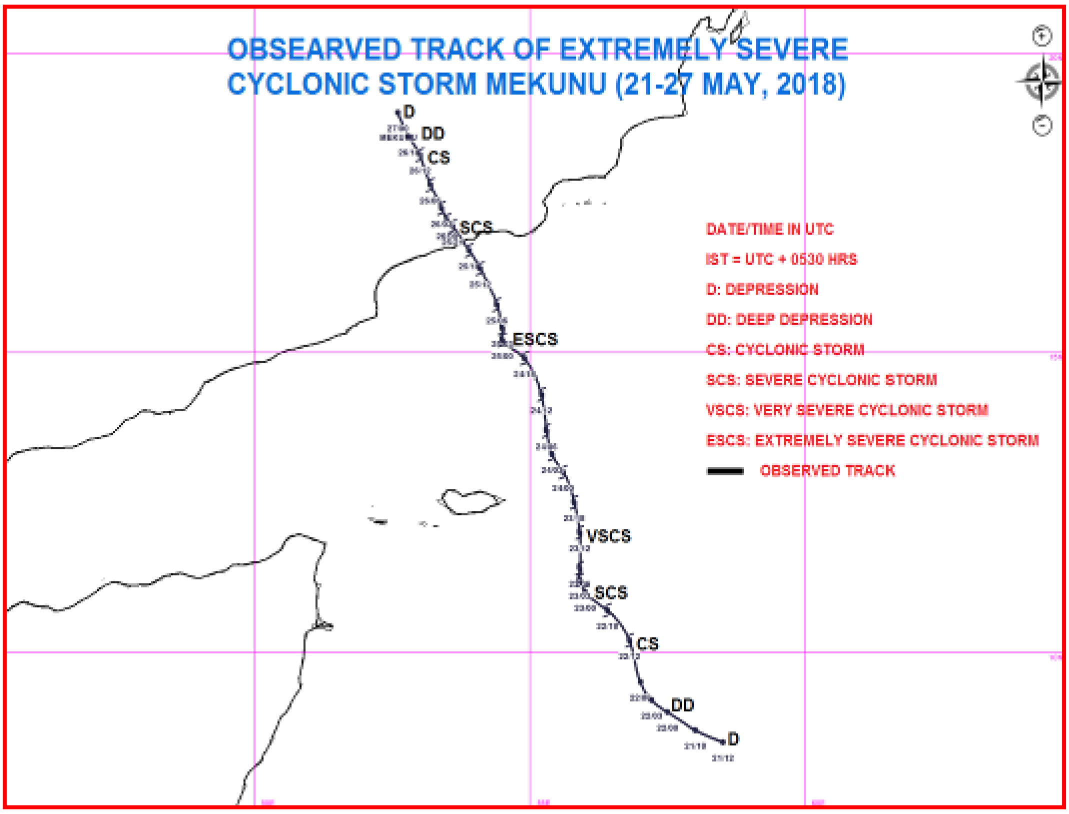


Fig.2.3.1Observed track of ESCS Mekunu (21- 27 May, 2018) over Arabian Sea

Table 2.3.1: Best track positions and other parameters of the Extremely Severe Cyclonic Storm, 'Mekunu' over the Arabian Sea during 21 May-27 May, 2018

Date	Time (UTC)	Centre lat.^{0} N/ long.^{0} E		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
21/05/2018	1200	8.5	58.5	1.5	1004	25	3	**D**
	1800	8.7	58.0	1.5	1003	25	4	D
22/05/2018	0000	9.0	57.5	1.5	1002	25	4	D
	0300	9.2	57.2	2.0	1001	30	5	**DD**

	0600	9.5	57.0	2.0	1000	30	6	DD
	1200	10.2	56.8	2.5	998	35	7	**CS**
	1500	10.5	56.7	2.5	998	35	7	CS
	1800	10.7	56.4	2.5	996	40	8	CS
	2100	10.8	56.2	2.5	996	40	9	CS
23/05/2018	0000	11.0	56.0	3.0	994	45	10	CS
	0300	11.2	55.9	3.5	984	55	15	**SCS**
	0600	11.4	55.9	3.5	980	60	18	SCS
	0900	11.8	55.9	3.5	978	65	20	**VSCS**
	1200	12.0	55.9	4.0	978	65	22	VSCS
	1500	12.3	55.9	4.0	976	70	24	VSCS
	1800	12.5	55.8	4.0	976	70	24	VSCS
	2100	12.8	55.7	4.0	976	70	24	VSCS
24/05/2018	0000	13.0	55.6	4.0	974	70	24	VSCS
	0300	13.3	55.4	4.5	972	75	28	VSCS
	0600	13.7	55.3	4.5	970	80	32	VSCS
	0900	14.0	55.2	4.5	970	80	32	VSCS
	1200	14.3	55.2	4.5	970	80	32	VSCS
	1500	14.6	55.1	4.5	970	80	32	VSCS
	1800	14.9	54.9	4.5	970	80	32	VSCS
	2100	15.1	54.7	4.5	970	80	32	VSCS
25/05/2018	0000	15.2	54.5	4.5	968	85	36	VSCS
	0300	15.4	54.5	4.5	964	90	40	**ESCS**
	0600	15.8	54.4	5.0	964	90	40	ESCS
	0900	16.2	54.2	5.0	962	90	42	ESCS
	1200	16.4	54.1	5.0	960	95	45	ESCS
	1500	16.5	54.0	5.0	960	95	45	ESCS
	1800	16.7	53.9	5.0	960	95	45	ESCS
	Crossed south Oman coast near Latitude 16.85^0 N and longitude 53.75^0 E during 1830 UTC and 1930UTC of 25th May 2018.							
	2100	17.1	53.6	-	964	90	40	ESCS
26/05/2018	0000	17.2	53.5	-	976	75	28	**VSCS**
	0300	17.4	53.4	-	986	60	18	**SCS**
	0600	17.8	53.2	-	988	50	12	SCS
	0900	18.1	53.1	-	990	45	10	**CS**
	1200	18.3	53.0	-	992	40	8	CS
	1500	18.5	52.9	-	994	35	7	CS
	1800	18.6	52.8	-	996	30	5	**DD**
27/05/2018	0000	19.0	52.6	-	1000	25	3	**D**
	0300	**Weakened into a well marked low pressure area over Saudi Arabia and adjoining areas of Oman & Yemen at 0300 UTC of 27th May 2018.**						

The total precipitable water imageries (TPW) during 22-27 May are presented in **Fig. 2.3.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system during 22nd to 24th. From 25th afternoon, the warm moist air advection into the core decreased significantly.

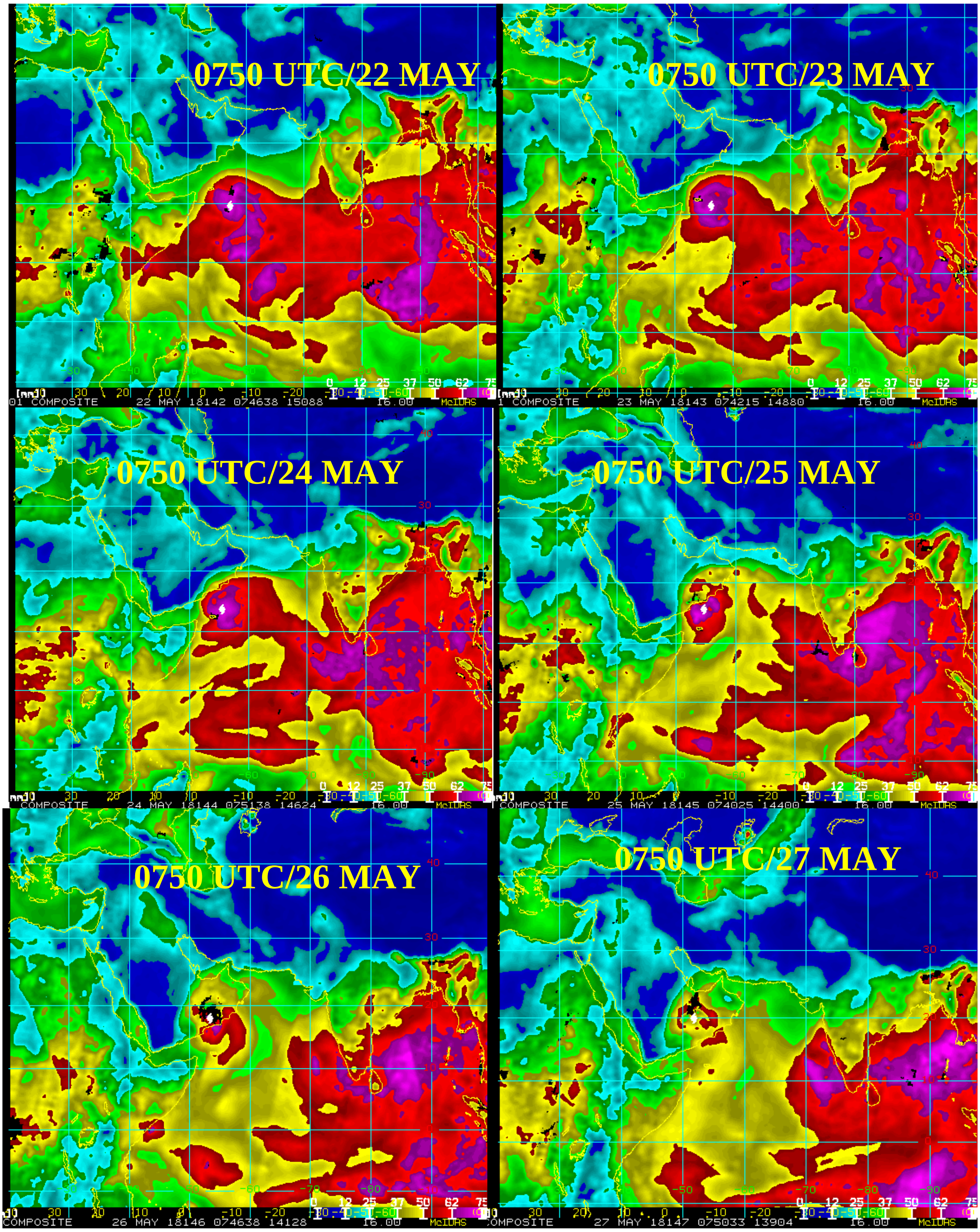


Fig. 2.3.2: Total Precipitable Water Imageries during 22-27 May, 2018

The mean wind speed in middle and deep layer around the system centre is presented in **Fig. 2.3.3**. The wind shear between lower to upper tropospheric levels around the system centre increased from 12 to 22 kt from 0000 UTC of 22nd to 0000 UTC of 23rd. It then decreased gradually to almost less than 2 kt during 1200 UTC of 25th to 0000 UTC of 26th. Thereafter, it increased gradually. The direction of wind shear between lower to upper tropospheric levels was nearly east-northeasterly upto 1200 UTC of 24th, it then became east-southeasterly till 1200 UTC of 25th and then east-northeasterly till 0000 UTC of 26th. It then became south-southeasterly. The wind shear between lower to middle tropospheric levels around the system was about 10 kt upto 0000 UTC of 24th, increased to 20 kt around 0300 UTC of 24th, thereafter it decreased gradually becoming less than 10 kt from 0000 UTC of 25th onwards. The direction of wind shear was south-southeasterly during genesis phase, becoming nearly easterly from 0000 UTC of 23rd to 1200 UTC of 25th. It became northerly at 0000 UTC of 26th. Thereafter, it gradually changed to northeasterly, easterly and then southerly around 0300 UTC of 27th. Hence the direction as well as the speed of shear was favourable for intensification of the system.

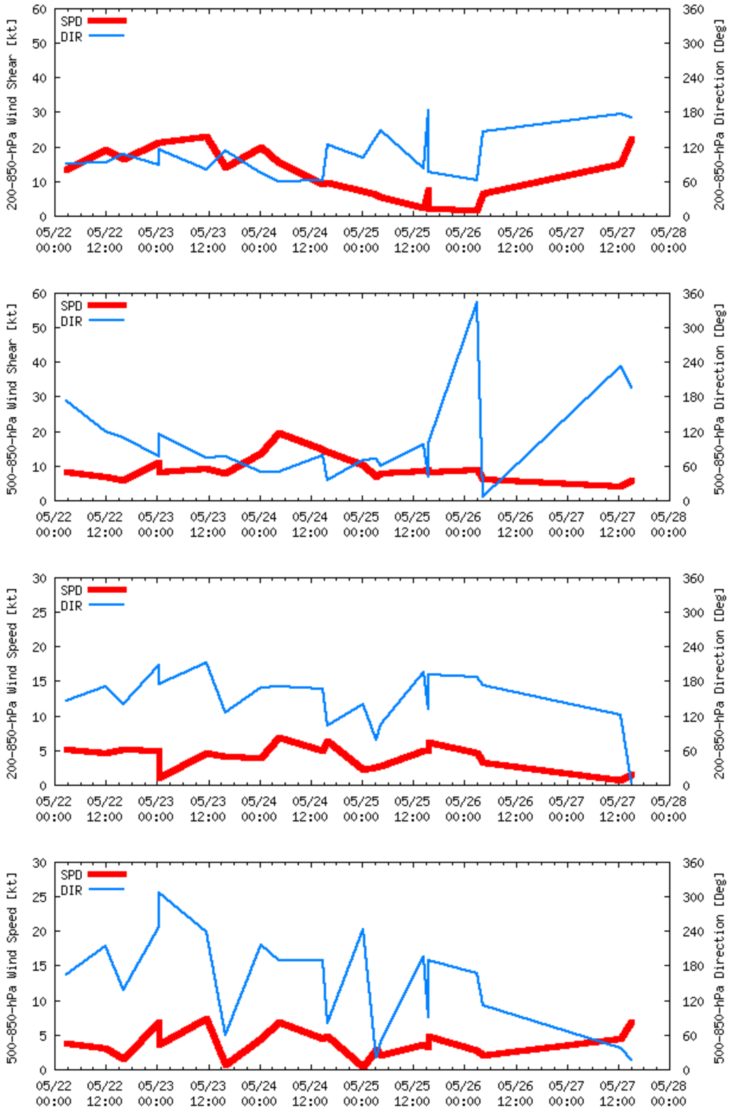


Fig.2.3.3.Wind shear and wind speed in the middle and deep layer around the system during 22nd to 28th May 2018.

2.3.3.3 Movement

From **Fig. 2.3.3**, the mean deep layer winds between 200-850 hPa levels steered the system north-northwestwards with a speed of 10 knots or less throughout the life period. The six hourly movement of ESCS Mekunu is presented in **Fig. 2.3.4 (a)**. The six hourly average translational speed of the cyclone was about 10.5 kmph and hence was slow moving in nature. The system had a track length of about 1385 km during its life period.

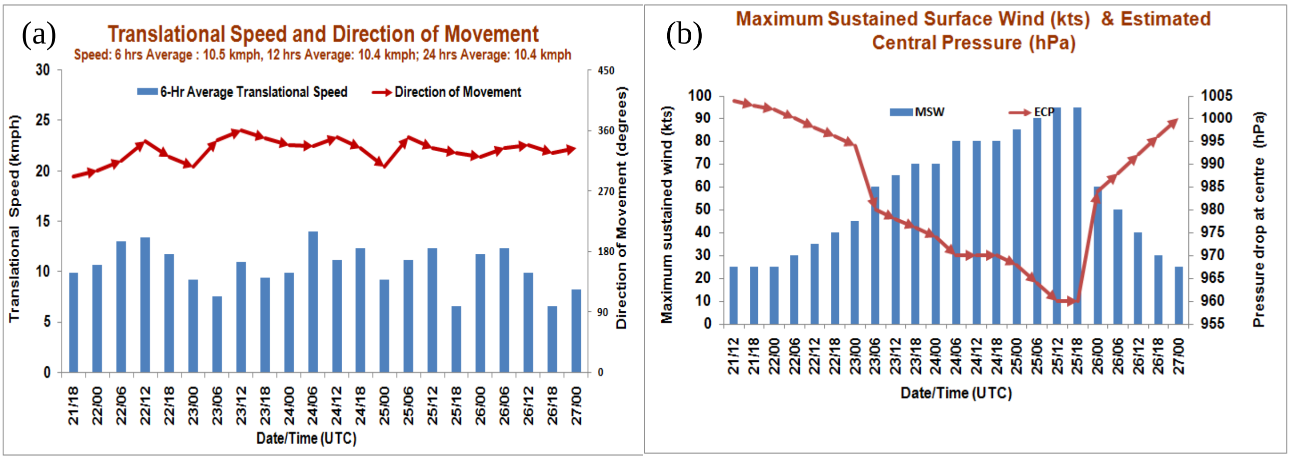


Fig.2.3.4 (a) Twelve hourly average translational speed (kmph) and direction of movement in association with ESCS Mekunu and (b) Lowest estimated central pressure and the maximum sustained wind speed

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

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig. 2.3.4 (b)**. The lowest estimated central pressure (ECP) had been 960 hPa during 1200 to 1800 UTC of 25th to 0300 UTC of 30th. The ECP gradually decreased from 1004 hPa at 1200 UTC of 21st to 994 hPa at 0000 UTC of 23rd. Thereafter, there was a sudden fall in pressure from 994 hPa to 990 hPa (14 hPa) during 0000 UTC of 23rd to 0600 UTC of 23rd. it then gradually decreased becoming minimum 960 hPa during 1200 to 1800 UTC of 25th. Thereafter, there was sudden rise in ECP from 960 hPa (at 1800 UTC of 25th) to 976 hPa at 0000 UTC of 26th. Thereafter it increased gradually to 1000 hPa at 0000 UTC of 27th. Similarly, in the wind field it is seen that there was gradual increase in maximum sustained wind speed (MSW) during 1200 UTC of 21st (25kt) to 0000 UTC of 23rd (45 kt), sudden rise of 15 kt during 0000 to 0600 UTC of 23rd, gradual increase in intensity of system reaching maximum of 95 kt at 1200 UTC of 25th. The system maintained its intensity upto 1800 UTC of 25th, thereafter there was sudden fall in MSW to 75 kt at 0000 UTC of 26th. The system then weakened gradually. Fig. 2.3.6 clearly indicates that there was sudden rise in intensity of system by 15 kt on 23rd during 0000 to 0600 UTC and another sudden peak was observed after landfall when the intensity sharply decreased by 20 kt during 1800 UTC of 25th to 0000 UTC of 26th. On all other occasions during the life cycle of system, there was gradual strengthening and weakening of system.

There was rapid intensification during 1200 UTC of 22nd to 1800 UTC of 23rd, when the wind speed increased from 35 knots to 70 knots.

2.3.5. Features observed through satellite

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

2.3.5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.3.5 (a-d)**.

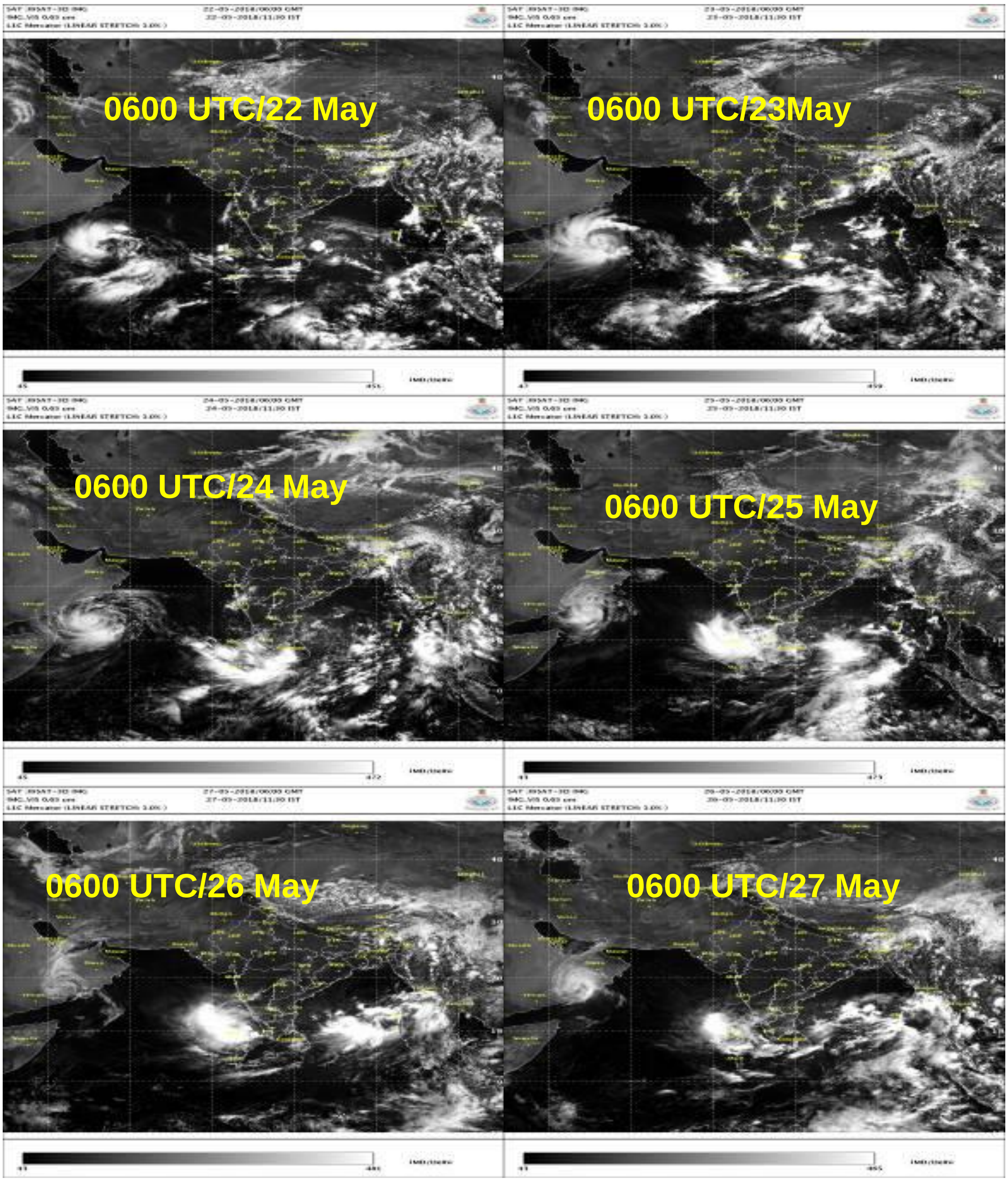


Fig. 2.3.5a: INSAT-3D visible imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

Intensity estimation using Dvorak‟s technique suggested that the system attained the intensity of **T 1.5** at 1200 UTC of 21st. The convection over south AS further organised and indicated curved banding features from northwest to southeast sector across southwest sector. Minimum cloud top temperature was -93^{0}C. At 0300 UTC of 22nd, the convection further organized and the system attained the intensity of **T2.0**. The convection showed curved banding features from northeast to southwest sector across northwest sector. Minimum CTT was -93^{0}C.

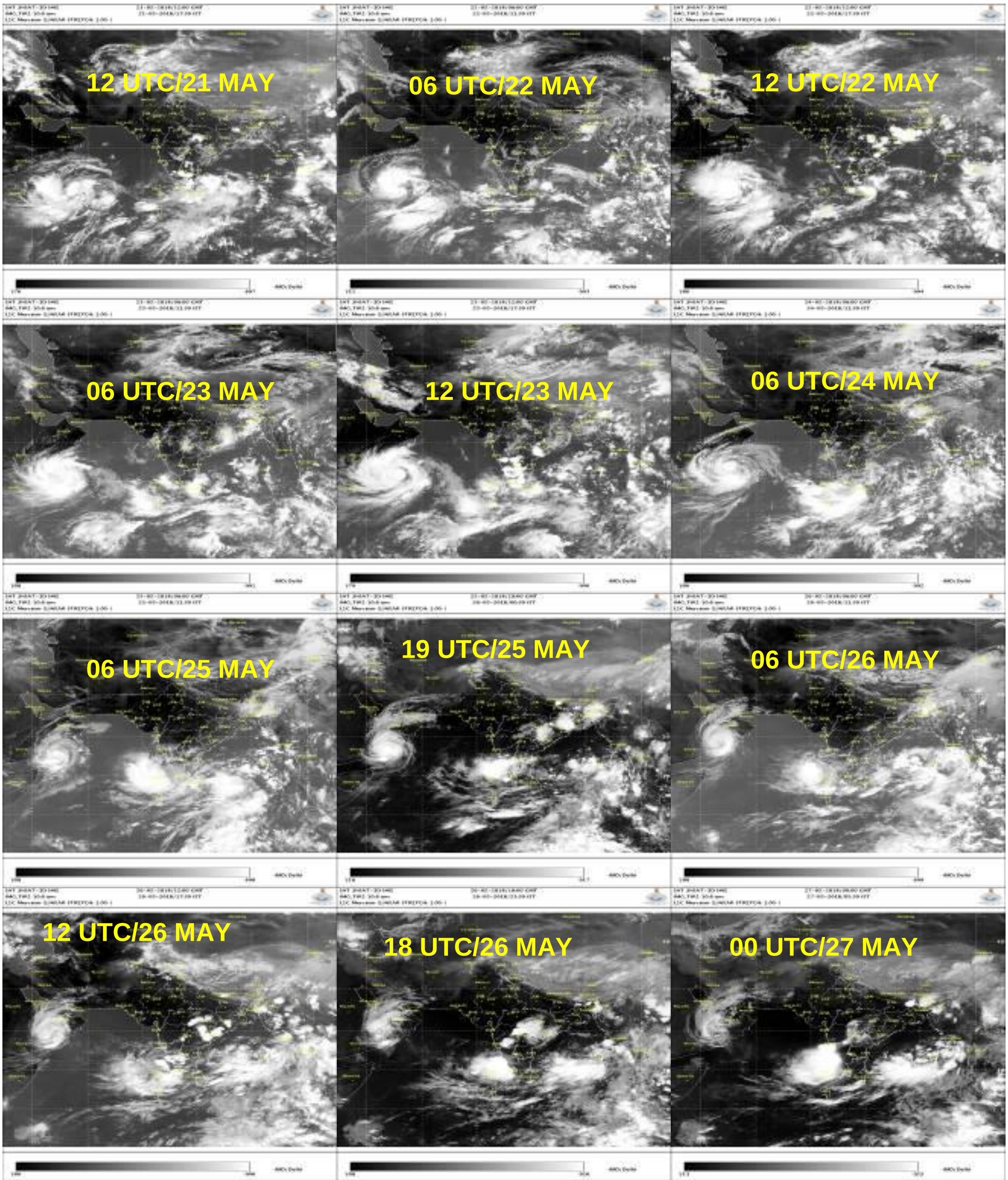


Fig. 2.3.5b: INSAT-3D IR imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

At 1200 UTC of 22nd, the system attained the intensity **T 2.5**. The cloud pattern indicated banding features from northeast to southwest sector across northwest sector. The intensity of the system was **T3.5**. The convection showed curved banding features from northeast to southwest sector across northwest sector. At 0900 UTC of 23rd, the system attained the intensity **T 4.0**. The convection increased over western and southern sector. With the consolidation of central dense overcast, satellite imagery indicated appearance of eye. It indicated intensification of the system. Minimum CTT was -93^{0}C. At 0300 UTC of 24th, the system further intensified and attained the intensity **T4.5**. The convection showed central dense overcast pattern with well defined spiral bands. Minimum CTT was -93^{0}C.

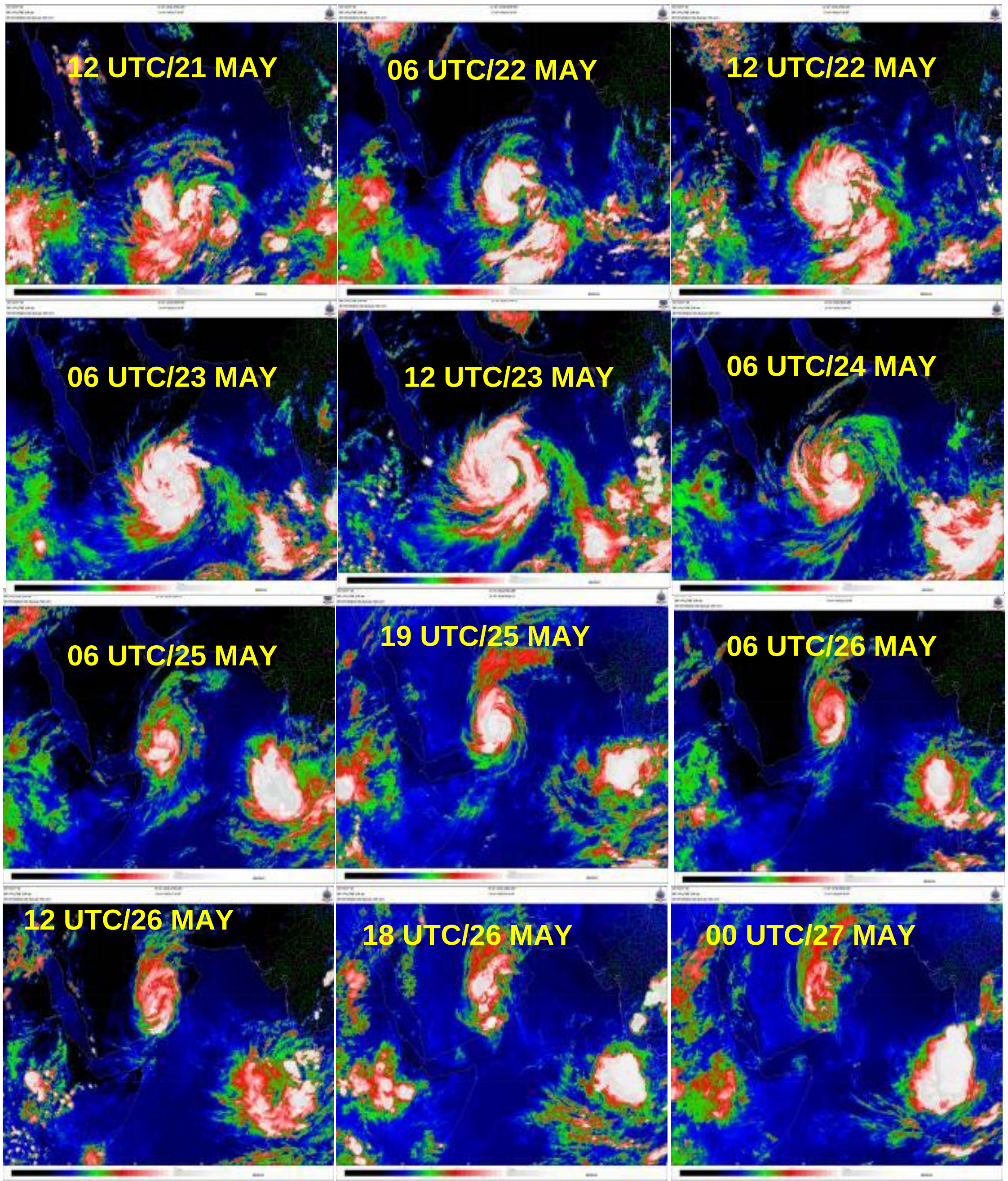


Fig. 2.3.5c: INSAT-3D enhanced colored imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

At 0300 UTC of 25th, the intensity of the system was **T 5.0**. The convection showed central dense overcast pattern with spiral bands. Associated broken low and medium clouds with embedded intense to very intense convection lay over westcentral and adjoining southwest AS between latitude 10.5⁰N & 18.5⁰N and longitude 51.0⁰E to 58.0⁰E. At 1800 UTC of 25th, the intensity of the system was **T 5.5**. The clouds got organized further and showed eye pattern. At 1800 UTC of 25th, the intensity of the system was T 5.5. The clouds got organized further and showed eye pattern. The system crossed Oman coast close to Salalah around 1900 UTC of 25th.

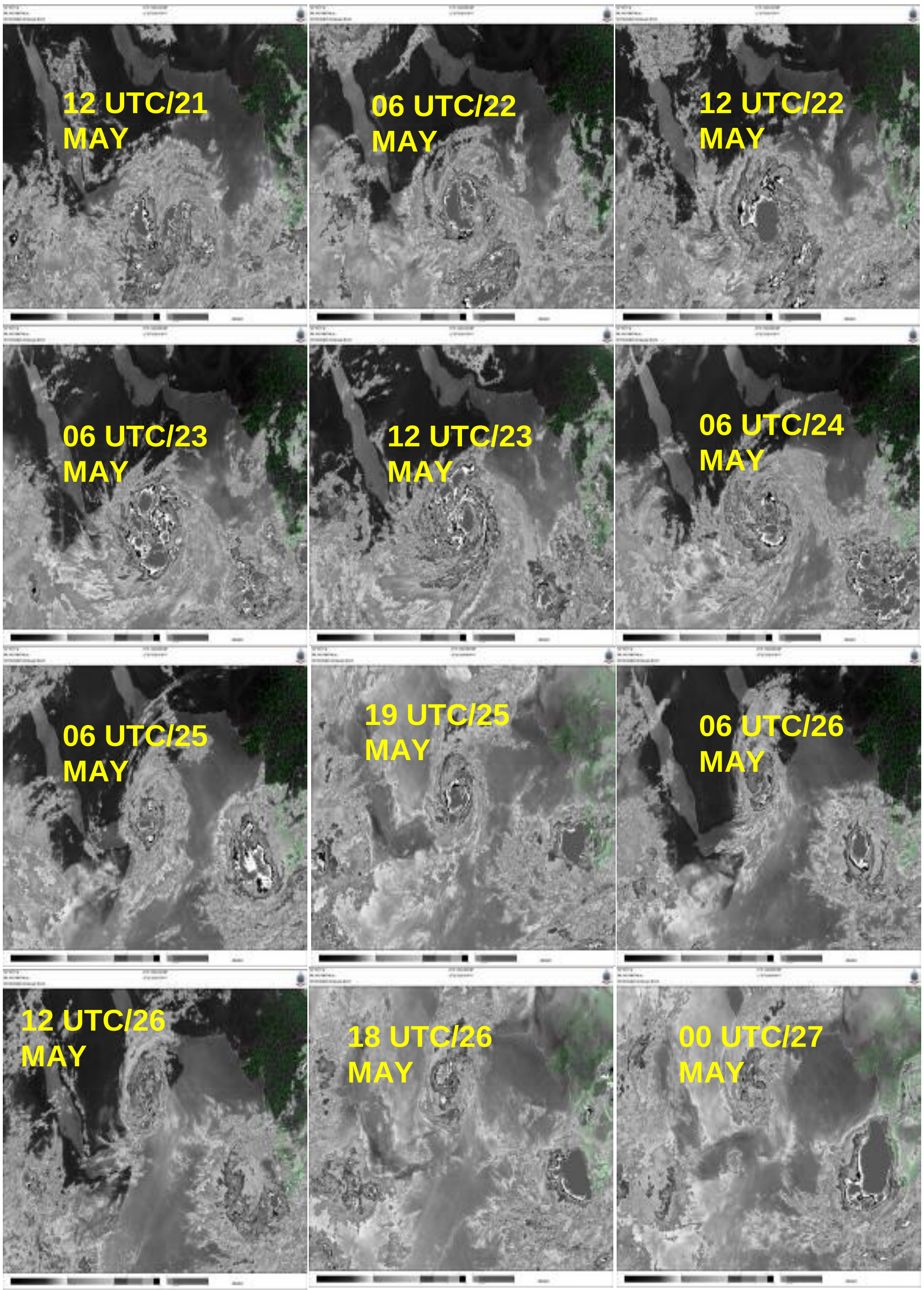


Fig. 2.3.5d: INSAT-3D cloud top brightness imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

2.3.5.2. Microwave Imageries:

Microwave imageries from polar orbiting satellites F-15, F-16, F-18, GCOM W1, GPM 89, NOAA-19 were utilised for determining the centre and area of intense convection. Typical microwave imageries during the life cycle of ESCS Mekunu are presented in **Fig. 2.3.5(e).**

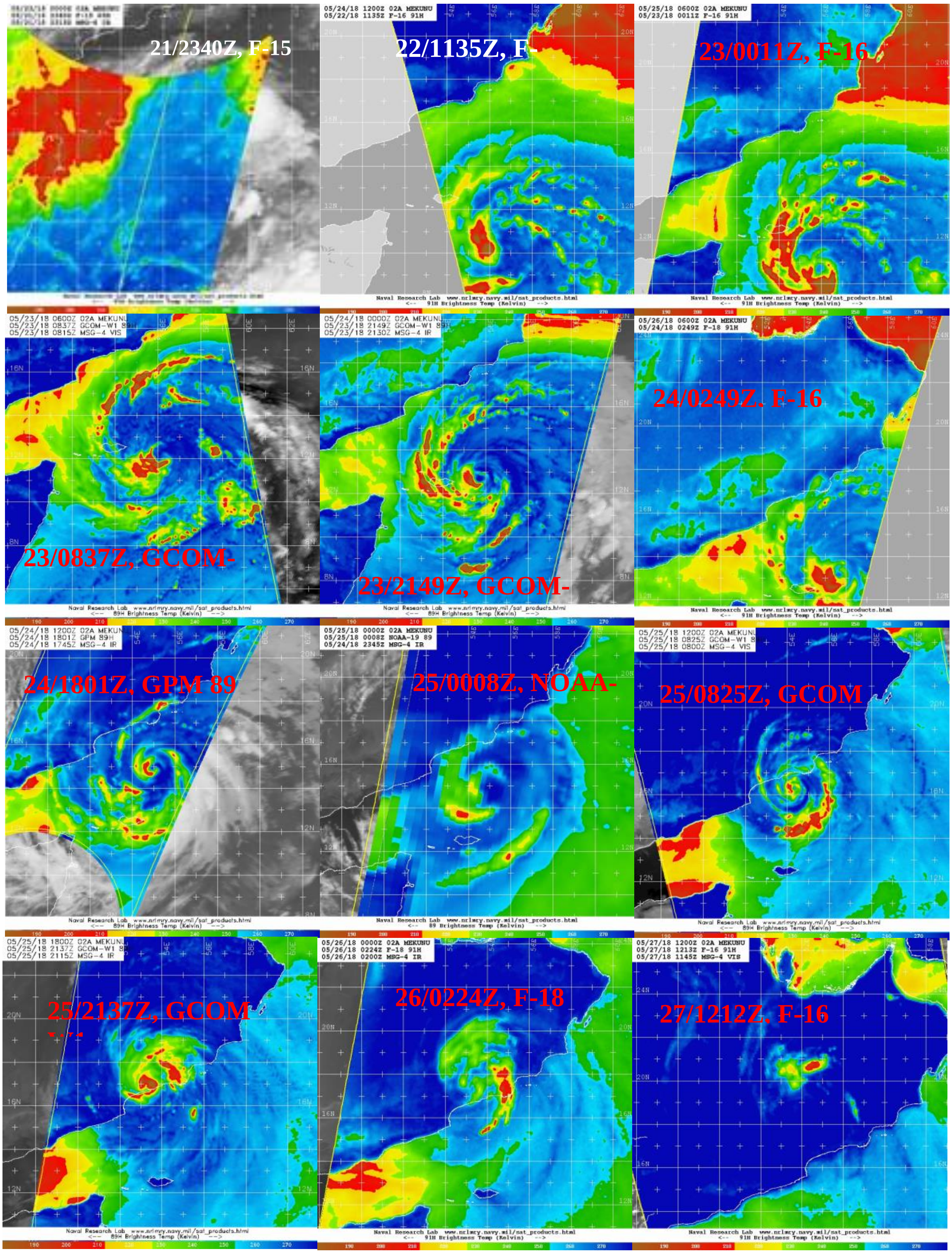


Fig. 2.3.5e: Microwave imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

When the system was over sea, imageries from ASCAT were also utilized for determination of centre, intensity and wind distribution around the centre of the system. Typical ASCAT imageries from Metop-B are presented in Fig. 2.3.5(f).

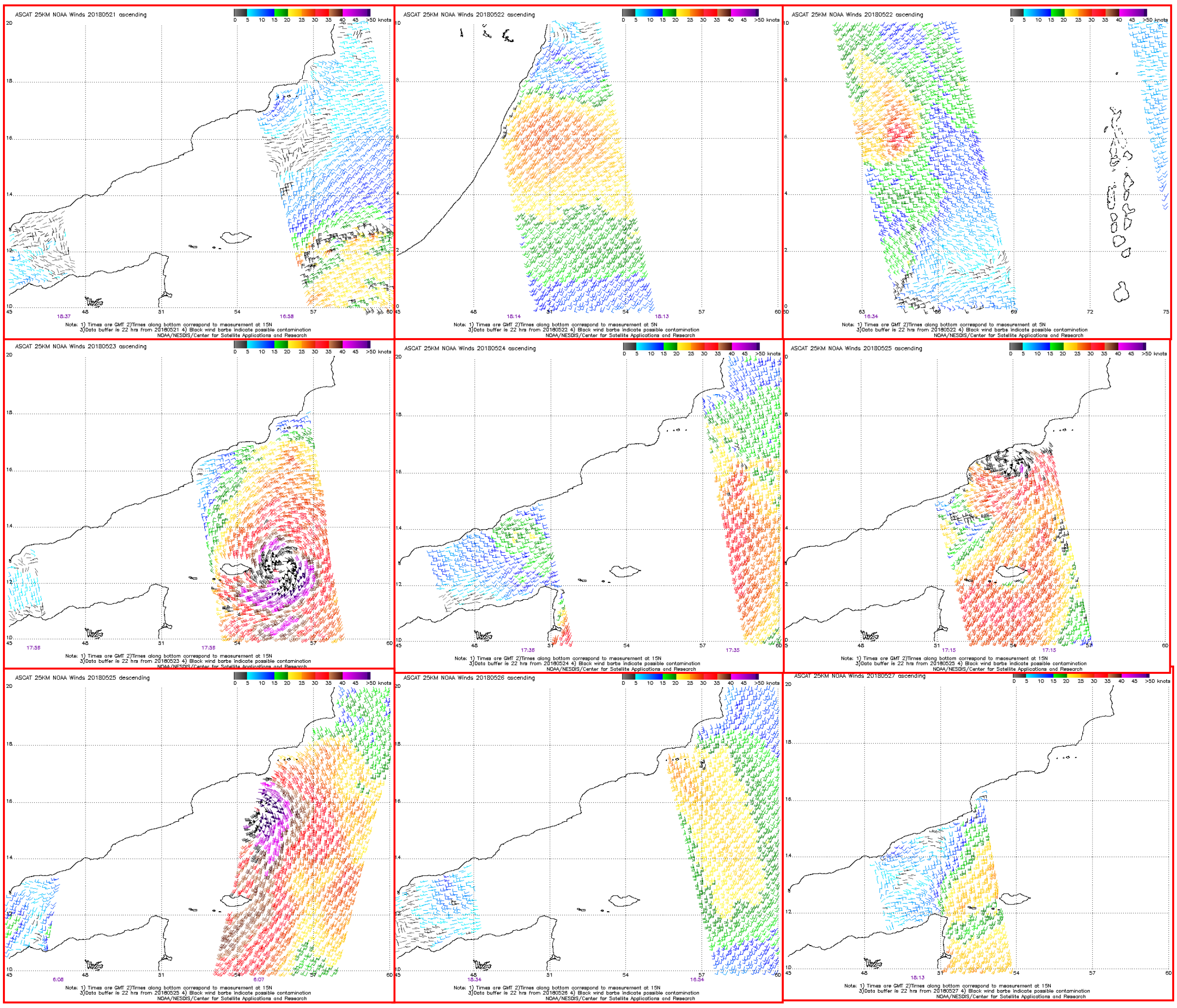


Fig. 2.3.5(f): ASCAT (Met-Op B) imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

Typical imageries from polar satellite, SCATSAT are presented in Fig. 2.3.9(b). SCATSAT passes are available twice a day at 0454 UTC and 1636 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 1636 UTC of 21st indicated cyclonic circulation over southwest Arabian Sea. Stronger winds were seen in northern sector. The imagery also indicated large scale cross equatorial flow, inflow of warm and moist air into the system centre from southeast sector. At 0454 UTC of 22nd May, the area of strong winds extended to southwest sector. At 1636 UTC of 23rd, stronger winds were seen in the northwest sector. At 0454 UTC of 24th, the centre was seen near

13.5N/56E, warm and moist air advection from southwest to northwest sector was seen. The estimated intensity was more than 60 kts. The maximum size in the southern sector was also due to higher southwesterly winds in the region. On 25th and 26th stronger winds were seen in the northeast sector. SCAT Sat imageries helped in determination of centre to a good extent. Intensity estimates beyond 60 kts cannot be done with the help of these imageries.

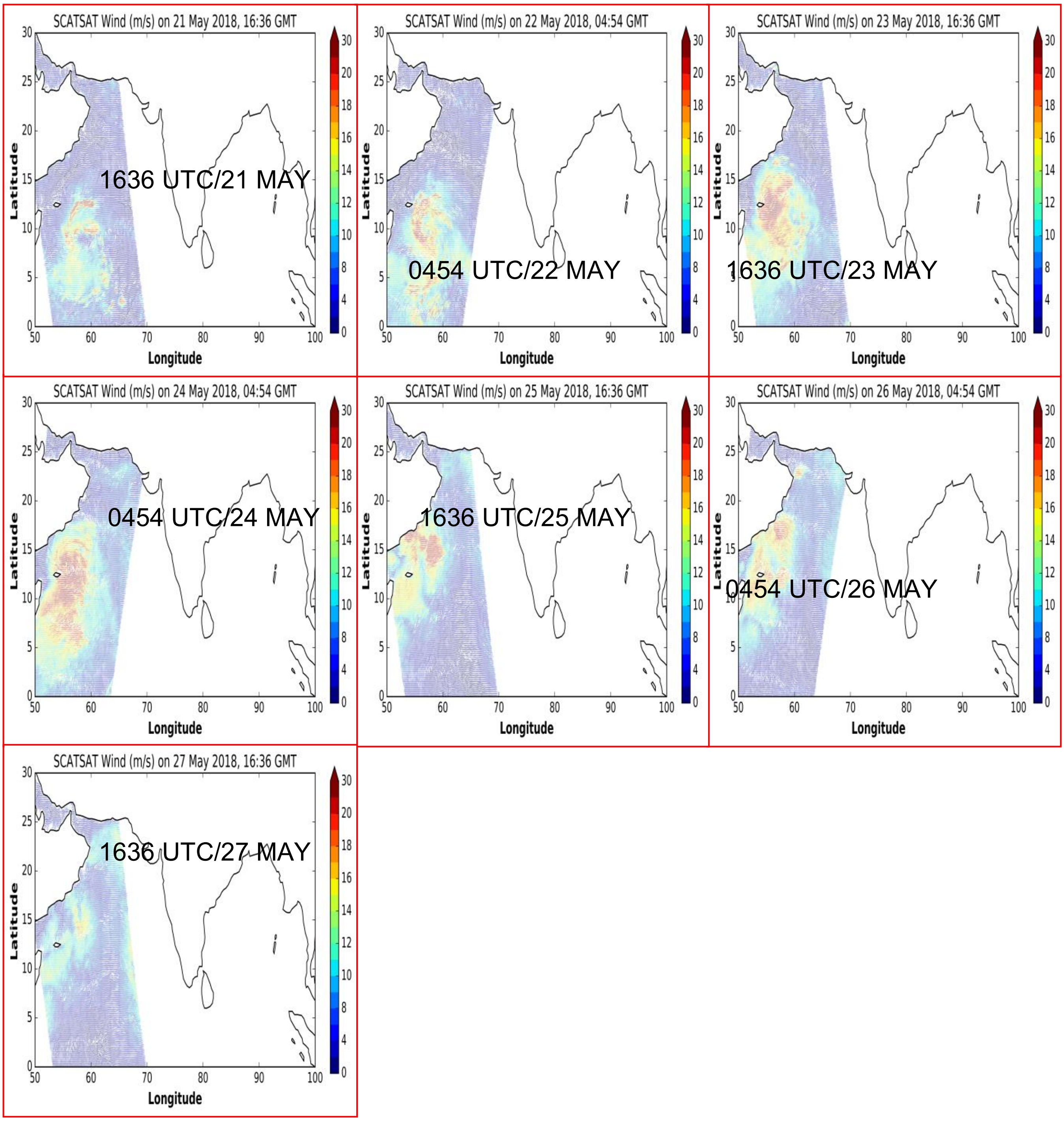


Fig. 2.3.5(g): SCAT SAT imageries during life cycle of ESCS Mekunu (21-27 May, 2018)

2.3.6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 21st to 27th May are presented in Fig. 2.3.6. GFS (T1534). Based on 0000 UTC observations of 21st, the model predicted a low pressure area over southeast and adjoining southwest AS. It indicated a cyclonic circulation over southeast AS extending upto 500 hPa level.

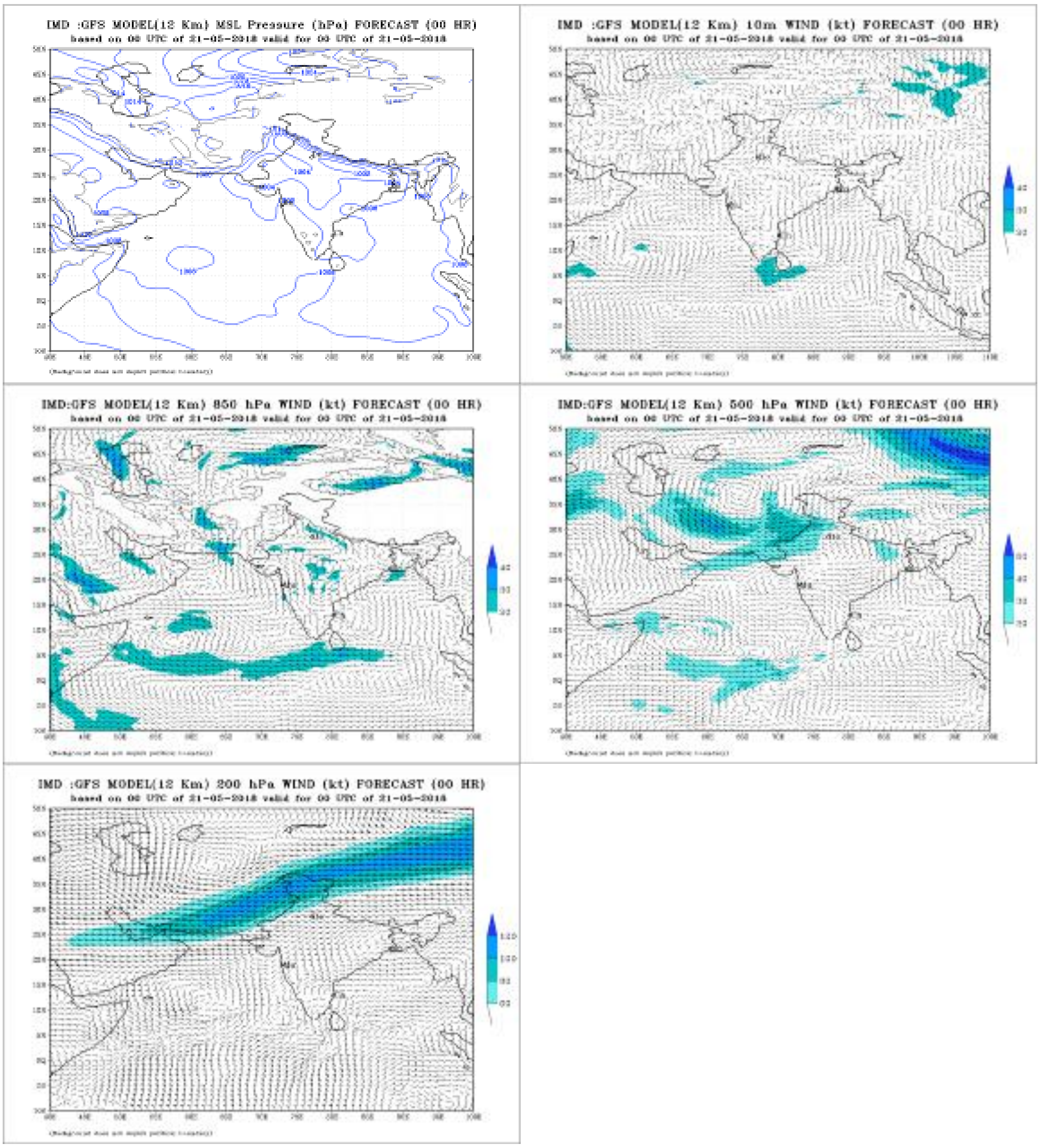


Fig. 2.3.6 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st May

Analysis based on 0000 UTC of 22nd May, predicted intensification of system into a deep depression over southeast AS. Vertically the system extended upto 500 hPa levels.

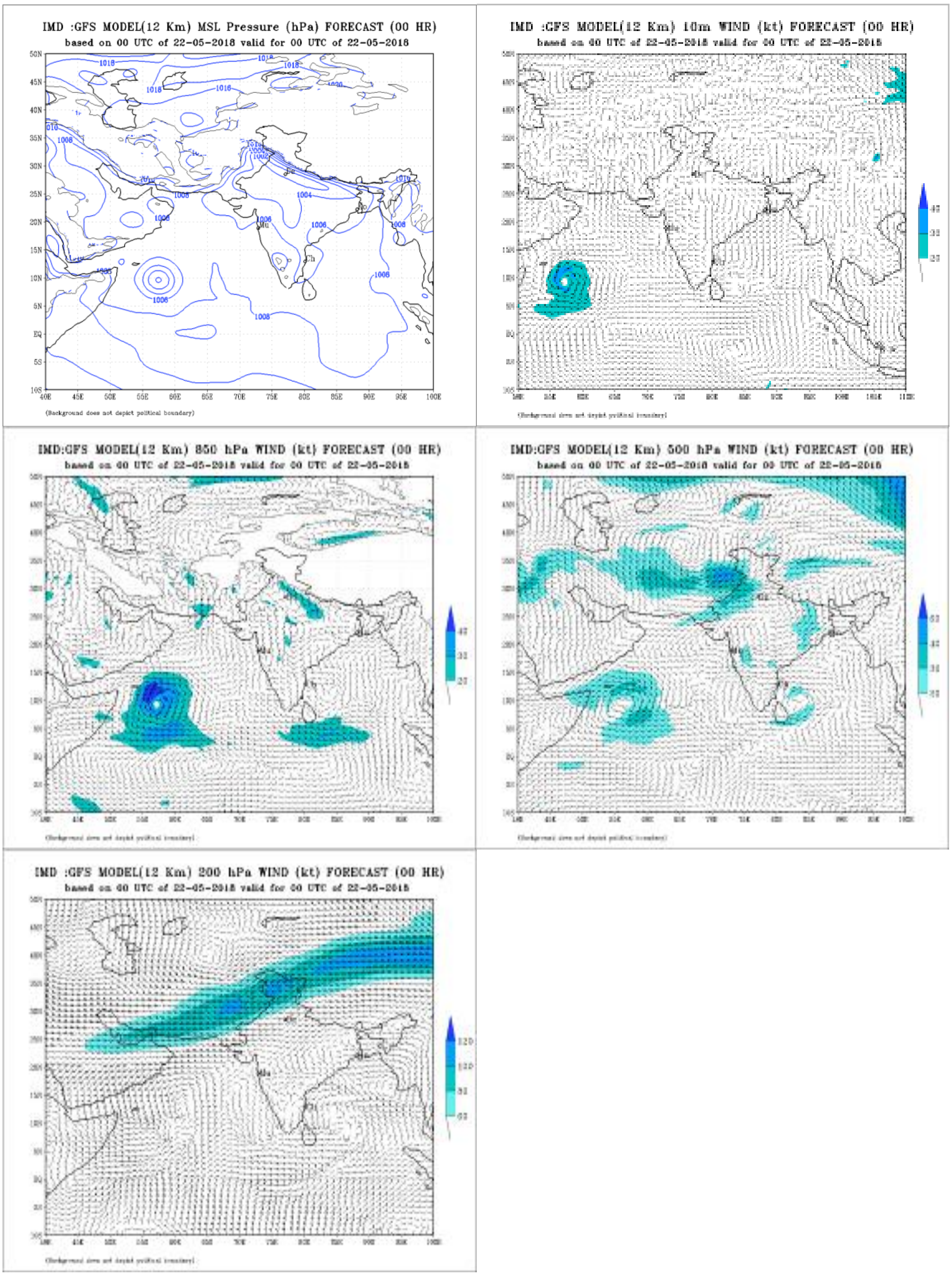


Fig. 2.3.6 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd May

Analysis based on 0000 UTC of 23rd May predicted northwards movement and further intensification of system into a severe cylonic storm over southeast AS. The circulation extended upto 500 hpa levels.

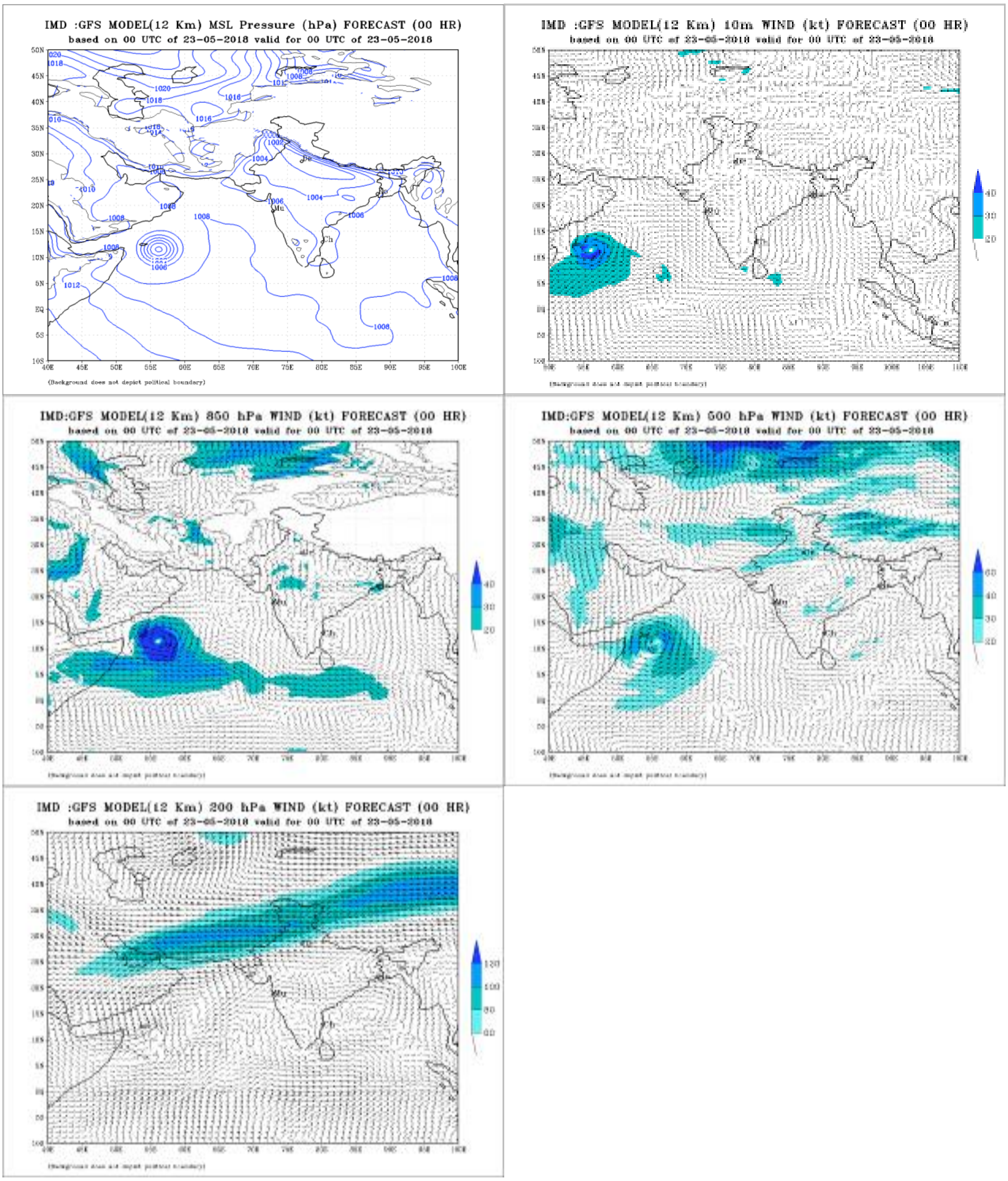


Fig. 2.3.6 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd May

Initial conditions based on 0000 UTC of 24th May indicated further intensification of the system to the east of Socotra Islands.

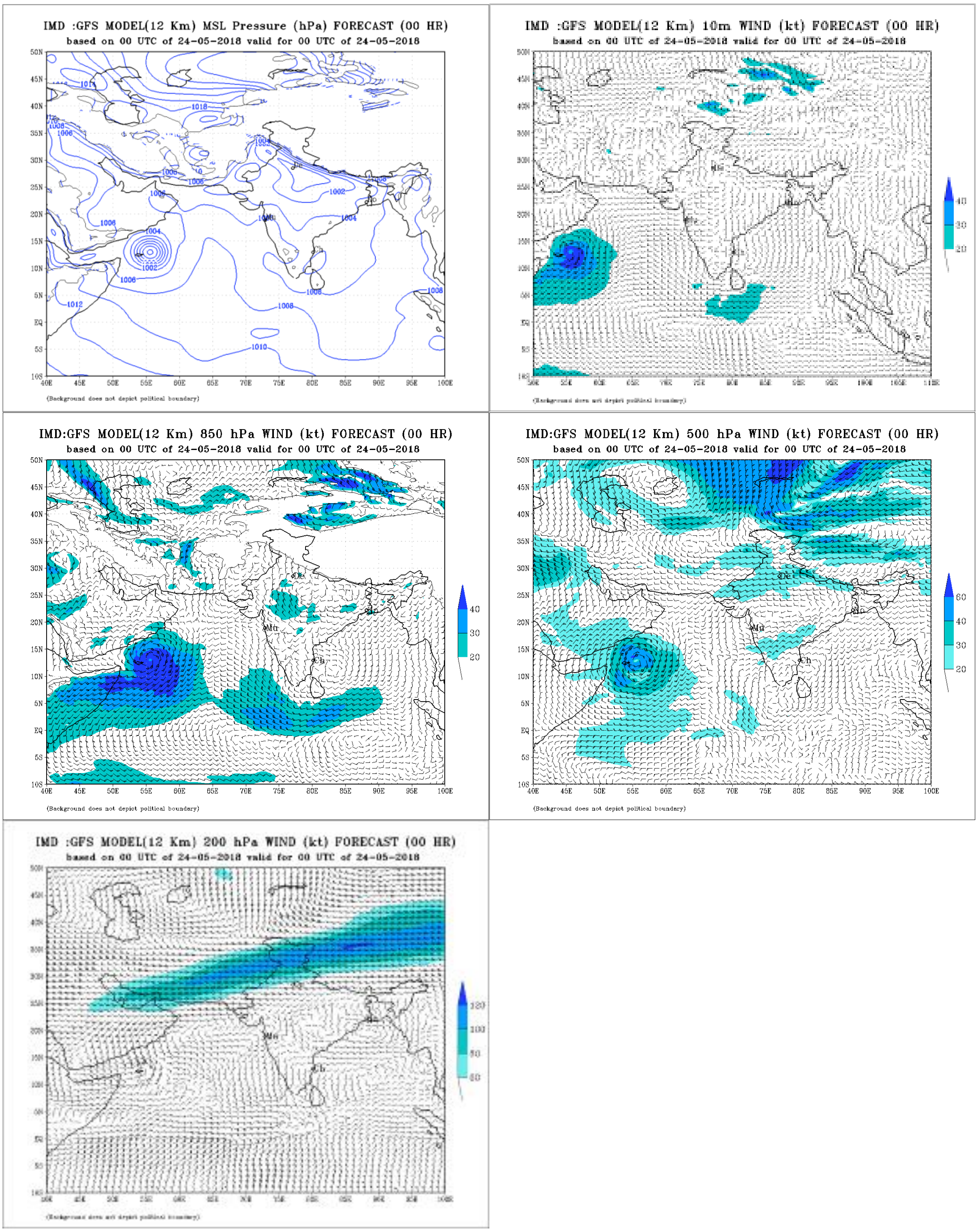


Fig. 2.3.6 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th May

Analysis based on 0000 UTC of 25th May indicated the northwards movement of system towards Salalah (Oman).

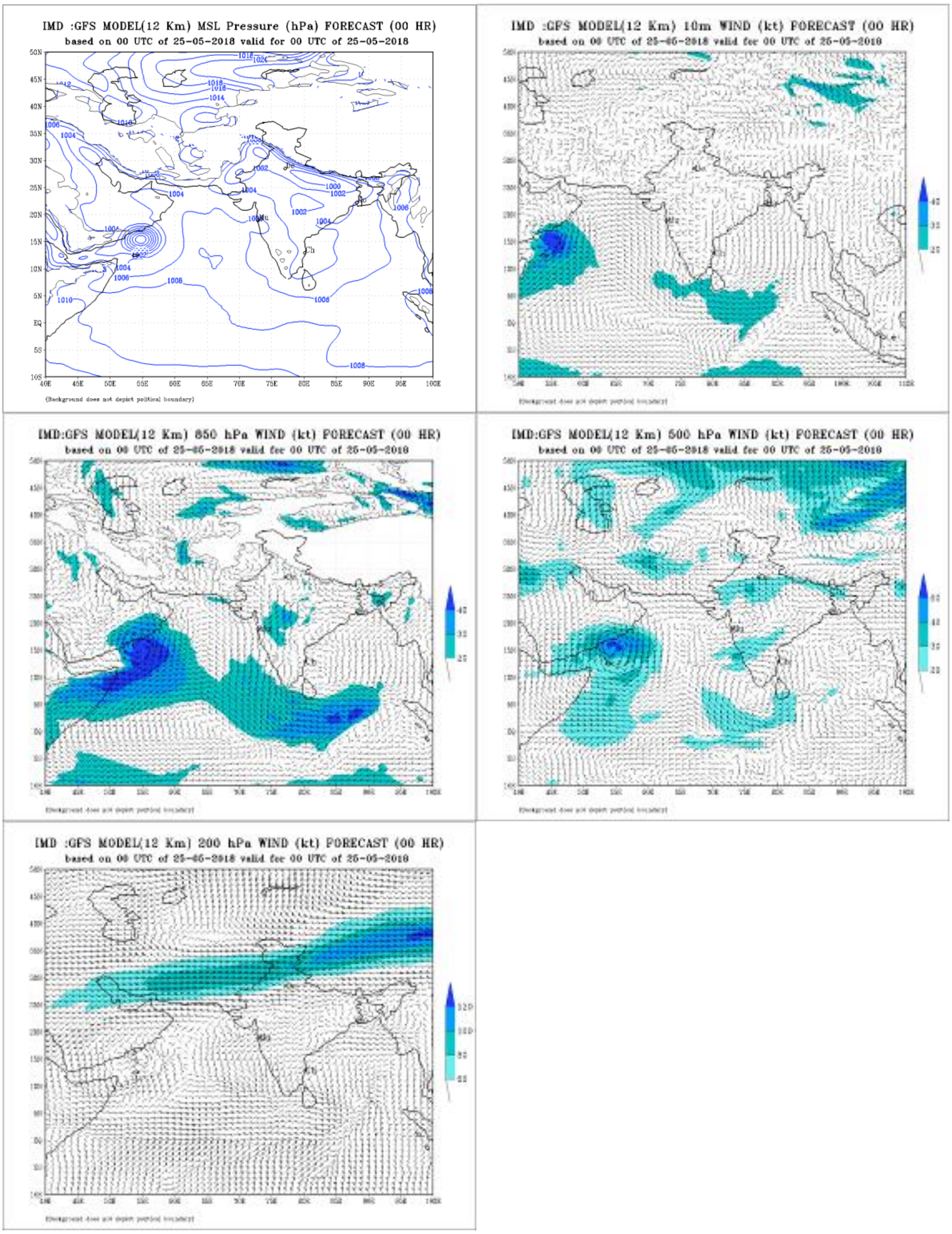


Fig. 2.3.6 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th May

The initial conditions based on 0000 UTC of 26th indicated the system crossing the Oman coast close to Salalah as a cyclonic storm.

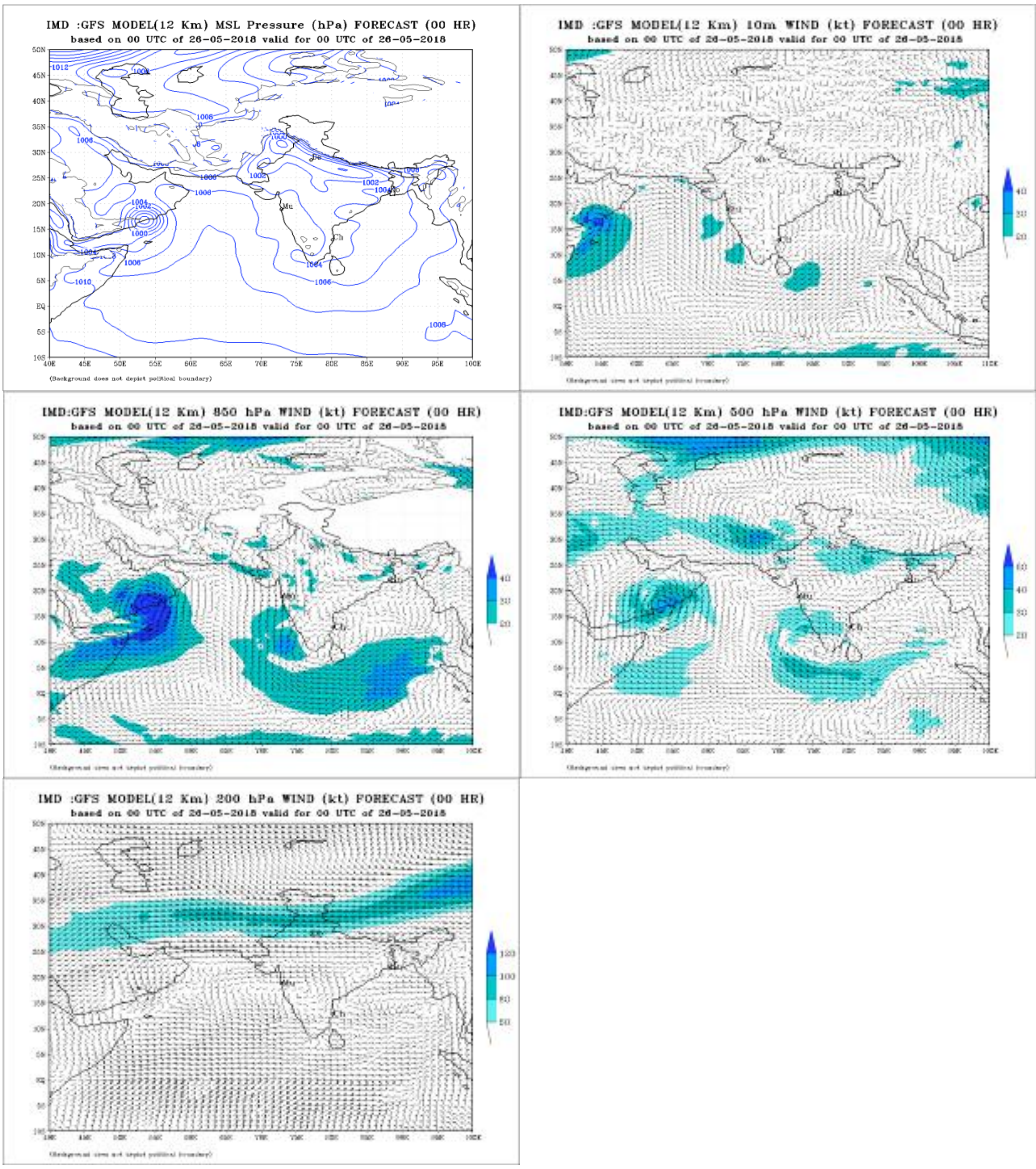


Fig. 2.3.6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 26th May

Hence to conclude, to a large extent IMD GFS could simulate the genesis, intensification, movement and landfall characteristics of the system. However, during landfall it predicted weakening of the system. Actually system crossed Oman coast with peak intensity as an ESCS.

2.3.7. Realized Weather:

2.3.7.1 Rainfall:

Rainfall associated with ESCS Mekunu based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig. 2.3.7**. It indicates the occurrence of extremely heavy rainfall over Oman and adjoining Yemen due to this cyclone.

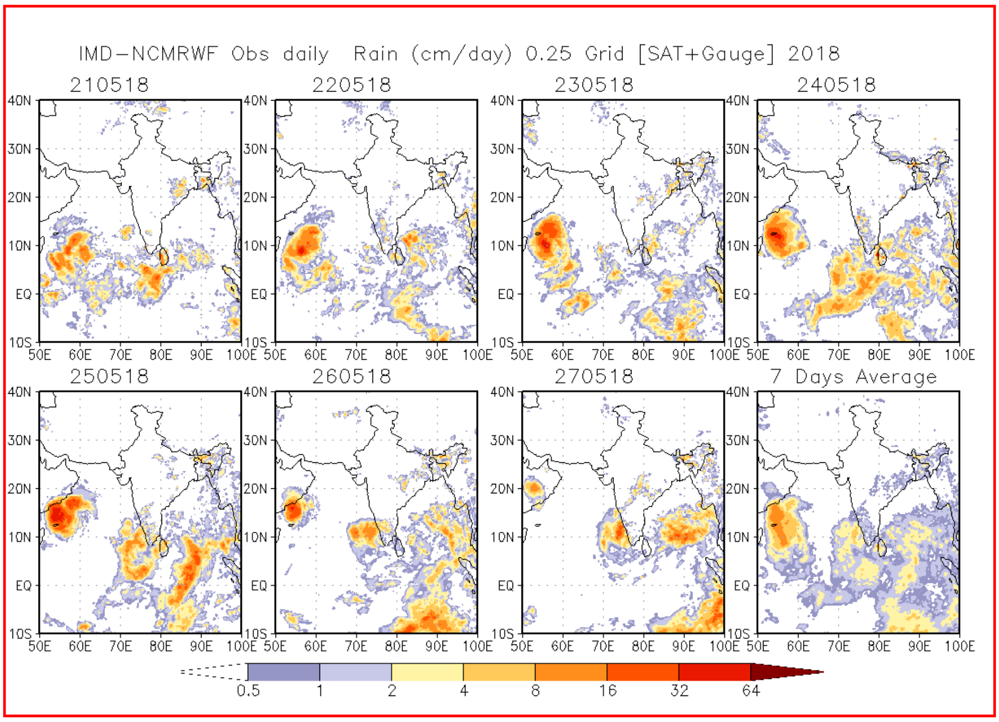


Fig.2.3.7: IMD-NCMRWF GPM merged gauge rainfall during 21st May– 27th May and 7 days average rainfall (cm/day)

2.3.8 Damage due to ESCS Mekunu

Damage over India:

No casualties were reported from any Indian state due to ESCS, Mekunu.

Damage over Socotra Islands: Socotra received widespread rainfall leading to flash flooding and downed power lines (Fig. 2.3.8(a)). About 20 persons lost their lives because of heavy rains and strong winds caused by cyclone Mekunu.

Fig.2.3.8 (a): People walking through floods (Source Middle East Eye, Screengrab/AFP)

Damage over Oman:

According to Oman's Public Authority for Civil Aviation (PACA), Salalah received 278.2 millimeters (10.95 inches) of rain in just 24 hours ending around 10:30 a.m. on May 26. This was over double the city's average yearly rainfall of about five inches in just 24 hours. In addition, Salalah reported 617 millimeters of rainfall during 23-27 May. As per media reports (Times News Service), Taqah recorded 275 mm, Mirbat received 221 mm, Rakhyoot had 214 mm, Thumrait recorded 196 mm, and Sadah received 180 mm. Moreover, the Sahalnoot Dam collected 6.4 million cubic metres of water. As per official records six persons lost their lives in Oman. Typical damage photographs are presented in Fig. 2.3.8(b and c).

Fig. 2.3.8 (b): Flooding in Salalah in southwest Oman on 26th May

Fig.2.3.8 (c): Destructive winds lashed western Oman during 25th – 26th May

2.4. Deep Depression over northeast Bay of Bengal (29-30 May, 2018)

2.4.1. Introduction

A depression formed over eastcentral and adjoining northeast Bay of Bengal around noon (0600 UTC) of 29th May. It moved northeastwards, intensified into a deep depression (DD) in the same evening and crossed Myanmar coast to the north of Kyakpyu between 1700 & 1800 UTC of same night. It continued to move northeastwards and weakened gradually into a depression in the early morning of 30th May over Myanmar and into a well marled low pressure area over Myanmar around noon (0600 UTC) of same day. Advisories were provided to WMO/ESCAP Panel member countries including Bangladesh and Myanmar. The track of the deep depression is presented in Fig. 2.4.1.

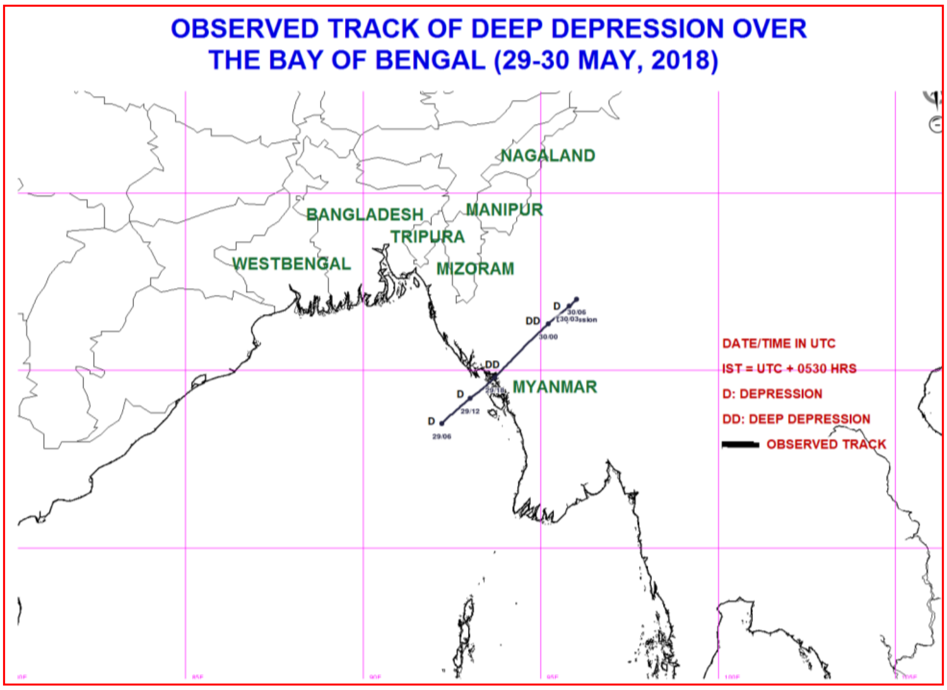


Fig. 2.4.1. Observed track of Deep Depression over northeast Bay of Bengal (29-30 May, 2018)

2.4.2. Brief life history

Under the influence of cyclonic circulation over north BoB & neighbourhood extending between 1.5 km & 7.6 km above mean sea level on 8th June, a low pressure area formed over north BoB and neighbourhood at 1200 UTC of 9th. At 1200 UTC of 9th, environmental conditions were supporting intensification of system. The sea surface temperature (SST) was 30-31^{0}C over norhteast BoB. The tropical cyclone heat potential was less than 50 KJ/ cm^{2} over north BoB. The low level relative vorticity was about 100x10^{-6} s^{-1} over northeast & adjoining eastcentral BoB. The vertical wind shear was low (5-10 knots) over northeast BoB. The lower level convergence was about 20 x10^{-5} s^{-1} and the upper level divergence was about 20 x10^{-5} s^{-1} northeast and adjoining eastcentral BoB off Myanmar coast. At 0600 UTC of 10th, similar sea conditions prevailed over north BoB and the environmental conditions further improved leading to formation of Depression over northeast BoB and adjoining Bangladesh. The low level relative vorticity was about 100x 10^{-6} s^{-1} to the northeast of the system centre. The lower level convergence was about 40 x10^{-5} s^{-1} to the northeast of the system centre. The upper level divergence was about 30 x10^{-5} s^{-1} to the northeast of the system centre. The vertical wind shear was moderate (10-20 knots) over the system area.

Similar conditions prevailed and it crossed Bangladesh coast close to south of Feni at night (1500 UTC) of 10th. Thereafter, due to land interactions, cut in moisture supply and increased vertical wind shear, it weakened into a WML in the morning (0000 UTC) of 11th June.

The best track parameters of the system are presented in Table 2.4.1. The typical satellite imageries are presented in Fig. 2.4.2.

Table 2.4.1: Best track positions and other parameters of the Deep Depression over northeast and adjoining eastcentral BoB during 29-30 May, 2018

Date	Time (UTC)	Centre lat.^{0} N/ long.^{0} E		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
29/05/2018	0600	18.5	92.2	1.5	998	25	3	**D**
	1200	19.2	93.0	1.5	992	30	4	D
	Crossed Myanmar coast to the north of Kyakpyu between 1700-1800 UTC							
	1800	19.8	93.7	2.0	994	30	4	**DD**
30/05/2018	0000	21.3	95.2	-	996	25	3	DD
	0300	21.8	95.8	-	998	20	2	**D**
	0600	**Weakened into a well-marked low pressure area over Myanmar at 06 UTC of 30th May 2018.**						

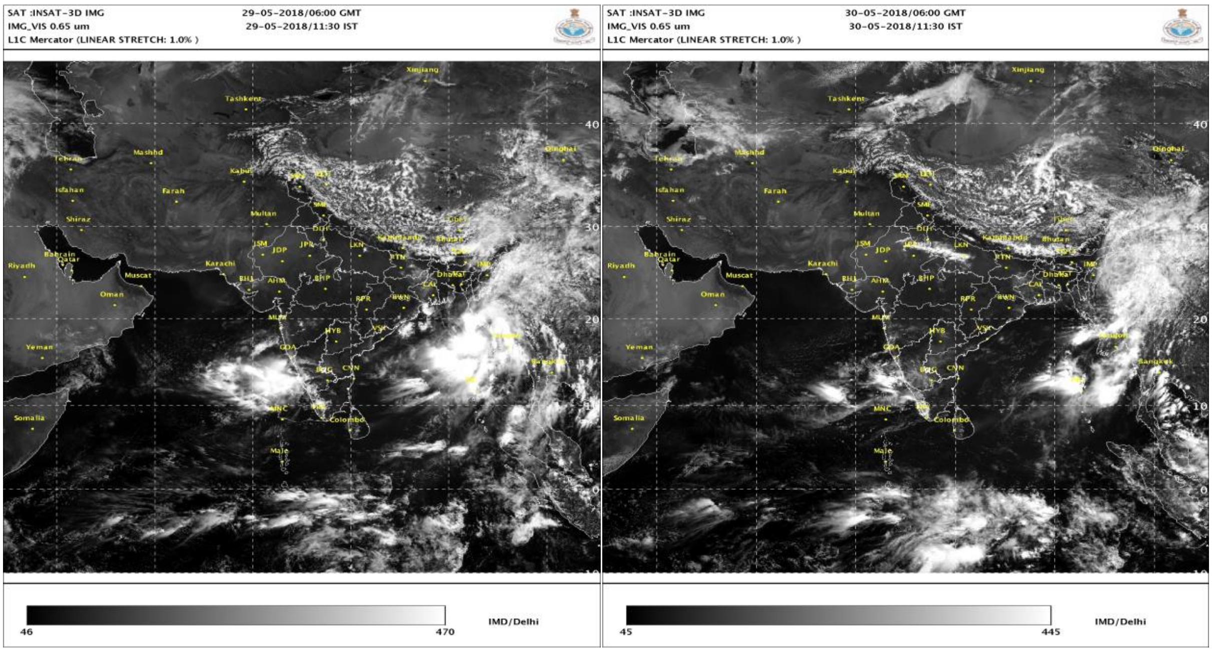


Fig. 2.4.2(i): INSAT-3D visible imageries of Deep Depression at 0600 UTC of 29 and 30 May, 2018

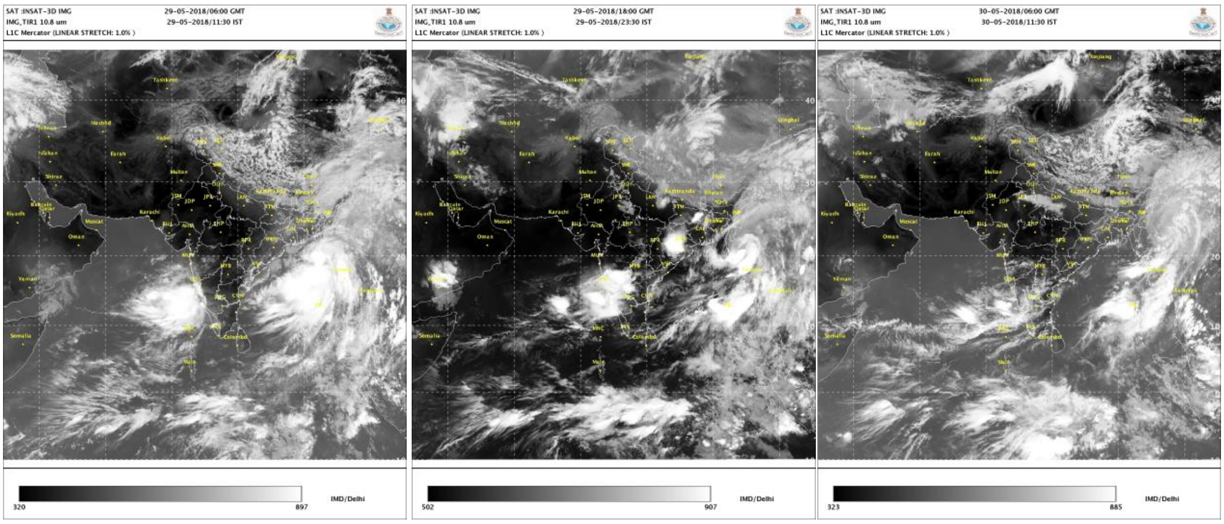


Fig. 2.4.2(ii): INSAT-3D IR imageries of Deep Depression at 0600, 1800 UTC of 29 and 0600 UTC of 30 May, 2018

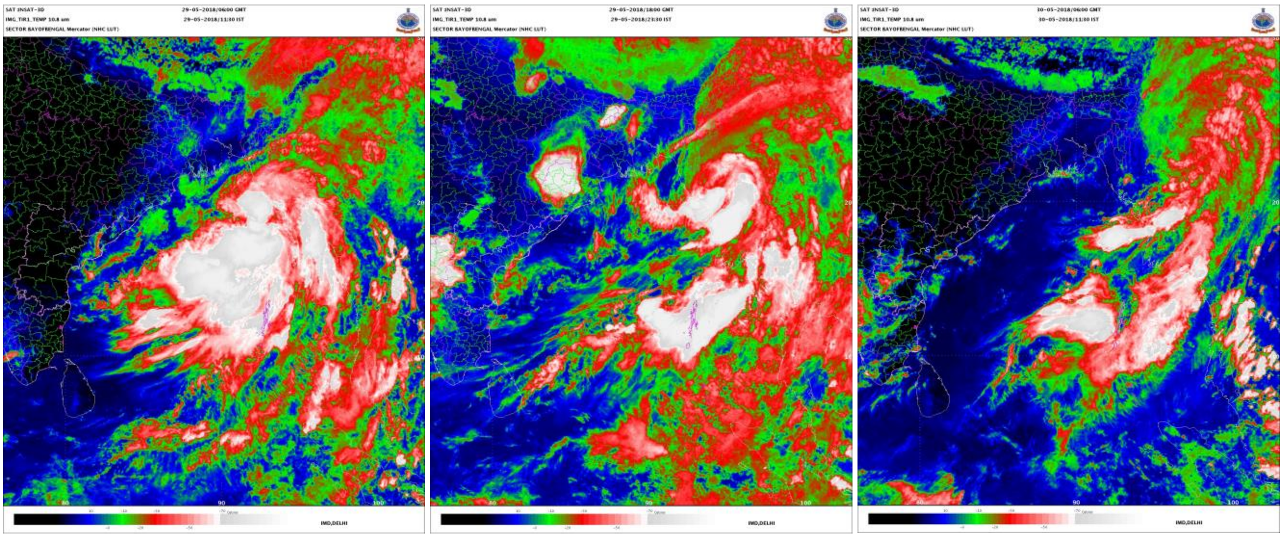


Fig. 2.4.2(iii): INSAT-3D enhanced coloured imageries of Deep Depression at 0600, 1800 UTC of 29 and 0600 UTC of 30 May, 2018

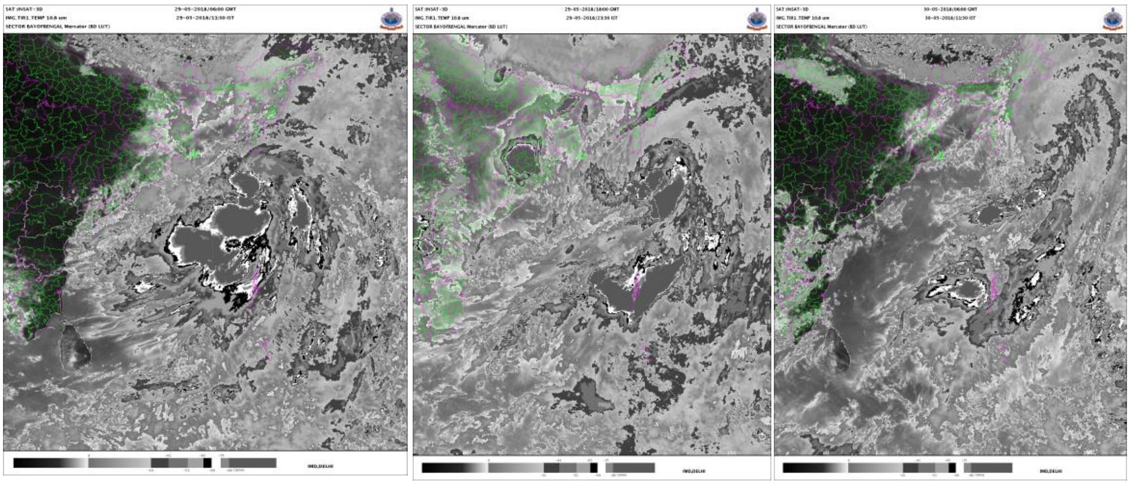


Fig. 2.4.2(iv): Cloud Top Brightness Imageries of Deep Depression at 0600, 1800 UTC of 29 and 0600 UTC of 30 May, 2018

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 accurately over northeast and adjoining eastcentral BoB and the associated circulation features during the life period of Depression. Initial conditions based on 1200 UTC indicated intensification of system into DD. The initial conditions based on 0000 UTC of 30th indicated weakening of system

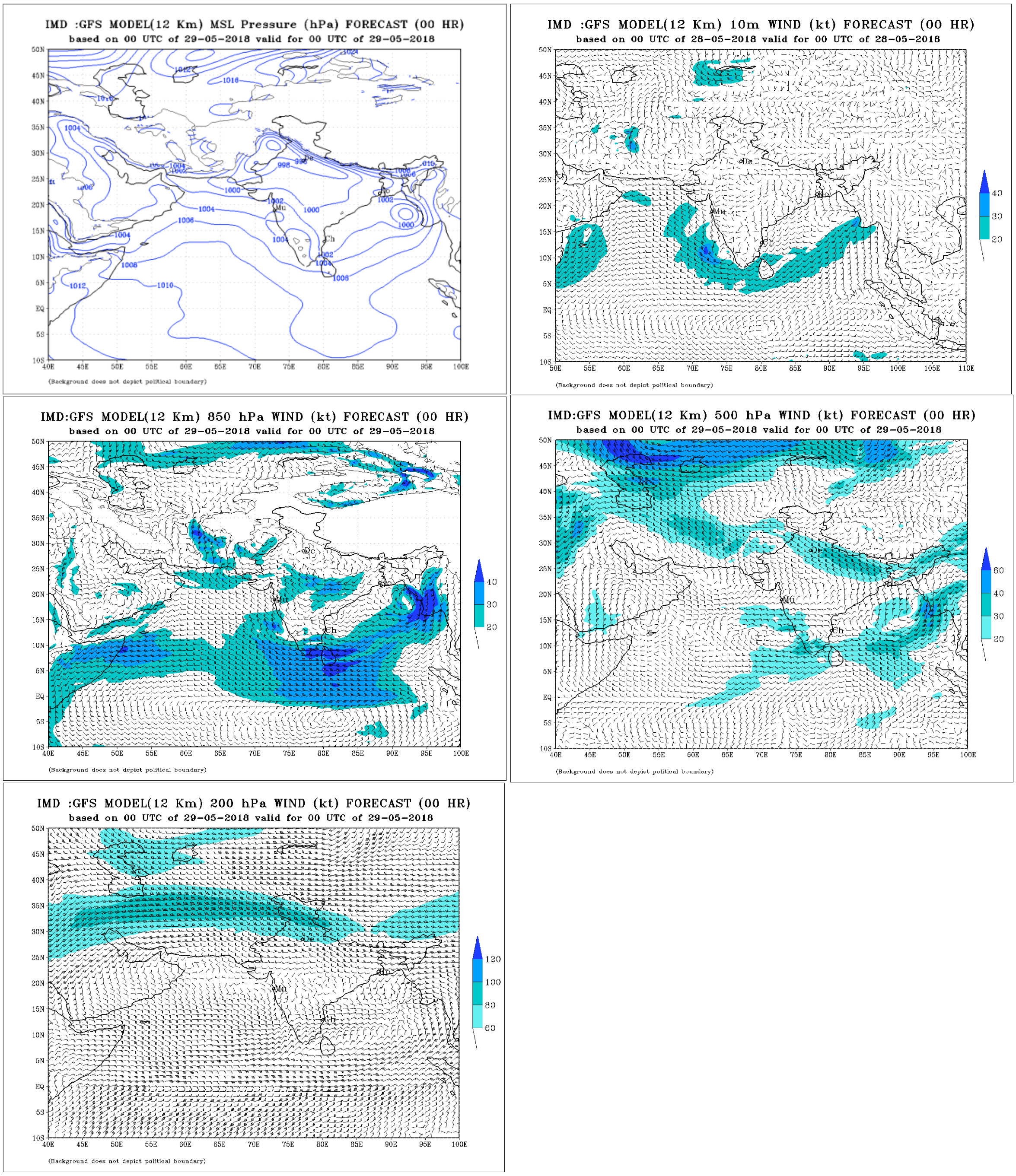


Fig. 2.4.3 (i): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 29th May

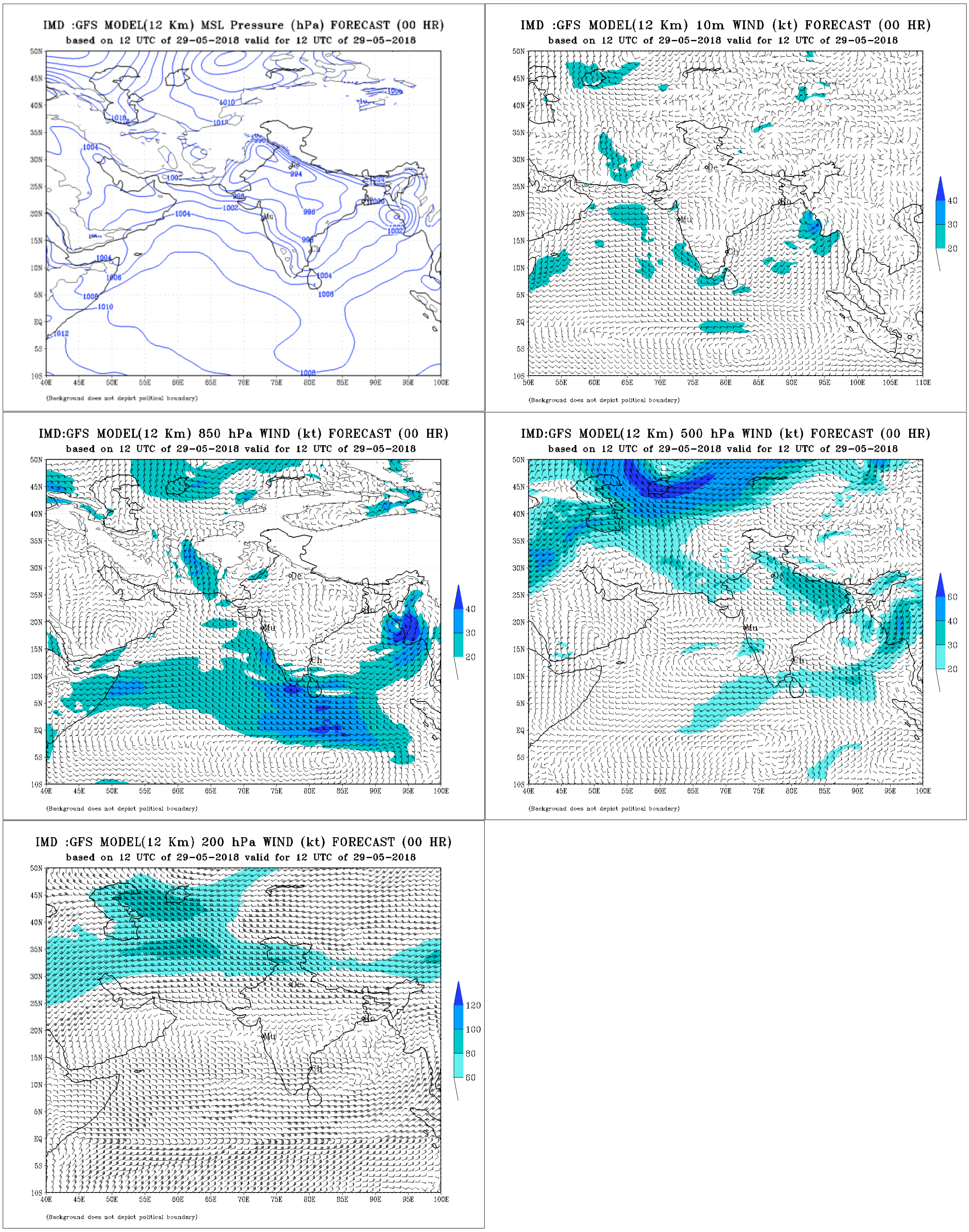


Fig. 2.4.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 1200 UTC of 29th May.

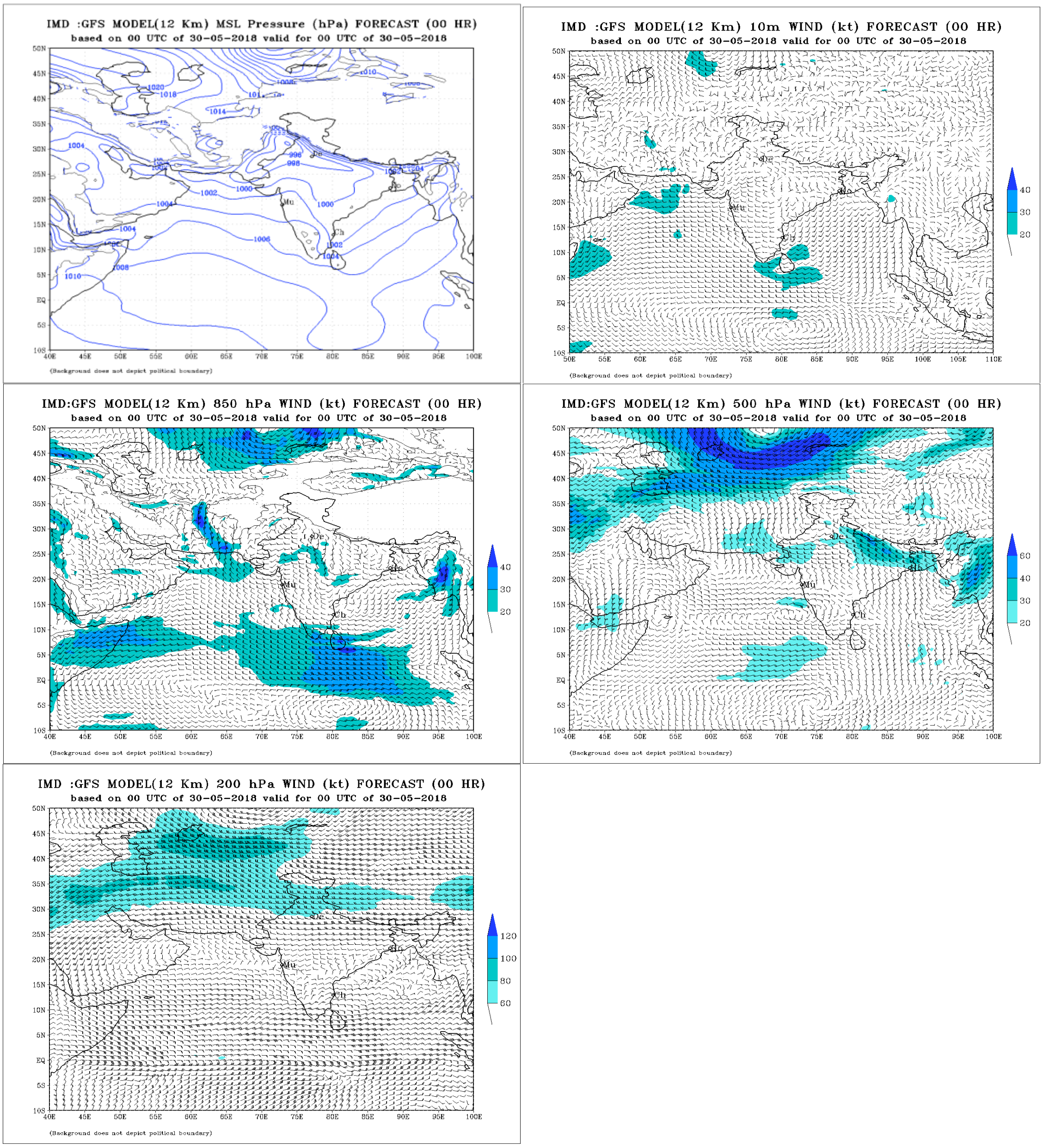


Fig. 2.4.3 (iii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 30th May.

2.4.4. Realized Weather:

2.4.4.1 Rainfall:

Realised weather:

Under the influence of this depression, heavy rainfall at isolated places occurred Gangetic West Bengal, Odisha and Jharkhand on 9th, over Gangetic West Bengal & Odisha on 10th and over Assam & Meghalaya on 11th. The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig.2.4.4.

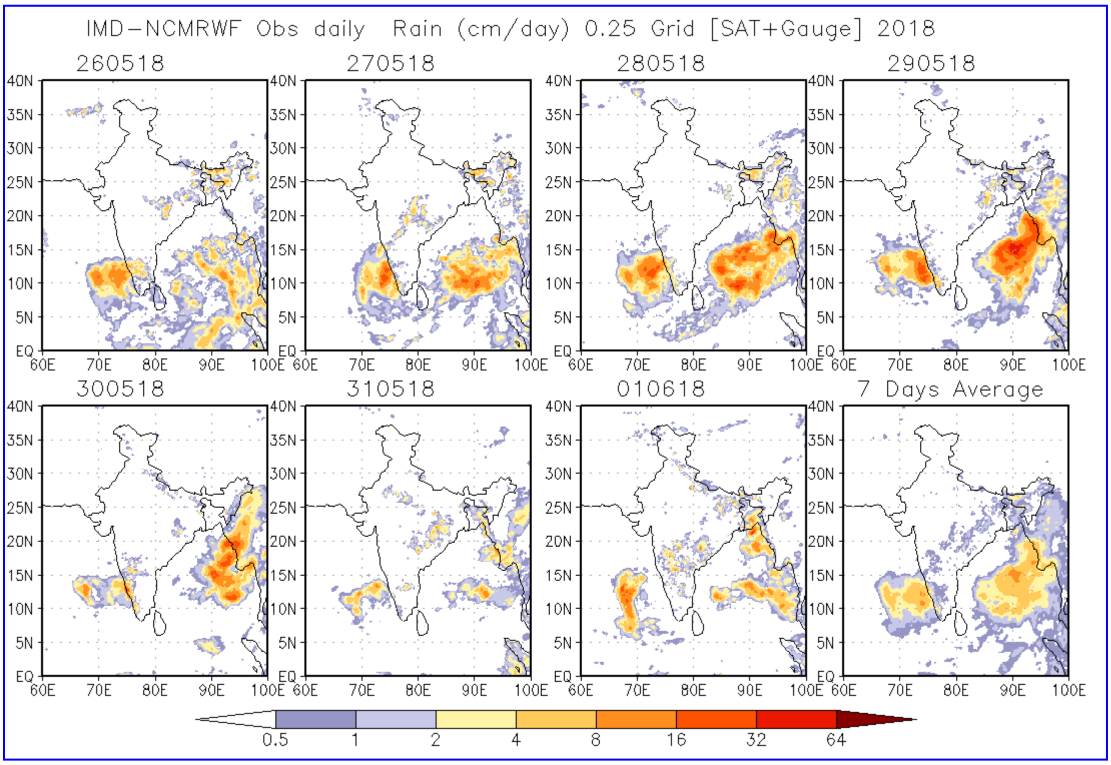


Fig. 2.4.4: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 29-30 May 2018.

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

9th June 2018

Gangetic West Bengal: Canning and Barrackpur (IAF)-7 each
Odisha: Nimpara-8 and Chandanpur & Sorada-7 each
Jharkhand: Ghatsila-7

10th June 2018

Gangetic West Bengal: Purihansa and Rampurhat (DRMS)-7 each
Odisha: Nawana-8

11th June 2018

Assam & Meghalaya: Beki Mathungari-7

2.5. Depression over northeast Bay of Bengal and adjoining Bangladesh (10-11 June, 2018)

2.5.1. Introduction

In association with active monsoon conditions, a low pressure area formed over north Bay of Bengal (BoB) and neighbourhood in the evening (1200 UTC) of 8th June. It lay as a well marked low pressure area (WML) over northeast BoB and adjoining Bangladesh in the morning (0300 UTC) of 10th June. It concentrated into a depression (D) around noon (0600 UTC) of 10th June over northeast BoB and adjoining Bangladesh near latitude 22.3ºN / longitude 91.5ºE. Moving nearly north-northwestwards, it crossed Bangladesh coast near latitude 23.1ºN / longitude 91.2ºE, south of Feni at night (around 1500 UTC) of 10th June and weakened into a WML over Bangladesh and neighbourhood in the early morning (0000 UTC) of 11th June. The system caused heavy rainfall at isolated places over Gangetic West Bengal, Odisha and Jharkhand on 9th, Gangetic West Bengal & Odisha on 10th and over Assam & Meghalaya on 11th June. On 12th, the system caused heavy to very rainfall at isolated places over Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura, Odisha and Bihar. On 13th, it caused heavy to very rainfall at isolated places over Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura and Odisha. The track of the depression is presented in Fig. 2.5.1.

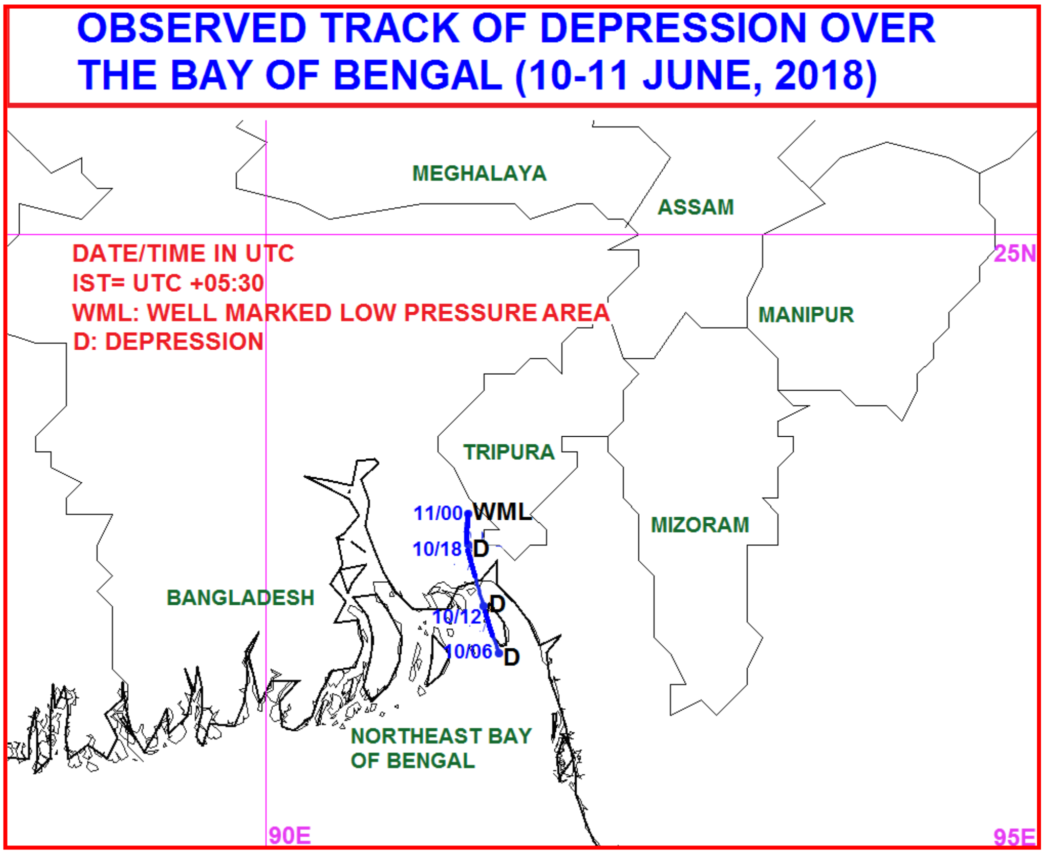


Fig. 2.5.1. Observed track of Depression over northeast Bay of Bengal and adjoining Bangladesh (10-11 June, 2018)

2.5.2. Brief life history

Under the influence of cyclonic circulation over north BoB & neighbourhood extending between 1.5 km & 7.6 km above mean sea level on 8th June, a low pressure area formed over north BoB and neighbourhood at 1200 UTC of 9th. At 1200 UTC of 9th, environmental conditions were supporting intensification of system. The sea surface temperature (SST) was 30-31^{0}C over norhteast BoB. The tropical cyclone heat potential was less than 50 KJ/ cm^2 over north BoB. The low level relative vorticity was about 100x10^{-6} s^{-1} over northeast & adjoining eastcentral BoB. The vertical wind shear was low (5-10 knots) over northeast BoB. The lower level convergence was about 20 x10^{-5} s^{-1} and the upper level divergence was about 20 x10^{-5} s^{-1} northeast and adjoining eastcentral BoB off Myanmar coast. At 0600 UTC of 10th, similar sea conditions prevailed over north BoB and the environmental conditions further improved leading to formation of Depression over northeast BoB and adjoining Bangladesh. The low level relative vorticity was about 100x 10^{-6} s^{-1} to the northeast of the system centre. The lower level convergence was about 40 x10^{-5} s^{-1} to the northeast of the system centre. The upper level divergence was about 30 x10^{-5} s^{-1} to the northeast of the system centre. The vertical wind shear was moderate (10-20 knots) over the system area. The system moved nearly northwards, as it lay close to south of the ridge in association with an anticyclonic circulation in upper & middle tropospheric levels to the east of system centre. The depression crossed Bangladesh coast close to south of Feni at night (1500 UTC) of 10th. Thereafter, due to land interactions, cut off in moisture supply and increased vertical wind shear, it weakened into a WML in the morning (0000 UTC) of 11th June.

The best track parameters of the system are presented in Table 2.5.1. The typical satellite imageries are presented in Fig. 2.5.2.

Table 2.5.1: Best track positions and other parameters of the Depression over northeast BoB during 10-11 June, 2018

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
10.06.2018	0600	22.3/91.5	1.5	990	25	3	D
	1200	22.7/91.4	1.5	988	25	4	D
	1500	Crossed Bangladesh coast near latitude 23.1ºN/longitude 91.2ºE south of Feni					
	1800		-	990	20	3	D
11.06.2018	0000	Weakened into a well marked low pressure area over Bangladesh and neighbourhood					

2.5.3. Features observed throuth Satellite

The Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. The satellite imageries during life cycle of the system are presented in Fig. 2.5.3 (i-iv)

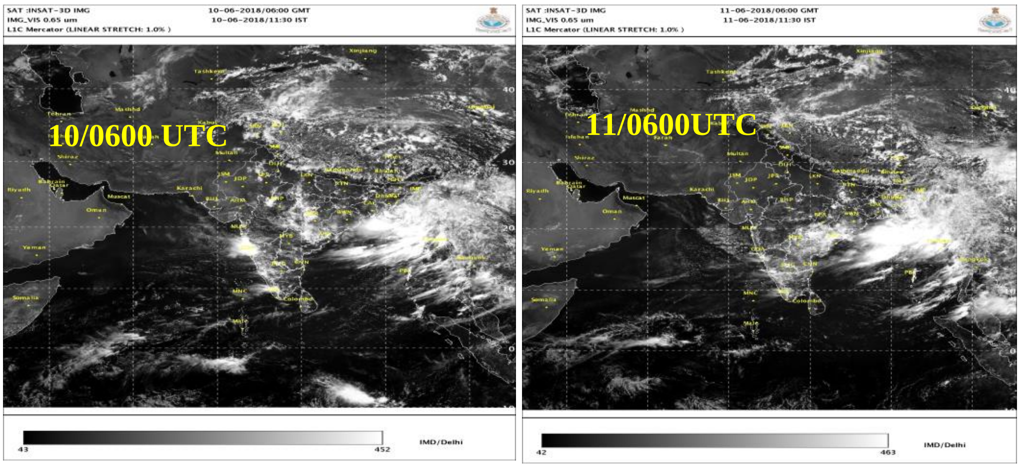


Fig. 2.5.3(i): INSAT-3D visible imageries at 0600 UTC of 11th June, 2018

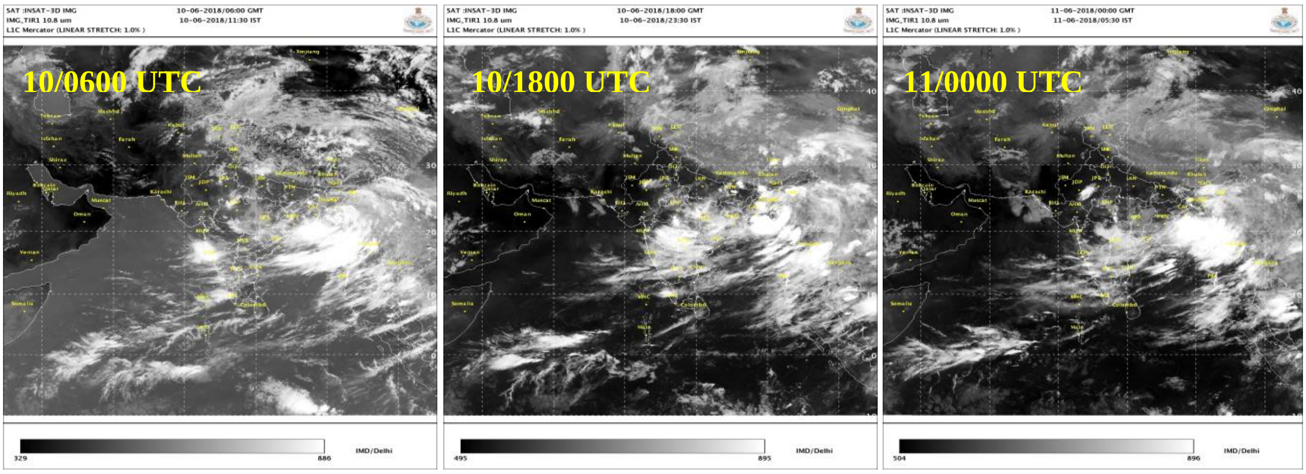


Fig. 2.5.3(ii): INSAT-3D IR imageries of Depression at 0600 and 1800 UTC of 10th and 0600 UTC of 11th June, 2018

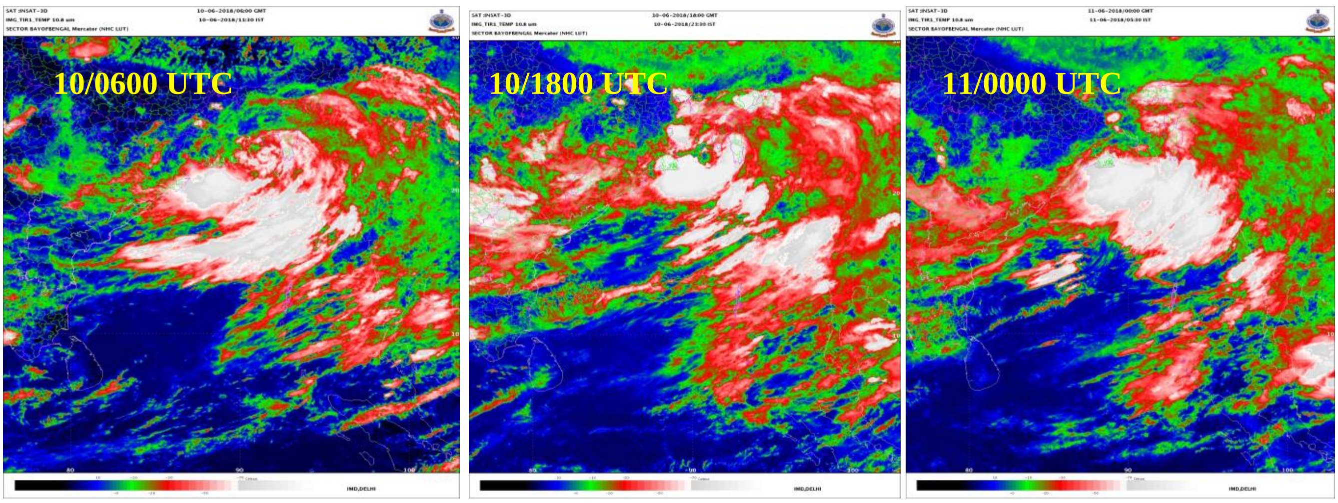


Fig. 2.5.3(iii): INSAT-3D enhanced coloured imageries at 0600 and 1800 UTC of 10th and 0600 UTC of 11th June, 2018

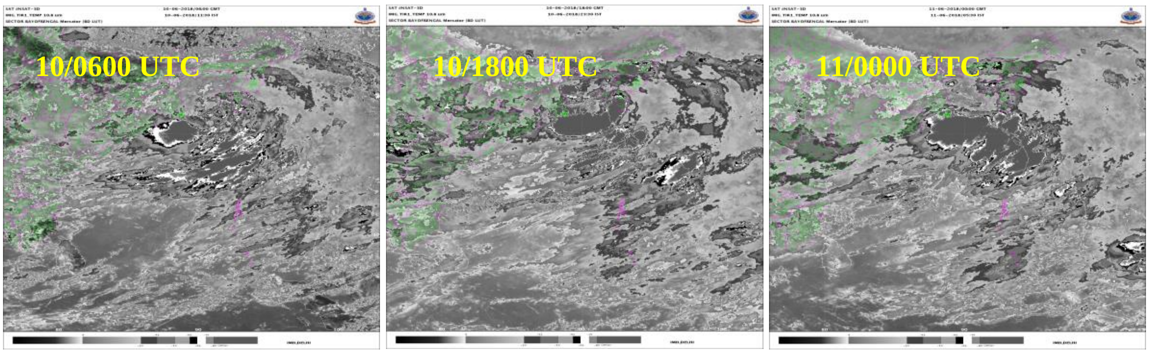


Fig. 2.5.3.(iv): Enhanced IR imageries at 0600 and 1800 UTC of 10th and 0600 UTC of 11th June, 2018

2.5.4. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.5.3. GFS (T1534) could not capture the genesis of system. However, it picked up the presence of associated cyclonic circulation upto middle tropospheric levels and anticyclone in middle and upper tropospheric levels over southeast Bangladesh and location of ridge near 22^0N.

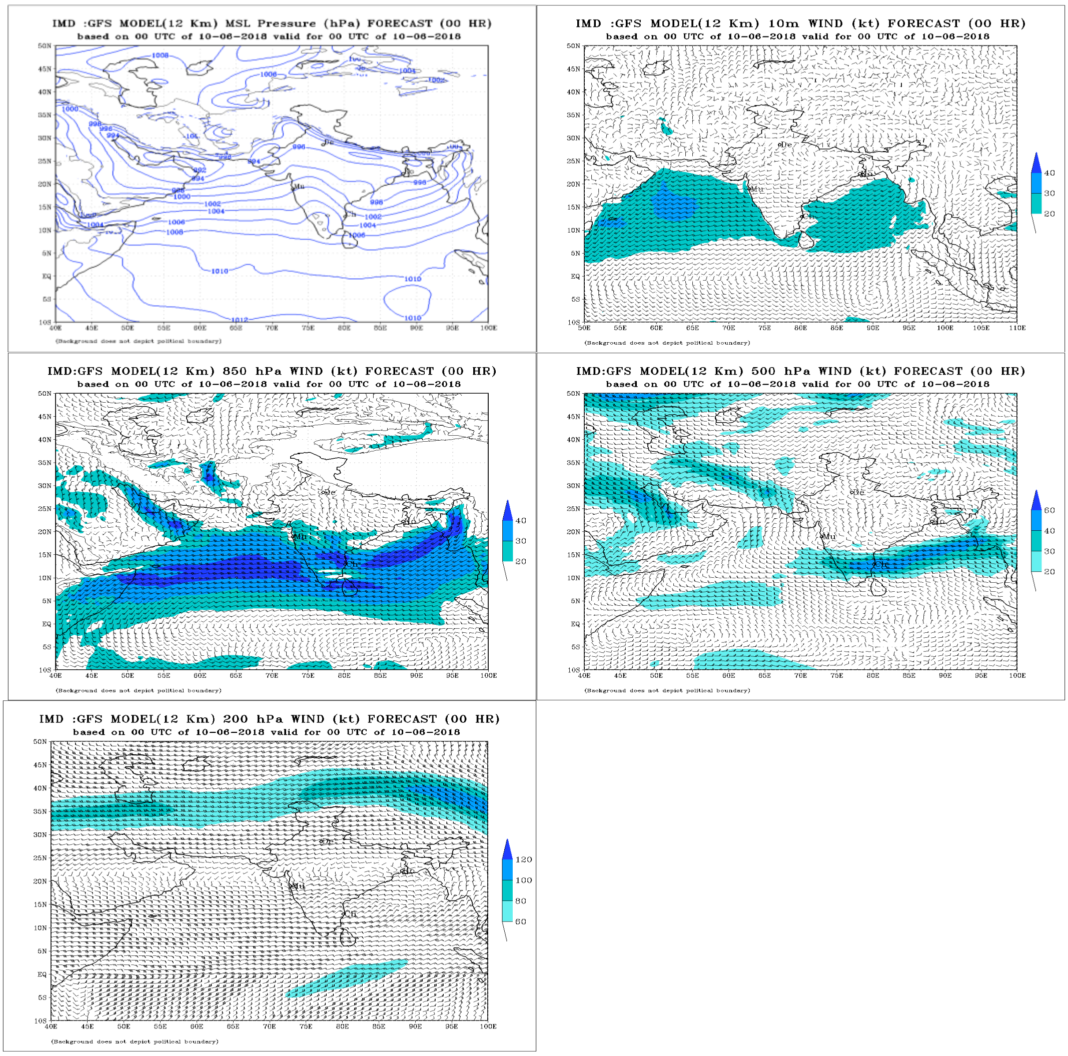


Fig. 2.5.4 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th June

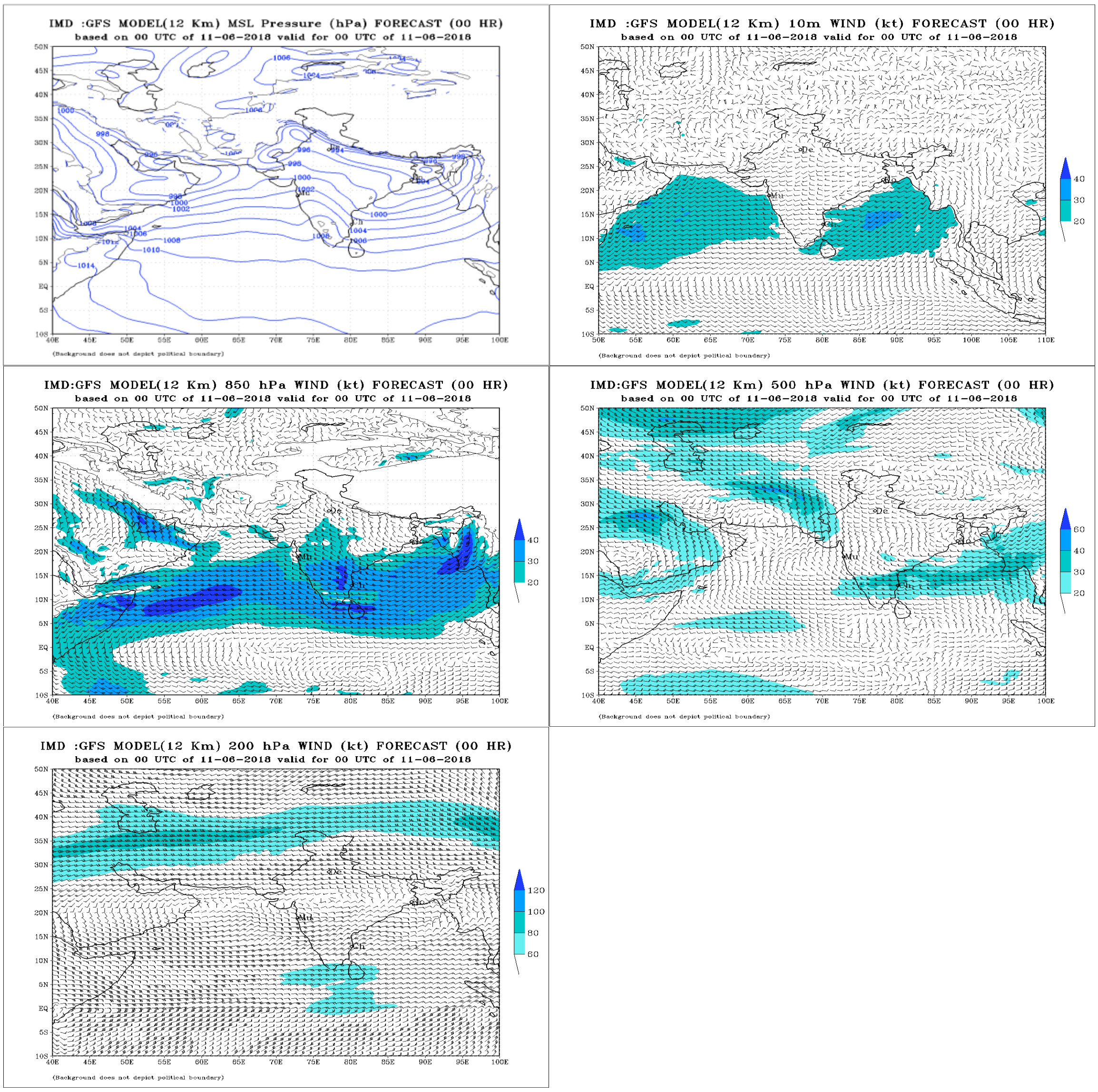


Fig. 2.5.4 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th June

2.5.5. Realized Weather:

2.5.5.1 Rainfall:

Realised weather:

Under the influence of this depression, heavy rainfall occurred at isolated places over Gangetic West Bengal, Odisha and Jharkhand on 9th, over Gangetic West Bengal & Odisha on 10th and over Assam & Meghalaya on 11th. On 12th, the system caused heavy to very rainfall at isolated places over Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura, Odisha and Bihar. On 13th, , it caused heavy to very rainfall at isolated places over Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura and Odisha. The daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during depression period is shown in Fig. 2.5.4.

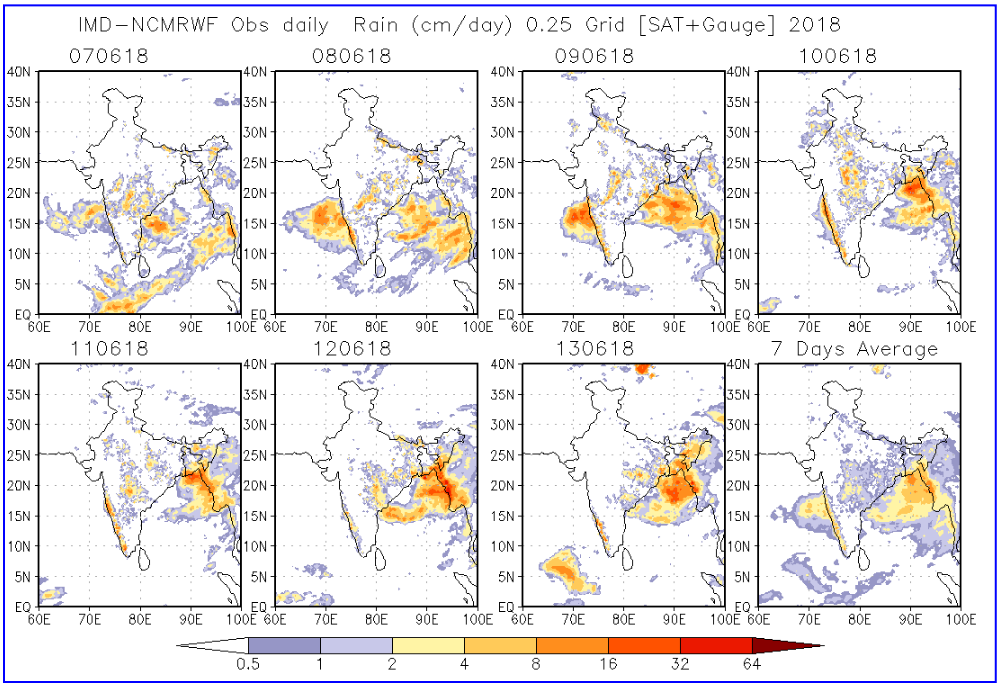


Fig. 2.5.5: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 10-11 June 2018.

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

9th June 2018

Gangetic West Bengal: Canning and Barrackpur (IAF)-7 each
Odisha: Nimpara-8 and Chandanpur & Sorada-7 each
Jharkhand: Ghatsila-7

10th June 2018

Gangetic West Bengal: Purihansa and Rampurhat (DRMS)-7 each
Odisha: Nawana-8

11th June 2018

Assam & Meghalaya: Beki Mathungari-7

12th June 2018

Assam & Meghalaya: Gharmura-11, Kampur, Matijuri & Cherrapunji (RKM) - 8 each and B P Ghat, Lakhipur & Dholai-7 each
Nagaland, Manipur, Mizoram & Tripura: Sabroom-27, Serchip (Hydro)-24, Aizwal-15 and Kailashahar Aero-14, Kolasib-11, Lengpui-10 and Dharmanagar/ Panisaga & Belonia-8 each
Odisha: Hemgiri, Burla & Hirakud-7 each,
Bihar: Bihpur-8

13th June 2018

Arunachal Pradesh: Bhalukpong-8, Itanagar-7
Assam & Meghalaya: Cherrapunji-21, Cherrapunji(RKM)-17, Kheronighat-15, Majbat-12, Silchar-11, Lumding-9 and A P Ghat & Jia Bharali N T Xing-7 each,
Nagaland, Manipur, Mizoram & Tripura: Sabroom-17, Bishalgarh-13, Sonamura-12, Serchip(Hydro)-10, Agartala Aero-9, Arundhutinagar-8,
Odisha: Soro-10, Mahanga (ARG)-7

2.6. Deep Depression over northwest Bay of Bengal (21-23 July, 2018)

2.6.1. Introduction

A low pressure area formed over northwest Bay of Bengal (BoB) and adjoining Gangetic West Bengal & Odisha in the morning (0300 UTC) of 19th July, 2018. It lay as a well marked low pressure area (WML) over northwest BoB and adjoining West Bengal & Odisha in the morning (0300 UTC) of 20th. It concentrated into a depression over northwest BoB in the morning (0300 UTC) of 21st and intensified into deep depression in the afternoon (0900 UTC) of 21st. Moving northwestwards, it crossed north Odisha - West Bengal coasts in the same evening (1100-1200 UTC) between Balasore and Digha. Moving further west-northwestwards, it weakened into depression in the evening (1200 UTC) of 21st and into a WML over northwest Jharkhand & neighbourhood in the morning (0300 UTC) of 23rd. The salient features of the system were as follows:

(i) It had a straight moving track.
(ii) It had a life period of 48 hours.
(iii) It had a track length of 590 km.
(iv) Under the influence of this system and its remnant low pressure area widespread and intense rainfall activity was observed over the northern and central parts of the country extending from Odisha, Gangetic West Bengal, Chattisgarh, Jharkhand, Madhya Pradesh, Uttar Pradesh, Uttarakhand, Himachal Pradesh, Rajasthan, Haryana, Chandigarh & Delhi. Extremely to exceptionally heavy rainfall occurred over Odisha on 20th & 21st leading to flood situations in some parts of the state.

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 and Myanmar. Its genesis, movement and associated adverse weather could be predicted well by IMD

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

2.6.2. Brief life history

Along the axis of monsoon trough, a low pressure area formed over northwest Bay of Bengal (BoB) and adjoining Gangetic West Bengal & Odisha at 0300 UTC of 19th July, 2018. Under favourable environmental conditions, It lay as a WML over northwest BoB and adjoining West Bengal & Odisha at 0300 UTC of 20th. On 20th, the Madden Julian Oscillation (MJO) index lay over phase 5 with amplitude greater than 1. MJO phase was favourable for enhancement of convective activity over BoB on 20th. The sea surface temperature (SST) was 28-30^{0}C over north BoB. The tropical cyclone heat potential was around 60-80 KJ/cm^2 over southern parts of north BoB. The low level relative vorticity was about 200x10^{-6}sec^{-1} over westcentral BoB and was oriented in northeast-southwest direction. It was extending upto 500 hpa level. The lower level convergence was about 30 x10^{-5}sec^{-1} to the southwest of system centre over westcentral BoB. The upper level divergence was about 40 x10^{-5} sec^{-1} over westcentral BoB. The vertical wind shear was low to moderate (10-15 knots) over northwest BoB off West Bengal & Odisha coasts. The upper tropospheric ridge ran along 28°N. All these conditions supported further intensification and west-northwestward movement of the system.

At 0300 UTC of 21st, the system concentrated into a depression and deep depression at 0900 UTC of 21st over northwest BoB. Considering the environmental conditions, the MJO index currently lay over phase 6 with amplitude greater than 1. The SST was 28-30^{0}C over north BoB. The low level relative vorticity increased and was about 150x10^{-6} sec^{-1} in the southwest sector of the system centre. The lower level convergence was about 20 x10^{-5}sec^{-1} to the southwest of system centre. The upper level divergence was about 20 x10^{-5} sec^{-1} to the southwest of the system centre. The vertical wind shear was moderate (10-20 knots) over northwest BoB between lower and middle tropospheric levels and high (> 20 knots) between lower and upper tropospheric levels. The steering flow suggested that the system would move west-northwestwards to northwestwards.

Moving northwestwards, the system crossed north Odisha-West Bengal coasts between Balasore and Digha in the same evening during 1100-1200 UTC. Though the environmental conditions and land interactions were not supporting intensification of system, the system maintained its intensity because of continuous moisture influx for next 36 hours and weakened into a WML at 0300 UTC of 23rd over northwest Jharkhand and neighbourhood. The observed track of deep depression over northwest BoB is presented in Fig.2.6.1.

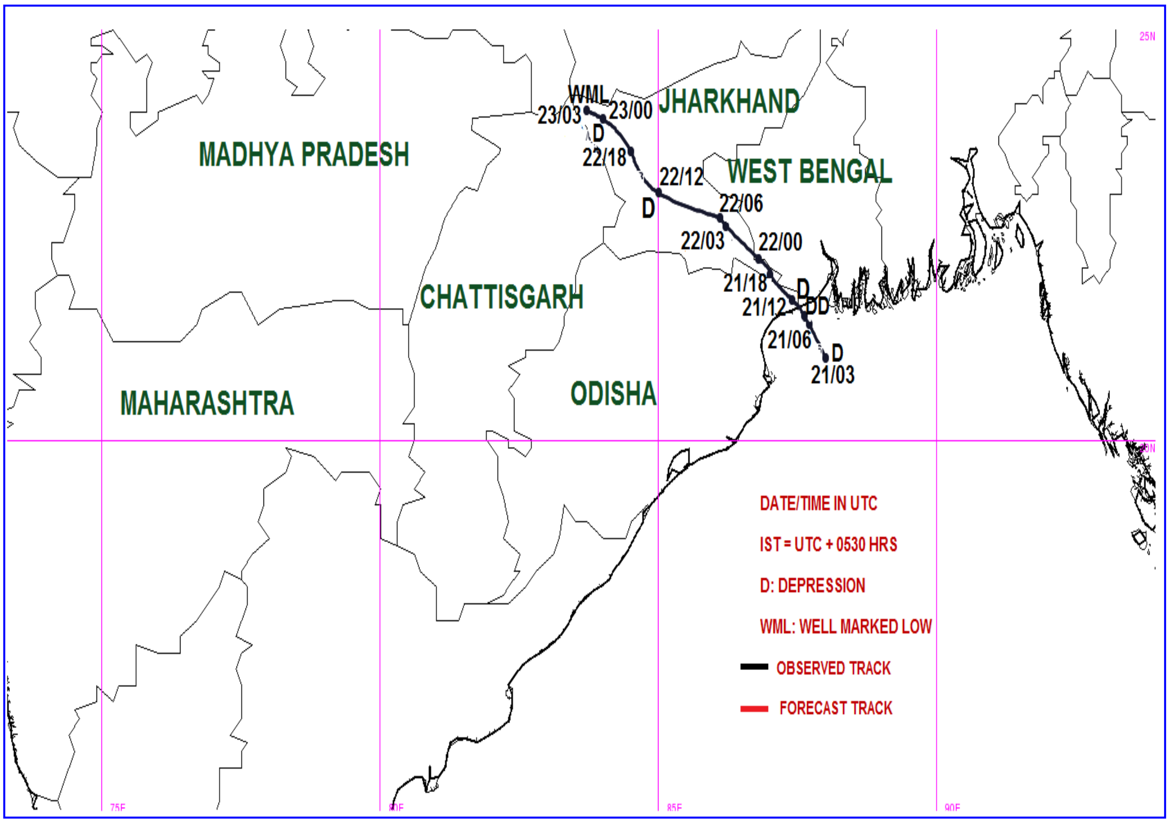


Fig.2.6.1. Observed track of Deep Depression over northwest Bay of Bengal (21-23 July, 2018)

The best track parameters of the system are presented in Table 1. The typical satellite imageries are presented in Fig. 2.6.2.

Table 2.6.1: Best track positions and other parameters of the Deep Depression over northwest BoB during 21-23 July, 2018

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
21.07.2018	0300	21.0/88.0	1.5	989	25	4	D
	0600	21.4/87.7	1.5	989	25	4	D
	0900	21.5/87.6	2.0	988	30	5	DD
	Crossed north Odisha-West Bengal coasts close to south of Digha during 1100-1200 UTC						
	1200	21.7/87.4	-	988	30	5	DD
	1800	22.0/87.0	-	990	25	3	D
22.07.2018	0000	22.2/86.8	-	992	25	3	D
	0300	22.6/86.2	-	992	25	3	D
	0600	22.7/86.1	-	992	25	3	D
	1200	23.0/85.0	-	992	25	3	D
	1800	23.5/84.5	-	993	20	3	D
23.07.2018	0000	23.9/84.0	-	993	20	3	D
	0300	Weakened into a Well Marked Low Pressure Area over northwest Jharkhand and neighbourhood at 0300 UTC					

2.6.3. Feature observed through Satellites:

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 and microwave & SCAT Sat imageries were also considered. Typical INSAT-3D IR, visible, enhanced colored and cloud top brightness temperature imageries are presented in Fig. 2.6.2.

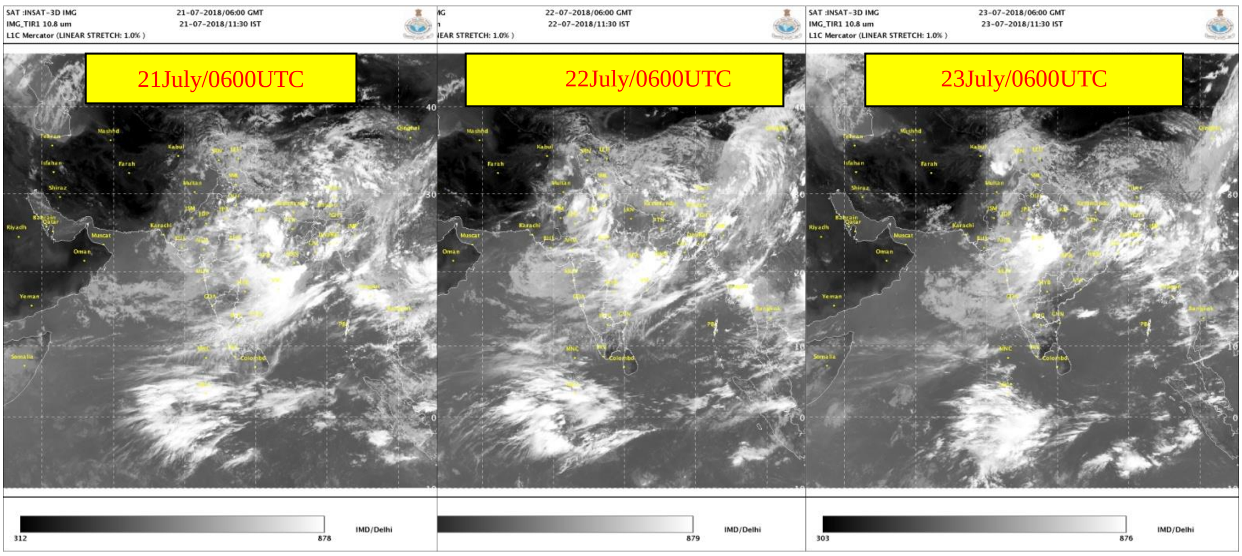


Fig. 2.6.2(i): INSAT-3D IR imageries based on 0600 UTC during 21-23 July, 2018

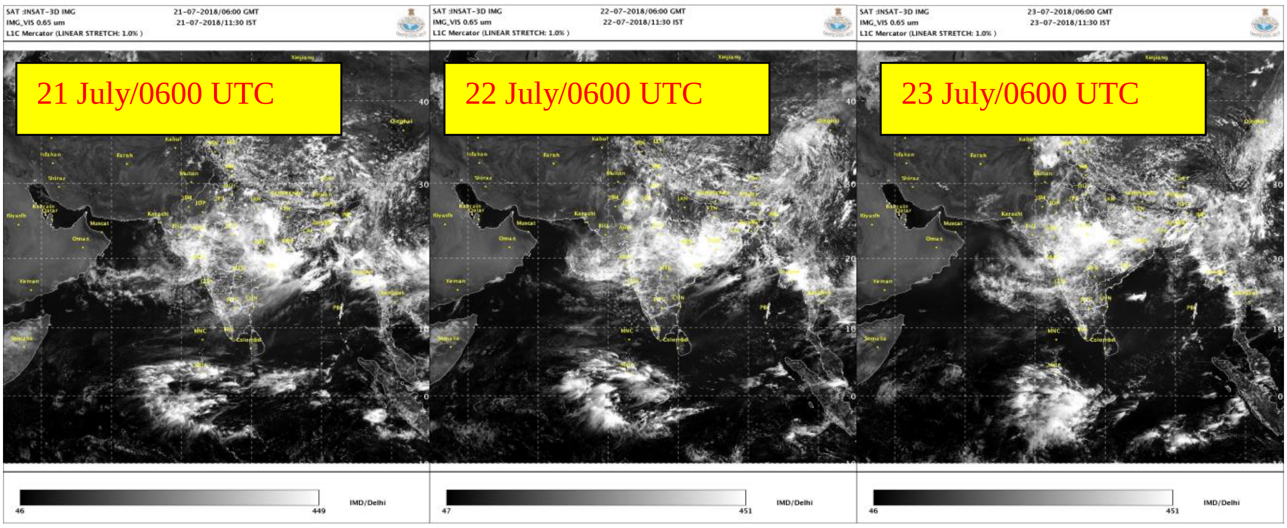


Fig. 2.6.2(ii): INSAT-3D Visible imageries based on 0600 UTC during 21-23 July, 2018

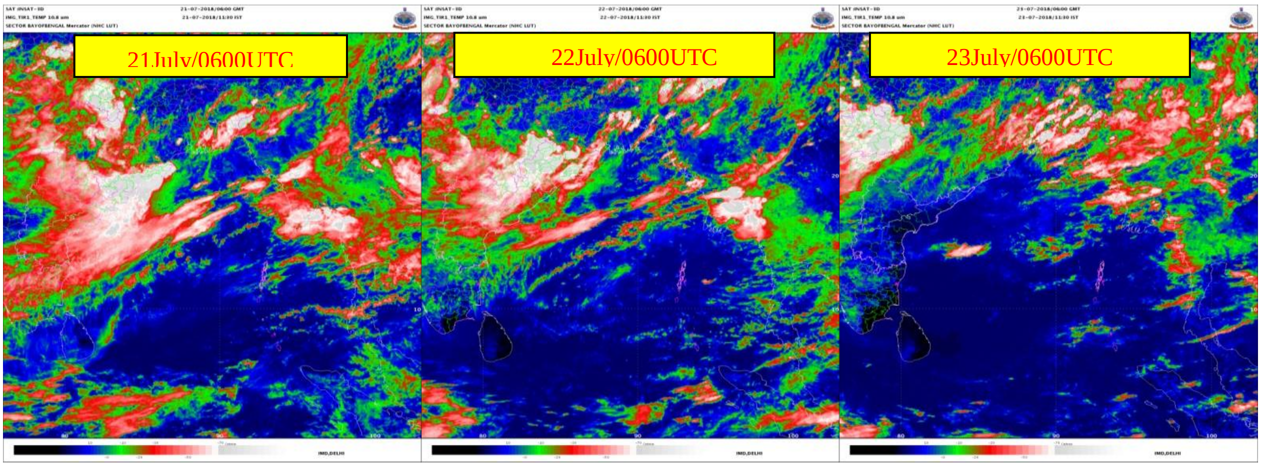


Fig. 2.6.2(iii): INSAT-3D enhanced coloured imageries based on 0600 UTC during 21-23 July, 2018

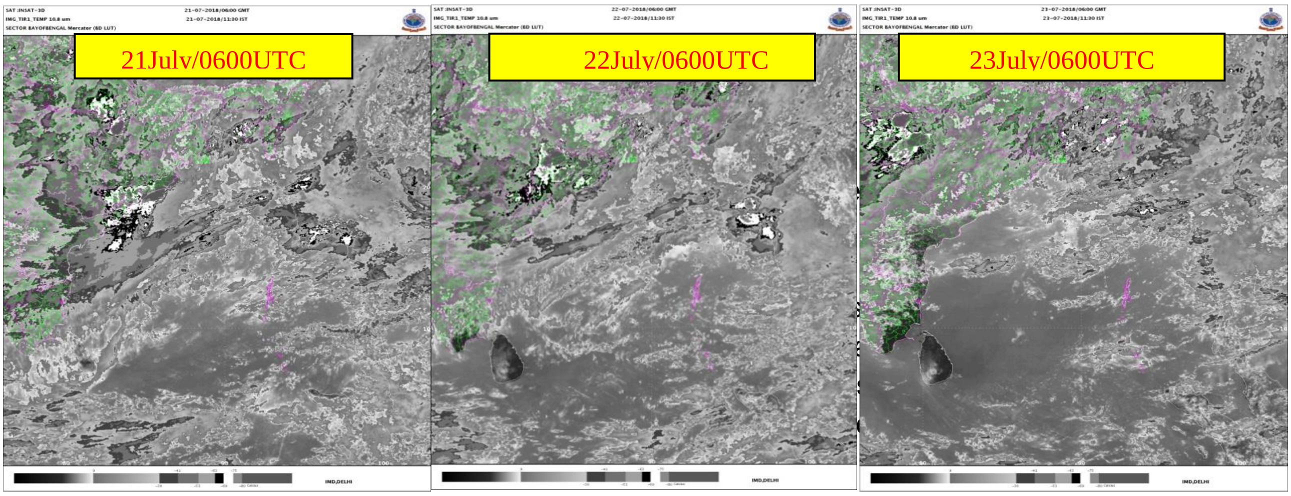


Fig. 2.6.2(iv): INSAT-3D BD imageries based on 0600 UTC during 21-23 July, 2018

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.2.6.4. The initial conditions of 0000 UTC of 21st July indicated the depression over northwest BoB & adjoining Gangetic West Bengal.

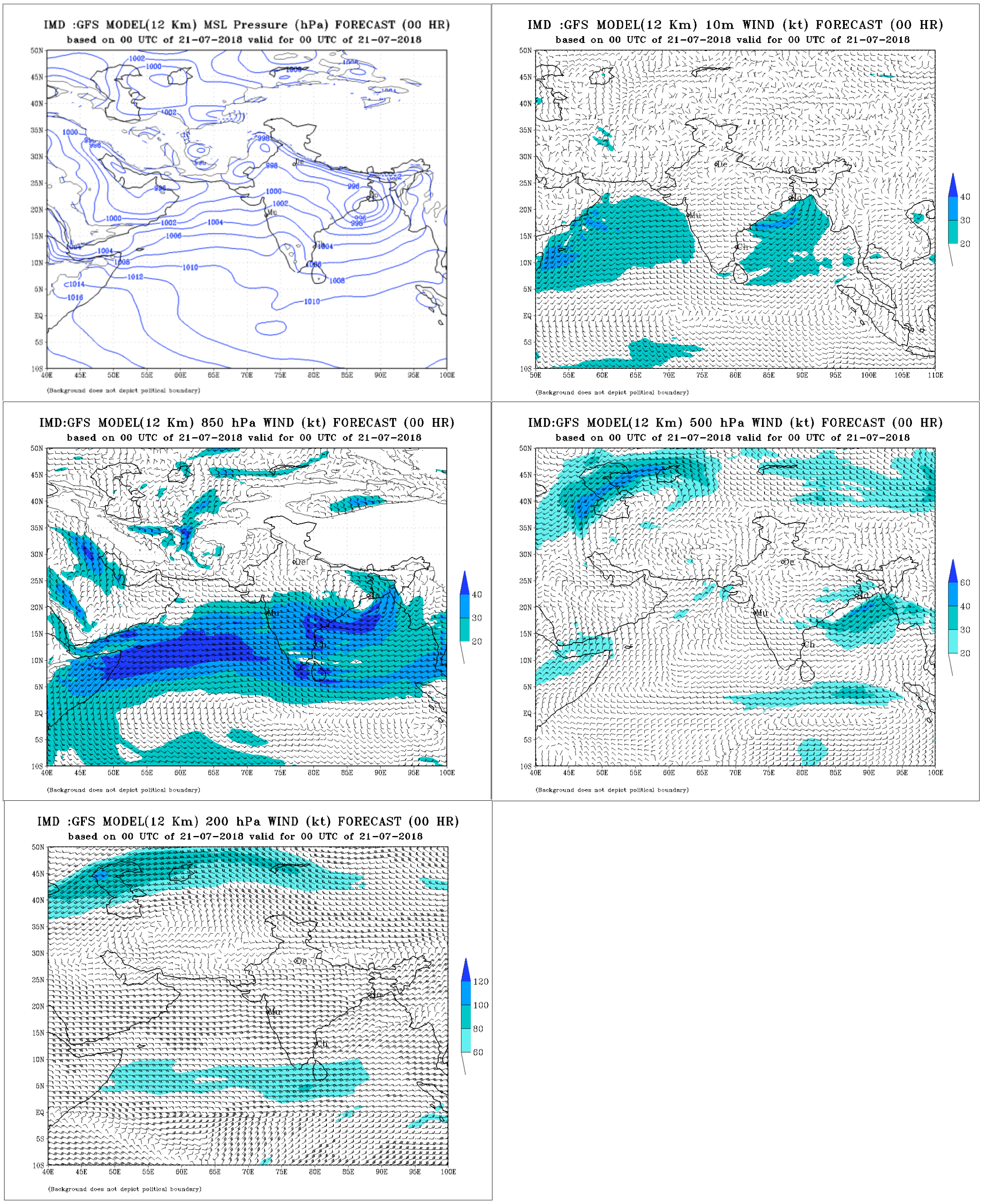


Fig. 2.6.3 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21st July

The initial conditions of 0000 UTC of 22nd July indicated the depression over Gangetic West Bengal and adjoining north Odisha.

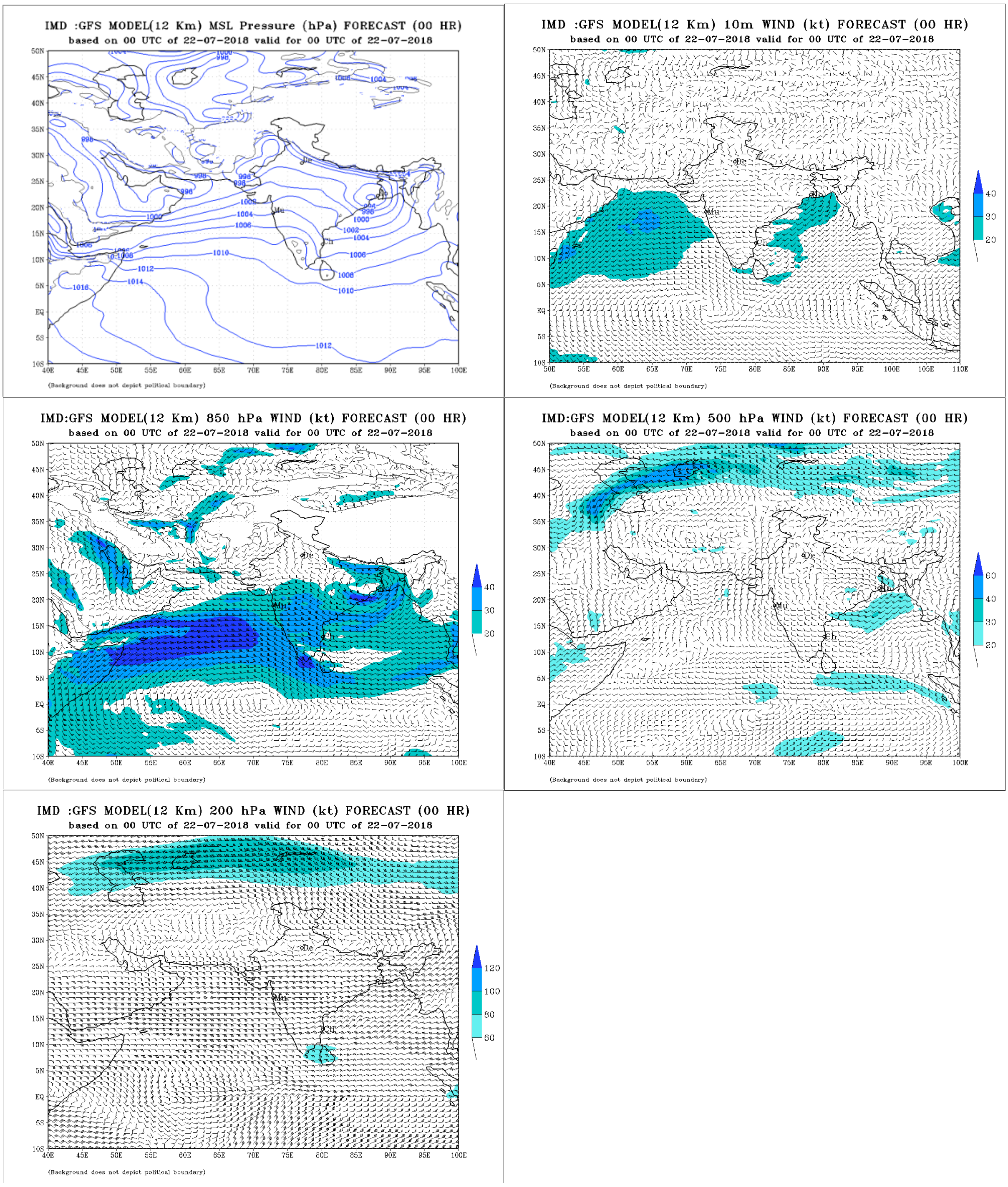


Fig. 2.6.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd July

The initial conditions based on 0000 UTC of 23rd indicated weakening of system into a WML over Jharkhand and adjoining areas.

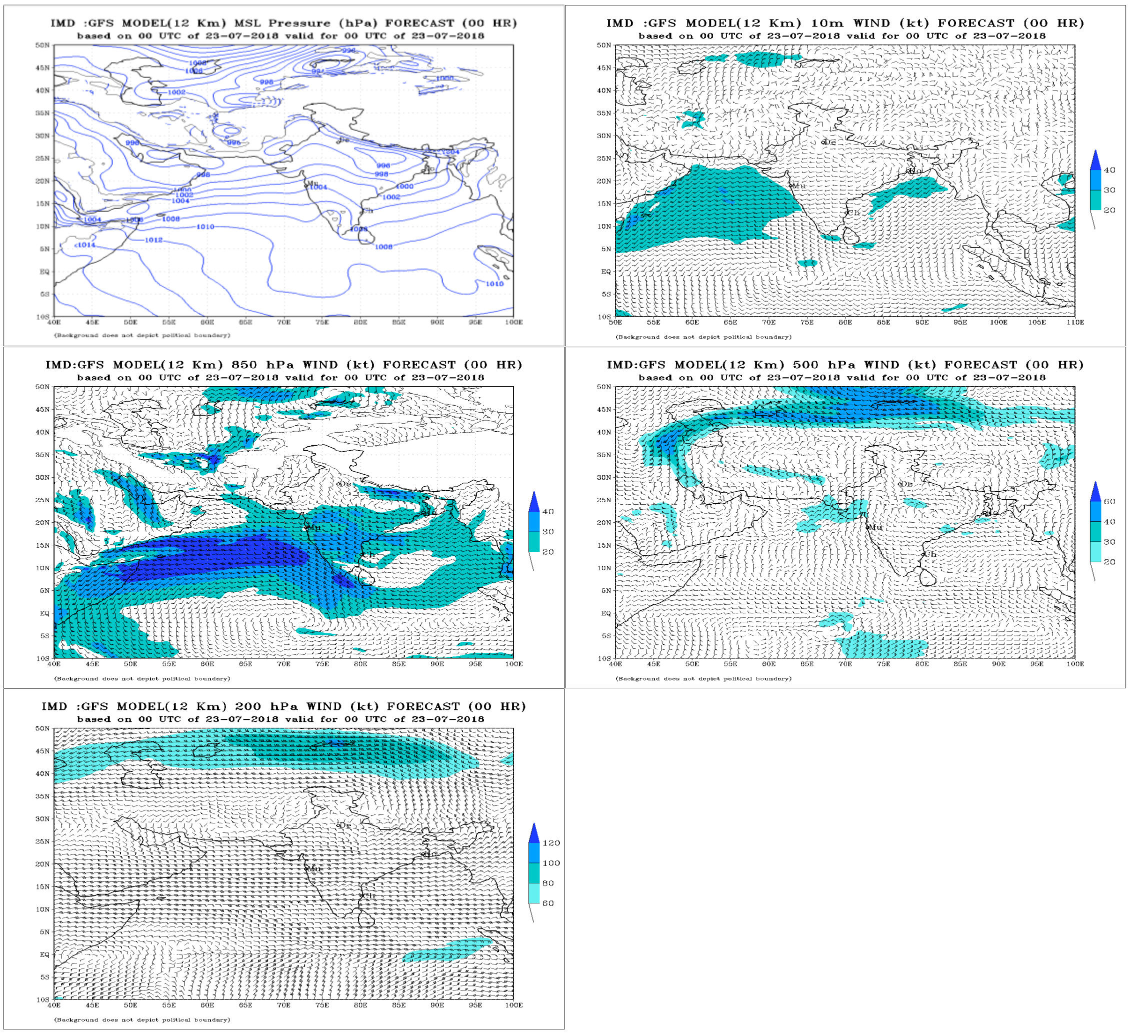


Fig. 2.6.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd July

Thus IMD GFS could capture the genesis, movement and weakening of the system well.

2.6.5. Realized Weather:

2.6.5.1 Rainfall:

Under the influence of this system, on 20th July, heavy to very heavy rainfall occurred at a few places with extremely heavy falls at isolated palces over Odisha, heavy to very heavy rainfall at a few places over Jharkhand & at isolated isolated places over north coastal Andhra Pradesh and heavy rainfall at isolated places over Telangana. On 21st, heavy to very heavy rainfall occurred at a few places with extremely heavy rainfall at isolated places over Odisha, heavy to very rainfall at isolated places over Chattisgarh and heavy rainfall at isolated places over Jharkhand, Gangetic West Bengal & west Madhya Pradesh. On 22nd heavy rainfall occurred at isolated places over Jharkhand, Chattisgarh, west Madhya Pradesh & east Rajasthan and at a few places over east Madhya Pradesh. On 23rd, heavy to very rainfall at isolated places occurred over west Madhya Pradesh and east Rajasthan, heavy rainfall at isolated places over east Madhya Pradesh and moderate rainfall at many places over Jharkhand. On 24th, heavy to very heavy rainfall occurred at isolated places over Bihar & east Rajasthan and heavy rainfall occurred at isolated places over Uttar Pradesh.

The daily rainfall distribution ending at 0300 UTC of each date during 17-23 July, 2018 based on merged gridded rainfall data of IMD/NCMRWF is shown in Fig. 2.6.4.

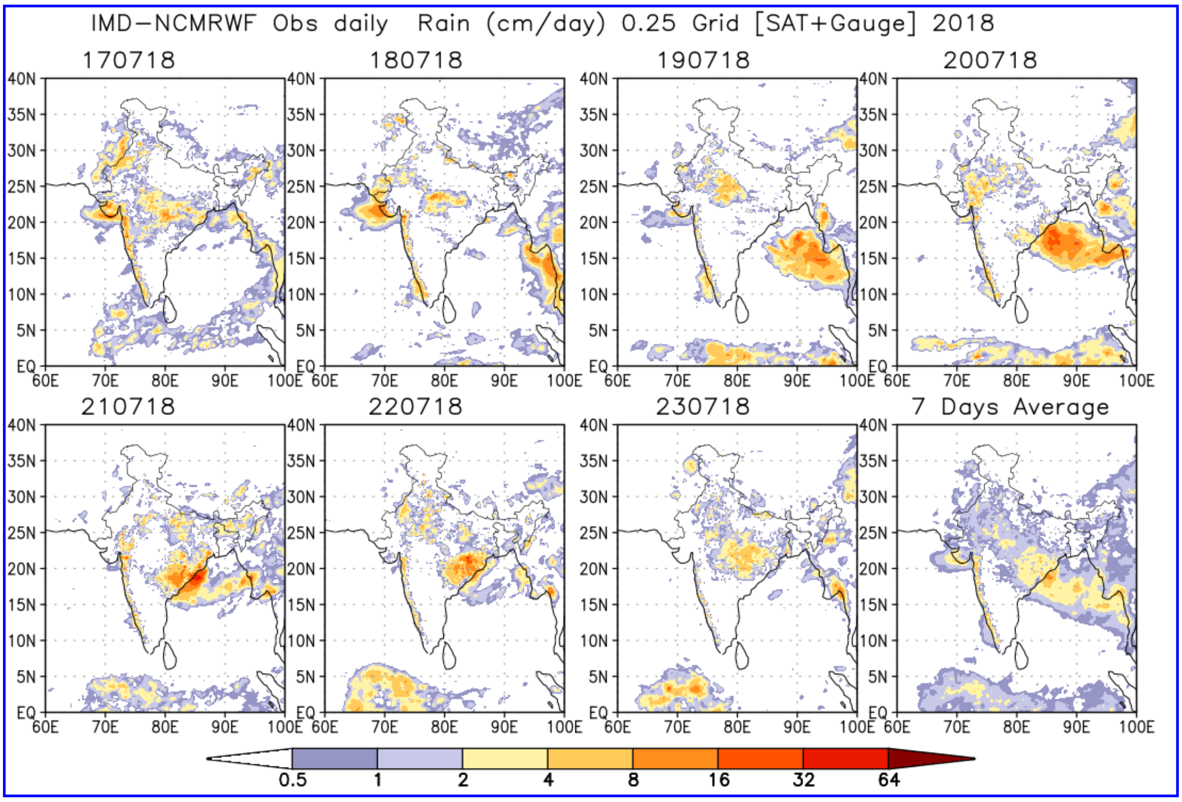


Fig. 2.6.4: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 17-23 July 2018

(Heavy rainfall distribution: Isolated places : upto 25%, A few places: 26-50%, Many places : 51-75%, Most places: 76-100% of total stations in the region;
Heavy rainfall: 64.5 – 115.5 mm, Very heavy rainfall: 115.6 – 204.4 mm, Extremely heavy rainfall: 204.5 mm or more).

The 24 hour cumulative rainfall (≥ 7 cm) ending at 0830 hours IST of date during 21st-25th July is presented below:

<u>21st July</u>

Odisha:

Brahmagiri -29, Puri-27, Junagarh-26, Tentulikhunti, Pipili & Kesinga -24 each, Kashipur-22, Narla, Cuttack & Jaipatna-21 each, Madanpur Rampur-20, Satyabadi, Bhubaneswar, Koraput & Similiguda -19 each, Mundali-17, Banki -16, Nuagada -15, Naraj & Jeypore -14 each, Bhawanipatna-13, Paralakhemundi, Nawarangpur & Salebhatta -12 each, Korei & Titlagarh-11 each, Balipatna, Tigiria, Krishnaprasad & Rajghat-10 each, Jajpur, Pottangi, R.Udaigiri, Akhuapada, Berhampur, Tangi, Gunupur, Kotagarh, Athgarh, Dhamnagar, Rayagada, Kantapada & Banpur-9 each, Lanjigarh, Malkangiri, Bolagarh, Paradeep, Gopalpur, Bonth, Astaranga, Kaptipada & Chandikhol-8 each, Dhenkanal, Danagadi, Dharmagarh, Kashinagar, Gop, Chhatrapur, Tarva, Kakatpur, Nayagarh, Kujanga, Kosagumda & Jaleswar-7 each

Coastal Andhra Pradesh:

Palasa-15, Sompeta & Mandasa-12 each, Tekkali & Pathapatnam-11 each, Ichchapuram-10, Araku Valley-9, Chintapalle-8 and Palakonda, Paderu & Kalingapatnam-7 each

22nd July

Chhattisgarh: Sarangarh -12, Saraipali -7.
Gangetic West Bengal: Canning - 7
Odisha: Burla – 62, Sambalpur – 57, Birmaharajpur – 43, Hirakud – 40, Atabira -35, Barh-31, Rairakhol - 30, Ullunda - 26, Jujumura – 22, Binika, Khairamal & Athmalik- 21 each, Rajkishorenagar, Barpalli , Jagannath Prasad & Batli – 19 each, Tikabali, Satyabadi & Salebhatta – 17 each, Odagaon , Phiringia , Brahmagiri AWS & Dunguripalli – 16 each, Sonepur & Banki – 15 each, Kuchinda – 14, Ambabhona & Daspalla – 13 each, Akhuapada, Puri, Kendrapara, G Udayagiri, Agalpur , Krishnaprasad, Altuma, Jajpur & Tikarpara -12 each, Bijepur, Nawana, Laikera, Korei , Naktideul, Jamankira, Kirmira , Telkoi, Belaguntha , Bhanjnagar, Derabis , Marsaghai , Kolabira & Kamakhyanagar - 11 each, Sohela, Kotagarh, Parjang , K Nuagaon , Nayagarh & Madanpur Rampur – 10 each, Banarpal , Hindol, Keonjharh, Binjharpur , Chandbali, Batagaon, Reamal, Madhabarida, Talcher, Gurundia , Gaisilet , Banpur, Thakurmunda, Tarva , Jharsuguda, Kaptipada , Pallahara, Kashipur, Lahunipara, Gania , Dhenkanal, Danagadi , Soro, Bamra , Rajkanika, Barmul, Junagarh, Bari , Chandanpur & Jenapur – 8 each and Astaranga , Phulbani, Deogaon, Baliguda, Tangi, Chandikhol , Rengali, Chendipada, Narsinghpur, Mohana, Jhumpura, Raikia , Purushottampur, Bolagarh , Jaipatna & Sorada – 7 each
Jharkhand: Chaibasa – 7.

23rd July

Odisha:
Kuchinda & Gaisilet - 9 each, Paikmal – 8, Jharbandh, Joshipur & Hirakud – 7 each,
Gangetic West Bengal:
Diamond Harbour -17 each, Alipore – 8
Jharkhand:
Rajmahal & Chakradharpur – 10 each, Raidih & Jamshedpur -7 each,
Chattisgarh:
Bemetara-10, Kawardha & Saraipali -9 each, Simga -8, Ambagarh Chowki & Jashpurnagar – 7 each
East Madhya Pradesh:
Bichhia – 11, Singrauli, Katni & Mandla – 9 each, Patan, Sagar & Kotma – 7 each
West Madhya Pradesh:
Ratlam – 11, Ashok Nagar – 9, Khachrod – 8

24 July

Bihar: Taibpur & Thakurganj-14 each and Kishanganj-7
East Rajasthan: Sawaimadhopur Tesil -12, Sawai Madhopur-10, Kishanganj, Manohar Thana & Shahabad-9 each, Anta-8, Dug and Kota-Aero, Chabra, Baran, Asnawar, Atru & Bakani Sr-7 each
West Madhya Pradesh: Nalkheda-13, Kolaras-11, Sabalgarh-10, Pachmarhi-9, Shivpuri, Gandhwani, Biaora & Kurwai-8 each and Dewas & Sarangpur-7 each
East Madhya Pradesh: Rehli & Deori-7 each

25 July

Bihar: Rajauli-17, Jhanjharpur-14, Palmerganj-11, Hisua-10, Madhwapur-8 and Nawada & Bhabhua-7 Each
East Uttar Pradesh: Gyanpur-10, Pratapgarh-9
West Uttar Pradesh: Meerut-9 and Budhana, Muzaffarnagar & Atrauli-7 each,
East Rajasthan: Neemkathana-19, Shahabad & Srimadhopur-14, Sanganer Tehsil-10, Jaipur Aero-9, Nayanagar/Beawar-8

2.7. Depression over northwest Bay of Bengal and neighbourhood (07-08 August, 2018)

2.7.1. Introduction

A low pressure area formed over northwest Bay of Bengal (BoB) and neighbourhood in the morning (0300 UTC) of 6^{th} July, 2018. It lay as a well marked low pressure area (WML) over northwest BoB and adjoining West Bengal & Odisha coasts in the early morning (0000 UTC) of 7^{th}. It concentrated into a depression over northwest BoB in the same afternoon (0900 UTC) of 7th. Moving west-northwestwards it crossed north Odisha-West Bengal coasts close to Balasore during same night (1430 to 1630UTC). Moving further west-northwestwards, it weakened into a WML over north Chattisgarh and neighbourhood in the morning (0300 UTC) of 8th August, 2018.

The salient features of the system were as follows:

(i) It had a straight moving track.
(ii) It had a life period of 18 hours.
(iii) It had a track length of 372 km.
(iv) Under the influence of depression, widespread rainfall activity with isolated heavy to extremely heavy rainfall was observed over eastcentral India including Gangetic West Bengal, Odisha, Chattisgarh, Madhya Pradesh and east Rajasthan during 6-10th August.

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. Its genesis, movement and associated adverse weather could be predicted well by IMD

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

2.7.2. Brief life history

Along the axis of monsoon trough, a low pressure area formed over northwest Bay of Bengal (BoB) and neighbourhood at 0300 UTC of 6^{th} August, 2018. Under favourable environmental conditions, it lay as a WML over northwest BoB and adjoining West Bengal & Odisha coasts at 0000 UTC of 7^{th}.

On 7^{th}, the Madden Julian Oscillation (MJO) index lay over phase 6 with amplitude greater than 1. MJO phase was not supporting convective activity over BoB on 7^{th}. The sea surface temperature (SST) was 29-30^{0}C over northwest BoB and adjoining Odisha coast. The tropical cyclone heat potential was around 40-60 KJ/cm^2 over major parts of central BoB and off Odisha coast. It was becoming less than 40 KJ/cm^2 over north BoB above 20^{0}N. The low level relative vorticity was about $100x10^{-6}sec^{-1}$ over northwest BoB and adjoining Odisha & West Bengal coasts. BoB and was oriented in northeast-southwest direction. It was extending upto 500 hpa level. The lower level convergence and upper level divergence were about 20 $x10^{-5}sec^{-1}$ over northwest BoB & adjoining westcentral BoB to the southwest of system centre. The upper level divergence was about 40 $x10^{-5}$ sec^{-1} over westcentral BoB. The vertical wind shear was low to moderate (10-15 knots) over northwest BoB off adjoining Odisha & West Bengal coasts. All these conditions supported further intensification and west-northwestward movement of the system.

At 0900 UTC of 7^{th}, similar environmental conditions prevailed. The divergence and convergence field further organized and the WML concentrated into a depression over northwest BoB and neighbourhood. No further intensification took place due to it‟s proximity with land surface. Under the influence of the system moved west-northwestwards and crossed north Odisha-West Bengal coasts close to Balasore during 1430-1630 UTC of same night. Moving west-northwestwards, the system gradually weakened into a WML over north Chattisgarh and neighbourhood at 0300 UTC of 8th.

The observed track of depression over northwest BoB is presented in Fig.2.7.1.

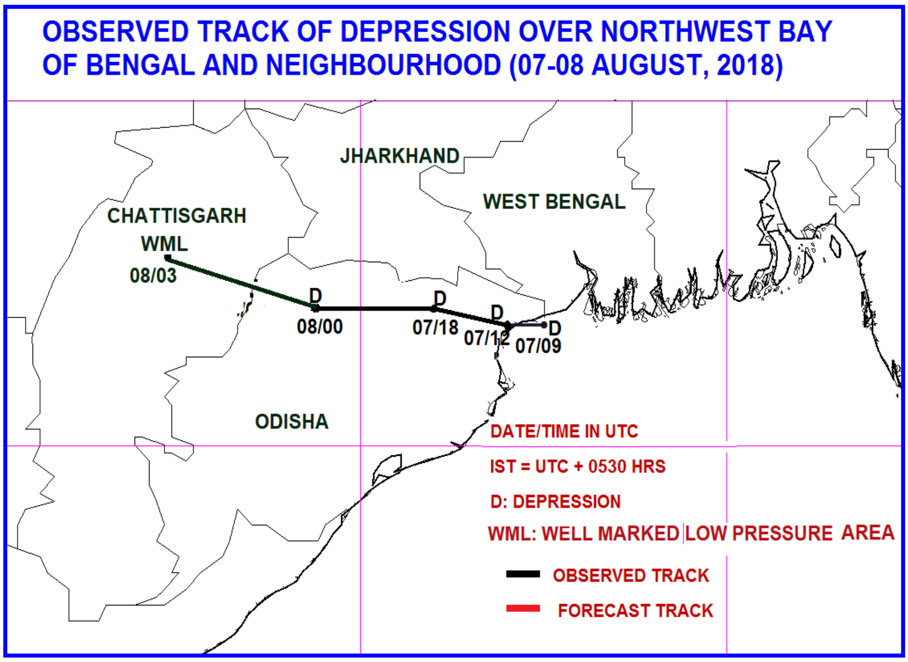


Fig.2.7.1. Observed track of Depression over northwest Bay of Bengal and neighbourhood (07-08 August, 2018)

The best track parameters of the system are presented in Table 2.7.1. The typical satellite imageries are presented in Fig. 2.7.2.

Table 2.7.1: Best track positions and other parameters of the Depression over northewest BoB during 07-08 August, 2018

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
07/08/2018	0900	21.5	87.5	1.5	992	25	4	**D**
	1200	21.5	87.0	1.5	994	25	3	D
	Crossed north Odisha-West Bengal coasts close to Balasore during 1430-1630 UTC							
	1800	21.6	86.0	-	995	25	3	D
08/08/2018	0000	21.7	84.5	-	996	20	3	D
	Weakened into a well-marked low pressure area over north Chattisgarh & neighborhood at 0300 UTC							

2.7.3. Feature observed through Satellites and Radar:

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 and microwave & SCAT Sat imageries were also considered. Typical INSAT-3D IR, visible, enhanced colored and cloud top brightness temperature imageries are presented in Fig. 2.7.2.

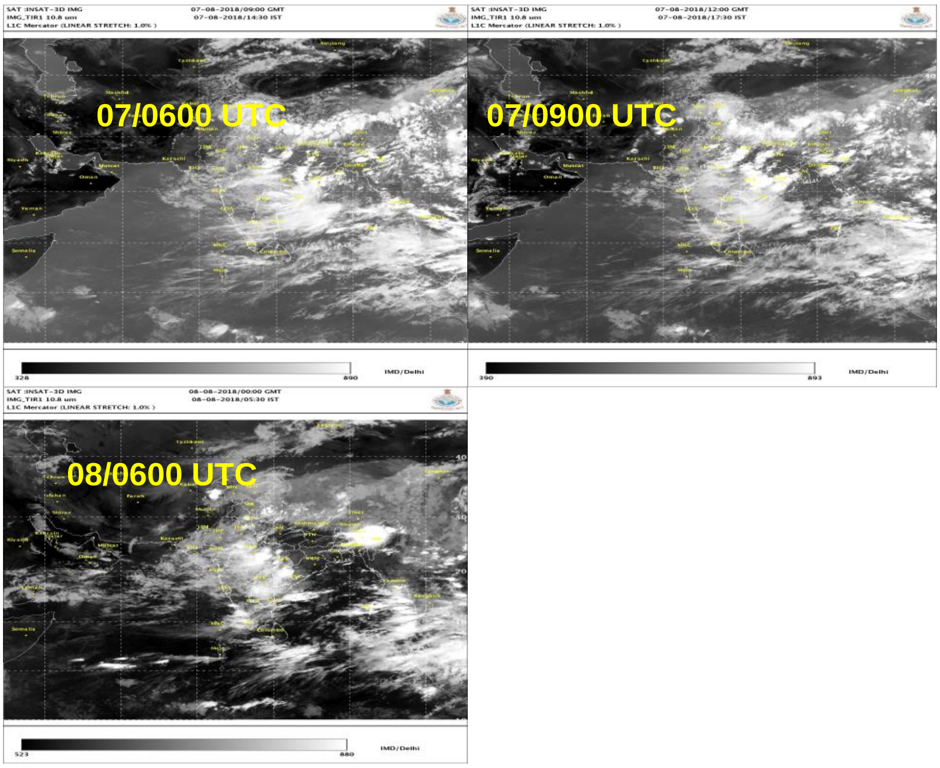


Fig. 2.7.2(i): INSAT-3D IR imageries based during 07-08 August, 2018

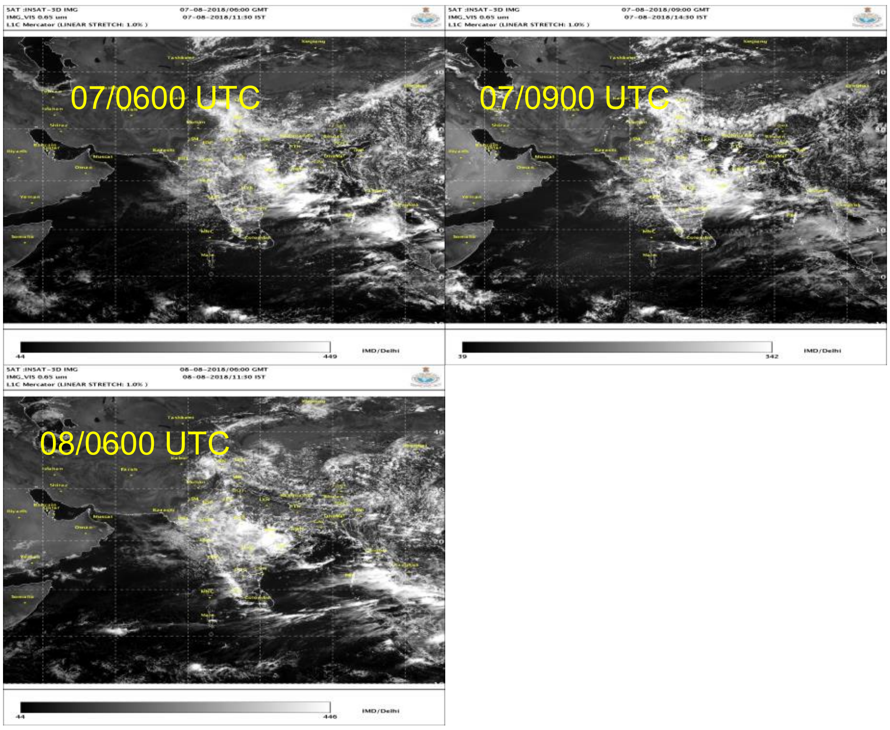


Fig. 2.7.2(ii): INSAT-3D Visible imageries during 06-08 August, 2018

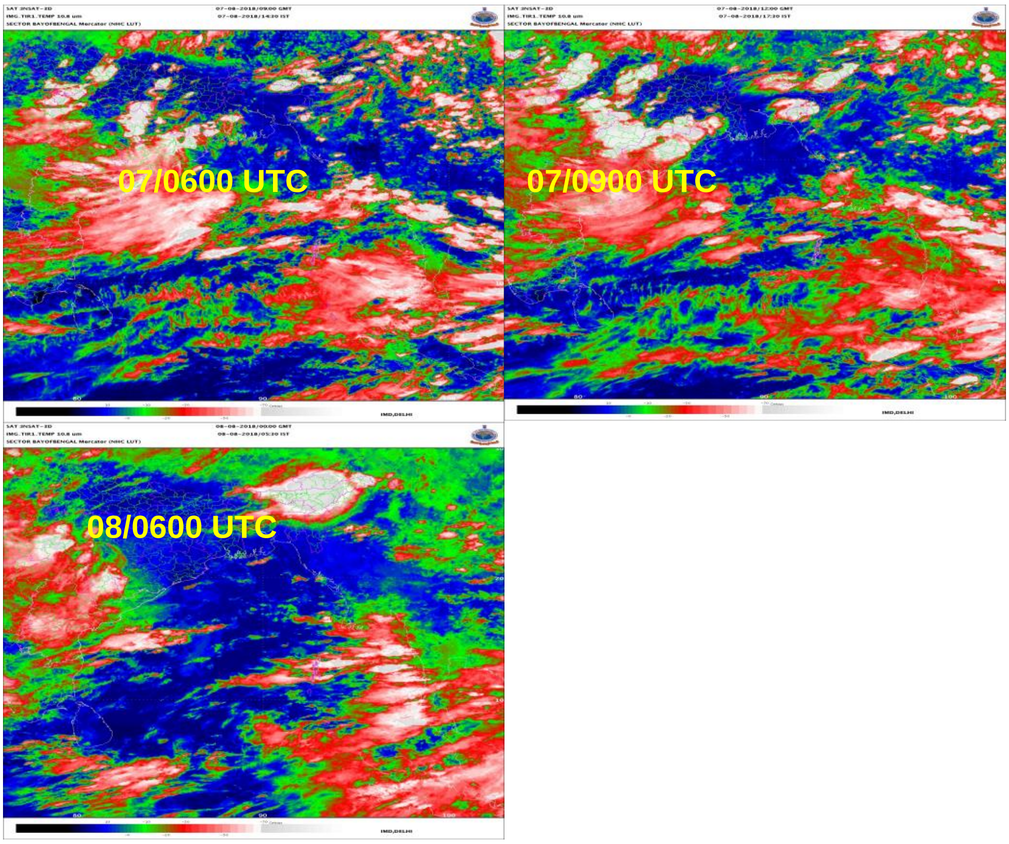


Fig. 2.7.2(iii): INSAT-3D enhanced coloured imageries during 07-08 August, 2018

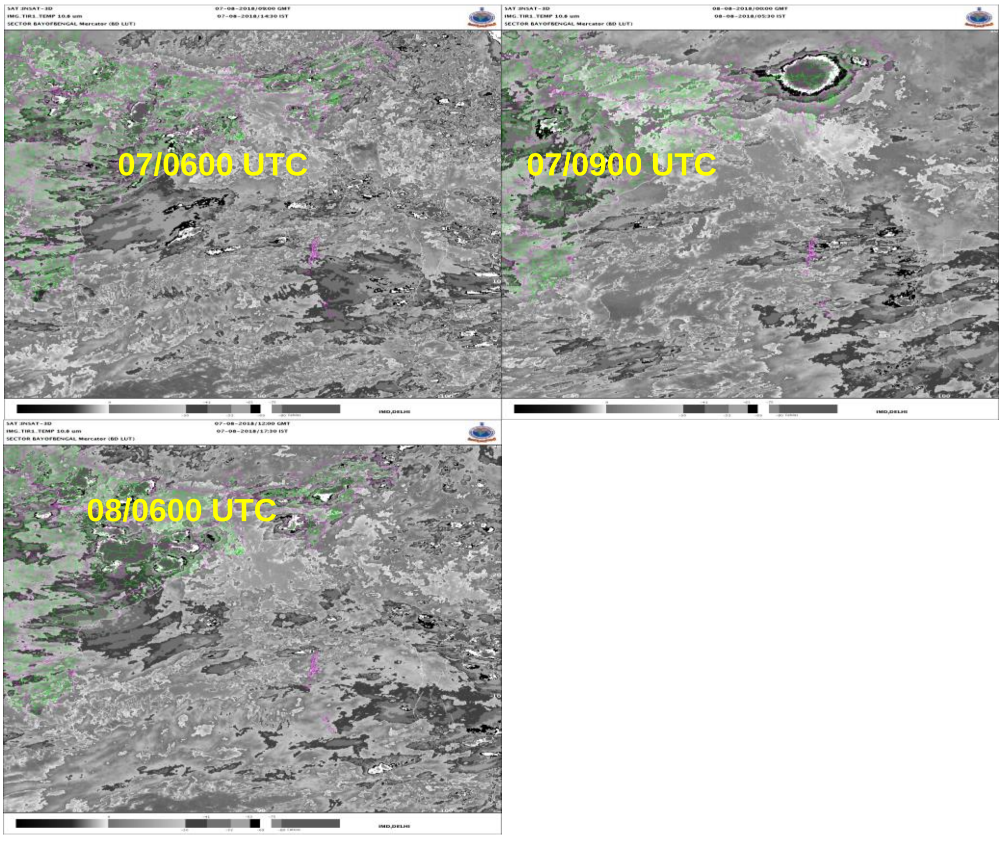


Fig. 2.7.2(iv): INSAT-3D enhanced colored imageries during 07-08 August, 2018

2.7.4. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig.2.7.4. At 0000 UTC of 6th August, it indicated a low pressure area over northwest BoB off West Bengal and Bangladesh coasts. The circulation was seen upto 500 hPa level tilting southeastwards with height.

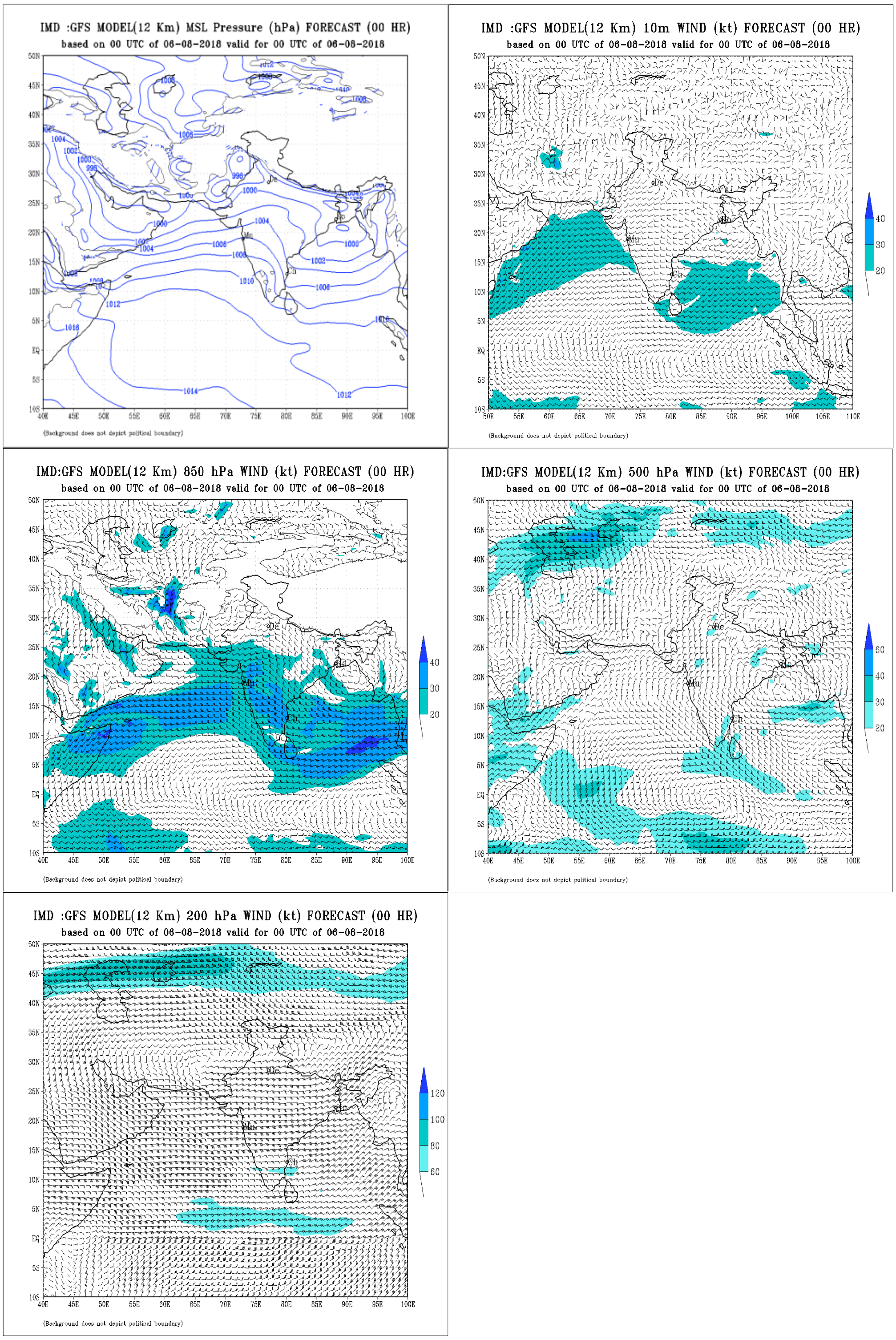


Fig. 2.7.4 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 6th August

The initial conditions of 0000 UTC of 7th August indicated low pressure area over Gangetic West Bengal and adjoining north Odisha coasts. The cyclonic circulation was extending upto 500 hPa level tilting southwestwards with height.

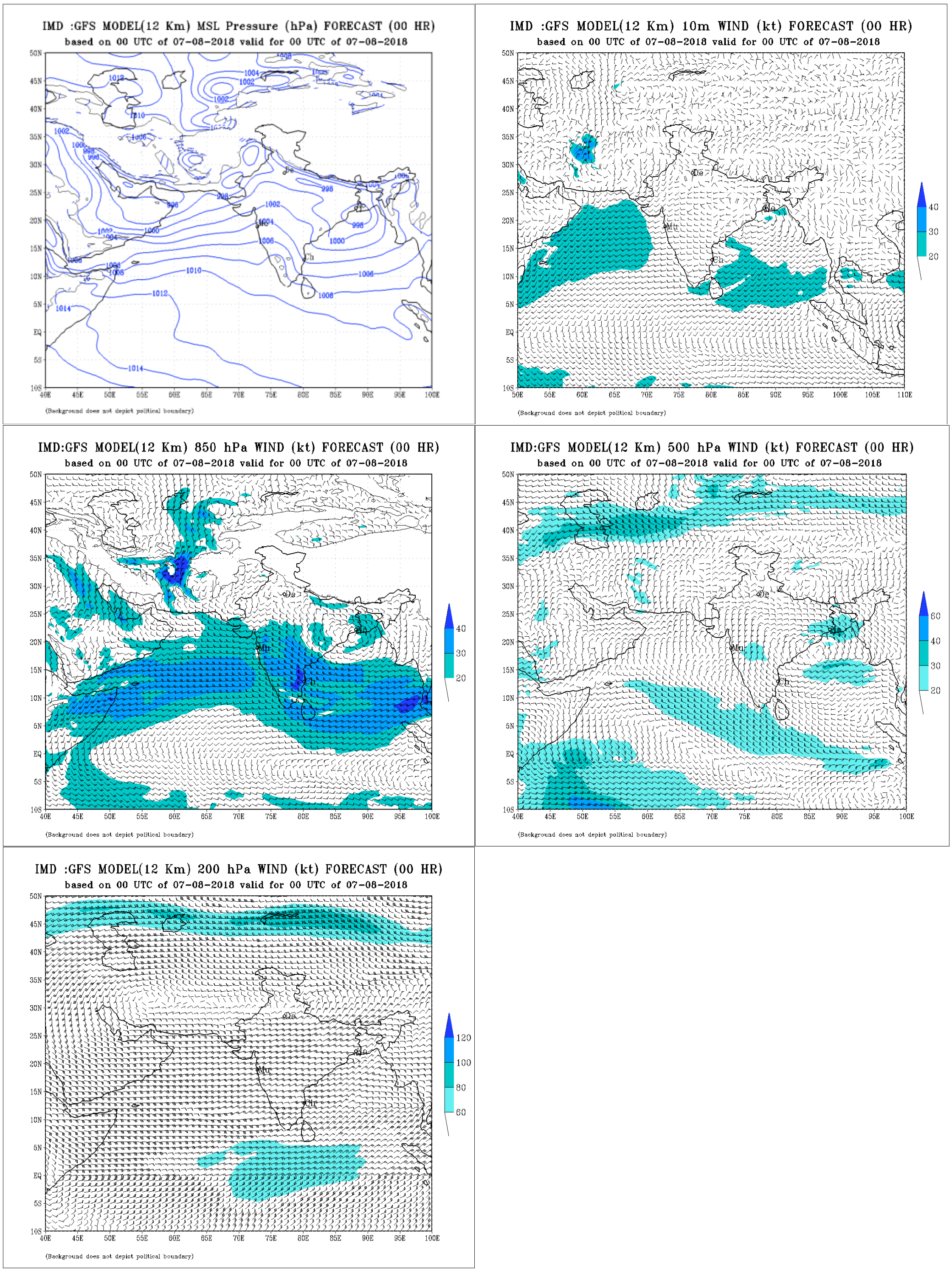


Fig. 2.7.4 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd July

The initial conditions based on 0000 UTC of 8th indicated an extended low over south Odisha and adjoining Chattisgarh. The circulation was seen extending upto 500 hPa level tilting southwestwards with height.

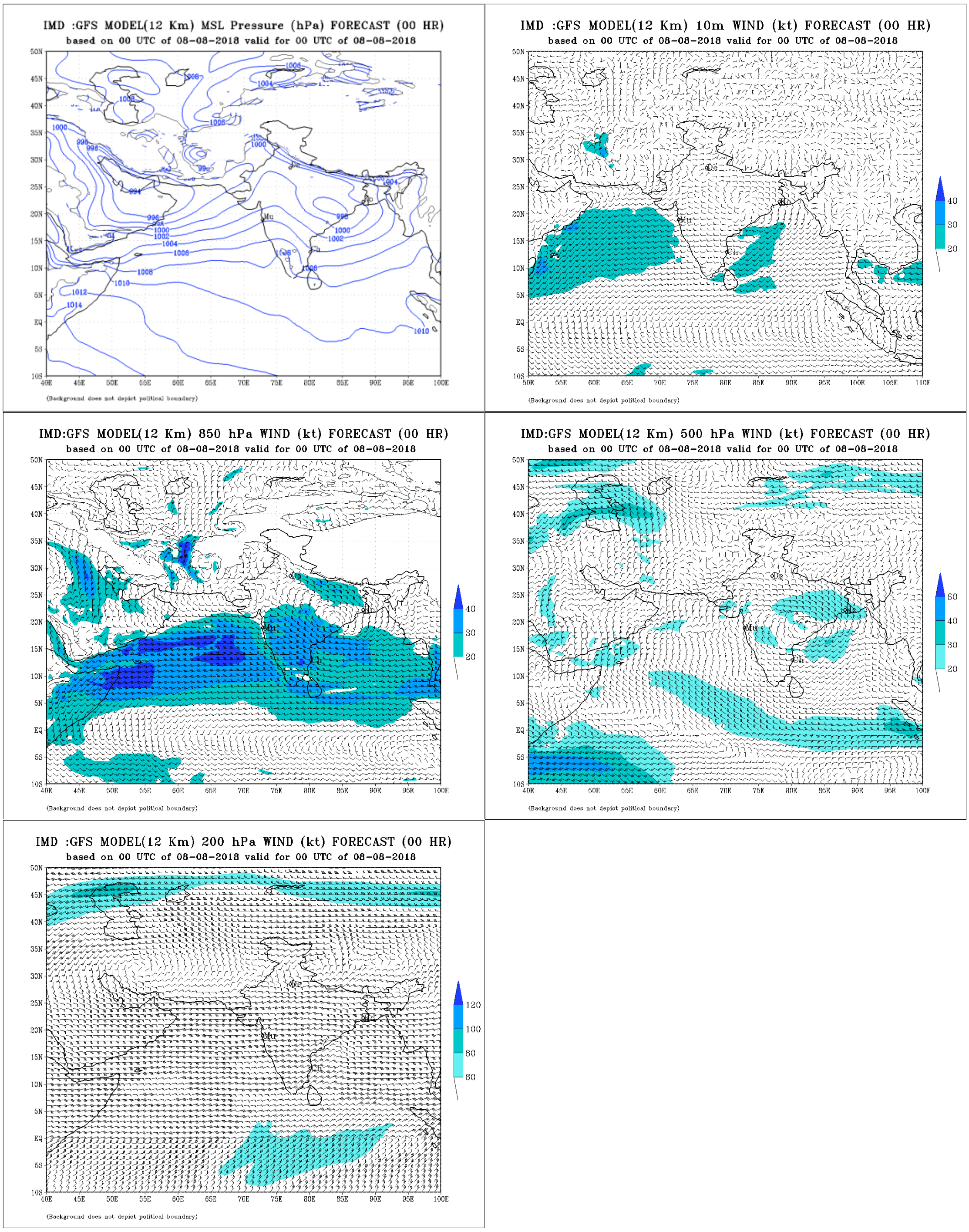


Fig. 2.7.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd July

Thus IMD GFS could not capture the genesis, intensification and weakening of the system.

2.7.5. Realized Weather:

2.7.5.1 Rainfall:

Under the influence of depression, widespread rainfall activity with isolated heavy to extremely heavy rainfall was observed over eastcentral India including Gangetic West Bengal, Odisha, Chattisgarh, Madhya Pradesh and east Rajasthan during 6-10th August. The 24 hour cumulative rainfall (≥ 7 cm) ending at 0830 hours IST of date during 7-11th August is presented below:

7th August

Gangetic West Bengal: Kharidwar 11,
Odisha: Puri 39, Satyabadi 18, Bhubaneswar & Brahmagiri 17 each, Pipili 16, Banki 15, Nimpara, Bolagarh & Paradeep 13 each, Niali 12, Khandapara 11, Kakatpur & Athgarh 10 each

8th August

Odisha: Junagarh -19, Deogaon – 15, Dharmagarh & Similiguda -13 each, Raighar, Kuchinda & Anandpur – 10 each, Jhorigam, Bijepur, Umarkote, Boden, Malkangiri, Jharsuguda, Hirakud, Lakhanpur & Kirmira – 9 each, Sinapali, Laikera, Bhawanipatna & Jeypore - 8 each and Kashipur, Marsaghai, Dabugan, Kankadahad, Kolabira, Tarva, Chandahandi, Ambabhona, Batli – 7 each

Chattisgarh: Deobhog – 15, Champa – 9, Sukma – 8 and Dantewara, Raigarh, Narayanpur & Sakti – 7 each

9th August
West Madhya Pradesh: Ashoknagar, Bhanpura & Neemuch – 8 each and Kurwai – 7 each
East Madhya Pradesh: Tendukheda – 7 each
Chhattisgarh: Kawardha – 9 and Simga & Bemetara – 8 each
East Rajasthan: Shahabad – 11, Chhotisadri – 9 and Bari-Sadri - 8

10th August
East Rajasthan: Pratapgarh and Dungla – 8 each
West Madhya Pradesh: Isagarh – 8 and Jawad -7
East Madhya Pradesh: Garhakota – 9 and Panna – 8

(Heavy rainfall distribution: Isolated places : upto 25%, A few places: 26-50%, Many places : 51-75%, Most places: 76-100% of total stations in the region;
Heavy rainfall: 64.5 – 115.5 mm, Very heavy rainfall: 115.6 – 204.4 mm, Extremely heavy rainfall: 204.5 mm or more).

The daily rainfall distribution ending at 0300 UTC of each date during 07-08 August, 2018 based on merged gridded rainfall data of IMD/NCMRWF is shown in Fig.2.7.4.

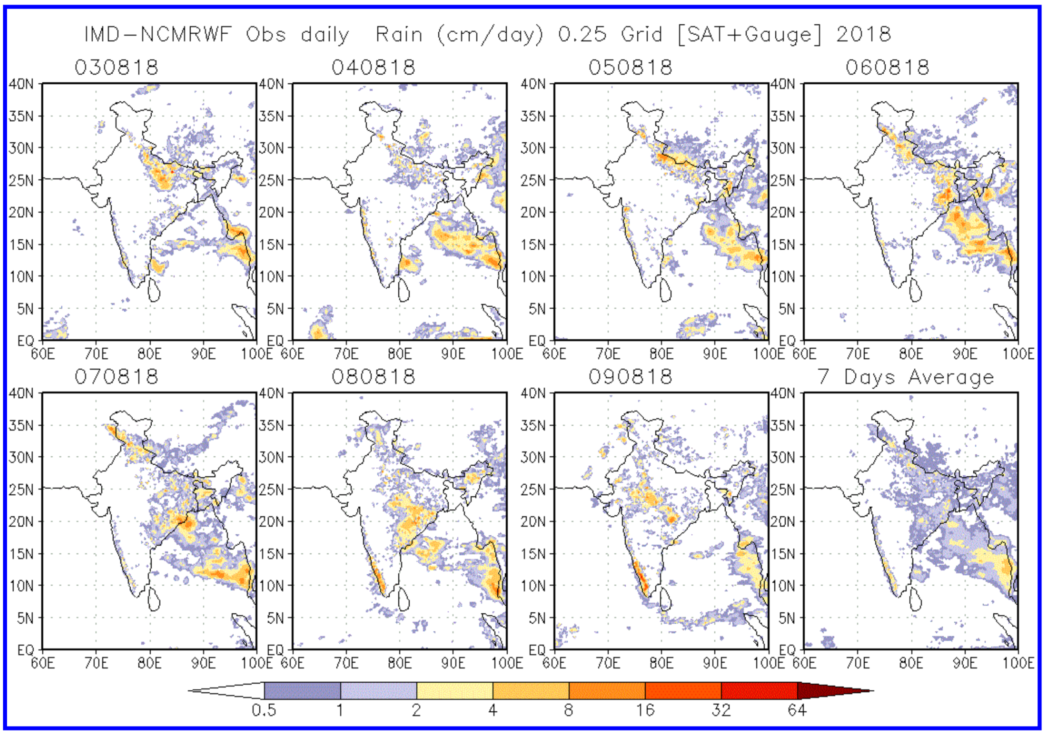


Fig.2.7.4: Daily rainfall distribution based on merged grided rainfall data of IMD/NCMRWF during 03-09 August, 2018

2.8. Depression over coastal Odisha (15-17 August, 2018)

2.8.1. Introduction

Under the influence of a cyclonic circulation over northwest Bay of Bengal (BoB) off West Bengal coast, a low pressure area (LPA) formed over the same region in the morning (0300 UTC) of 13th. It lay as a well marked low pressure area (WML) over northwest BoB off West Bengal-north Odisha coasts in the afternoon (0900 UTC) of 14th. It concentrated into a depression over coastal Odisha in the morning (0300 UTC) of 15th. It moved west-northwestwards and weakened gradually into a WML over southwest Madhya Pradesh and neighbourhood in the morning (0300 UTC) of 17th and LPA in the same evening (0900 UTC). The system became less marked over east Rajasthan and neighbourhood in the morning (0300 UTC) of 18th August.

The salient features of the system were as follows:

(i) It had a straight moving track and moved west-northwestwards throughout it"s life period.
(ii) It had a life period of 48 hours (depression to depression).
(iii) It had a track length (depression to depression) of 1145 km and moved with an average speed of 25 kmph.
(iv) Under the influence of this system and its remnant low pressure area widespread and intense rainfall activity was observed over the northern and central parts of the country extending from Odisha, Chattisgarh, Vidarbha, Telangana, Madhya Pradesh, Marathwada, Konkan & Goa, Gujarat and East Rajasthan. Extremely heavy rainfall occurred over Chattisgarh on 16th and west Madhya Pradesh on 17th.
(v) Under its influence, the lower level westerly/southwesterly winds over the Arabian Sea along & off Kerala coast strengthened. The interaction of the stronger westerly/southwesterly winds with the Western Ghats resulted in heavy to extremely heavy rainfall activity over Kerala during this period.

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. Its genesis, movement and associated adverse weather could be predicted well by IMD

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

2.8.2. Brief life history

A cyclonic circulation lay over westcentral BoB & adjoining south coastal Andhra Pradesh at 7.6 km above mean sea level on 9th. It persisted over the same region and was seen at 5.8 km above mean sea level on 10th. It lay over south Odisha - north Andhra Pradesh coasts between 3.1 km & 5.8 km above mean sea level, tilting southwestwards with height on 11th. It lay over north coastal Odisha & neighbourhood extending upto 7.6 km above mean sea level and tilting south-southwestwards with height on 12th. Under its influence, a low pressure area formed over northwest BoB off West Bengal coast with the associated cyclonic circulation extending upto 7.6 km above mean sea level tilting southwestwards with height on 13th. It lay as a WML over northwest BoB off West Bengal-north Odisha coasts with the associated cyclonic circulation extending upto 7.6 km above mean sea level, tilting southwestwards with height on 14th.

At 0300 UTC of 14th, Madden Julian oscillation Index currently lay in phase 6 with amplitude greater than 1. The low level relative vorticity is about $100\times10^{-5}sec^{-1}$ over westcentral BoB and was oriented along northeast to southwest. The lower level convergence is about 20 $\times10^{-5}sec^{-1}$ over westcentral & adjoining northwest BoB to the southwest of system centre. The upper level divergence was about 40 $\times10^{-5}sec^{-1}$ over west central BoB to the southeast of system centre. The vertical wind shear was moderate (10-20 knots) around system centre and along the expected direction of movement of depression. Under these conditions, the system lay as a WML over northwest BoB off West Bengal-north Odisha coasts. The upper tropospheric ridge lay far to the north of the system centre in association with the Tibetan High. There were east-southeasterly winds over the region. All these conditions supported further intensification of WML into a depression at 0300 UTC of 15th August and its west-northwestward movement. With the similar environmental conditions, the system maintained its intensity of depression till morning of 17th August and moved west-northwestwards with a faster speed (25 kmph). It weakened into a WML over southwest Madhya Pradesh and neighbourhood at 0300 UTC and an LPA at 0900 UTC of 17th. It became less marked over east Rajasthan and neighbourhood at 0300 UTC of 18th. The observed track and best track parameters of depression over coastal Odisha are presented in Fig. 2.8.1 and Table 2.8.1.

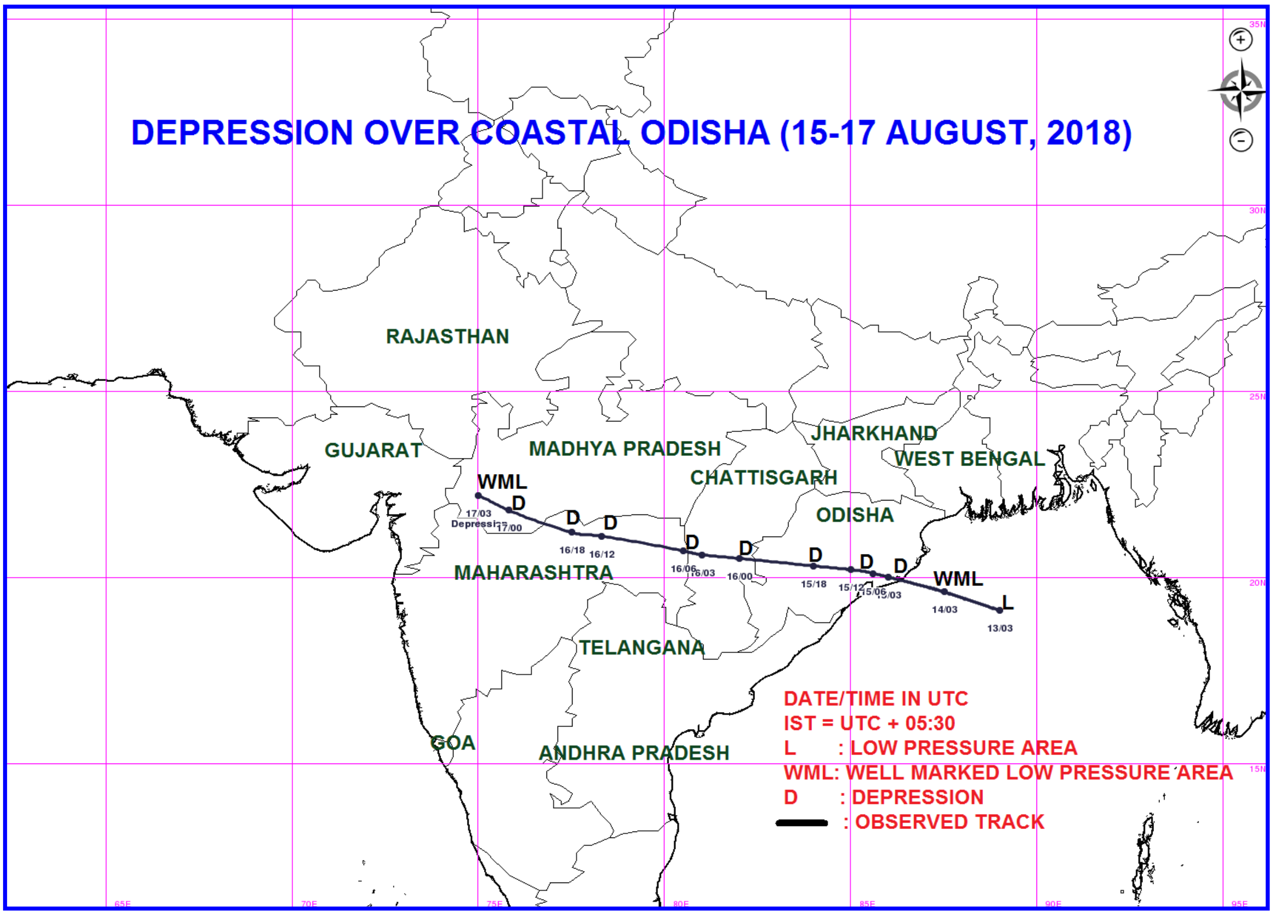


Fig. 2.8.1. Observed track of Depression over northwest Bay of Bengal and neighborhood (15-17 August, 2018)

Table 2.8.1: Best track positions and other parameters of the Depression over coastal Odisha during 15-17 August, 2018

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
15/08/2018	0300	20.0	86.0	-	993	25	4	D
	0600	20.1	85.6	-	993	25	4	D
	1200	20.2	85.0	-	993	25	4	D
	1800	20.3	84.0	-	993	25	4	D
16/08/2018	0000	20.5	82.0	-	994	25	3	D
	0300	20.6	81.0	-	994	20	3	D
	0600	20.7	80.5	-	994	20	3	D
	1200	21.1	78.3	-	994	20	3	D
	1800	21.2	77.5	-	994	20	3	D
17/08/2018	0000	21.8	75.8	-	994	20	3	D
	0300	**Weakened into a well-marked low pressure area over southwest Madhya Pradesh and adjoining Gujarat & north Madhya Maharashtra**						

2.8.3. Feature observed through Satellites and Radar:

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-8 imageries were also considered. Typical INSAT-3D IR, visible, enhanced colored and cloud top brightness temperature imageries are presented in Fig. 2.8.2. The imageries indicate the shear pattern of clouds associated with the depression. The convective clouds were sheared to the southwest of system centre.

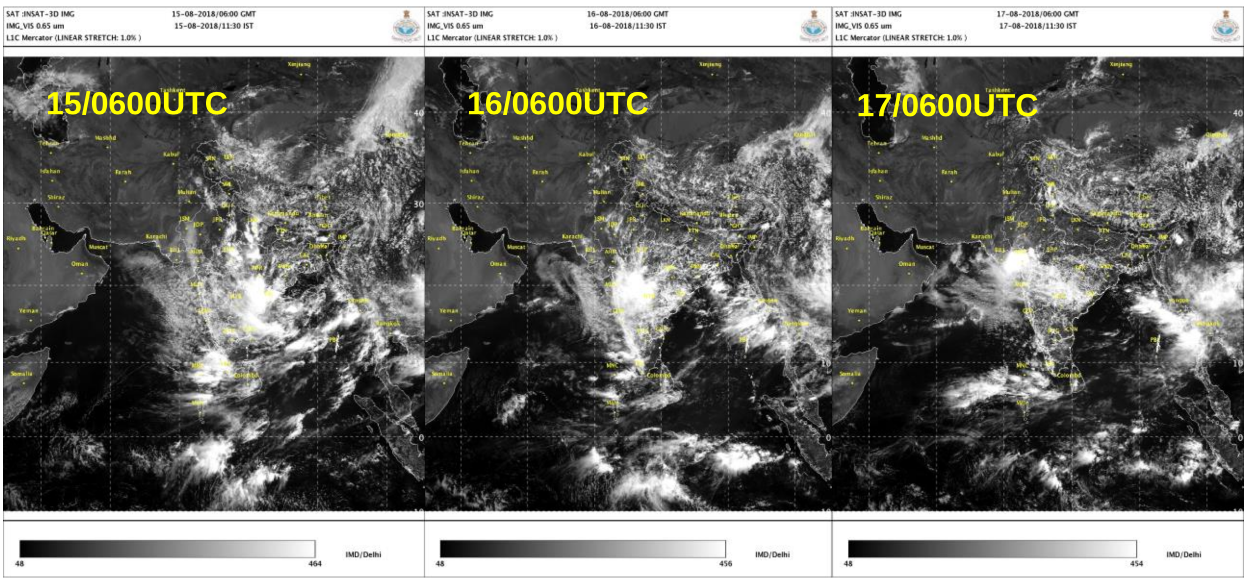


Fig. 2.8.2(i): INSAT-3D visible imageries during 15-17 August, 2018

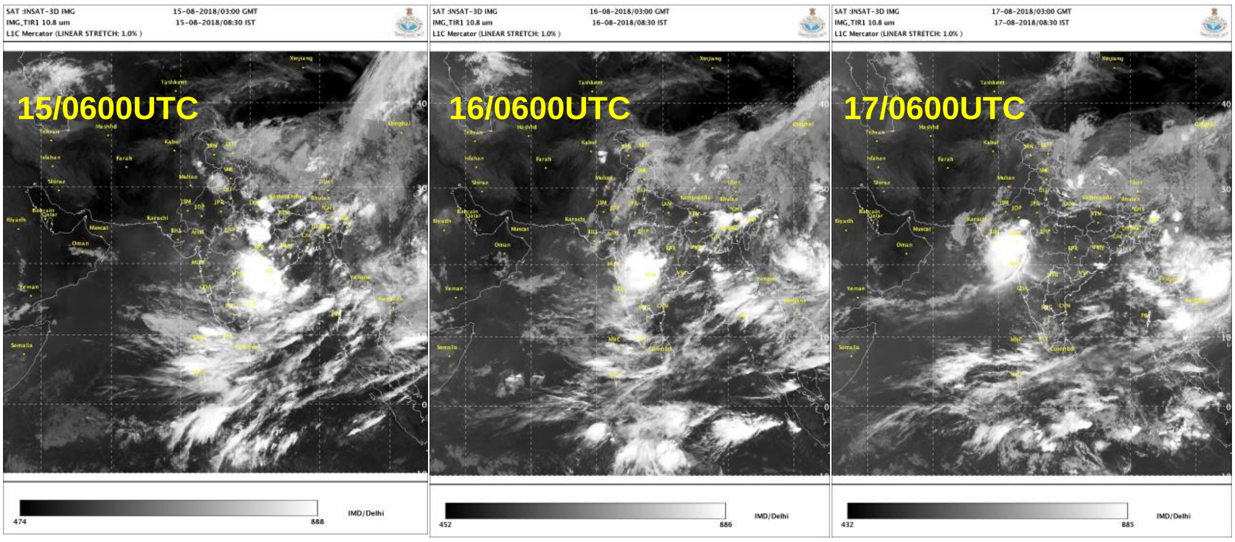


Fig. 2.8.2(ii): INSAT-3D enhanced colored imageries during 15-17 August, 2018

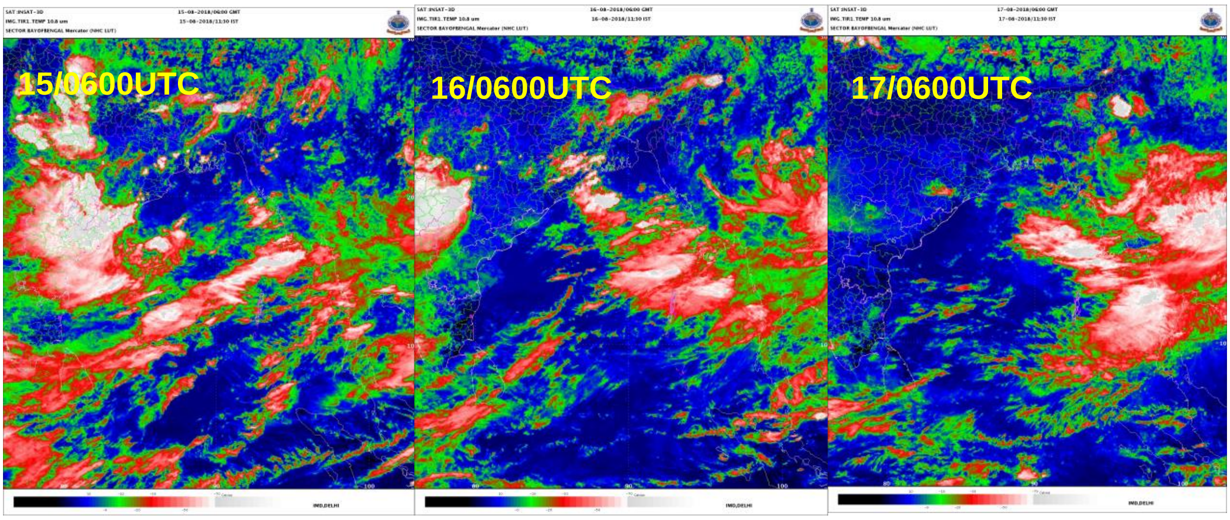


Fig. 2.8.2(iii): INSAT-3D enhanced colored imageries during 15-17 August, 2018

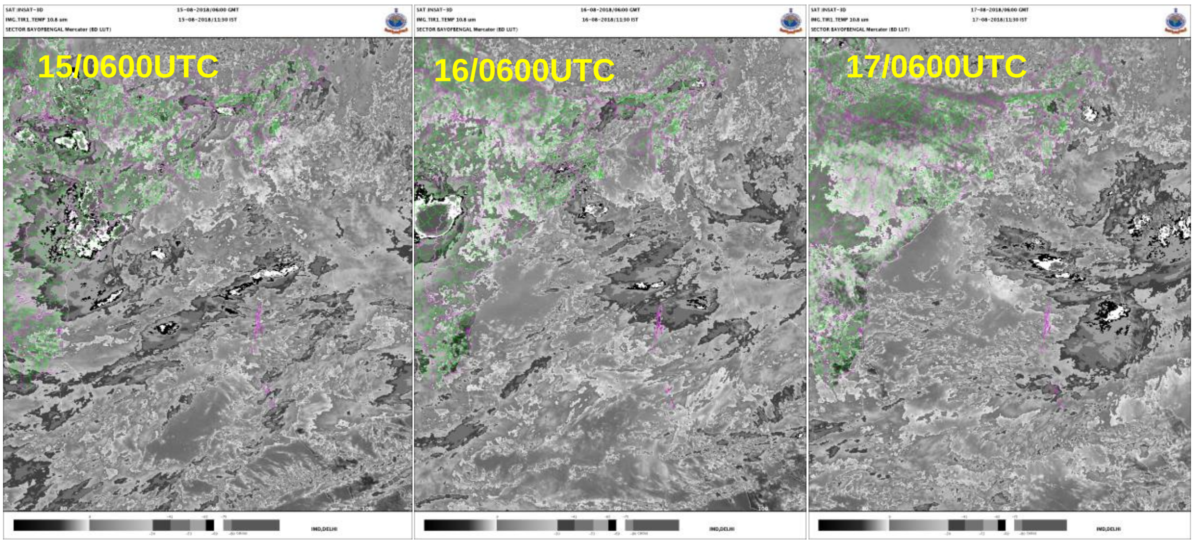


Fig. 2.8.2(iii): INSAT-3D cloud top brightness temperature imageries during 15-17 August, 2018

2.8.4. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.8.4. At 0000 UTC of 15th August, it indicated a low pressure area over northwest BoB off Odisha coast. The circulation was seen upto 500 hPa level tilting southwestwards with height. The ridge at 200 hPa level was far to the north in association with anticyclonic circulation near 31^0N/86^0E. The winds over the depression at 200 hPa level were nearly easterly. At 0300 UTC of 15th, the system lay as a depression over coastal Odisha.

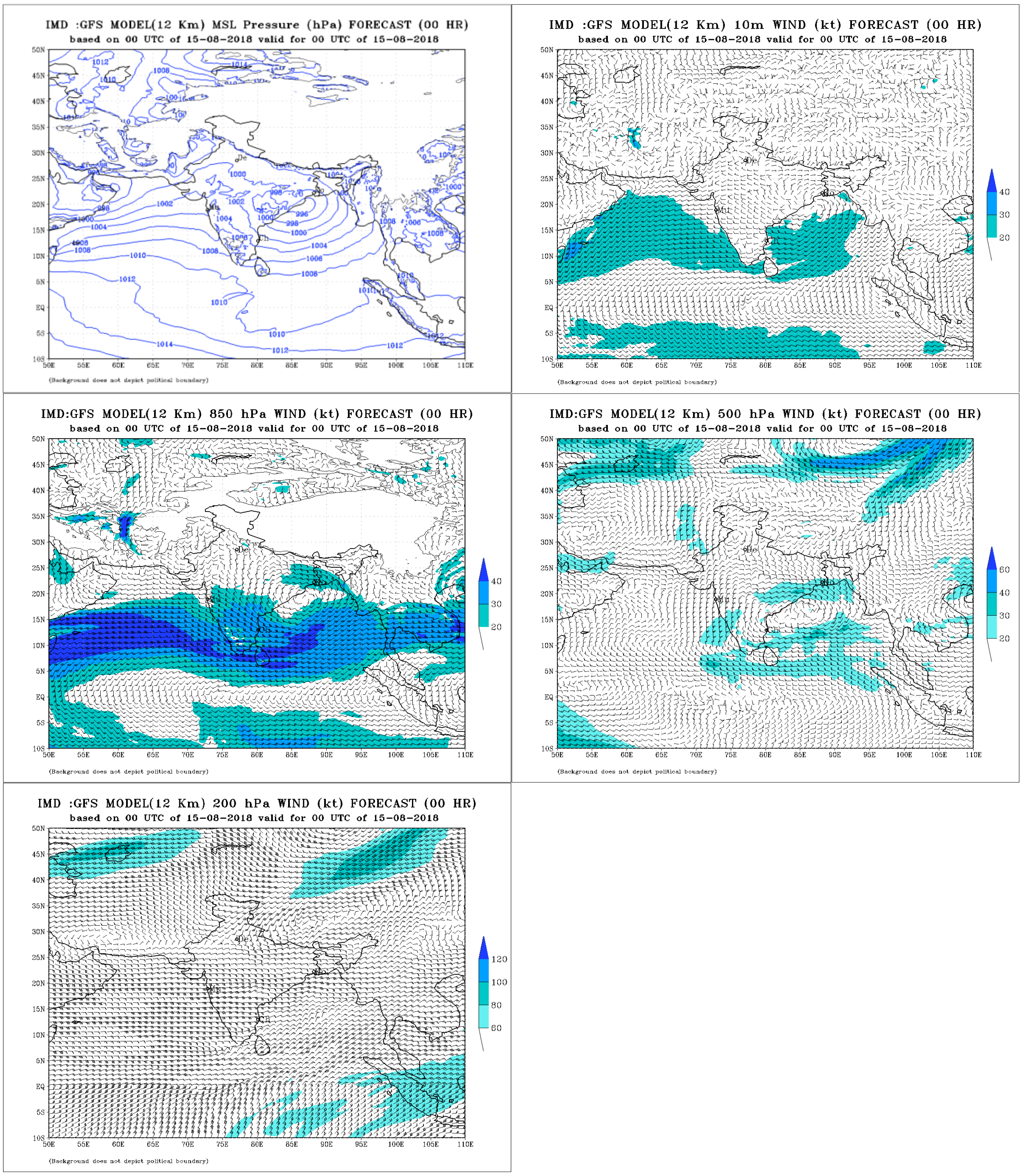


Fig. 2.8.4 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th August

At 0000 UTC of 16th August, it indicated a low pressure area over east Vidarbha. The circulation was seen upto 500 hPa level tilting southwestwards with height. Ridge was seen to the far north in association with anticyclonic circulation near 31^0N/86^0E. The winds over the depression at 200 hPa level were nearly easterly. At 0300 UTC of 16th, the system lay as a depression over Chattisgarh.

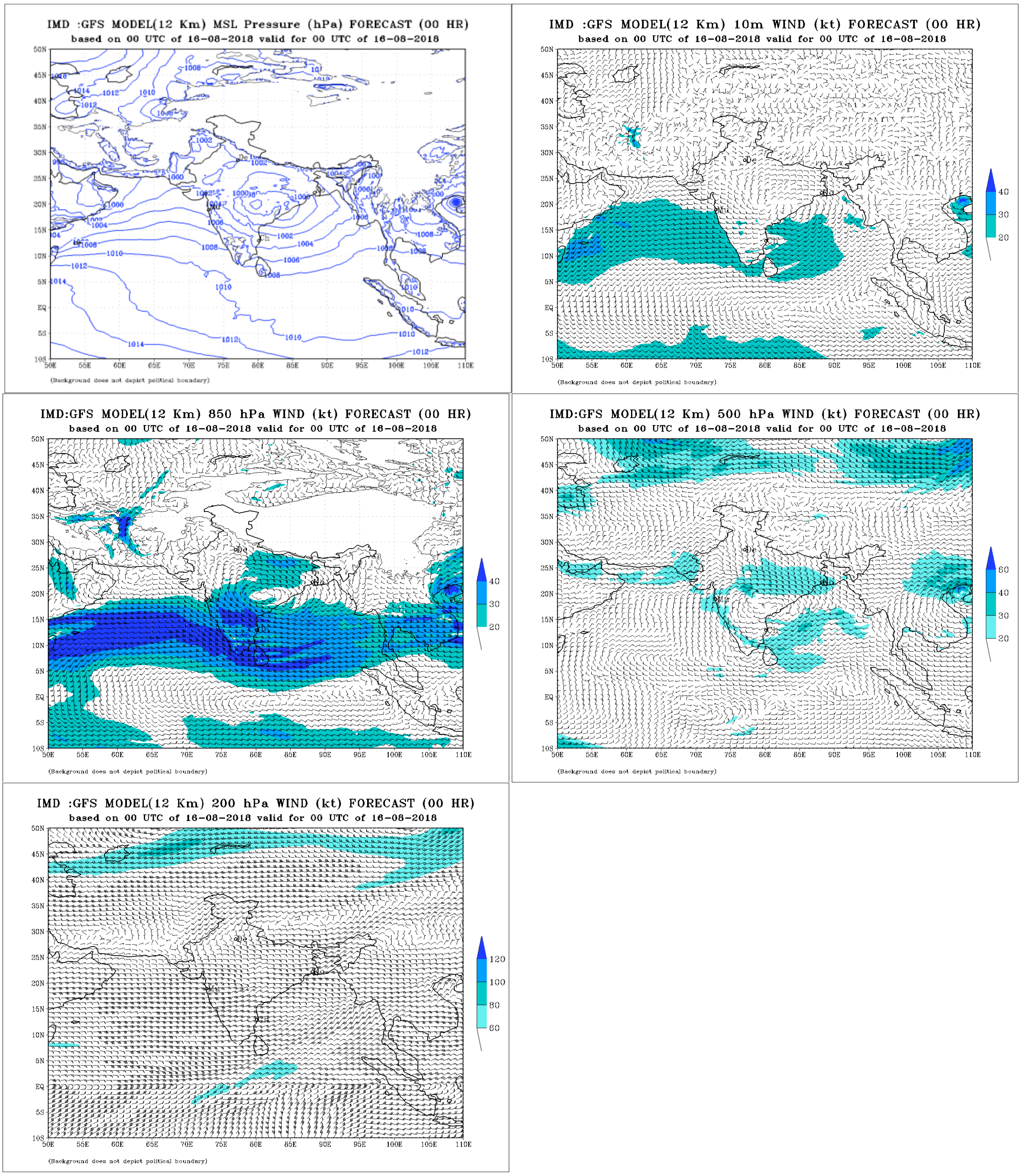


Fig. 2.8.4 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th August

The initial conditions based on 0000 UTC of 17th indicated an extended low over south Madhya Pradesh and adjoining Maharashtra. At 0300 UTC of 17th, the system weakened into a WML over southwest Madhya Pradesh and neighbourhood.

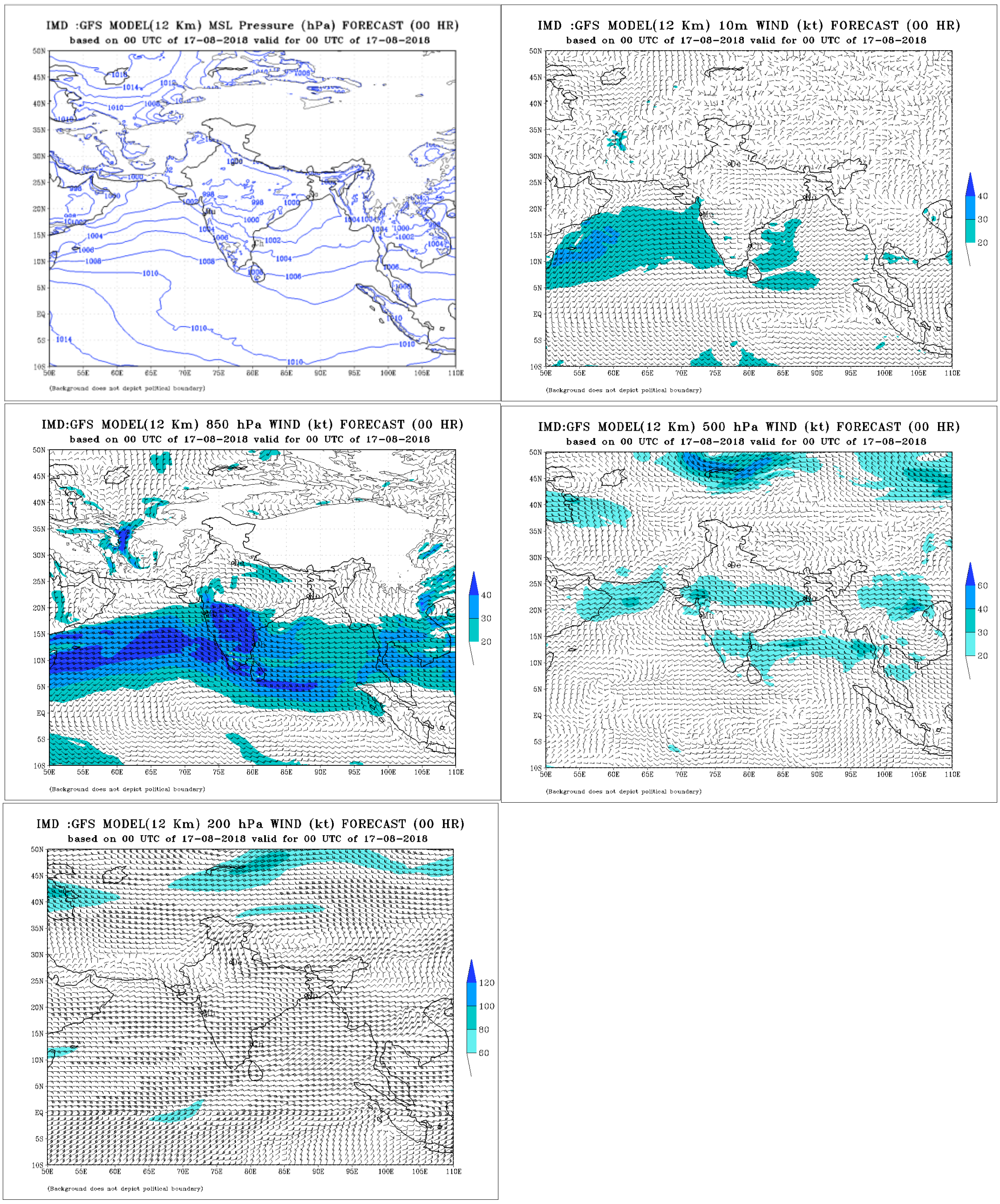


Fig. 2.8.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th August

Thus IMD GFS underestimated the genesis and intensification, as it predicted only a low pressure area. Also the area of occurrence was low was also misplaced on 15th and 16th August. However, it could pick up the near westward movement of system correctly.

2.8.5. Realized Weather:

2.8.5.1 Rainfall:

Under the influence of depression, on 14th, heavy to very heavy rainfall occurred at a few places over Odisha and coastal Andhra Pradesh with extremely heavy falls at isolated places over Odisha. On 15th August, heavy rainfall occurred at a few places over Odisha, Vidarbha, Chattisgarh, Telangana and at isolated places over Madhya Pradesh, Madhya Maharashtra and Marathwada with very heavy rainfall at isolated places over Odisha, Vidarbha, Telangana & Chattisgarh and extremely heavy rainfall at isolated over Chattisgarh. On 16th, the system caused heavy to very heavy rainfall at many places over Vidarbha, Marathwada, Madhya Maharashtra, Gujarat, west Madhya Pradesh & Goa and at isolated places over Telangana with extremely heavy rainfall at isolated places over & west Madhya Pradesh. On 17th, it caused heavy to very rainfall at isolated places over Gujarat, Saurashtra & Kutch, Vidarbha, Madhya Maharashtra and Marathwada. On 18th, it caused, heavy rainfall at isolated places over Gujarat, Saurashtra & Kutch, Madhya Maharashtra, Konkan & Goa and at many places over Telangana with very heavy falls at isolated places. On 19th, it caused heavy rainfall at isolated places over Gujarat, Saurashtra & Kutch, Vidarbha, Konkan & Goa, Marathwada and east Rajasthan.

The daily rainfall distribution ending at 0300 UTC of each date during 17-23 July, 2018 based on merged gridded rainfall data of IMD/NCMRWF is shown in Fig. 2.8.4.

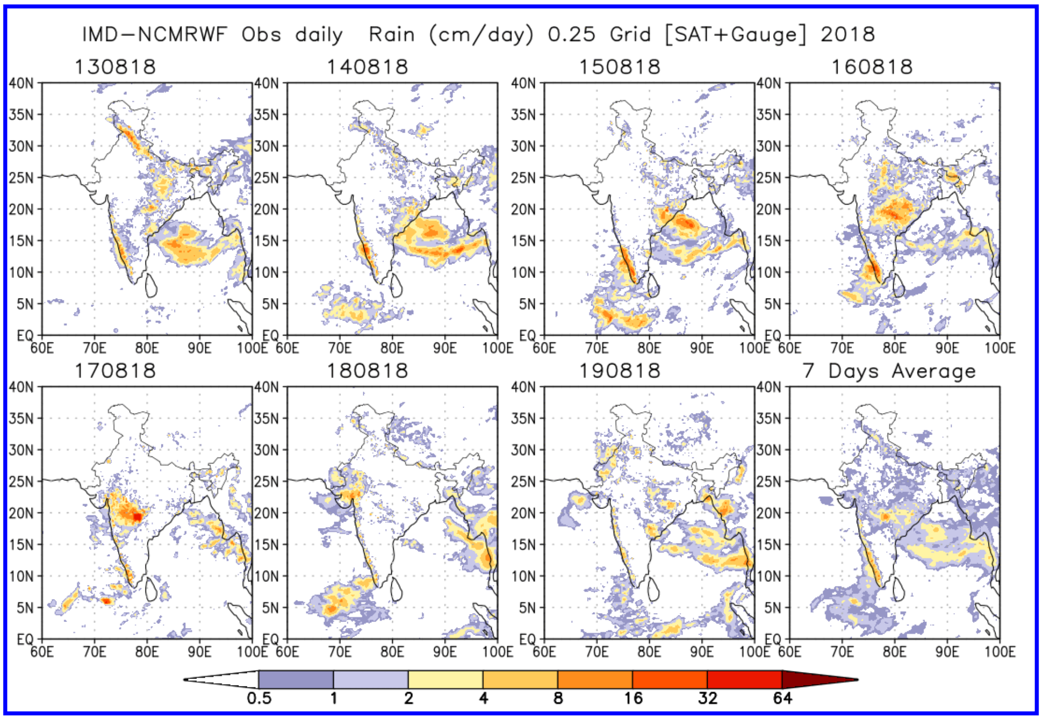


Fig. 2.8.4: Daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during 13-19 August, 2018

(Heavy rainfall distribution: Isolated places: upto 25%, A few places: 26-50%, Many places: 51-75%, Most places: 76-100% of total stations in the region;

Heavy rainfall: 64.5 – 115.5 mm, Very heavy rainfall: 115.6 – 204.4 mm, Extremely heavy rainfall: 204.5 mm or more).

The 24 hour cumulative rainfall (≥ 7 cm) ending at 0830 hours IST of date during 15-20th August is presented below:

15th August:

Odisha: Lanjigarh-28, Madanpur Rampur-25, Ambadola 7 Narla-24 each, Bhawanipatna-22, Kashipur-19, Koraput, Nuagada, Jaipatna & Tentulikhunti-15 each, nawarangpur-13, Kashinagar, R. Udaigiri & Jeypore-12 each, Kesinga & Junagarh-10 each, Similiguda 7 Pottangi-9 each, Muniguda, Raghunathpur, Paralakhemundi & Dabugan-8 each and Niali, Chandanpur & Banki-7 each

Coastal Andhra Pradesh: Palakonda-13, Ranastalam-11, Vepada & Kalingapatnam-10 each, Mandasa-9, Garividi, Pathapatnam & Cheepurupalle-8 each and Gantyada & Palasa-7 each

16th August:

Odisha: Malkangiri & Sinapali – 15 each, Junagarh, Boden, & Patnagarh – 12 each, Nawapara -11, Narla, Raighar & Dharmagarh – 10 each, Bhawanipatna, Saintala & Jharbandh – 9 each, Ambadola, Dabugan, Hindol, Nischintakoili, & Similiguda, Lanjigarh & Jeypore – 8 each and Khaprakhol, Kesinga, Paikmal & Chandahandi- 7 each

West Madhya Pradesh: Gwalior, Sonkatch & Isagarh – 8 each and Kolaras - 7

East Madhya Pradesh: Dindori- 8 and Tendukheda - 7

Vidarbha: Lakhandur – 13, Bhadravati & Ahiri – 12 each, Korpana 11, Mohadi & Sadakarjuni -10 each, Bramhapuri, Chandrapur & Bhandara – 9 each, Ballarpur, Lakhani, Gondia, Nagbhir & Mulchera - 8 each and Chimur, Deori, Umrer, Mul, Tumsar, Arjuni, Morgaon, Warora, Sindewahi & Desaiganj 7

Chhattisgarh: Bhopalpatnam – 40, Bijapur 14, Kanker 11, Gariabund & Jagdalpur 9, Rajim, Mahasamund, Mana-Raipur & Simga 8 each and Arang & Deobhog – 7 each

Telangana: Perur - 19, Sirpur – 17, Asifabad – 13, Kaleswaram, Utnur & Chennur – 11 each, Manthani, Ibrahimpatnam & Adilabad – 9 each, Ramgundam, Venkatapuram, Metpalle, Bhupalpalle & Mudhole – 8 each and Sarangapur, Eturnagaram, Bhiknur , Boath & Julapalle – 7 each

Madhya Maharashtra: Mahabaleshwar- 14

Marathwada: Mahur, Tuljapur, Bhum & Kinwat – 7 each

17th August:

Vidarbha: Barshitakli -16, Digras, Karanjalad & Arni-13 each, Manora & Buldana – 12 each, Deolgaon Raja & Pusad – 11 each, Patur, Malkapur & Sindkhed Raja – 10 each, Murtajapur, Darwha, Jalgaon Jamod, Motala, Mangrulpir, Joiti & Umerkhed - 9, Mahagaon, Malegaon, Lonar, Chikhli, Akola & Dharni-8 each and Washim, Mehkar, Korpana & Risod-7 each

Marathwada: Kinwat & Mahur – 19 each, Kannad-17, Aurangabad-16, Phulambri & Jalna-15 each, Pathri, Jafrabad & Selu – 14 each, Mantha, Manvat, Partur & Ghansawangi-13 each, Ardhapur-12, Himayatnagar, Badnapur, Vaijapur & Aundha Nagnath – 11 each, Purna, Jintur, Nanded, Sillod, Hadgaon & Bhokardan -10 each, Sonpeth, Paithan, Manjlegaon, Kallamnuri & Osmanabad – 9 each, Ambad & Parbhani – 8 each and Kandhar, Vasmat, Soegaon, Gangapur, Kaij, Georai, Mudkhed & Hingoli – 7 each

Madhya Maharashtra: Mahabaleshwar - 16, Raver, Navapur & Jamner-14 each, Jalgaon - - 13, Lonavala -12, Dhadgaon/Akrani -10, Peth, Dhule, Parola & Erandol -10 each, Shirpur, Bodwad, Pachora, Surgana & Chalisgaon – 9 each and Gidhade, Yaval, Dahigaon, Shrirampur, Girnadam & Igatpuri – 7 each
Konkan & Goa: Valpoi-14, Bhira & Matheran – 9 each and Dodamarg-8
Gujarat Region: Chhota Udepur-14, Tilakwada-13, Ukai, Quant & Valod-12, Godhra & Wanakbori -10 each, V.Vidyanagar-9, Vyara, Subir & Vadodara-8 each and Nizer, Vansda, Garudeshwar, Dhanpur, Garbada, Bodeli, Sagbara & Uchchhal -7 each
North Interior Karnataka: Londa-8
Telangana: Boath - 19, Adilabad-10 and Sarangapur-7
West Madhya Pradesh: Bhikangaon - 23, Shegaon - 21, Khandwa & Burhanpur - 17 each, Khargone, Thikri & Sendhwa - 13 each, Badwani – 12, Jhabua – 11, Manawar, Pandhana, Nepanagar, Sardarpur & Kasarwad – 10 each, Maheshwar & Gandhwani – 9 each and Kukshi, Khaknar & Barwaha – 8 each

18th August:
Gujarat Region: Kapadvanj-15, Godhra-13 and Matar-12
Saurashtra & Kutch: Kandla New & Sayla-11 each, Muli & Chotila-9 each and Wadhvan, Dhrangadhra, Surendranagar & Limbdi – 7 each.
Vidarbha: Chandur Bazar-7
Madhya Maharashtra: Radhanagari-10 and Mahabaleshwar-8
Marathwada: Jalna-16 and Vasmat-7

19th August:
Gujarat Region: Kaprada-8
Saurashtra & Kutch: Anjar & Gandhidham-10 each and Kandla Airport- 9
Madhya Maharashtra: Mahabaleshwar- 9 and Radhanagari & Shahuwadi-7 each
Konkan & Goa: Karjat & Sangameshwar Devrukh-7 each

20th August:
Gujarat Region: Tarapur-7,
Saurashtra & Kutch: Kotdasangani-7,
Konkan & Goa: Bhira -8 and Alibag-7
East Rajasthan: Lalsot-10 and Amer & Nagar-7 each

2.9. Deep Depression over northwest Bay of Bengal and adjoining West Bengal & Odisha coasts (06-07 September, 2018)

2.9.1. Introduction

Under the influence of a cyclonic circulation over north Bay of Bengal (BoB) and adjoining areas of Bangladesh & West Bengal coast, a low pressure area (LPA) formed over northwest BoB and neighbourhood in the early morning (0000 UTC) of 5th September. It lay as a well marked low pressure area (WML) over the same region in the evening (1200 UTC) of same day. Moving west-northwestwards, it concentrated into a depression (D) over northwest BoB and adjoining West Bengal Bangladesh coasts in the early morning (0000 UTC) of 6th. It moved slightly westwards, intensified into a deep depression (DD) over the same region in the same morning (0300 UTC) and crossed West Bengal coast close to Digha in the same forenoon during 0430-0530 UTC. It continued to move west-northwestwards and maintained it"s intensity of DD for next 21 hours and weakened into a D over northwest Odisha and neighbourhood in the early morning (0000) of 7th.Thereafter, it moved northwestwards and weakened into a WML around the noon (0600 UTC) of same day over north Chattisgarh and neighbourhood. It weakened into an LPA over east Rajasthan and neighbourhood in the early morning (0000 UTC) of 9th. .

The salient features of the system were as follows:

(i) It moved initially nearly westwards till early morning (0000 UTC) of 7th and then northwestwards.

(ii) It had a life period of 30 hours (depression to depression).

(iii) Under the influence of this system and its remnant low pressure area widespread rainfall activity was observed over the northern and central parts of the country extending from Gangetic West Bengal, Odisha, Chhattisgarh, Jharkhand, Vidarbha, Madhya Pradesh, and East Rajasthan. Extremely heavy rainfall occurred over Odisha on 6th.

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. Its genesis, movement and associated adverse weather could be predicted well by IMD

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

2.9.2. Brief life history

A cyclonic circulation extending upto 4.5 km above mean sea level lay over north BoB and adjoining areas of Bangladesh & West Bengal on 4th September, 2018. Under its influence, a low pressure area formed over northwest BoB & neighbourhood with the associated cyclonic circulation extending upto 7.6 km above mean sea level and tilting southwestwards with height on 5th September, 2018 morning. Another, cyclonic circulation at 7.6 km above mean sea level lay over westcentral BoB off south Odisha - north Andhra Pradesh coasts on 4th September, 2018. It merged with the cyclonic circulation associated with the low pressure area over northwest BoB & neighbourhood on 5th September, 2018.

It lay as a WML over the same region in the evening (1200 UTC) of 5th. At 1200 UTC of 5th. The low level relative vorticity at 850 hPa level was about $100x10^{-6}$ sec^{-1} over northwest BoB, was circularly organized and extended upto 500 hPa level. The wind shear was moderate about 15-20 knot (kt) over northwest BoB. It was low to moderate (10-15 kt) along the expected direction of motion of system. The lower level convergence was about 10-15x10^{-5}sec^{-1} over northwest & adjoining westcentral BoB. The upper level divergence was about 10 x10^{-5}sec^{-1} over northwest and adjoining westcentral BoB.

Under these favourable conditions, the system intensified into a D at 0000 UTC of 6th. At 0000 UTC of 6th, the sea surface temperature (SST) was more than 26^{0}C over northwest BoB & adjoining Odisha-West Bengal coasts. The tropical cyclone heat potential was about 40-50 KJ/cm2 over north BoB to the north of 20^{0}N. Madden Julian Oscillation (MJO) index lay in phase 8 with amplitude equal to 1. The low level relative vorticity was about 150x10^{-6}sec^{-1} over northwest BoB & adjoining west central BoB to the southwest of the system centre. It extended upto 500 hPa level. The lower level convergence was about 10 x10^{-5}sec^{-1} off Odisha coast. The upper level divergence increased and was about 20x10^{-5}sec^{-1} over south coastal Odisha to the southwest of system centre. The vertical wind shear was low to moderate (5-15 kt) over the north BoB. The mid-level wind shear was nearly easterly over north BoB. The upper tropospheric ridge lay far to the north of the system centre abd hence the easterly to east-southeasterly winds prevailed over the region in the upper troposphere. Under these conditions the system intensified into a DD at 0300 UTC of 6th and moving slightly westwards crossed West Bengal coast close to Digha during 0430-0530 UTC of 6th. Similar conditions continued and the system maintained its intensity of DD till 1800 UTC of 6th.

At 1800 UTC of 6th, the region of maximum vorticity (150x10^{-6}sec^{-1}) lay over north Odisha and it extended upto 500 hPa level. The lower level convergence decreased and was about 5x10^{-5}sec^{-1} near system centre. The upper level divergence decreased and was about 10x10^{-5}sec^{-1} over north Chattisgarh and adjoining Odisha. The vertical wind shear was low to moderate (5-15 kt) over the north BoB. Under these conditions, the system weakened into a D at 0000 UTC of 7th and WML at 0600 UTC of 7th. The middle to upper level winds were southeasterly. As a result the system moved northwestwards from 0000 UTC of 7th. The observed track and best track parameters of the deep depression are presented in Fig. 2.9.1 and Table 2.9.1.

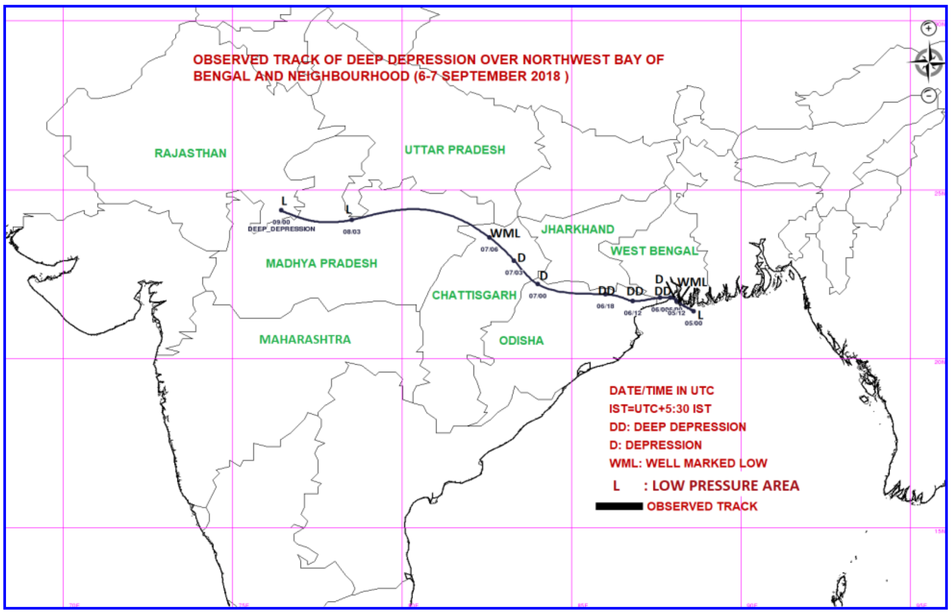


Fig. 2.9.1. Observed track of Depression over northwest Bay of Bengal and neighborhood (06-07 September, 2018)

Table 2.9.1: Best track positions and other parameters of the Deep Depression over northwest BoB and adjoining West Bengal - Odisha coasts during 06-07 September, 2018

Date	Time (UTC)	Centre		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
		lat. ^{0}N	long ^{0}E					
06/09/2018	0000	21.8	88.0	1.5		25	4	D
	0300	21.8	87.9	2.0		30	5	DD
	Crossed West Bengal coast close to Digha between during 0430-0530 UTC							
	0600	21.8	87.6	-		30	5	DD
	1200	21.7	86.8	-		30	5	DD
	1800	21.9	86.0	-		30	5	DD
07/09/2018	0000	22.2	84.0	-		25	4	D
	0300	22.9	83.3	-		20	3	D
	0600	**Weakened into a well-marked low pressure area over north Chhattisgarh & neighbourhood**						

2.9.3. Feature observed through Satellites and Radar:

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 and ASCAT & SCAT Sat imageries were also considered. Typical INSAT-3D IR, visible, enhanced colored and cloud top brightness temperature imageries, ASCAT & SCAT SAT imageries are presented in Fig. 2.9.2.

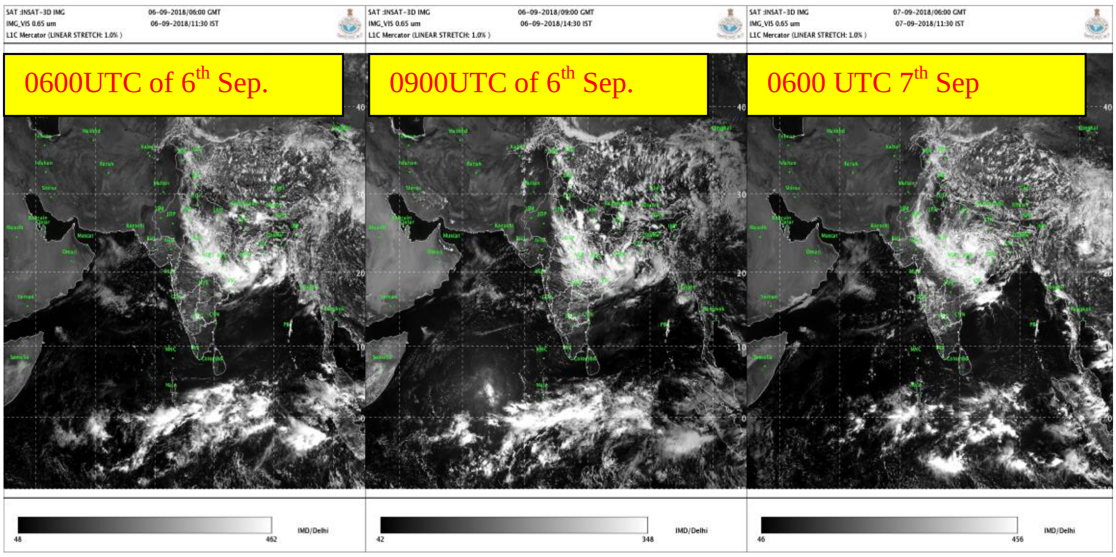


Fig. 2.9.2(i): INSAT-3D visible imageries during 6-7 September, 2018

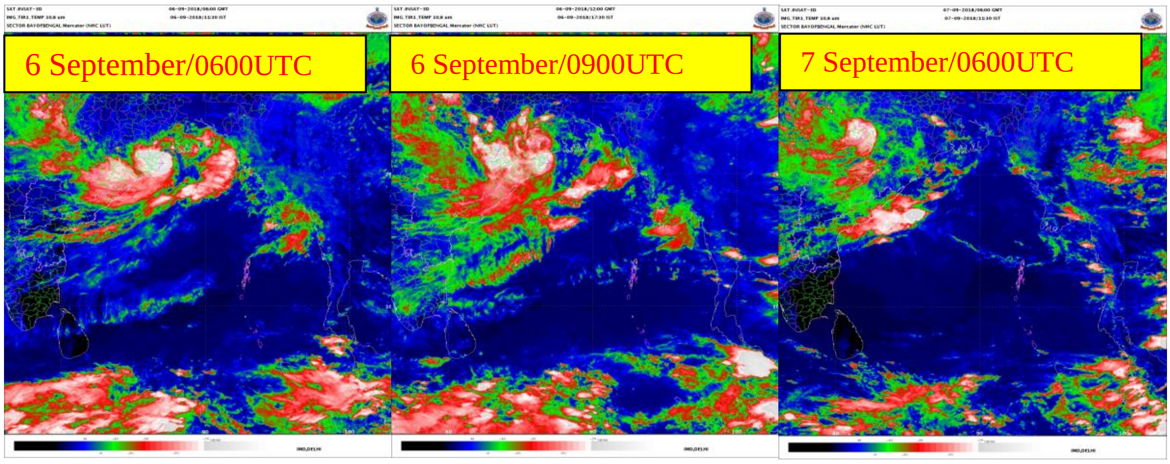


Fig. 2.9.2(ii): INSAT-3D enhanced colored imageries during 6-7 September, 2018

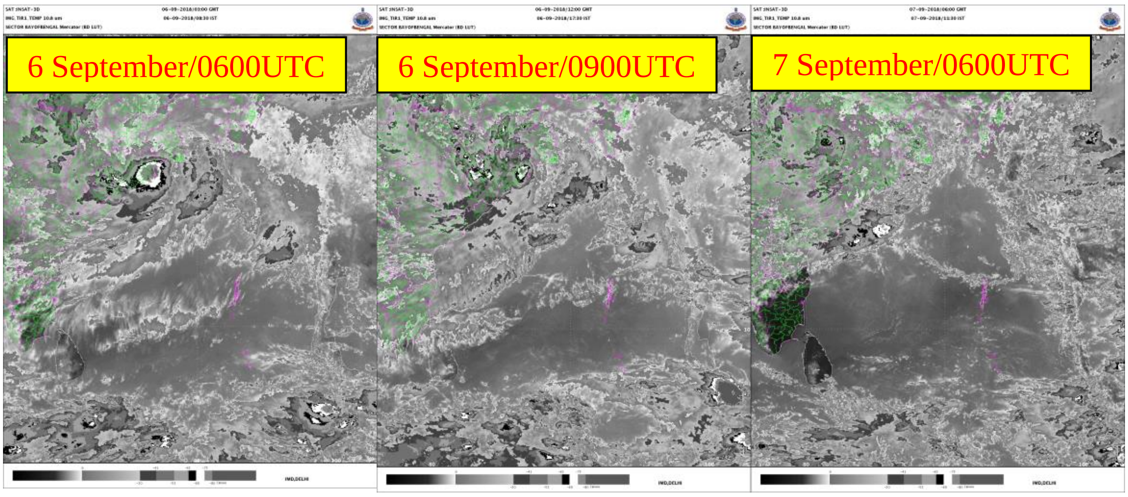


Fig. 2.9.2(iii): INSAT-3D enhanced grey scale imageries during 6-7 September, 2018

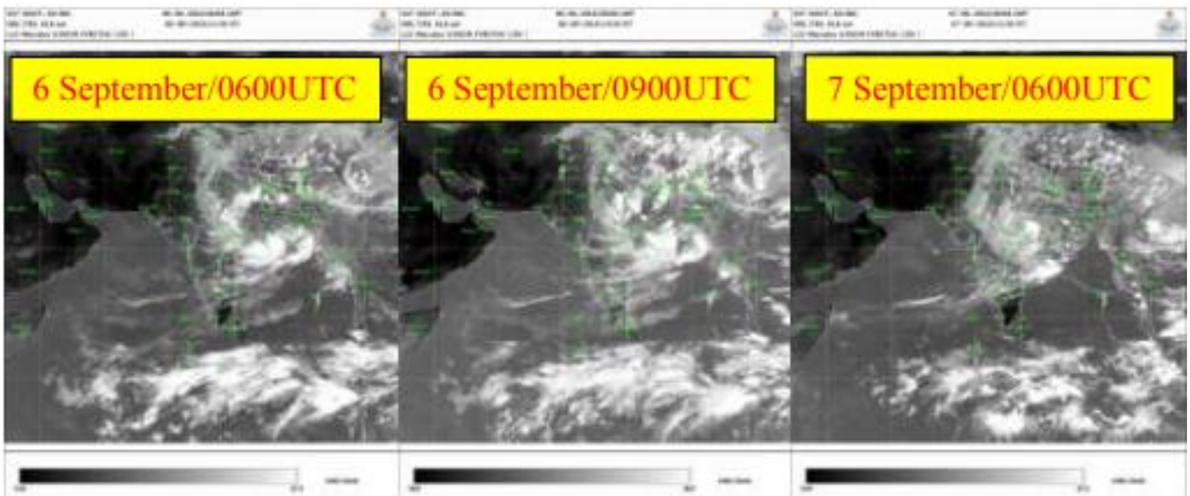


Fig. 2.9.2(iv): INSAT-3D IR imageries during 6-7 September, 2018

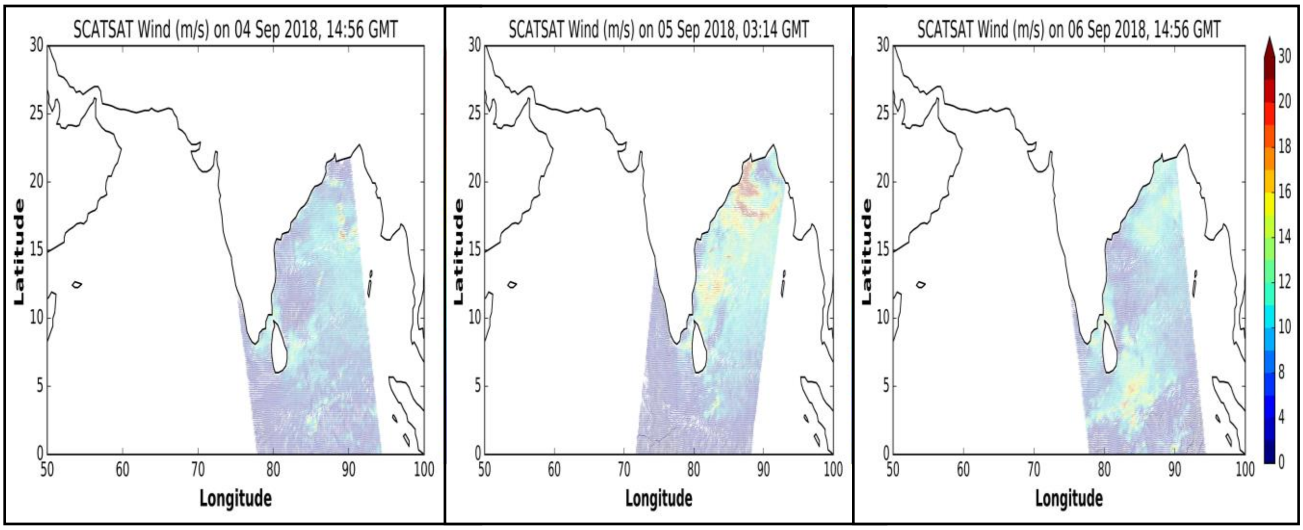


Fig. 2.9.2(v): SCAT SAT imageries during 6-7 September, 2018

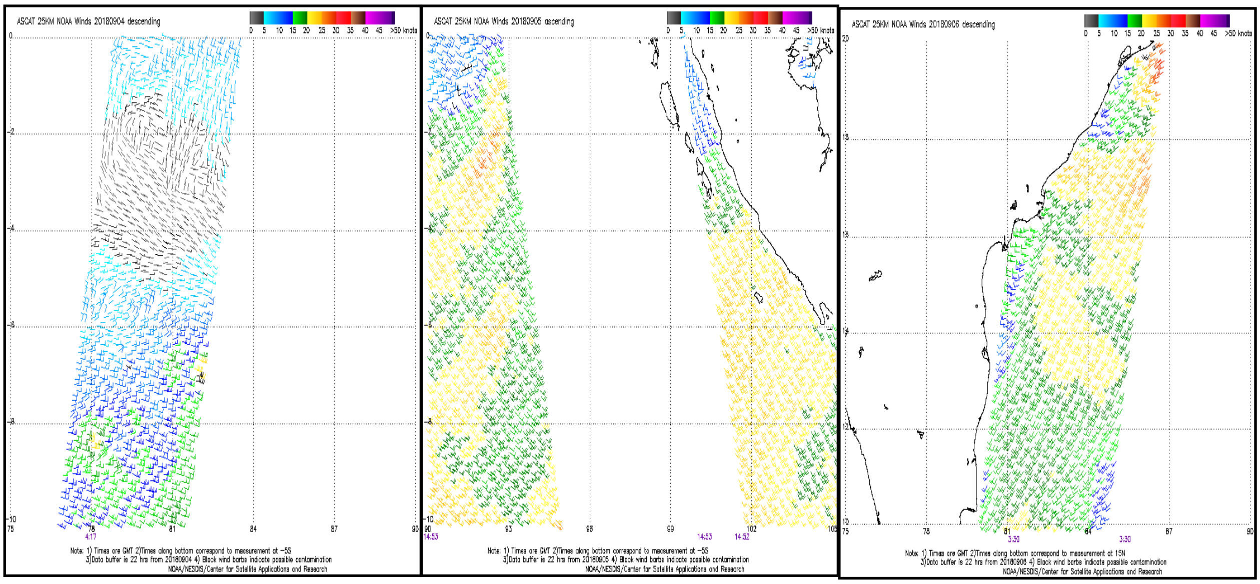


Fig. 2.9.2(vi): ASCAT imageries during 6-7 September, 2018

2.9.4. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.9.4. At 0000 UTC of 6th September, it indicated a depression over northwest BoB off west Bengal and Odisha coast. The circulation was seen upto 500 hPa level tilting southwestwards with height. Ridge was seen near 32^0N in association with anticyclonic circulation near 32^0N/99^0E. At 0000 UTC of 6th, the system lay as a depression over northwest BoB and adjoining West Bengal coast.

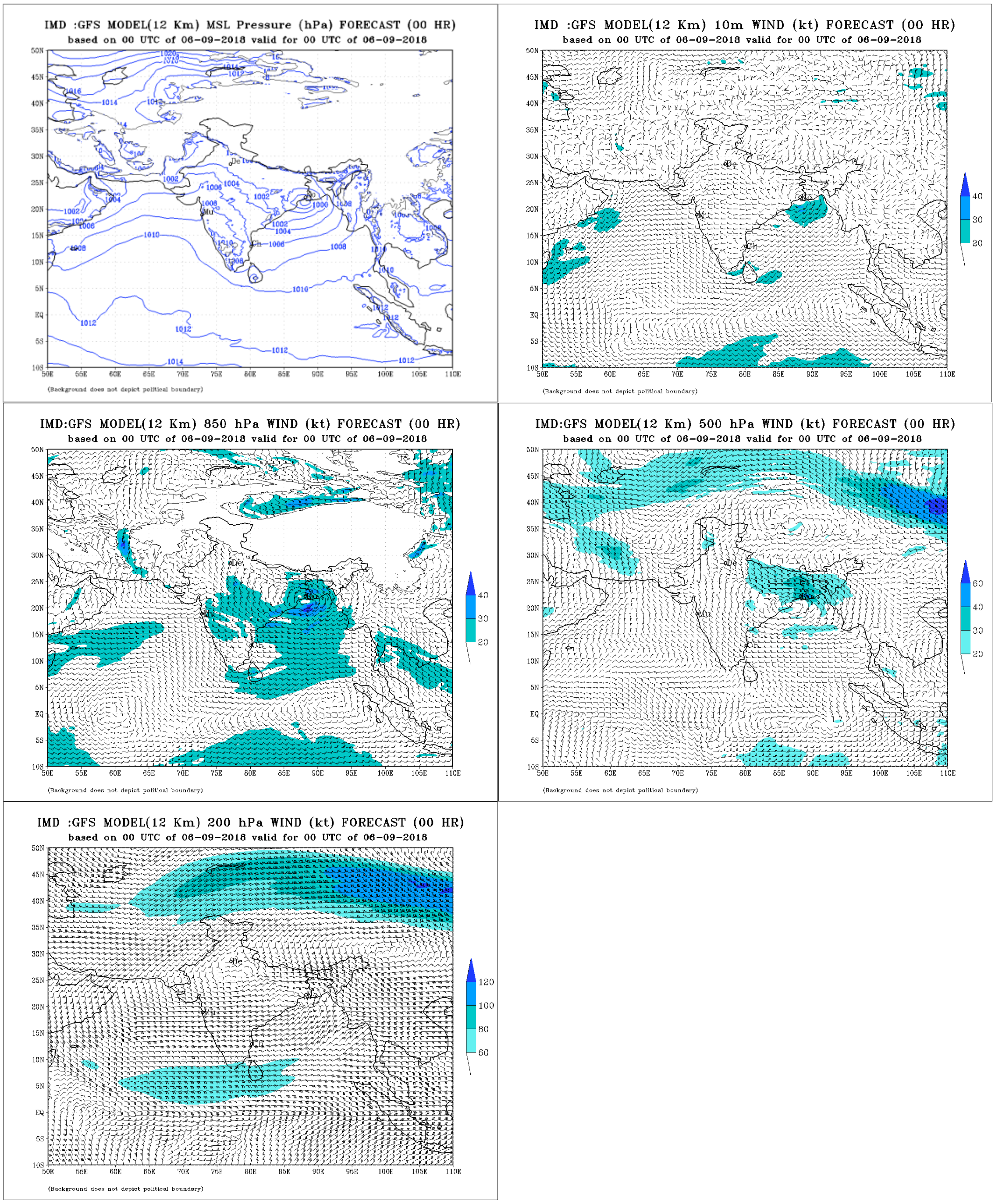


Fig. 2.9.3 (i): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 6th September

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10 m, 850, 500 and 200 hPa levels are presented in Fig. 2.9.4. At 0000 UTC of 7th September, it indicated a D over southwest Jharkhand and adjoining northwest Odisha and north Chhattisgarh. The circulation was seen upto 500 hPa level tilting southwestwards with height. Ridge was seen near 28^{0}N in association with anticyclonic circulation near 30^{0}N/95^{0}E. At 0000 UTC of 7th, the system lay as a depression over northwest Odisha and neighbourhood.

.

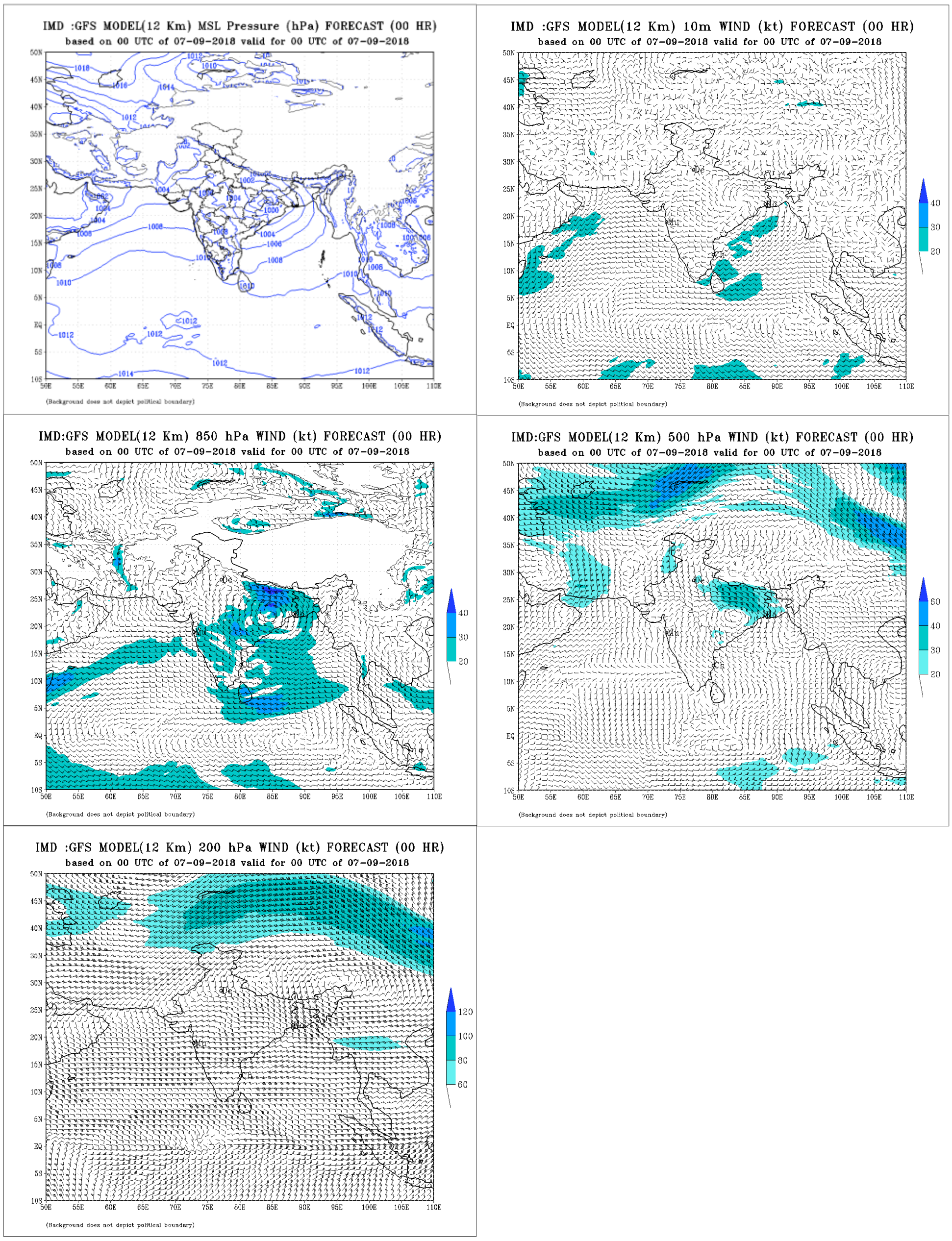


Fig. 2.9.3 (ii): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 7th September

Thus, IMD GFS could capture the genesis, intensification and movement of the system reasonably well.

2.9.5. Realized Weather:

2.9.5.1 Rainfall:

Under the influence of the system, on 5th September, isolated heavy rainfall occurred over Odisha & West Bengal. On 6th, heavy to very heavy rainfall occurred at isolated places over Gangetic West Bengal, heavy to very heavy at a few places with extremely heavy rainfall at isolated places occurred over Odisha and heavy rainfall at isolated places occurred over

Jharkhand, Chhattisgarh and Madhya Pradesh. On 7th, heavy to very heavy rainfall at a few places over Odisha & at isolated places over Chhattisgarh and heavy rainfall at isolated places over Jharkhand & Madhya Pradesh was registered. On 8th, isolated heavy rainfall over West Madhya Pradesh, Chhattisgarh & Vidarbha and isolated heavy to very heavy rainfall over East Madhya Pradesh was recorded. On 9th, heavy to very heavy rainfall at isolated places over west Madhya Pradesh and East Rajasthan was observed.

The daily rainfall distribution ending at 0300 UTC of each date during September, 2018 based on merged gridded rainfall data of IMD/NCMRWF is shown in Fig. 2.9.4.

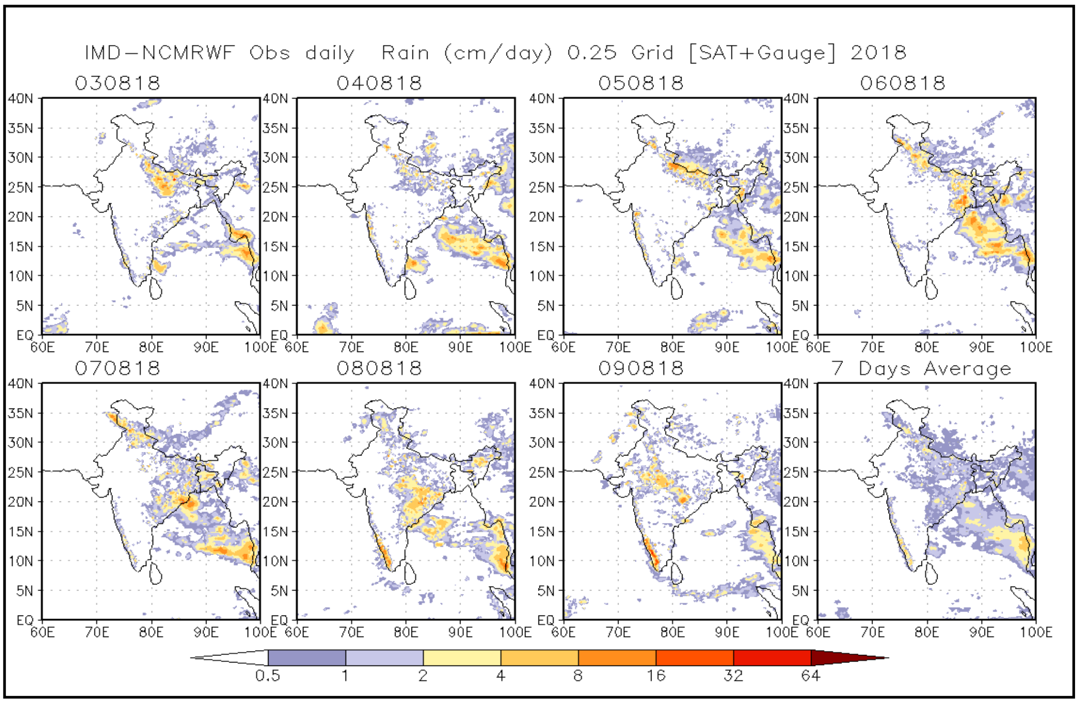


Fig. 2.9.4: Daily rainfall distribution based on merged gridded rainfall data of IMD/NCMRWF during 3-9 September, 2018

(Heavy rainfall distribution: Isolated places: upto 25%, A few places: 26-50%, Many places: 51-75%, Most places: 76-100% of total stations in the region;
Heavy rainfall: 64.5 – 115.5 mm, Very heavy rainfall: 115.6 – 204.4 mm, Extremely heavy rainfall: 204.5 mm or more).

The 24 hour cumulative rainfall (≥ 7 cm) ending at 0830 hours IST of date during 5th-9th September is presented below:

5th September

West Bengal

Alipore - 7

Odisha:

Chandanpur – 7

6th September

Gangetic West Bengal: Tusuma - 14, Kharidwar- 13, D.P.Ghat- 11, Kansabati Dam & Phulberia– 8 each, Simula– 7

Odisha: Paradeep - 41, Kujanga - 37, Kendrapara & Marsaghai – 34 each, Pattamundai - 31, Derabis - 30, Bari - 27, Tirtol - 26, Salepur - 25, Binjharpur & Garadapur – 24 each, Raghunathpur & Alipingal – 21 each, Jagatsinghpur, Chandbali, Jajpur – 19 each, Rajkanika - 18, Mahanga, Kantapada & Niali – 15 each, Balikuda - 14, Kakatpur, Chandikhol, Balipatna & Akhuapada – 13 each, Joshipur, Nischintakoili & Dhamnagar – 12 each, Nimpara, Phiringia, Astaranga & Cuttack – 11 each, Pipili, Tihidi & Bhubaneswar – 10 each, Gop, Banki, Naraj, Athmalik, Birmaharajpur & Danagadi – 9 each, Kalinga - 8, Boudhgarh, Mundali, Madanpur Rampur, G Udayagiri, Baliguda, Tikabali, Bhadrak & Batlig – 7 each
Jharkhand: Bokaro - 8, Chandil - 7
West Madhya Pradesh: Udaipura & Mehgaon – 7 each
East Madhya Pradesh: Sagar & Panna – 9 each, Gadarwara – 8, Narsinghpur - 7
Chhattisgarh: Ramanujganj & Manendragarh – 9 each

7th September

Odisha: Phiringia & Ambabhona – 19 each, , K Nuagaon - 18 , Binika - 17 , Batli - 16 , Baliguda & Nawana - 15 each, Rajkanika & Narsinghpur – 14 each, Birmaharajpur, Joda, Ullunda, Raikia, Chandbali & Binjharpur – 13 each, Jhumpura & Dunguripalli - 12 each, Tensa, Jajpur, Akhuapada, Tihidi & Sonepur – 11 each, Khairamal, Korei, Danagadi, Salebhatta, Pattamundai, Gania, Athmalik & Rajkishorenagar - 10 each, Deogarh, Daringibadi, Panposh, Boudhgarh, Barpalli, Rairakhol, Daspalla & Dhamnagar – 9 each, Bonth, Bargarh, Barmul, Tikabali, Sukinda, Kantamal, Banki, Hindol & Joshipur - 8 each, Bargaon, Daitari, Rajgangpur, Jamankira, Madanpur Rampur, Saintala & Mandira Dam – 7 each
Jharkhand: Kurdeg – 8
Chhattisgarh: Raigarh - 13 , Gharghoda & Janakpur – 9 each
East Madhya Pradesh: Umaria & Dindori – 8 each, Satna & Anuppur - 7 each

8th September

West Madhya Pradesh: Guna & Sheopur – 11 each, Biaora - 8, Begumganj & Rajgarh – 7 each
East Madhya Pradesh: Umaria - 16, Panna, Chahtarpur & Khurai – 9 each, Tikamgarh - 8, Buxwaha & Katni – 7 each
Chhattisgarh: Pathalgaon & Manendragarh - 7 each,
Vidarbha: Mul – 7

9th September

East Rajasthan: Pisagan - 12, Mangrol -11, Bakani & Degod – 10 each, Bijoliya, Hindoli, Patan, Bundi & Kotri – 9 each, Jahazpur, Anta, Pachpahar – 8 each, Talera, Sarwar, Mandalgarh, Banera, Arai & Kota – 7 each
West Madhya Pradesh: Neemuch -11, Bhanpura – 8

2.10. Cyclonic Storm “DAYE” over Bay of Bengal (19– 22 September 2018)

2.10.1. Introduction

Cyclonic Storm (CS) Daye originated from a low pressure area (LPA) which formed over eastcentral Bay of Bengal (BoB) and adjoining Myanmar in the afternoon (0900 UTC) of 18th September. It lay as a well marked low pressure area (WML) over the same region in the morning (0300 UTC) of 19th September.

Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the night (1500 UTC) of 19th September. Moving nearly west-northwestwards, it intensified into a deep depression (DD) over westcentral BoB in the morning (0300 UTC) of 20th September and further into a cyclonic storm (CS) **“Daye**” in the same night (1500 UTC). It crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a cyclonic storm with a wind speed of 60-70 kmph gusting to 80 kmph during 1900-2000 UTC of 20th September. It continued to move west-northwestwards, weakened into a DD in the early morning (0000 UTC) of 21st , into a D in the same evening (1200 UTC) and into a WML over west Madhya Pradesh and adjoining east Rajasthan in the evening (1200 UTC) of 22nd September. It lay as a WML over southeast Rajasthan in the morning (0300 UTC) of 23rd. It lay over north Rajasthan and adjoining southwest Uttar Pradesh & south Haryana in the early morning (0000 UTC) of 24th and lay as an LPA over south Haryana and neighbourhood on 24th morning. It became less marked on 25th morning.

2.10.2. Salient Features:

The salient features of the system were as follows:

- It was the first cyclonic storm to develop over the north Indian Ocean in the month of September after 2005 when the cyclonic storm, Pyarr crossed Andhra Pradesh coast near Kalingapatnam on 21 September 2005.
- The system had intensification close to the coast 4 hrs prior to landfall.
- The system maintained the intensity of cyclonic storm for about six hrs only.
- It had straight and west-northwestward moving track till 0000 UTC of 20th which recurved northwards thereafter.
- The track length of the cyclone was 1550 km.
- It moved faster, as the 12 hour average translational speed of the cyclone was 26.2 kmph against LPA (1990-2013) of 13.7 kmph over north Indian Ocean.
- The peak maximum sustained surface wind speed (MSW) of the cyclone was 60-70 kmph gusting to 80 kmph (35 knots gusting to 45 knots) during 1500 UTC of 21st to 2100 UTC of 21st Sep.
- The lowest estimated central pressure was 992 hPa (from 1500 UTC to 1800 UTC of 21st Sep).
- The life period (D to D) of cyclone was 87 hours (3 days & 15 hours) against long period average (LPA) (1990-2013) of 4.45 days for cyclonic storm over Bay of Bengal.
- The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 0.35 X10^2 knots, 0.12 X 10^4 knots^2 and 0.04 X10^6 knots^3 respectively against LPA (1990-2013) of 0.49 X10^2 knots, 0.2 X 10^4 knots^2 and 0.08 X10^6 knots^3 during monsoon season for BoB.

2.10.3. Monitoring of CS, 'DAYE'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it"s genesis as low pressure area over BoB from 18th Sep onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations, Doppler Weather Radar (DWR) and available ships & buoy observations in the region. Various national and international numerical weather prediction 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 including Yemen, Oman and Somalia, National & State Disaster Management Agencies, general public and media since inception of the system over AS.

2.10.4. Brief life history

2.10.4.1. Genesis

Cyclonic Storm (CS) Daye originated from a low pressure area (LPA) which formed over eastcentral Bay of Bengal (BoB) and adjoining Myanmar in the afternoon (0900 UTC) of 18^{th} September. It lay as a well marked low pressure area (WML) over the same region in the morning (0300 UTC) of 19^{th} September. Under favorable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the night (1500 UTC) of 19^{th} September.

According to satellite imageries, intensity of the system was T 1.5. The maximum sustained wind speed is 15-20 kts gusting to 30 knots. The estimated central pressure was 1002 hPa. Associated broken low and medium clouds with embedded intense to very intense convection over west central bay and neighborhood. The minimum cloud top temperature was minus 93^0C.

Considering the environmental conditions, the sea surface temperature (SST) was 27-29^0C over central BoB & adjoining north BoB. The tropical cyclone heat potential was about 60-80 kj/cm2 over this region. Madden Julian Oscillation index lies in phase 3 with amplitude less than 1 favoring cyclogenesis and further intensification. The low level relative vorticity is about $150x10^{-6}sec^{-1}$to the northeast of system centre. The lower level convergence is about 20 $x10^{-5}sec^{-1}$ to the southwest of centre of system.The upper level divergence is about 20 $x10^{-5}sec^{-1}$ to the southwest of the centre of system and is about 20 $x10^{-5}sec^{-1}$ to the southeast of the centre of system. The vertical wind shear is moderate (10-25 knots) around the system centre and it incerases towards north Andhra and Odisha coasts. The upper tropospheric ridge runs along 26^{o}N. hence, the winds are east southeasterly over the region in upper troposphere. Under these conditions, the well marked low pressure area concentrated into a depression on 19th morning.

2.10.4.2. Intensification and movement

According to satellite imageries, intensity of the system was C.I. 2.0 at 0300 UTC of 20th September. Associated Broken low to medium clouds with embedded intense to very intense convection lay over west central bob and neighborhood. The minimum cloud top temperature was minus 93^0C. the maximum sustained wind speed was 25-30 knots gusting to 35 knots. The estimated central pressure was 996 hpa. The sea condition is very rough over the region of the deep depression.

Considering the environmental conditions, the sea surface temperature (SST) was 28-30^{0}C over north BoB & adjoining west central BoB. The tropical cyclone heat potential was about 50-80 kj/cm2 over this region. Madden Julian Oscillation index continued in phase 3 with amplitude less than 1. The low level relative vorticity was about 150x10^{-6}sec^{-1} to the northeast of system centre. The lower level convergence was about 30 x10^{-5}sec^{-1} to the southwest of system centre. The upper level divergence was about 20 x10^{-5}sec^{-1} to the southwest of the centre of system. The vertical wind shear was low to moderate (10-20 knots) to the northwest of the system centre and is high elsewhere. The upper tropospheric ridge ran along 26^0 N. Hence, the upper troposphere winds were predominantly east-north easterlies becoming east southeasterly towards the coast. thus, the system intensified into DD and moved west-northwestwards towards south Odisha and adjoining north Andhra coast.

Under similar environmental conditions, it moved west-northwestwards and intensified further into a cyclonic storm (CS) “DAYE” in the night (1500 UTC) of 20th September.

It crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a cyclonic storm with a wind speed of 60-70 kmph gusting to 80 kmph during 1900-2000 UTC of 20th September. It continued to move west-northwestwards, weakened into a DD in the early morning (0000 UTC) of 21st, into a D in the same evening (1200 UTC) and into a WML over west Madhya Pradesh and adjoining east Rajasthan in the evening (1200 UTC) of 22nd September. It lay as a WML over southeast Rajasthan in the morning (0300 UTC) of 23rd. It lay over north Rajasthan and adjoining southwest Uttar Pradesh & south Haryana in the early morning (0000 UTC) of 24th and lay as an LPA over south Haryana and neighbourhood on 24th morning. It became less marked on 25th morning The observed track of the system during 19th – 22nd September is presented in **Fig. 2.10.1**.

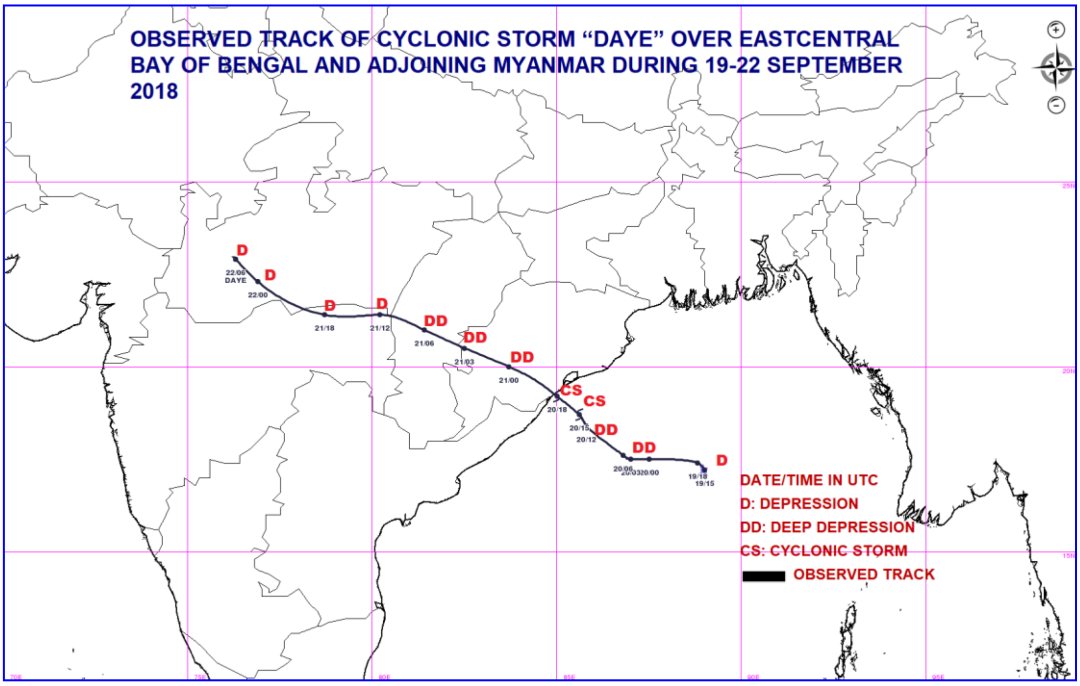


Fig. 2.10.1 Observed track of CS Daye (19-22 September, 2018) over Bay of Bengal

Table 2.10.1: Best track positions and other parameters of the Cyclonic Storm, 'Daye' over the Bay of Bengal during 19-22 September, 2018

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
19/09/2018	1500	17.2	89.0	**1.5**	997	25	3	**D**
	1800	17.4	88.8	**1.5**	996	25	4	D
20/09/2018	0000	17.5	87.5	**1.5**	996	25	4	D
	0300	17.5	87.0	**2.0**	995	30	5	**DD**
	0600	17.6	86.8	**2.0**	995	30	5	DD
	1200	18.4	85.8	**2.0**	994	30	6	DD
	1500	18.7	85.6	**2.5**	992	35	8	**CS**
	1800	19.2	85.0	**2.5**	992	35	8	CS
		Crossed south Odisha and adjoining north Andhra Pradesh coasts close to Gopalpur near 19.27^{0}N/84.92^{0}E between 1900-2000 UTC of 20th September 2018						
21/09/2018	2100	19.6	84.4	-	993	35	7	CS
	0000	20.0	83.7	-	994	30	6	**DD**
	0300	20.5	82.5	-	994	30	6	DD
	0600	21.0	81.4	-	995	30	5	DD
	1200	21.4	80.2	-	996	25	4	**D**
	1800	21.4	78.7	-	996	25	4	D
22/09/2018	0000	22.3	76.9	-	997	25	4	D
	0300	22.9	76.3	-	998	20	3	D
	0600	22.9	76.3	-	999	20	3	D
	1200	Weakened into a well-marked low pressure area over west Madhya Pradesh and adjoining east Rajasthan						

The TPW imageries during 20-21 Sep. 2018 are presented in **Fig. 2.10.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system, even when the system was located over land. However, over the land surface, there was land interaction and moisture supply also reduced relatively. As a result, though the system weakened, it maintained the intensity of depression/deep depression till 22nd September 2018.

The wind speed in middle and deep layer around the system centre is presented in **Fig. 2.10.3**. The wind shear around the system between 200 & 850 hPa levels remained high(20-30 knots). However, it decreased gradually from the genesis stage to dissipation stage. The direction of 200-850 hPa wind shear was northeasterly during the period. It caused the convective cloud mass to be sheared to the southwest of the system centre.

From **Fig. 2.10.3**, it indicates that from the genesis stage, the mean deep layer winds between 200-850 hPa levels steered the system initially north-morthwestwards and then northwestwards. till 17th and then southwestwards.

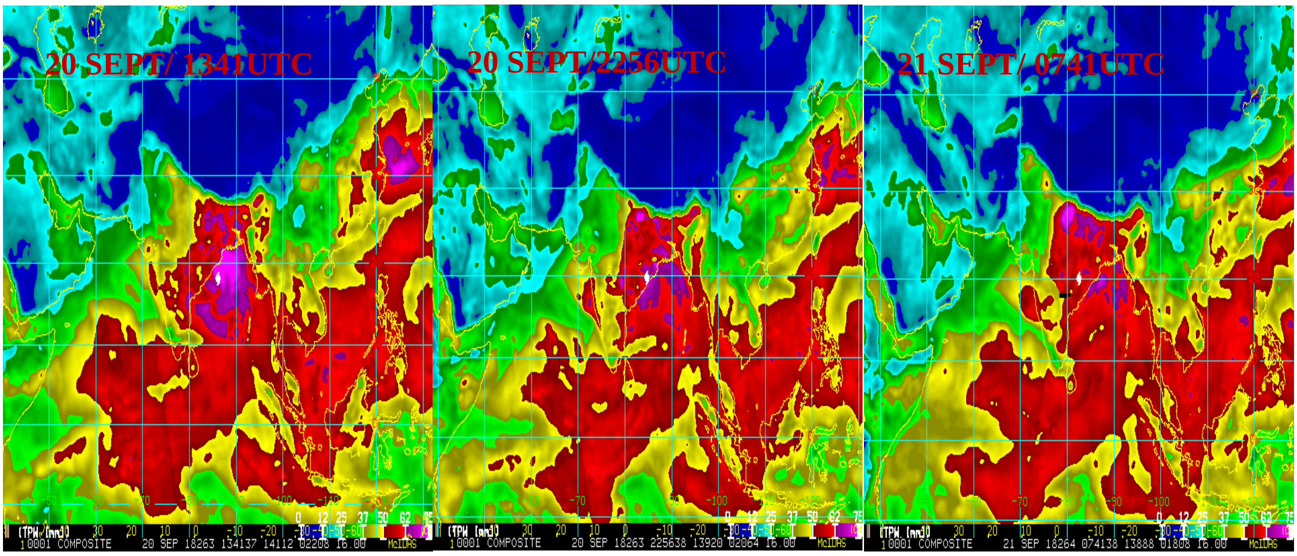


Fig. 2.10.2: Total Precipitable Water (TPW) imageries during 19-22 September, 2018

The twelve hourly movement of CS Daye is presented in **Fig. 2.10.4**. The 12 hour average translational speed of the cyclone was about 26 kmph and hence the cyclone was fast moving in nature.

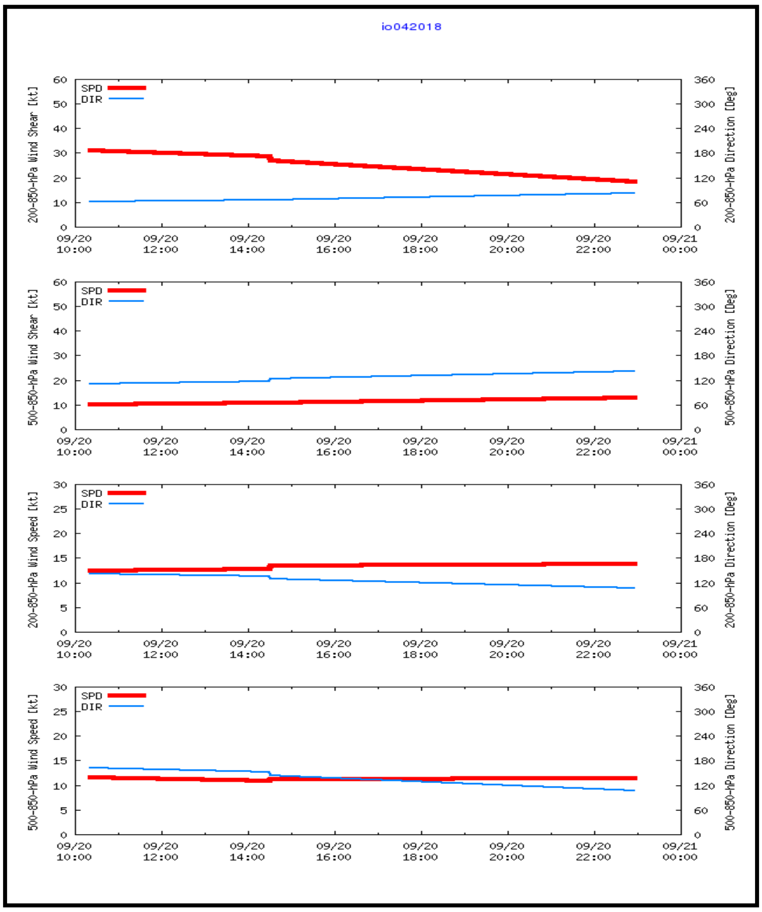


Fig. 2.10.3 Wind shear and wind speed in the middle and deep layer around the system during 19-22 September 2018.

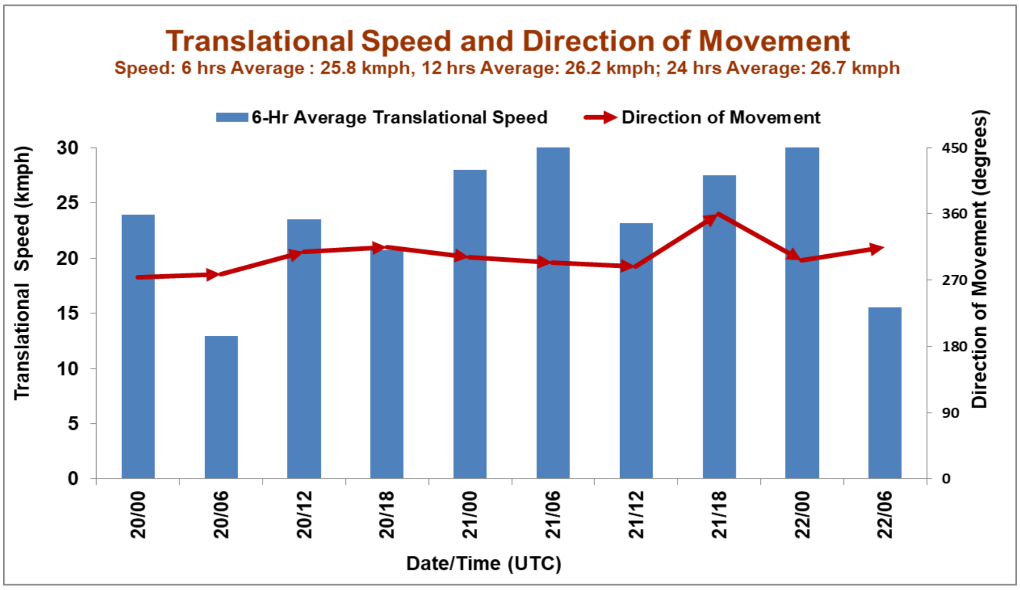


Fig. 2.10.4 Twelve hourly average translational speed (kmph) and direction of movement in association with CS Daye

2.10.5. Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig. 2.10.5**. The lowest estimated central pressure had been 992 hPa during 1500-1800 UTC of 20th. The estimated maximum sustained surface wind speed (MSW) was 35 knots during the same period. At the time of landfall, the ECP was 992 hPa and MSW was 35 knots (cyclonic storm).

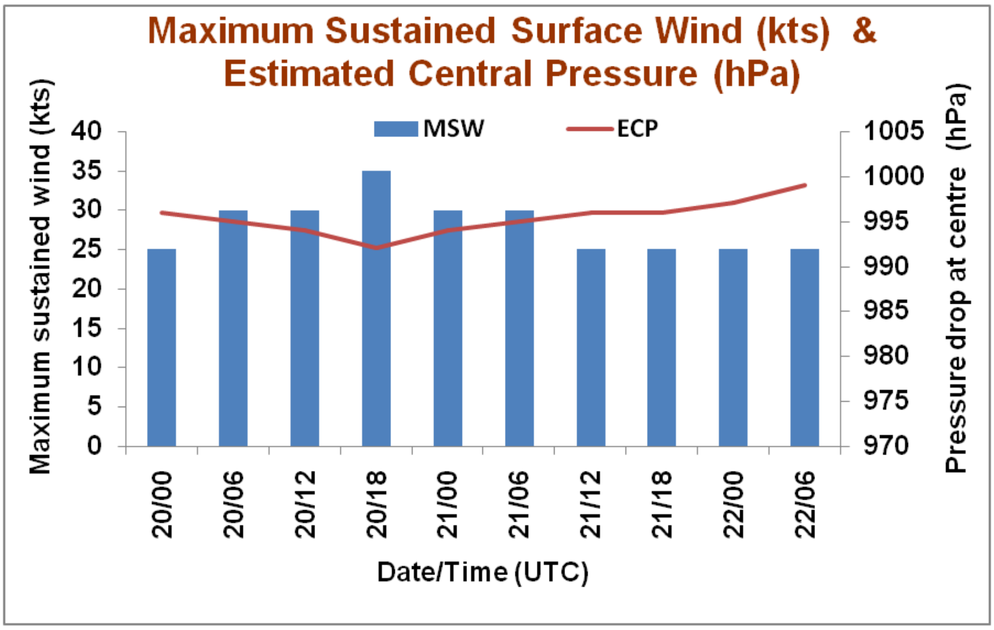


Fig. 2.10.5. Lowest estimated central pressure and the maximum sustained wind speed

2.10.6. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.10.6**. The imageries indicated the shear patter of the system and the convective clouds were sheared to the southwest of the system centre.

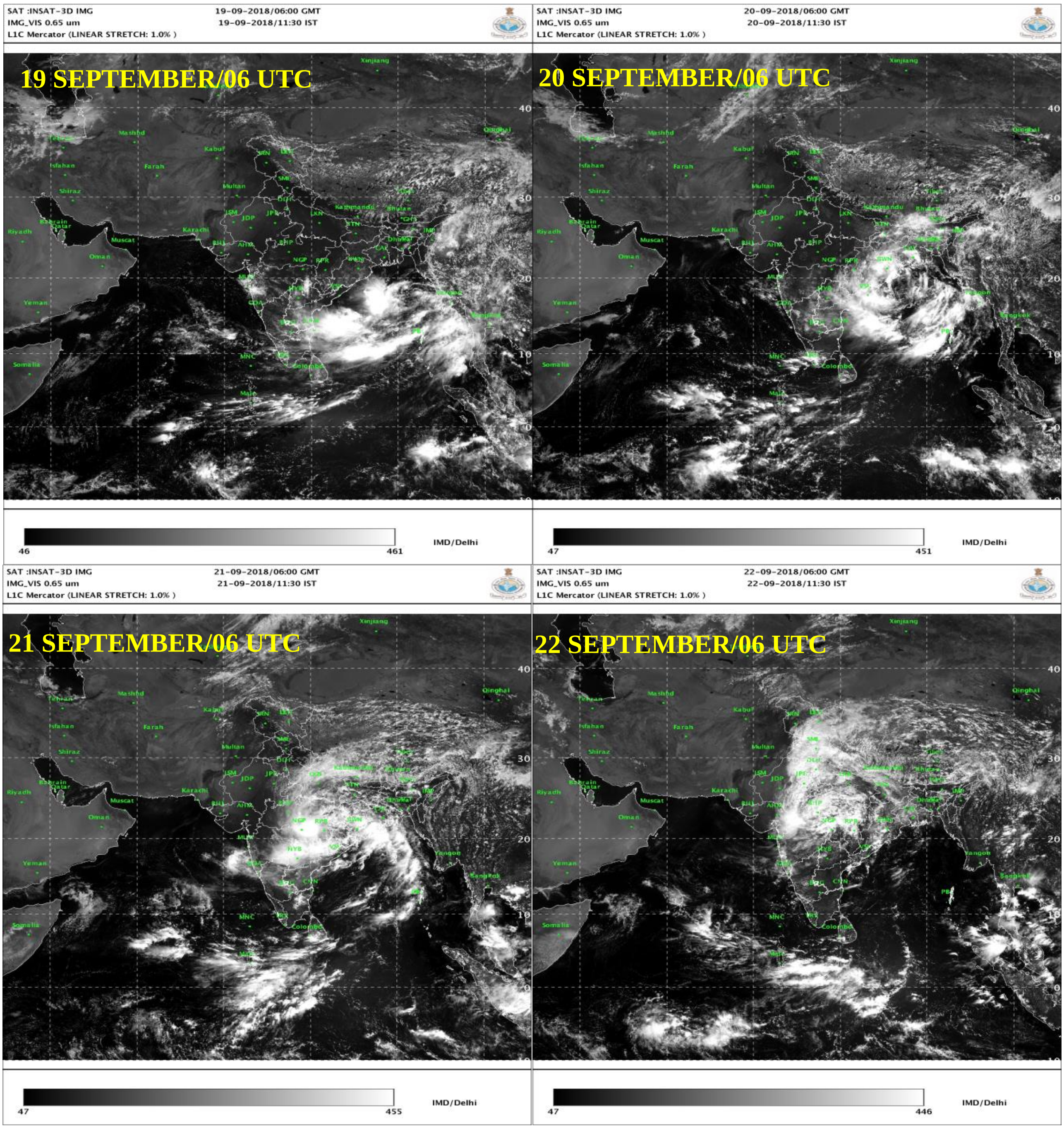


Fig. 2.10.6a: INSAT-3D visible imageries during life cycle of CS DAYE (19-22 September, 2018)

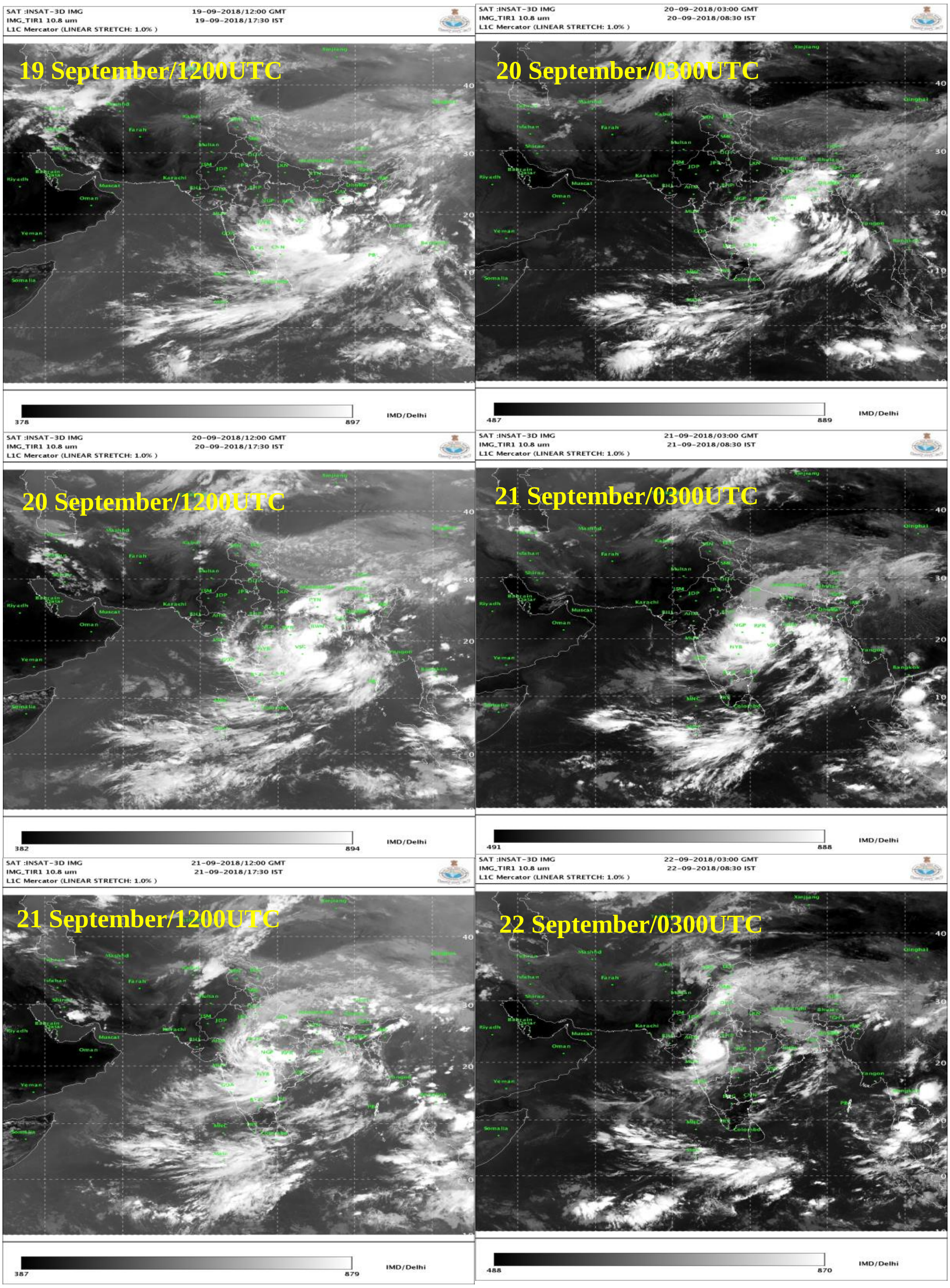


Fig. 2.10.6b: INSAT-3D IR imageries during life cycle of CS DAYE (19-22 September, 2018)

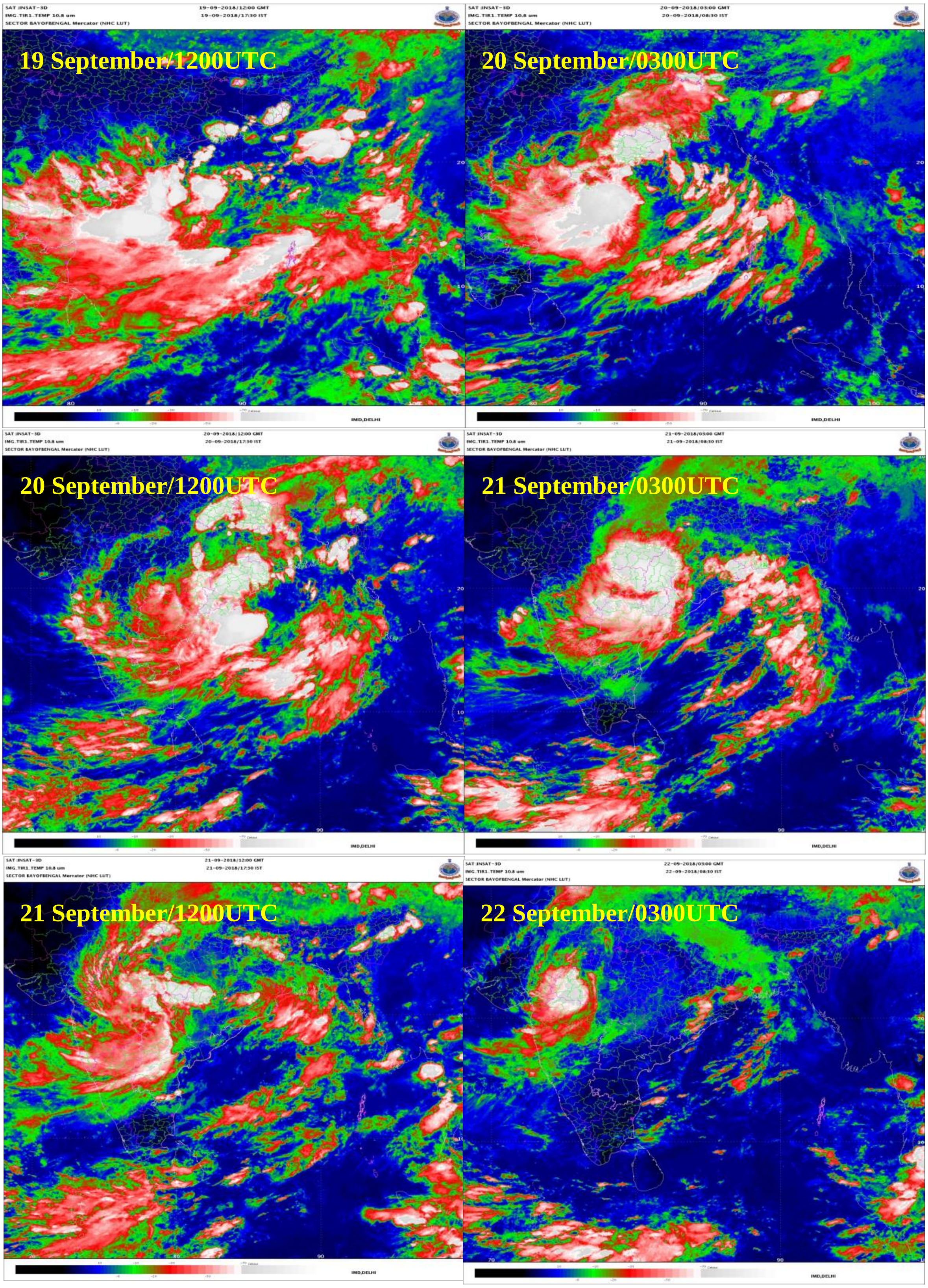


Fig. 2.10.6c: INSAT-3D enhanced colored imageries during life cycle of CS DAYE (19-22 September, 2018)

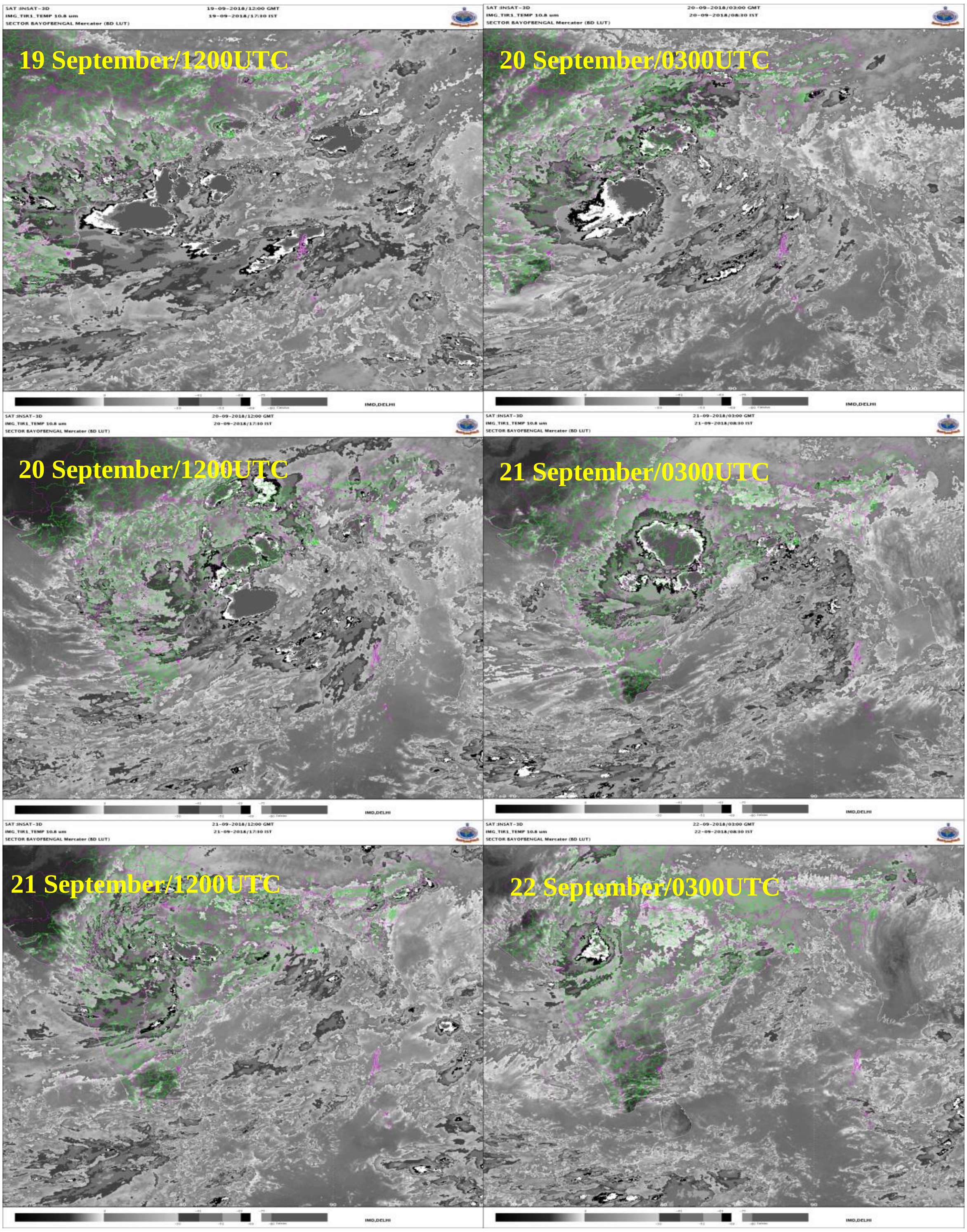


Fig. 2.10.6d: INSAT-3D cloud top brightness temperature imageries during life cycle of CS DAYE (19-22 September, 2018)

2.10.7. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 19th-21st September are presented in Fig. 2.10.7. GFS (T1534). Analysis based on 0000 UTC of 19th to 22th September, indicates that the model highly underestimated the intensity of the system. Based on 0000 UTC observations of 19th, the model indicated formation of low over eastcentral BOB with associated cyclonic circulation extending upto 500 hPa level. Similar was the situation of underestimation of intensity on 20th and 21st. However, the model could detect the track of the system.

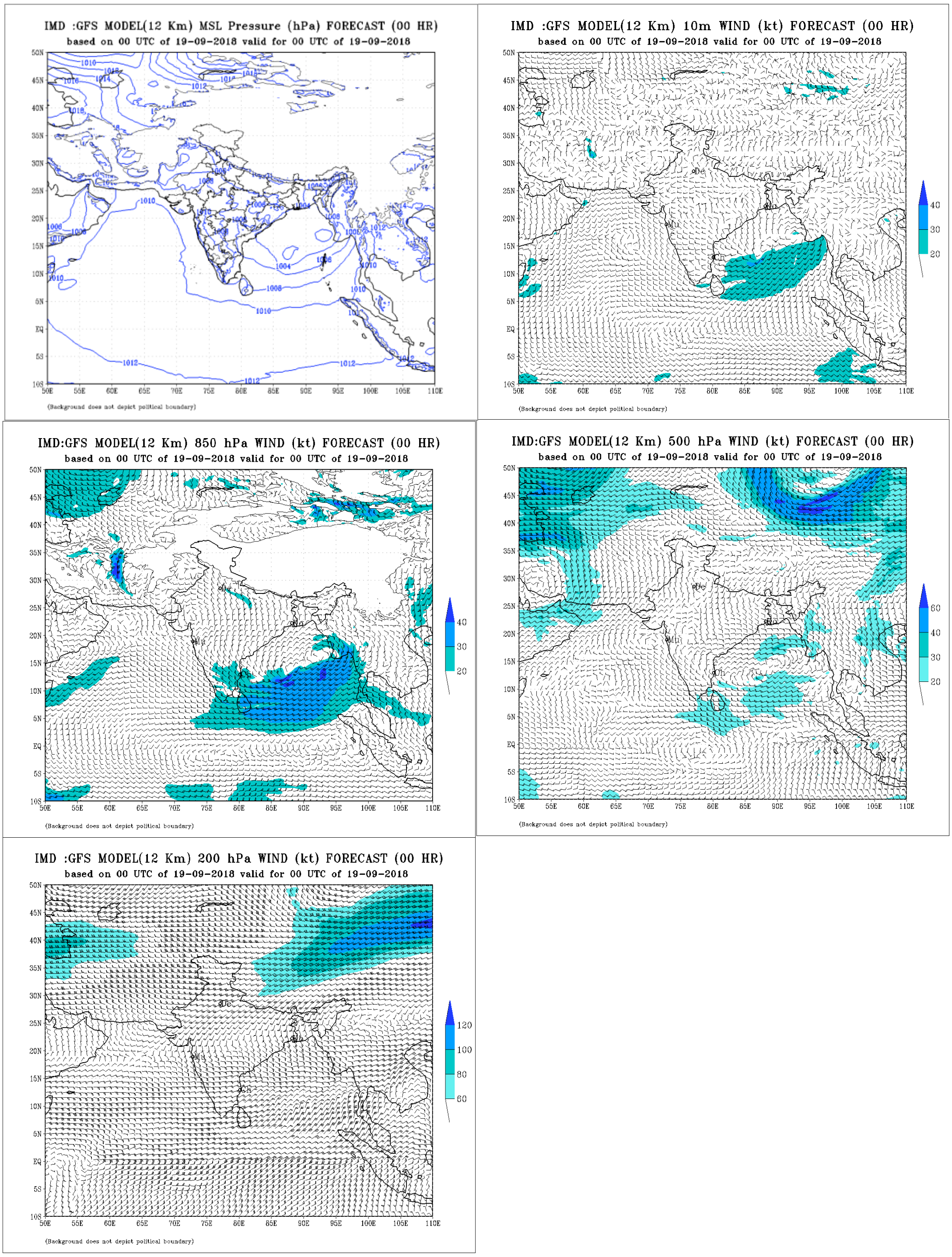


Fig. 2.10.7(a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th September 2018

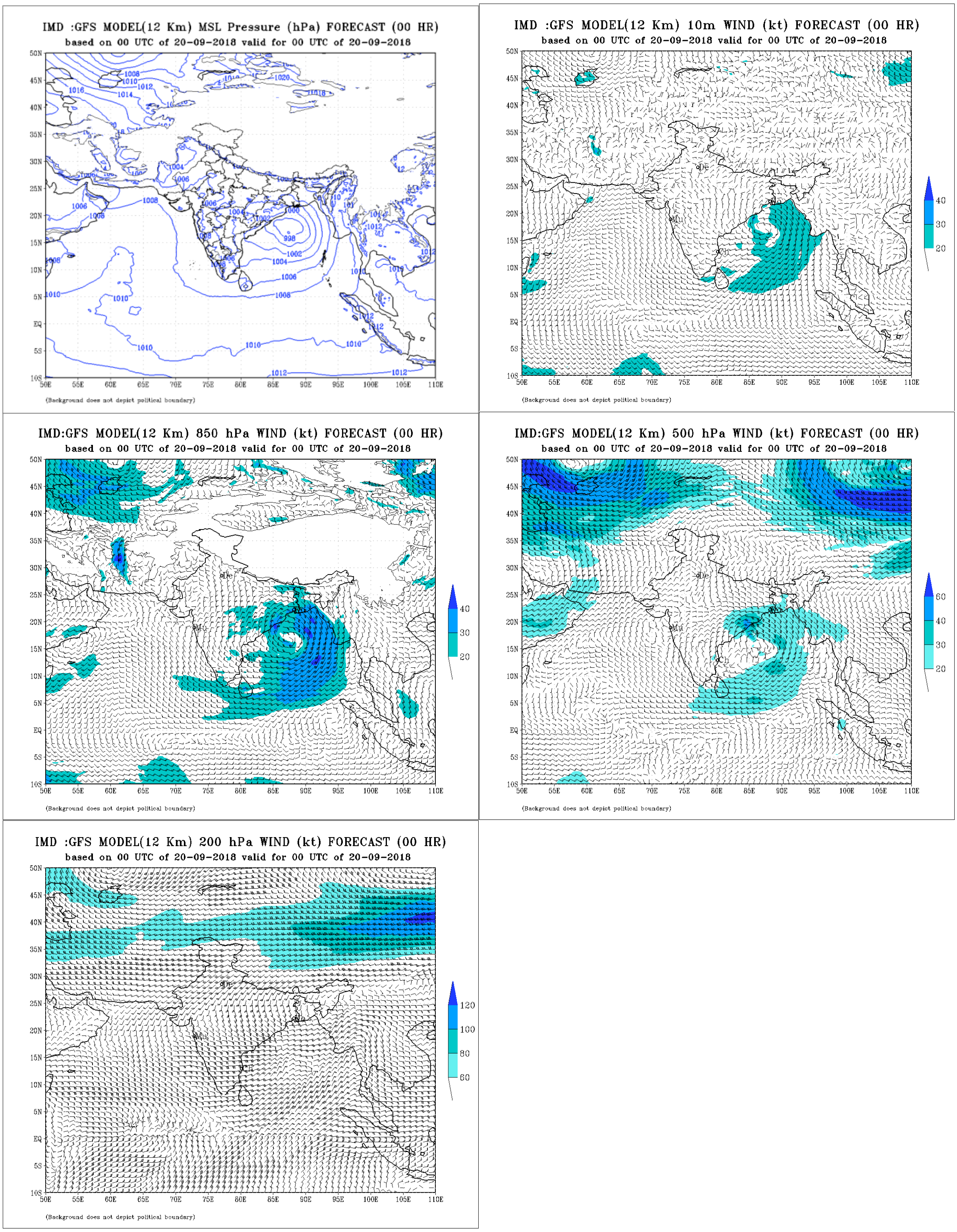


Fig. 2.10.7(b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th September 2018

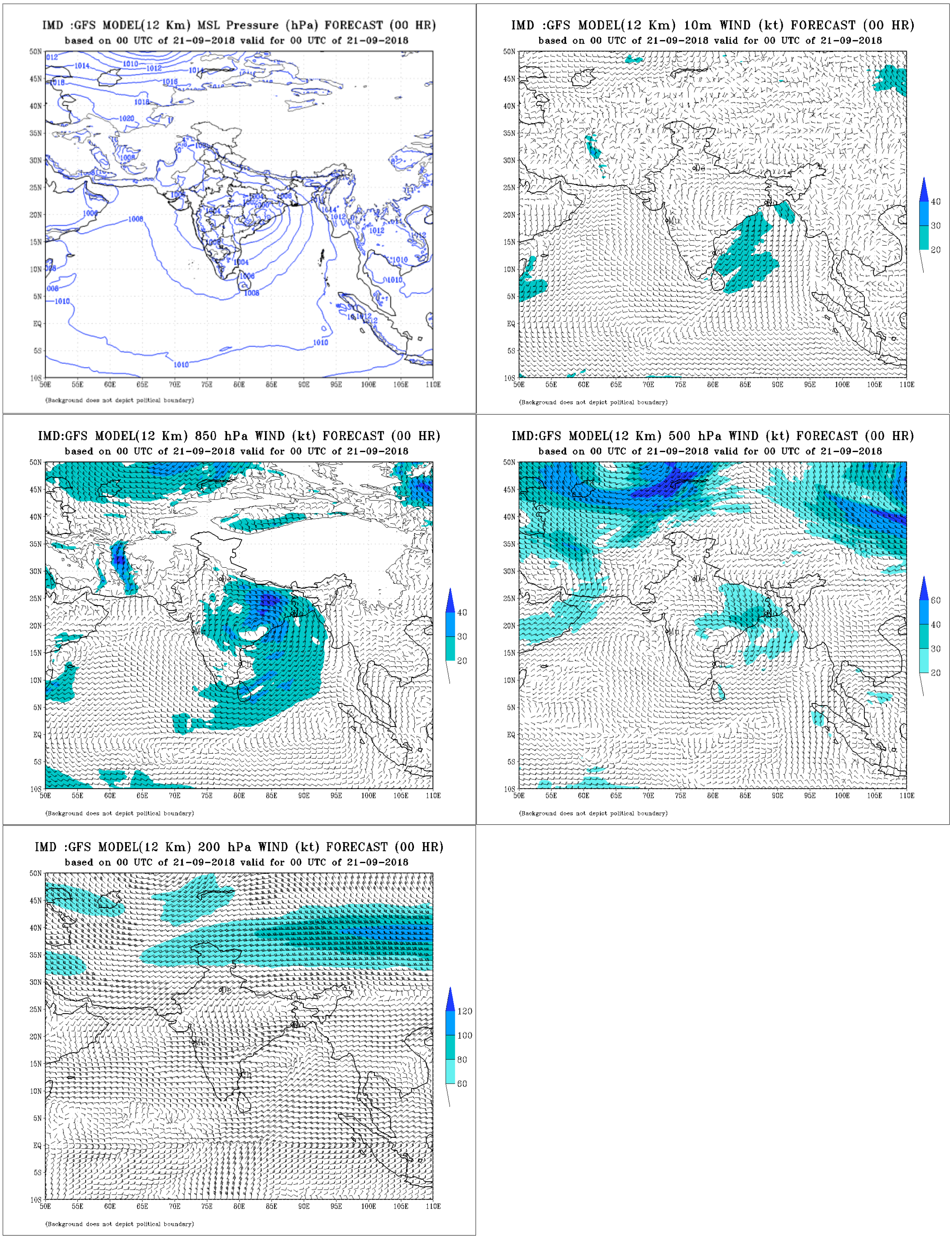


Fig. 2.10.7(c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21^th^ September 2018

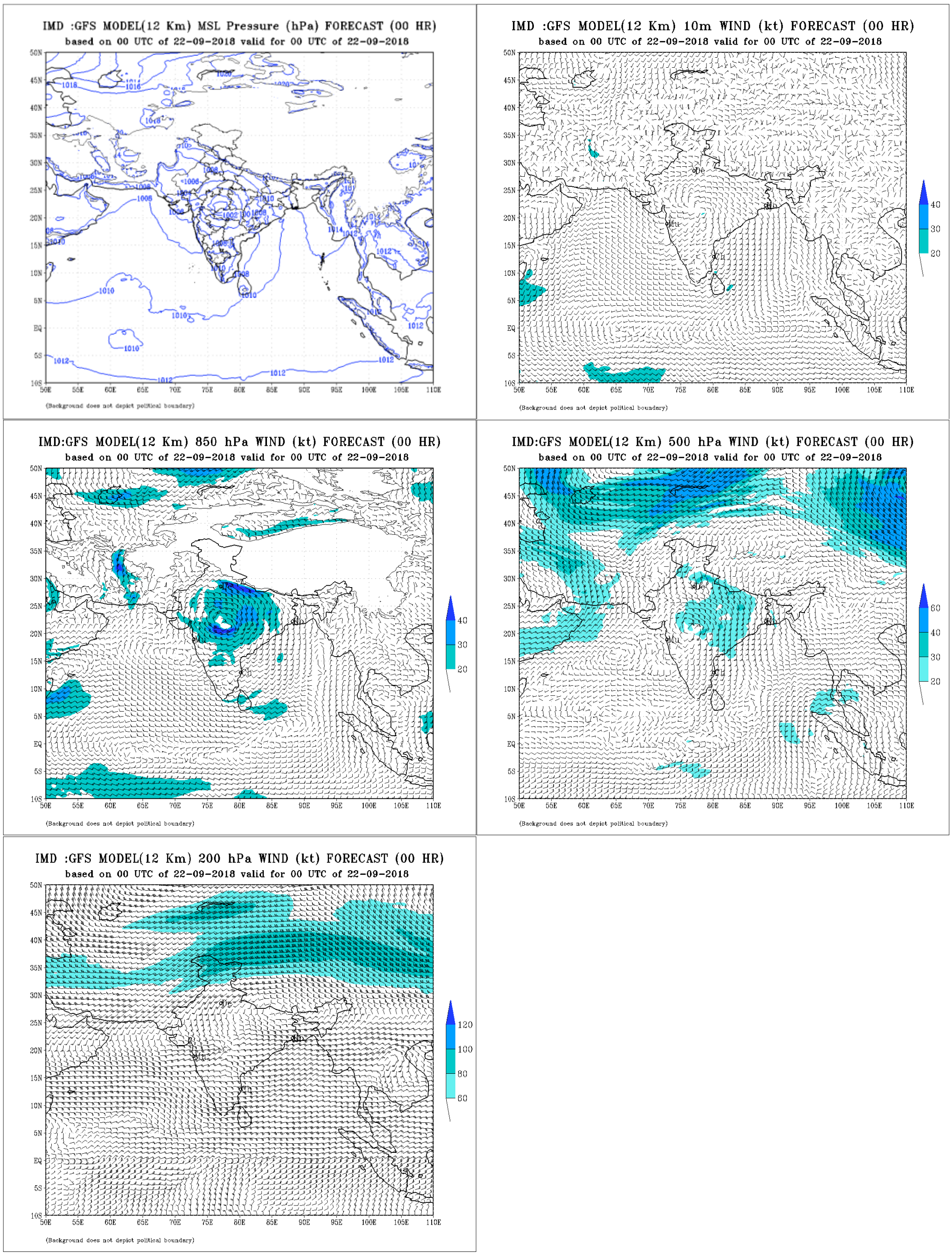


Fig. 2.10.7(d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th May

2.10.8. Realized Weather:

2.10.8.1. Rainfall

Rainfall associated with CS Daye based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 2.10.8**.

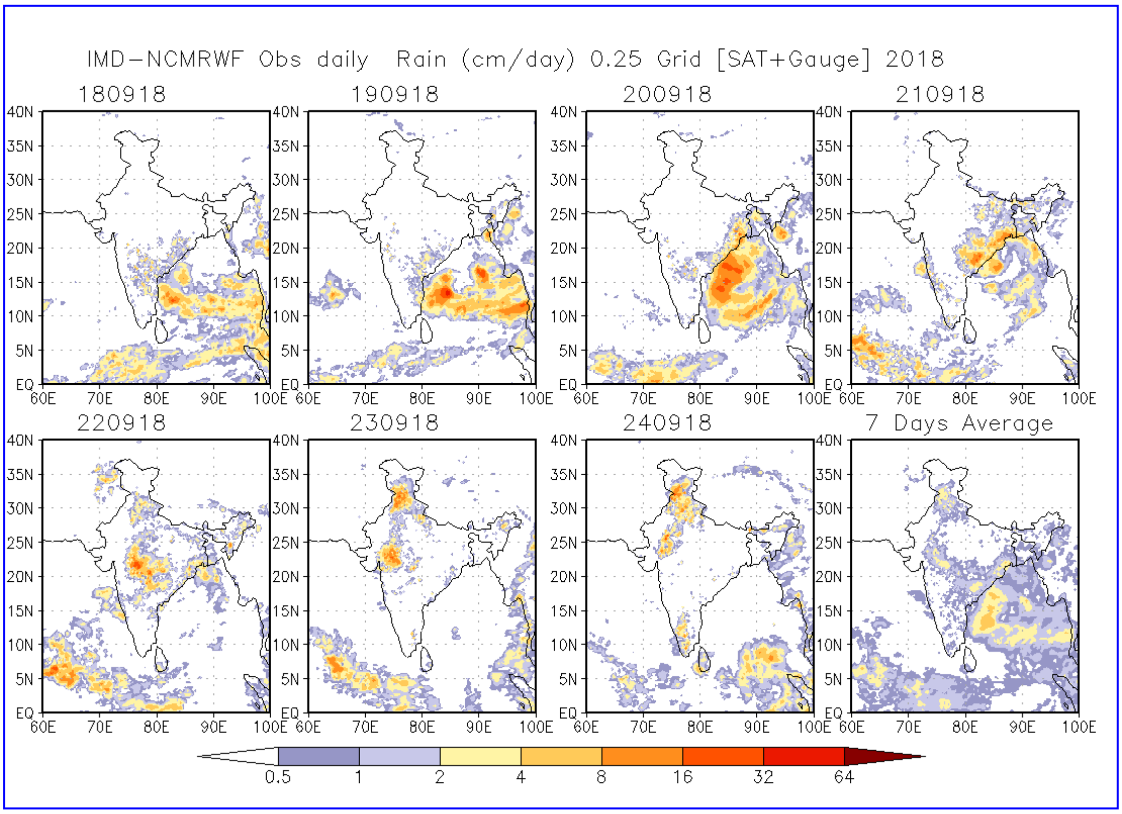


Fig.2.10.8: IMD-NCMRWF GPM merged gauge rainfall during during 18 – 24 September and 7 days average rainfall (cm/day)

Under the influence of this system, on 20th rainfall occurred at most places with heavy to extremely heavy rainfall (20 cm or more in 24 hrs) at isolated places over Odisha with heavy to very heavy rainfall at isolated places over north Andhra Pradesh and Chhattisgarh. On 21st, rainfall occurred at most places with heavy to very heavy rainfall at a few places and extremely heavy falls at isolated places over Vidarbha during past 24 hours. It caused rainfall at many places with heavy to very heavy rainfall at a few places over Telangana. Rainfall occurred at many places with isolated heavy falls over Marathwada, Madhya Maharashtra, East Rajasthan, Himachal Pradesh, Chattisgarh and moderate rainfall activity occurred over Uttar Pradesh, Uttrakhand, Haryana, Chandigarh and Delhi. On 22nd, rainfall occurred at most places with heavy to very heavy rainfall at a few places over west Madhya Pradesh, east Rajasthan, Punjab & Himachal Pradesh and heavy to very heavy falls at isolated places over Gujarat during past 24 hours. On 23rd and 24th, It caused rainfall at many places with heavy rainfall at isolated places over west Uttar Pradesh, Uttrakhand and Haryana & Chandigarh and rainfall at a few places with heavy rainfall at isolated places over Jammu & Kashmir. Moderate rainfall activity was observed at a few places over west Rajasthan, east Uttar Pradesh, Madhya Maharashtra and at most places over Delhi. Realized 24 hrs accumulated rainfall (≥5cm) ending at 0830 hrs IST of date during the life cycle of the system is presented below:

21st September

Odisha: Jaipur - 29, Malkangiri - 28, Similiguda - 21, Udala - 19, Remuna - 17, Balasore - 14, Daitari - 13, Kaptipada - 12, Soro, Jeypore, Balimundali, NH5 Gobindpur, Talcher, Anandpur & Nilgiri – 11 each, Narsinghpur, K Nuagaon, Koraput, Tikabali, Rajghat, Bhograi, Hindol & Jaleswar – 10 each, Komna, Harichandanpur, Gania, Pottangi, Berhampur, Jamsolaghat, Parjang, Baripada, Sukinda, Danagadi & Paikmal – 9 each, Betanati, Daspalla, Khandapara, Nawapara, Bonth, Gopalpur & Binjharpur – 8 each, Banki, Chandanpur, Nawarangpur, Satyabadi, Phulbani, Ghatagaon, Batagaon, Akhuapada, Jajpur, Athgarh, Dhamnagar, Ranpur, Raghunathpur, Tikarpara, Mundali, Tangi, Kosagumda, Kalinga, Tentulikhunti, Joshipur & Korei – 7each

Coastal Andhra Pradesh: Chintur - 10, Bobbili - 8, Pathapatnam & Kunavaram – 7 each

Gangetic West Bengal: Contai - 25, Barrackpur & Durgachack – 9 each, Midnapore, Mohanpur & Digha – 8 each, Midnapore & Diamond Harbour – 7 each

Chattisgarh: Konta & Sukma – 9 each and Jagdalpur – 8

22nd September

Himachal Pradesh: Renuka / Dadhau - 7

East Rajasthan: Bakani - 8

Madhya Maharashtra: Raver - 7

Marathwada: Vasmat - 7

Vidarbha: Hinganghat - 23 , Warora - 13 , Deoli, Wardha, Dharni & Chikhalda - 12 each, Chandur & Selu – 9 each, Chandur Bazar - 8 , Samudrapur, Tiwsa, Ralegaon & Kharangha – 7 each ,

Telangana: Utnur - 13 , Manthani - 11 , Shriramsag.Pocha - 10 , Adilabad, Karimnagar, Mallial & Karimnagar - 9 each, Julapalle, Jagtial, Thimmapur, Metpalle, Mogullapalle & Bhupalpalle - 8 each, Nirmal, Sultanabad, Khanpur, Mortad, Sirsilla, Kammar Palle, Sarangapur & Kaleswaram - 7 each

23rd September

West Uttar Pradesh: Shahjahapur & Shahjahanpur – 7 each,

Uttarakhand: Banbasa - 9,

Haryana, Chandigarh & Delhi: Chandigarh & Naraingarh – 8 each, Guhla, Chandigarh, & Chandigarh SASE – 7 each

Punjab: Hoshiarpur - 17, Adampur & Nangal – 15 each, Halwara - 14, Jalandhar - 13, Anandpur Sahib - 12, Hoshiarpur & Salern (District: Hoshiarpur) – 11 each, Nawanshahr & Khanna – 10 each, Balachaur - 9, Patiala Rev, Sirhind, Pathankot , Mukerian & Ludhiana – 8 each, Tibri, Fatehgarh Sahib, Sangrur, Derabassi (Basi), Gurudaspur, Kharar & Malakpur – 7 each

Himachal Pradesh: Naina Davi - 18, Sarkaghat - 14, R L Bbmb, Mehre (Barsar), Manali, Dharmsala & Aghar – 13 each, Una & Barthin – 12 each, Jogindarnagar, Sujanpur Tira, Kasauli & Bharari – 11 each, Nadaun, Kangra & Baijnath – 10 each, Palampur & Seo Bagh – 9 each, Ghamroor, Dharampur, Gulern & Kahu – 8 each, Nagrota Surian, Bhuntar & Sangraha – 7 each

Jammu & Kashmir: Udhampur - 10, Jammu & Katra – 9 each, Samba - 7

East Rajasthan: Bhungra - 15, Pipalkhunt - 14, Banswara, Khushalgarh, Sallopat - 13, Pratapgarh - 11, Arnod - 10, Ghatol & Shergarh – 9 each, Bhilwara Tehsil, Bhilwara, Garhi, Dug, Aspur, Jagpura, Salumber, Loharia, Gangdhar, Arthuna, Kherwara & Chhotisadri – 7 each,

Gujarat Region: Godhra - 10, Dahod - 9, Morva Hadaf - 8, Quant, Meghraj, Santrampur, Modasa, Chhota Udepur, Jhalod, Garbada & Fatepura – 7 each

West Madhya Pradesh: Jhabua AWS - 19, Badnagar - 14, Jaora, Khachrod & Gandhwani - 13 each, Sailana & Kasarwad - 12 each, Depalpur - 11, Manawar, Nalchha, Dhar-AWS, Sardarpur & Thandla - 10 each, Neemuch AWS, Badnawar, Maheshwar, Mahidpur & Gautampura - 9 each, Bhikangaon & Mandsaur AWS - 8 each, Jabot, Jawad, Ratlam-Aws, Thikri & Petlawad - 7 each,

24th September 2018

West Madhya Pradesh: Jawad - 9,

Gujarat Region: Bhiloda - 14, Vijaynagar - 8, Idar - 7

East Rajasthan: Deogarh - 17, Jawaja - 17, Nayanagar/Beawar - 16, Tatgarh, Bhim – 11 each, Amet, Pipalkhunt, Veja, Arnod, Kanva, Pratapgarh – 9 each, Raipur, Nimarana, Chittorgarh – 8 each, Gangrar, Rashmi, Aspur, Sahada – 7 each

West Rajasthan: Raipur - 7,

Punjab: Pathankot - 24, Gurudaspur - 24, Kapurthala - 23, Taran Taran - 21, Amritsar - 20, Tibri - 18, Mukerian - 17, Ranjit Sagar Dam Site - 15, Malakpur - 15, Madhopur - 15, Shahpur Kandi - 14, Phangota - 14, Nakodar - 9, Salern - 9, Hoshiarpur - 9, Rajpura - 8, Patiala Rev - 8, Adampur, Samana, Khanna, Raya, Patiala, Faridkot, Faridkot, Muktsar – 7 each

Himachal Pradesh: Dalhousi Alha - 17, Kheri - 16, Dharmshala - 14, Dehra Gopipur, Manali, Kangra, Naina Davi, Chamba – 12 each, Guler, Palampur – 11 each, Ghamroor - 10, Nagrota Surian, Bangana, Amb – 9 each, Tissa, Bharwain, Nadaun, Baijnath – 8 each, Sujanpur Tira - 7,

Haryana, Chandigarh and Delhi: Assandh - 16, Karnal - 14, Thanesar - 12, Kurukshetra - 12, Nilokheri - 11, Jagadhari, Radaur – 9 each, Safidon - 8, Bilaspur, Karnal Rev, Indri, Gurgaon Rev, Chhachhrauli, Panipat, Bhiwani, Bhiwani Rev, Guhla – 7 each

West Uttar Pradesh: Gautam Buddha Nagar - 12, Moradabad, Gunnaur – 7 each,

Uttarakhand: Banbasa - 8, Purola, Roorkee-7 each

25th September

West Uttar Pradesh: Muzaffarnagar - 16, Thakurdwara - 13, Budhana, Dhampur, Bijnor – 10 each, Meerut, Mawana – 8 each, Moradabad, Gautam Buddha Nagar – 7 each

Uttarakhand:

Banbasa - 11, Pantnagar, Haldwani – 7 each,

Haryana, Chandigarh & Delhi: Guhla - 11, Sonepat - 9, Pilukhera - 8, Chandigarh - 7

Punjab: Hoshiarpur - 15, Nangal, Hoshiarpur – 14 each, Khanna - 13, Fatehgarh Sahib - 10, Patiala - 9, Anandpur Sahib, Ludhiana – 8 each, Samrala, Ropar, Patiala Rev – 7 each

Himachal Pradesh: Jhandutta - 19, Naina Davi - 18, Una, Mehre (Barsar) – 14 each, Una Rampur - 13, R L Bbmb, Dharampur – 10 each, Banjar, Sarkaghat – 9 each, Gohar, Barthin, Bharari – 8 each, Aghar, Ghumarwin, Bangana - 7 each,

2.10.8. Damage due to CS, Daye

No significant damage was reported due to this storm. However, it caused flood over Odisha due to heavy rainfall.

2.11. Very Severe Cyclonic Storm, 'LUBAN' over the Arabian Sea (06 – 15 October 2018)

2.11.1. Introduction

2.11.1.1. Brief Life History:

- Very Severe Cyclonic Storm (VSCS) Luban originated from a low pressure area (LPA) which formed over southeast Arabian Sea (AS) and neighbourhood in the morning (0830 IST/0300 UTC) of 5th October. It lay as a well marked low pressure area (WML) over southeast and adjoining eastcentral AS in the morning (0530 IST/0000UTC) of 6th October.
- Under favourable environmental conditions, it concentrated into a Depression (D) over southeast and adjoining eastcentral AS in the afternoon (1430 IST/0900 UTC) of 6th October. Moving west-northwestwards, it intensified into a deep depression (DD) over the same region in the afternoon (1430 IST/0900 UTC) of 7th October. It further intensified into a cyclonic storm (CS) **"Luban**" in the early morning (0530 IST/0000 UTC) of 8th October over westcentral and adjoining south & eastcentral AS.
- Moving further west-northwestwards it intensified, into a severe cyclonic storm (SCS) in the afternoon (1430 IST/0900 UTC) of 9th over westcentral AS.
- It then moved northwestwards and further intensified into a very severe cyclonic storm (VSCS) in the early morning (0530 IST/0000 UTC) of 10th over westcentral AS. It attained it‟s peak intensity of 75 kts around noon (1130 IST/0600 UTC) of 10th.It maintained it‟s peak intensity till early morning(0530 IST/0000 UTC) of 11th.
- Thereafter, it experienced unfavourable environment like colder sea and dry & cold air advection from Arabian Peninsula and hence, it started weakening. It weakened into an SCS in the morning (0830 IST/0300 UTC) of 12th and into a CS in the same midnight (2330 IST/1800 UTC).
- It crossed Yemen and adjoining south Oman coasts near 15.8^{0}N and 52.2^{0}E during 1100-1130 hrs IST (0530 to 0600 UTC) of 14th as a CS with the wind speed of 70-80 gusting to 90 kmph.
- After landfall, it weakened quickly into a DD in the afternoon (1430 IST/0900 UTC) of 14th, into a D in the same midnight (2330 hrs IST/1800 UTC) and into a WML over Yemen and adjoining Saudi Arabia in the morning (0830 IST/0300 UTC of 15th)**.**

The observed track of the system during 06th-15th October is presented in **Fig. 2.11.1**. The best track parameters of the system are presented in **Table 2.11.1**.

2.11.1.2. Salient Features:

The salient features of the system were as follows:

- Luban was the third cyclonic storm to cross Arabia & African coasts after CS Sagar and extremely severe cyclonic storm (ESCS) Mekunu during May 2018. Thus there had been three landfalling cyclones over Arabia & African coasts during 2018 against 8 such cyclones during the entire satellite era (1961-2017). Hence, the frequency of landfalling cyclones over the region has been significantly higher this year.
- Similarly there has been genesis of three cyclonic storms over the AS so far during 2018 against about one cyclone per year over the AS. 62 cyclones developed over the AS during the satellite era (1961-2017).
- Just after the genesis of VSCS, Luban over Arabian Sea, another cyclonic storm Titli developed over Bay of Bengal simultaneously. It was one of the rarest of rare events

that simultaneously two very severe cyclonic storms developed over Arabian Sea and Bay of Bengal. Simultaneous occurrence of such two VSCSs last occurred in November 1977, viz. (i) Bay of Bengal Super Cyclonic Storm (14-20 Nov., 1977) which crossed Andhra Pradesh coast near Chirala on 19th Nov. and (ii) Bay of Bengal VSCS (09-23rd Nov., 1977) which crossed Tamil Nadu coast close to south of Nagapattinam on 12th Nov. and then emerged into Arabian Sea, made a looping track, intensified into an SCS, weakened thereafter and crossed Karnataka coast to the north of Mangalore on 29th Nov. as a depression. The observed track of these simultaneous systems viz. Titli and Luban is presented in **Fig. 2.11.2**.

- The system exhibited rapid intensification during 0600 UTC of 9th to 0600 UTC of 10th Oct with increase in maximum sustained wind speed from 45 knots at 0600 UTC of 9th to 75 knots at 0600 UTC of 10th.
- The peak maximum sustained surface wind speed (MSW) of the cyclone was 135-145 kmph gusting to 160 kmph (75 knots gusting to 85 knots) during 0600 UTC of 10th to 0000 UTC of 11th Oct. The lowest estimated central pressure was 978 hPa during the period.
- The system crossed Yemen and adjoining Oman coasts near 15.8^{0}N and 52.2^{0}E during 0530 to 0600 UTC of 14th as a cyclonic storm with maximum sustained wind speed of 40 kts (70-80 kmph gusting to 90 kmph) .
- The life period (D to D) of the system was 210 hours (8 days & 18 hours) against long period average (LPA) (1990-2013) of 107 hours for VSCS over Arabian Sea during post monsoon season.
- It moved slower with 12 hour average translational speed of 10.4 kmph against LPA (1990-2013) of 13.8 kmph for VSCS over Arabian Sea.
- The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 14.1 X10^2 knots, 8.11 X 10^4 knots^2 and 4.92 X10^6 knots^3 respectively.
- The track of the system was unique in the sense that the system experienced very slow movement and multiple recurvatures during 0000 UTC of 9th to 0600 UTC of 12th and change from westward to northwestward movement on 14th Oct. (six hours before landfall).

2.11.2. Monitoring of VSCS, 'LUBAN'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it"s genesis as low pressure area over Arabian Sea from 8th October onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, ASCAT, polar orbiting satellites, scatterometer observations and available ships & buoy observations in the region. Various national and international numerical weather prediction 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 World Meteorological Organisation (WMO), WMO/ESCAP Panel member countries including Yemen, Oman, Saudi Arabia, Iran, Qatar, Sri Lanka, Maldives, National & State Disaster Management Agencies, general public along the west coast of India and media since inception of the system over AS. Typical satellite imageries are presented in **Fig. 2.11.4**.

2.11.3. Brief life history

2.11.3.1. Genesis

An upper air cyclonic circulation lay over southeast AS and adjoining Lakshadweep & Maldives area extending upto mid-tropospheric levels at 0300 UTC of 4th October 2018. Under it‟s influence, an LPA formed over southeast AS and neighbourhood at 0300 UTC of 5th October 2018. Considering the environmental conditions at 0300 UTC of 5th, the Madden Julian Oscillation (MJO) index was in phase 1 with amplitude more than 1. The sea surface temperature (SST) was 29°-31˚C over southeast and eastcentral AS. It was around 26°-29°C over westcentral and southwest AS. The SST was decreasing slightly towards Oman coast. The tropical cyclone heat potential was about 60-80 KJ/cm^2 over southeast and adjoining eastcentral AS off Oman coast. It was less than 50 KJ/cm^2 to the north of 17.0° N and west of 60.0^0E. The low level relative vorticity was east-west oriented and was around 50-70 $x10^{-5}$ sec^{-1} over south AS. The lower level convergence and upper level divergence were about 20 $x10^{-5}sec^{-1}$ over southeast AS and was east-west oriented. The vertical wind shear was low (5-10 knots(kt)) over central & south AS and Lakshadweep. It was increasing becoming more than 20 kt to the north of 20^0N over north AS & near Oman coast. The upper tropospheric ridge ran along 15^0N. The similar environmental conditions prevailed and the LPA lay as a WML over southeast and adjoining eastcentral AS at 0000 UTC of 6th October.

Under the favourable environmental conditions, at 0900 UTC of 6th, the system intensified into a depression over the same region and lay centered near 11.2°N and longitude 67.0°E, 730 km west-northwest of Minicoy (43369). The MJO index lay in phase 1 with amplitude more than 1. Similar thermodynamical conditions prevailed over the AS like previous day. The low level relative vorticity organised during previous 12 hours. The low level relative vorticity was around 50 $x10^{-5}$ sec^{-1} to the south of system centre. The positive vorticity zone was extending upto 500 hpa level. The lower level convergence was about 10 $x10^{-5}sec^{-1}$ over southeast AS to the southwest of system centre. The upper level divergence was the same about 20 $x10^{-5}sec^{-1}$ to the northwest of system centre. The vertical wind shear was low to moderate (5-15 kt) around the system centre and (10-20 kt) over central parts of AS. It was increasing becoming more than 25 kt to the north of 15^0N over AS & near Oman coast. The upper tropospheric ridge runs along 16^0 N.

2.11.3.2. Intensification and movement

The depression moved west-northwestwards, intensified into a DD and lay centered at 0900 UTC of 7th over southeast & adjoining eastcentral AS near latitude 12.0°N and longitude 64.8°E, about 1280 km east-southeast of Salalah (41316), 1180 km east-southeast of Socotra Islands (41494) and 980 km west-northwest of Minicoy (43369). The MJO index lay in phase 1 with amplitude more than 1. The low level relative vorticity increased significantly and was around 100 $x10^{-5}sec^{-1}$ to the south of system centre. The vorticity zone was extending upto 500 hpa level. The lower level convergence was about 10 $x10^{-5}sec^{-1}$ to the south and 20 $x10^{-5}sec^{-1}$ to the west of system centre. The upper level divergence increased and was of the order 30 x 10^{-5} sec^{-1} to the northwest of system centre. The vertical wind shear was moderate (10-15 kt) around the system centre. The animation of total precipitable water (TPW) imageries indicated, the warm and moist air advection to the core of the system. The upper tropospheric ridge ran along 16^0N. Hence, during it‟s west-northwestwards movement, the system intensified gradually. However, it was expected that as the system would reach near the coast, it would experience unfavourable conditions like high wind shear, lower SST & ocean heat content and cold air advection from land areas and would weaken.

At 0000 UTC of 8th, the system moved west-northwestwards, intensified into a CS and lay centered over westcentral and adjoining southwest AS near latitude 12.3°N and longitude 62.4°E, about 1040 km east-southeast of Salalah (Oman), 920 km east-southeast of Socotra Islands (Yemen). The low level relative vorticity increased significantly and was around 200 $x10^{-5}sec^{-1}$ around system centre. Tthe vorticity zone extended upto 200 hpa level. The lower level convergence increased significantly and was about 40 $x10^{-5}sec^{-1}$ to the southwest of the system centre and divergence also increased and was of the order 40 $x10^{-5}sec^{-1}$ to the southwest of the system centre. The vertical wind shear was moderate (15-25 kt) around the system centre. The animation of TPW imageries indicated the warm and moist air advection to the core of the system. The upper tropospheric ridge continued to run along 16^0 N making system to move west-northwestwards.

The CS further intensified into an SCS and lay centered at 0900 UTC of 09th October, over westcentral & adjoining southwest AS, near latitude 13.2°N and longitude 60.0°E, about 760 km east-southeast of Salalah (41316), 660 km east of Socotra Islands (41494) and 900 km eastsoutheast of Al-Ghaidah (41398). The MJO lay in phase 1 with amplitude more than 1. The low level relative vorticity increased and was around 250 $x10^{-5}sec^{-1}$ around the system centre. The lower level convergence was about 30 $x10^{-5}sec^{-1}$ to the southwest of the system centre and divergence was of the order 30 $x10^{-5}sec^{-1}$ to the southwest of the system centre. The vertical wind shear was low to moderate (10-15 kt) around the system centre.

Thereafter, the system moved northwestwards, intensified into a VSCS and lay centered at 0000 UTC of 10th, over westcentral AS, near latitude 14.1°N and longitude 59.0°E, about 610 km east-southeast of Salalah (Oman), 570 km east-northeast of Socotra Islands (Yemen) and 770 km east-southeast of Al-Ghaidah (Yemen). The MJO lay in phase 1 with amplitude more than 1. The SST was around 28-29^{0}C around the system centre. TCHP was about 60-80 KJ/cm^2 near the system centre. It was less than 50 KJ/cm^2 to the north of 17.0^{0}N and west of 60.0^{0}E. The low level relative vorticity was about 250 $x10^{-5}sec^{-1}$ around the system centre and was extending upto 200 hpa level. The lower level convergence was about 20 $x10^{-5}sec^{-1}$ around the system centre and upper level divergence was of the order 30 $x10^{-5}sec^{-1}$ around the system centre. The vertical wind shear was low to moderate (10-15 kt) around the system centre and also along the forecast track. The animation of TPW imageries indicated the warm and moist air advection to the core of the system. The upper tropospheric ridge lay along 18^0 N. These features indicated the system would experience low to moderate wind shear, warmer SST & low ocean heat content and cold air advection from land areas while moving west-northwestwards. Under these conditions, the system moved west-northwestwards reached it‟s peak intensity of 75 kts at 0600 UTC of 10th. Thereafter, from 0300 UTC of 11th, it started weakening. At 0300 UTC of 11th, the system lay over westcentral AS, near latitude 14.5°N and longitude 58.0°E, about 500 km east-southeast of Salalah and 670 km eastsoutheast of Al-Ghaidah. MJO lay in phase 2 with amplitude more than 1 and was favouring of convective activity. The SST was 26-27^{0}C over westcentral and southwest AS. TCHP was less than 50 KJ/cm^2 to the west of 63.0^{0}E. The low level relative vorticity was around 300 x10-5sec-1 around the system centre and was extending upto 200 hpa level. The lower level convergence was about 20 $x10^{-5}$ sec^{-1} to the southeast of the system centre and upper level divergence was of the order 30 $x10^{-5}$ sec^{-1} to the southwest of system centre. The vertical wind shear was low (05-10 kt) around the system centre and also along the forecast track. The animation of TPW imageries indicated a relative reduction in the warm and moist air advection to the core of the system. The upper tropospheric ridge lay along 17^0 N. Lower SST and TCHP and decrease in warm moist air incursion into the core of system led to its gradual weakening.

At 0300 UTC of 12th, it weakened into an SCS. The low level relative vorticity decreased and was around 250 x$10^{-5}$$sec^{-1}$ around the system centre. The lower level convergence was about 30 x10-5sec-1 and upper level divergence was of the order 30 x10^{-5} sec^{-1} around the system centre. The vertical wind shear was low (05-10 kt) around the system centre and also along the forecast track. TPW imageries indicated a further reduction in the warm and moist air advection to the core of the system. In addition, it also indicated cold and dry air entrainment from the northwest reaching upto southern sector of the system. As a result the system showed disorganisation of clouds and hence slight weakening was expected during next 12 hrs.

At 1800 UTC of 12th, similar conditions prevailed and the system weakened further into a CS. Continuing to move west-northwestwards, it crossed Yemen and adjoining Oman coasts near 15.8^{0}N and 52.2^{0}E during 0530 to 0600 UTC of 14th as a CS with wind speed of 70-80 kmph gusting upto 90 kmph. The system weakened rapidly into a DD at 0900 UTC and into D at 1800 UTC of 14th due to land interaction and cold and dry air incursion from the west.

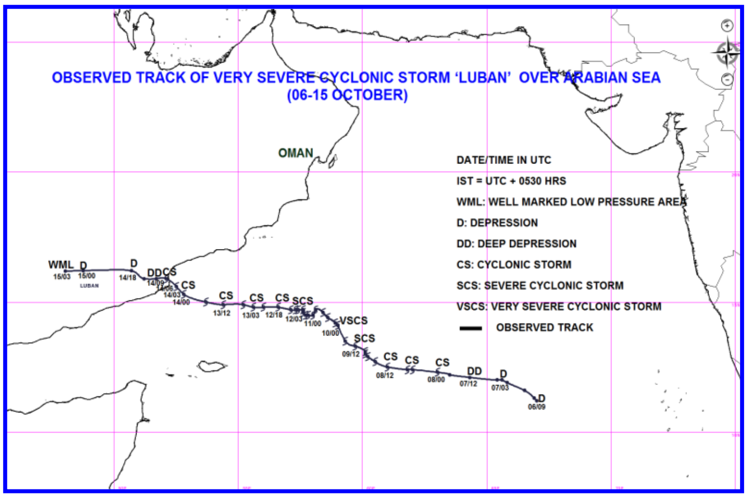


Fig. 2.11.1 Observed track of VSCS Luban (06-15 October, 2018) over Arabian Sea

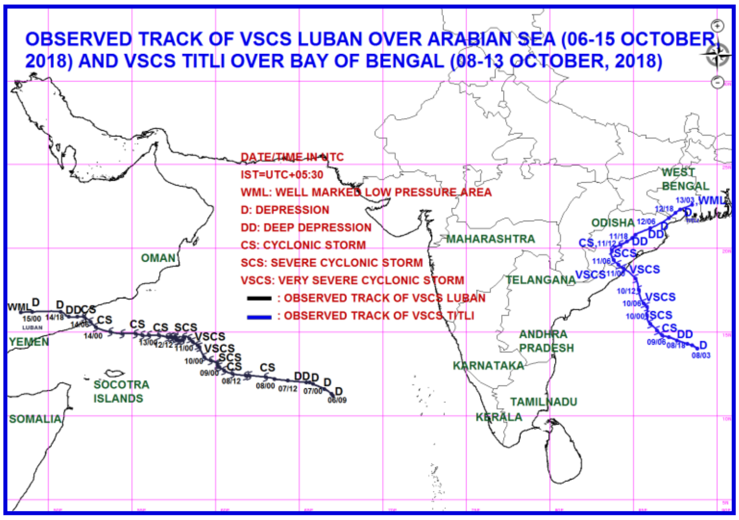


Fig. 2.11.2: Observed track of simultaneous systems viz. VSCS Luban over Arabian Sea (06-15 October, 2018) and VSCS Titli over Bay of Bengal (08-13 October, 2018)

Table 2.11.1: Best track positions and other parameters of the Very Severe Cyclonic Storm, 'LUBAN' over the Arabian Sea during 06-15 October, 2018

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
06/10/2018	0900	11.2	67.0	1.5	1003	25	3	**D**
	1200	11.3	66.9	1.5	1002	25	4	D
	1800	11.6	66.5	1.5	1002	25	4	D
07/10/2018	0000	11.9	65.8	1.5	1002	25	4	D
	0300	12.0	65.6	1.5	1002	25	4	D
	0600	12.0	65.4	1.5	1002	25	4	D
	0900	12.0	64.8	2.0	1001	30	5	**DD**
	1200	12.1	64.3	2.0	1001	30	5	DD
	1800	12.2	63.5	2.0	1000	30	6	DD
08/10/2018	0000	12.3	62.4	2.5	999	35	7	**CS**
	0300	12.4	62.0	2.5	998	40	8	CS
	0600	12.4	61.8	2.5	997	40	9	CS
	0900	12.5	61.5	3.0	996	45	10	CS
	1200	12.5	61.0	3.0	996	45	10	CS
	1500	12.6	60.8	3.0	996	45	10	CS
	1800	12.7	60.5	3.0	994	45	12	CS
	2100	12.8	60.2	3.0	994	45	12	CS
09/10/2018	0000	12.9	60.2	3.0	994	45	12	CS
	0300	13.0	60.1	3.0	994	45	12	CS
	0600	13.1	60.1	3.0	994	45	12	CS
	0900	13.2	60.0	3.5	992	50	14	**SCS**
	1200	13.3	59.7	3.5	990	55	16	SCS
	1500	13.4	59.5	3.5	990	55	16	SCS
	1800	13.5	59.3	3.5	990	55	16	SCS
	2100	13.6	59.1	3.5	988	60	18	SCS
10/10/2018	0000	14.1	59.0	4.0	985	65	21	**VSCS**
	0300	14.1	59.0	4.0	984	65	22	VSCS
	0600	14.2	58.9	4.5	978	75	28	VSCS
	0900	14.4	58.7	4.5	978	75	28	VSCS
	1200	14.4	58.6	4.0	978	75	28	VSCS
	1500	14.5	58.5	4.0	978	75	28	VSCS
	1800	14.6	58.4	4.0	978	75	28	VSCS
	2100	14.6	58.4	4.0	978	75	28	VSCS

11/10/2018	0000	14.7	58.1	4.0	978	75	28	VSCS
	0300	14.5	58.0	4.0	980	70	26	VSCS
	0600	14.5	57.8	4.0	980	70	26	VSCS
	0900	14.5	57.8	4.0	980	70	26	VSCS
	1200	14.5	57.7	4.0	980	70	26	VSCS
	1500	14.5	57.7	4.0	980	70	26	VSCS
	1800	14.6	57.6	4.0	980	70	26	VSCS
	2100	14.7	57.6	4.0	980	65	26	VSCS
12/10/2018	0000	14.7	57.6	3.5	984	60	22	VSCS
	0300	14.7	57.4	3.5	987	55	25	**SCS**
	0600	14.7	57.3	3.0	990	50	16	SCS
	0900	14.7	57.2	3.0	990	50	16	SCS
	1200	14.7	57.1	3.0	991	50	15	SCS
	1500	14.7	56.9	3.0	992	50	14	SCS
	1800	14.8	56.6	3.0	994	45	12	**CS**
	2100	14.8	56.3	3.0	994	45	12	CS
13/10/2018	0000	14.8	56.0	3.0	994	45	12	CS
	0300	14.8	55.6	2.5	994	40	12	CS
	0600	14.9	55.2	2.5	994	40	12	CS
	0900	14.9	54.8	2.5	994	40	12	CS
	1200	14.9	54.4	2.5	994	40	12	CS
	1500	14.9	54.0	2.5	994	40	12	CS
	1800	15.0	53.7	2.5	996	40	10	CS
	2100	15.1	53.3	2.5	996	40	10	CS
14/10/2018	0000	15.3	52.8	2.5	998	40	8	CS
	0300	15.6	52.5	2.5	998	40	8	CS
		Crossed Yemen and adjoining Oman coasts near 15.8^0N and 52.2^0E during 0530 to 0600 UTC						
	0600	15.9	52.1	**-**	999	35	7	CS
	0900	15.9	51.7	**-**	1000	30	6	**DD**
	1200	15.9	51.2	**-**	1001	30	5	DD
	1800	16.2	50.7	**-**	1002	25	4	**D**
15/10/2018	0000	16.2	49.0	**-**	1003	25	3	**D**
	0300	**Weakened into a well-marked low pressure area over Yemen and adjoining Saudi Arabia**						

The total precipitable water imageries (TPW) during 6-14 Oct. 2018 are presented in **Fig. 2.11.3**. These imageries indicated continuous warm and moist air advection from the southeast sector into the system during 8-11 and cold air advection thereafter from the northwest.

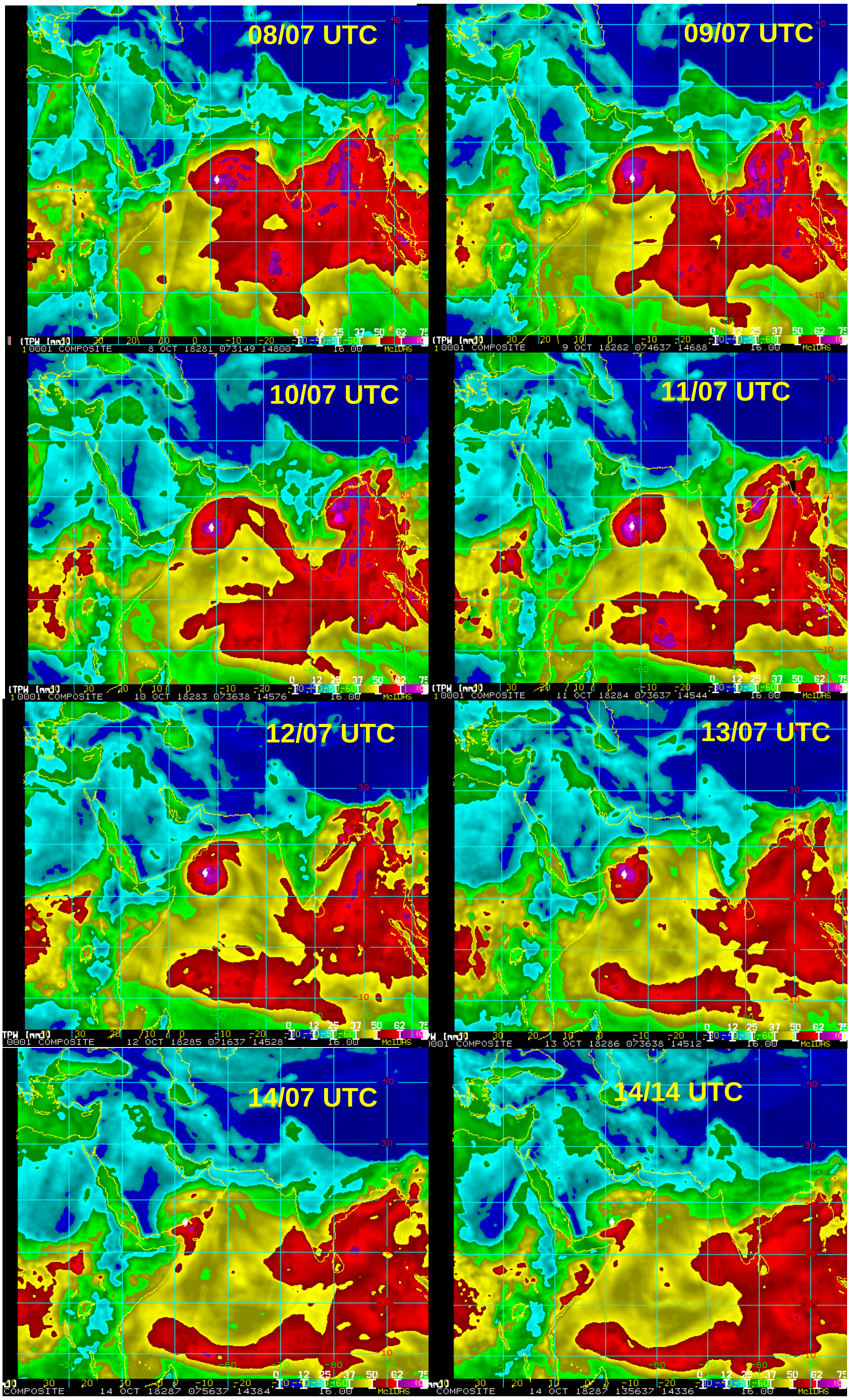


Fig. 2.11.3: Total Precipitable Water Imageries during 06-15 October, 2018

The mean wind speed in middle and deep layer around the system centre is presented in **Fig. 2.11.4**. The wind shear between lower to upper tropospheric levels around the system centre was less than 10 kt throughout the life period of the system since 9th morning. It was 10-20 kt during 6th-9th. However, the wind shear was minimum, less than 5 kt from 10th afternoon to 12th morning. This very low wind shear alongwith other environmental features helped in rapid intensification of the system attaining maximum intensity of 75 kts during this period. With increase in wind shear alongwith colder SST, system started weakening from 12th onwards. The wind shear variation between 850-500 hPa level showed similar variations. Considering the mean wind speed between 200-850 hPa levels, the mean wind speed was 5-10 kt till 9th morning. It then decreased gradually becoming less than 5 kt during 10th & 11th. It then increased gradually during 12th-14th becoming more than 5 kt on 14th. Considering the mean wind speed between 500-850 hPa level, wind speed was similar to above and the mean wind direction suggested west-northwestwards movement till 11th morning and thereafter, the mean wind was variable indicating practically stationary system. From 12th onwards, the mean wind speed increased and the system moved northwestwards as per the mean wind speed between 200-850 hPa level. Hence the system was mainly steered by 200-850 hPa level.

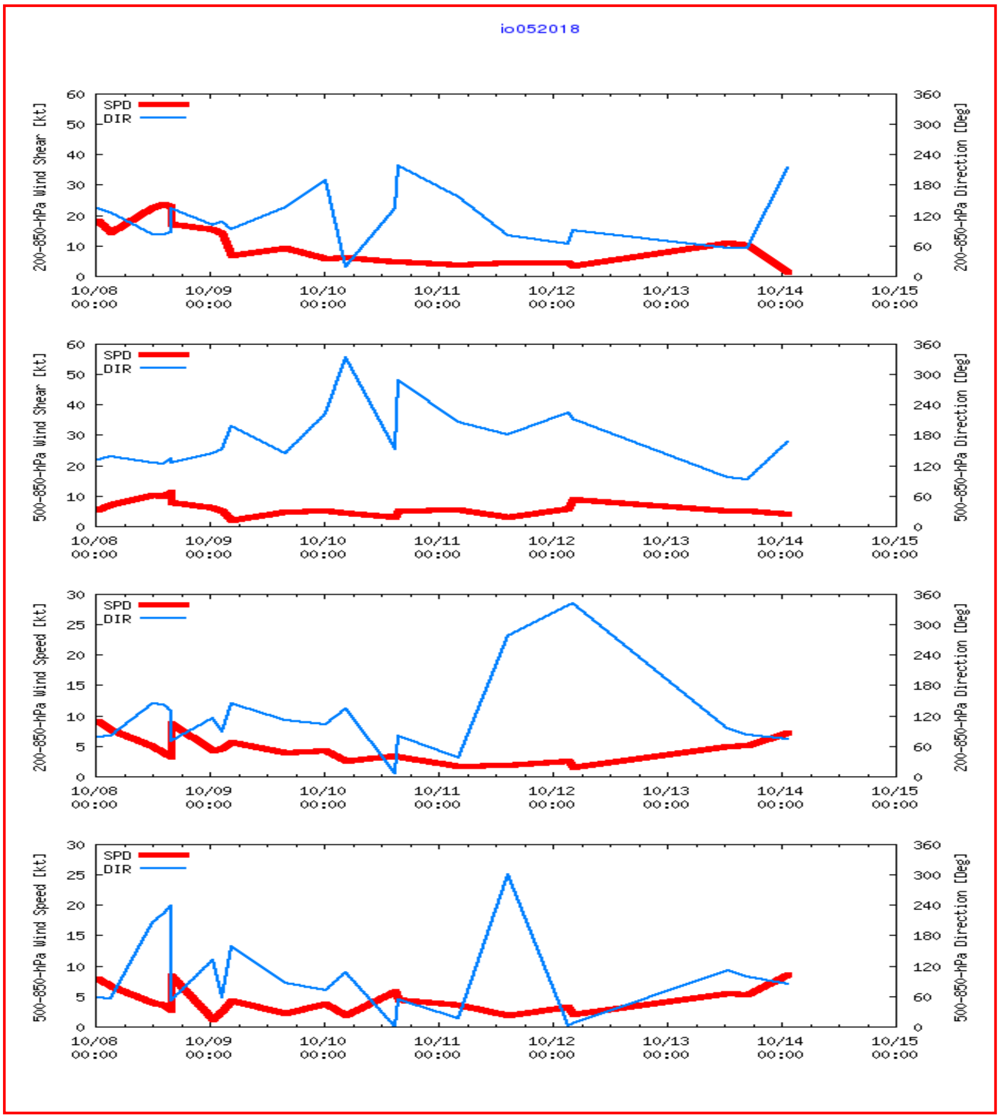


Fig. 2.11.4 Wind shear and wind speed in the middle and deep layer around the system during 10th to 15th October 2018.

The six hourly movement of VSCS Luban is presented in **Fig. 2.11.5**. The six hourly average translational speed of the cyclone was about 10.5 kmph and hence was slow moving in nature. The system had a track length of about 1385 km during its life period.

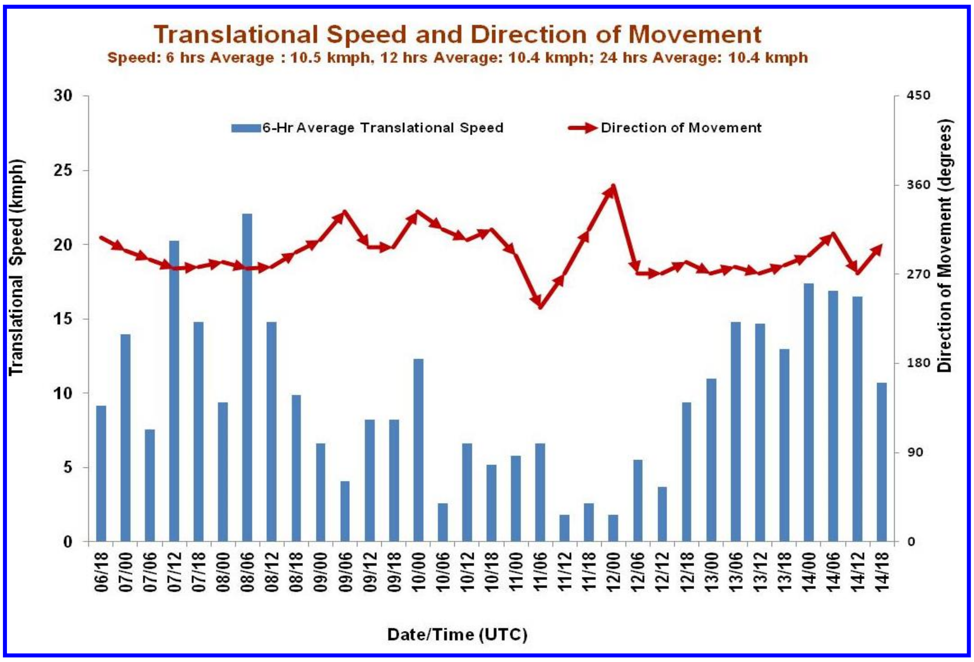


Fig. 2.11.5. Twelve hourly average translational speed (kmph) and direction of movement in association with VSCS Luban

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

The lowest estimated central pressure and the maximum sustained wind speed are presented in Table 2.11.1. The lowest estimated central pressure (ECP) had been 978 hPa during 0600 of 10th to 0000 UTC of 11th. The ECP gradually decreased from 1003 hPa at 0900 UTC of 6th to 994 hPa at 0600 UTC of 9th. Thereafter, there was a rapid decrease from 994 hPa to 978 hPa (16 hPa) during 0600 UTC of 9th to 0600 UTC of 10th (within 24 hrs). There was rise in ECP from 978 hPa (at 0300 UTC of 11th) to 994 hPa at 1800 UTC of 12th. Thereafter it increased gradually to 1003 hPa at 0000 UTC of 15th. Similarly, in the wind field it is seen that there was gradual increase in maximum sustained wind speed (MSW) till 0600 UTC of 9th. There was rapid intensification by 30 knots as it increased from 45 knots at 0600 UTC of 9th to 0600 UTC of 10th. The system maintained its peak intensity of 75 knots during 0600 UTC of 10th to 0000 UTC of 11th. The system then weakened gradually.

2.11.4. Features observed through satellite

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

2.11.4.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.11.6 (a-d)**.

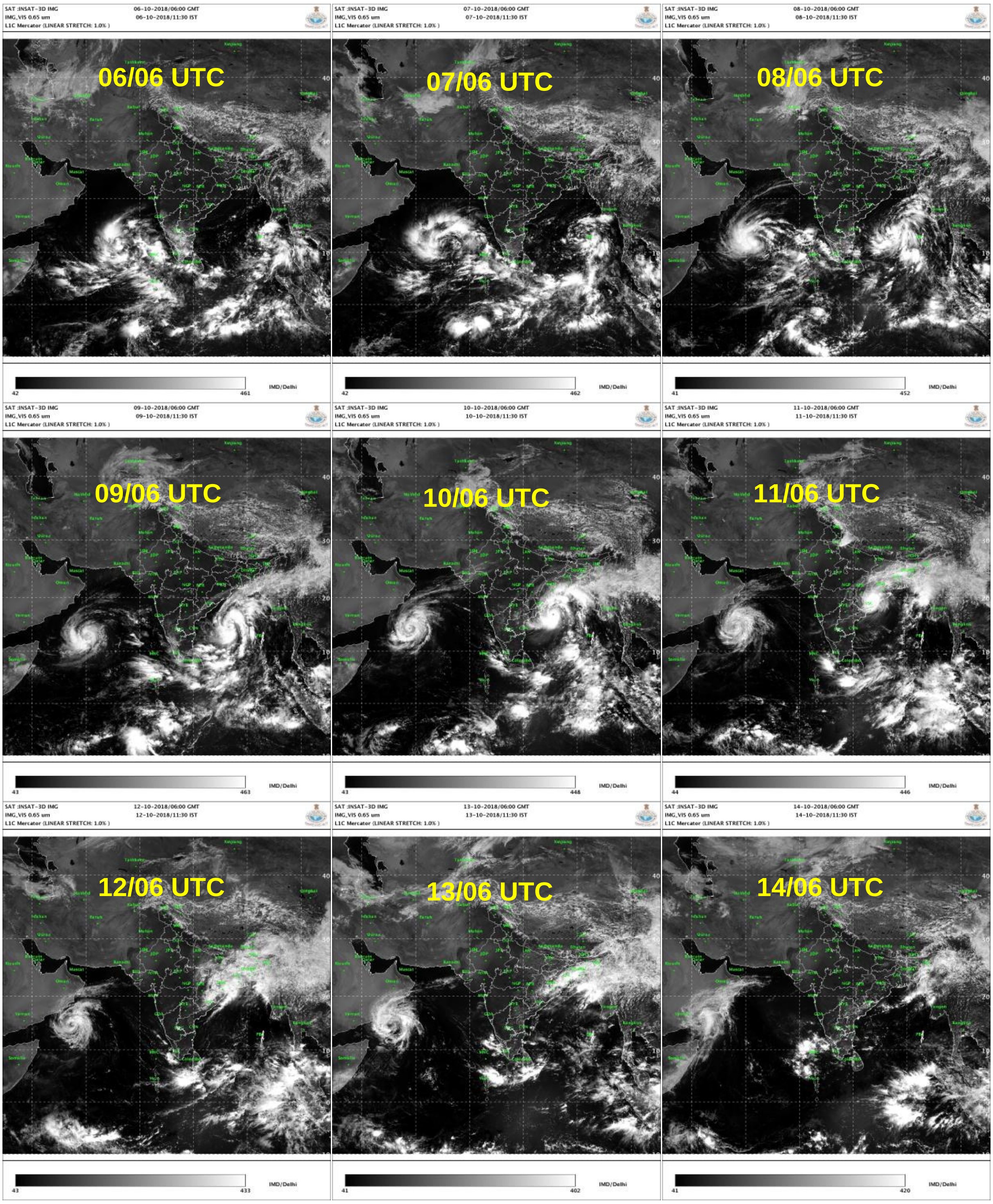


Fig. 2.11.6a: INSAT-3D visible imageries during life cycle of VSCS LUBAN (06-15 October, 2018)

Intensity estimation using Dvorak‟s technique suggested that the system attained the intensity of **T 1.5** at 0900 UTC of 06^{th}. The convection over south AS further organised and indicated curved banding features from northeast to southwest sector across northwest sector. Minimum cloud top temperature was -93^{0}C. At 0900 UTC of 7^{th}, the convection further organized and the system attained the intensity of **T2.0**. The convection showed curved banding features from northeast to southwest sector across northwest sector. Minimum CTT was -93^{0}C.

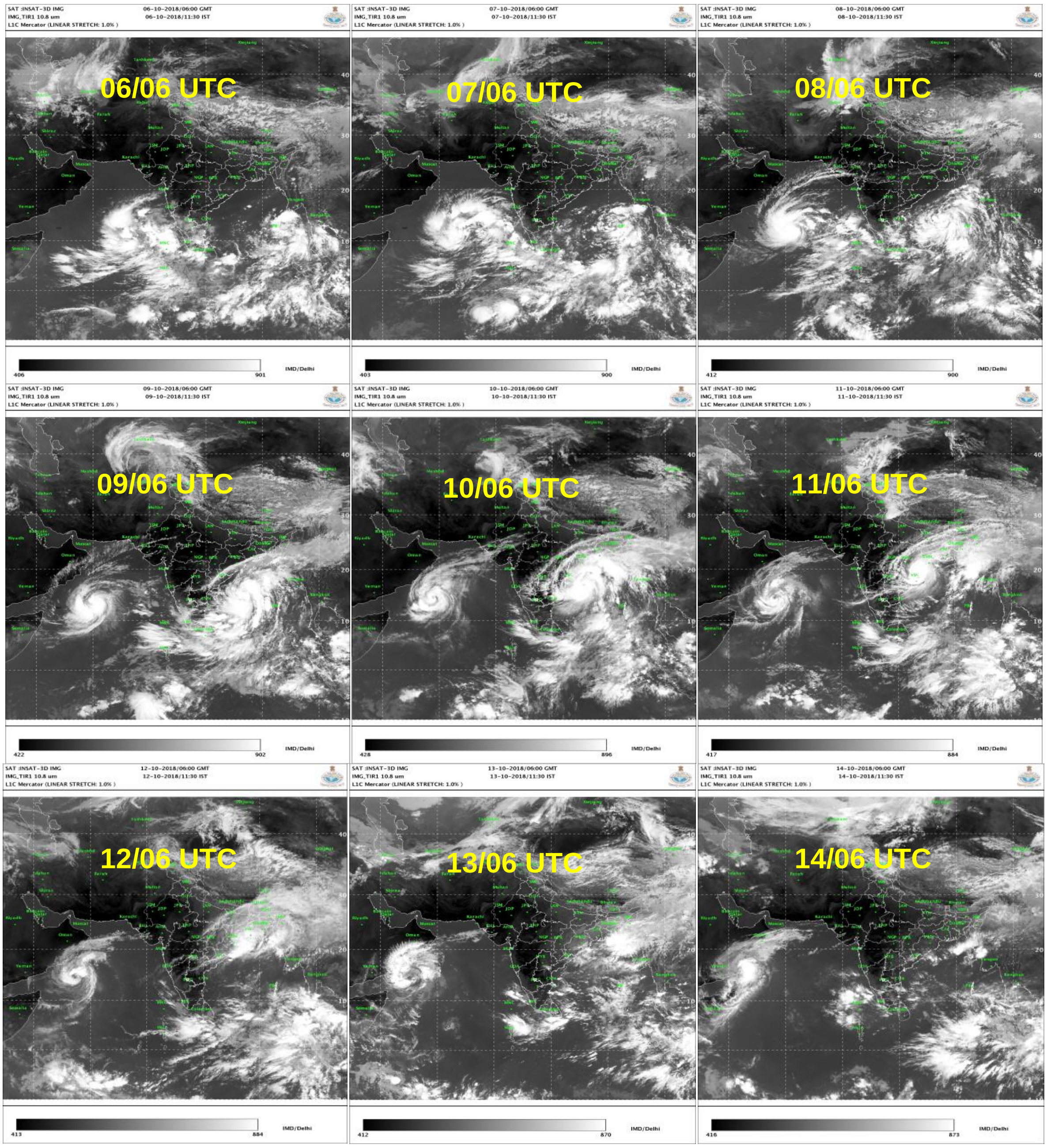


Fig. 2.11.6b: INSAT-3D IR imageries during life cycle of VSCS Luban (06-15 October, 2018)

At 0000 UTC of 08th, the system attained the intensity **T 2.5**. The cloud pattern indicated banding features from northeast to southwest sector across northwest sector. The intensity of the system was **T3.5** at 0900 UTC of 9th with a central dense overcast (CDO) pattern. The convection showed curved banding features. At 0000 UTC of 10th, the system attained the intensity **T 4.0** with a CDO and embedded eye pattern. The convection increased over western and southern sector. With the consolidation of central dense overcast, satellite imagery indicated appearance of eye. It indicated intensification of the system. Minimum CTT was -93^{0}C. At 0300 UTC of 24th, the system further intensified and attained the intensity **T4.5** at 1200 UTC of 10th. The convection showed central dense overcast pattern with well defined spiral bands and eye. Minimum CTT was -93^{0}C.

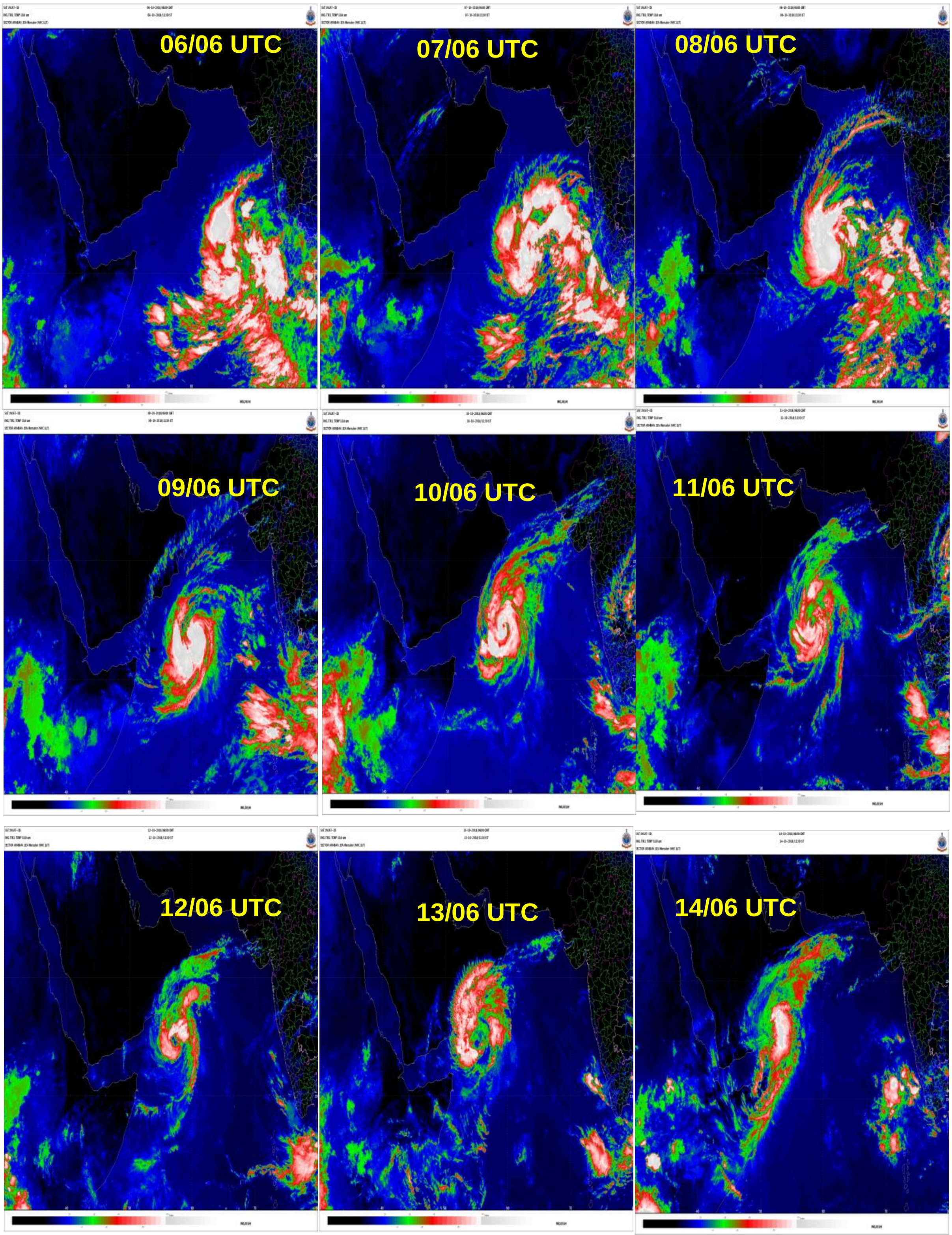


Fig. 2.11.6c: INSAT-3D enhanced colored imageries during life cycle of VSCS Luban (06-15 October, 2018)

At 0300 UTC of 11th, the intensity of the system was **T 4.0** with weakening of the system. It further decreased to T 3.0 at 1500 UTC of 12th and T 2.5 at 0000 UTC of 14th.

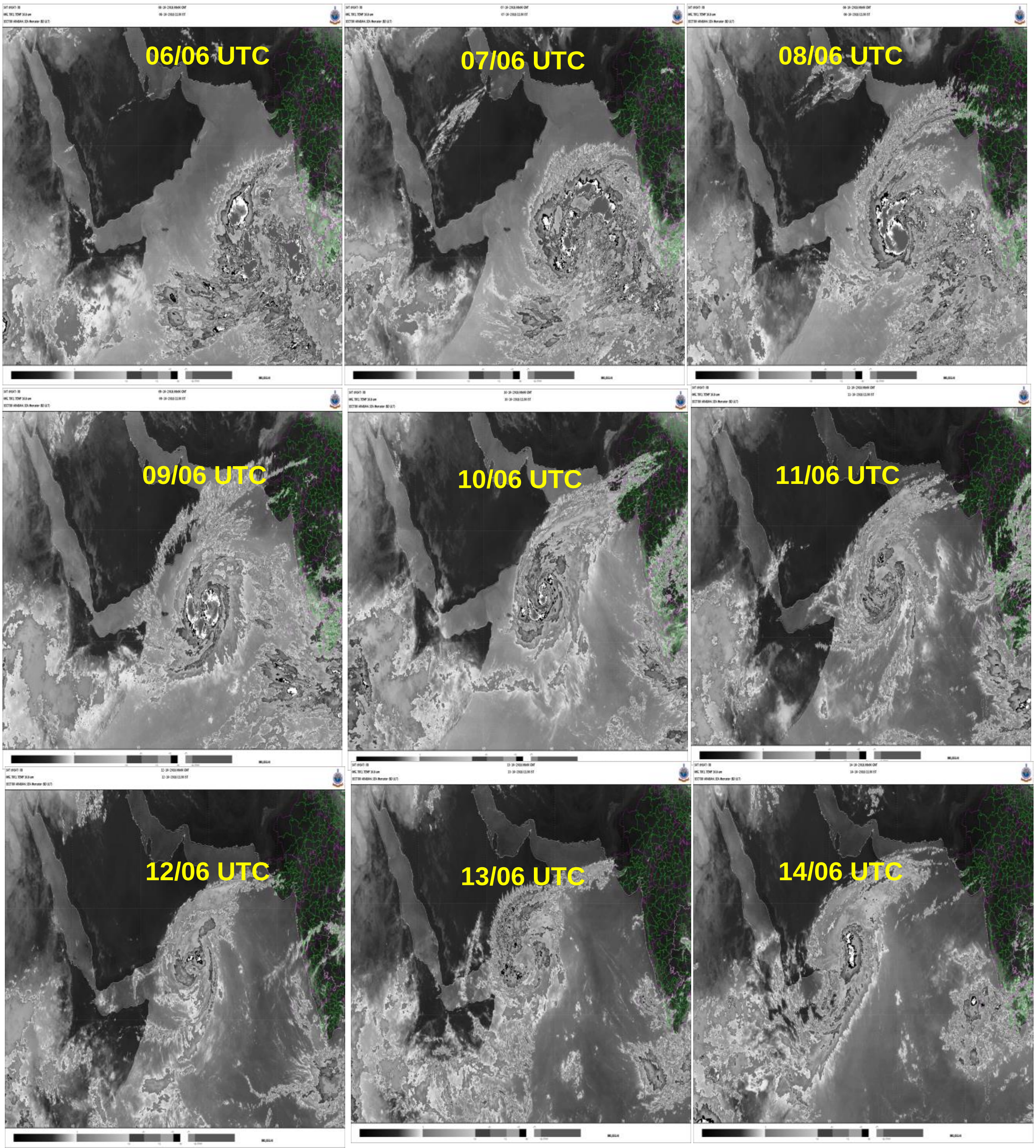


Fig. 2.11.6d: INSAT-3D cloud top brightness imageries during life cycle of VSCS Luban (06-15 October, 2018)

2.11.4.2. Microwave Imageries:

Microwave imageries from polar orbiting satellites F-15, F-16, F-18, GCOM W1, GPM 89, NOAA-19 were utilised for determining the centre and area of intense convection.

Typical microwave imageries during the life cycle of VSCS Luban are presented in **Fig. 2.11.6 (e).** The eye was visible since 0000 UTC of 10th Oct.

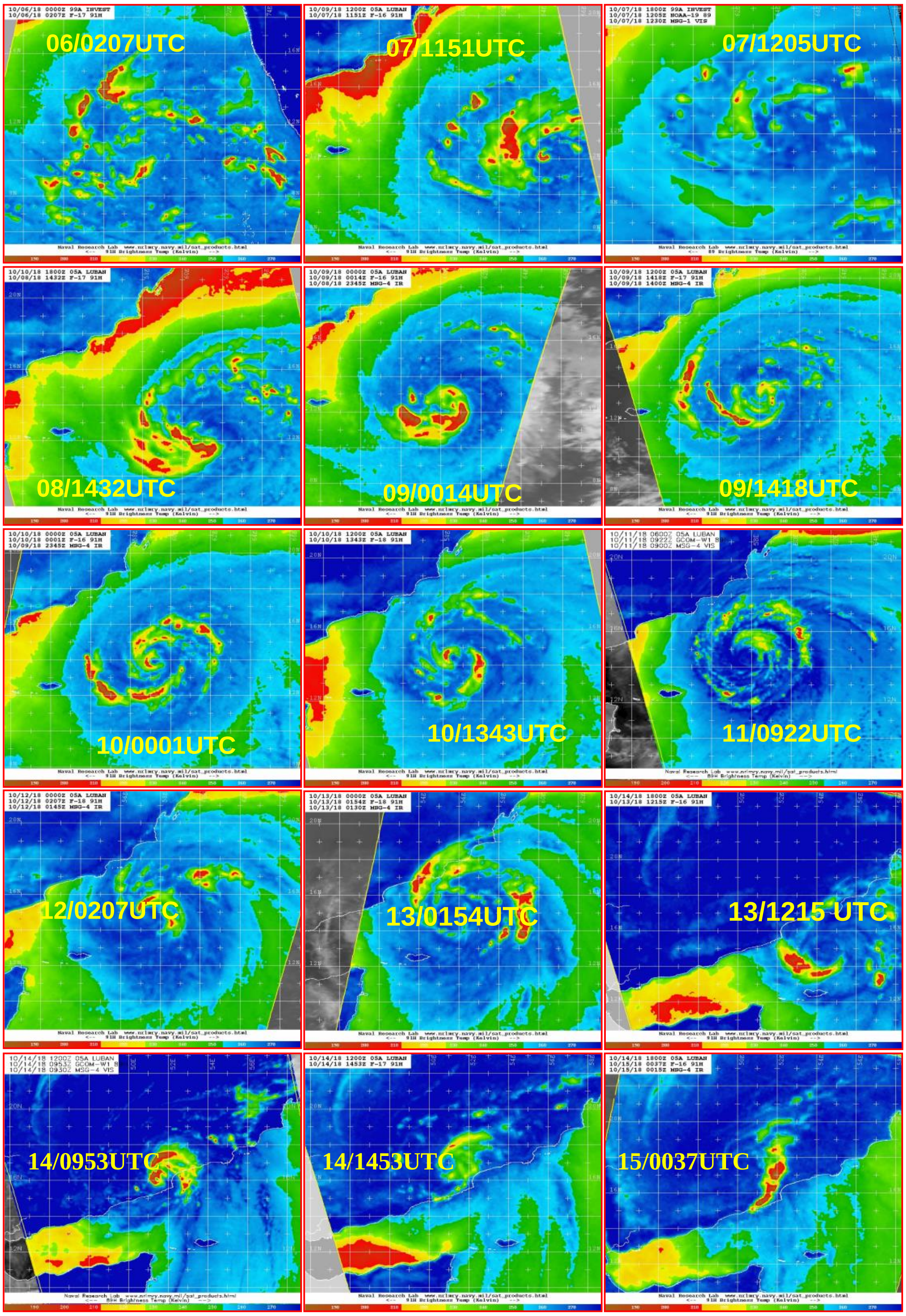


Fig. 2.11.6e: Microwave imageries during life cycle of VSCS Luban (06-15 October, 2018)

2.11.4.3. Scatterometer observations

When the system was over sea, imageries from ASCAT were also utilized for determination of centre, intensity and wind distribution around the centre of the system. Typical ASCAT imageries from Metop-B are presented in Fig. 2.11.6(f).

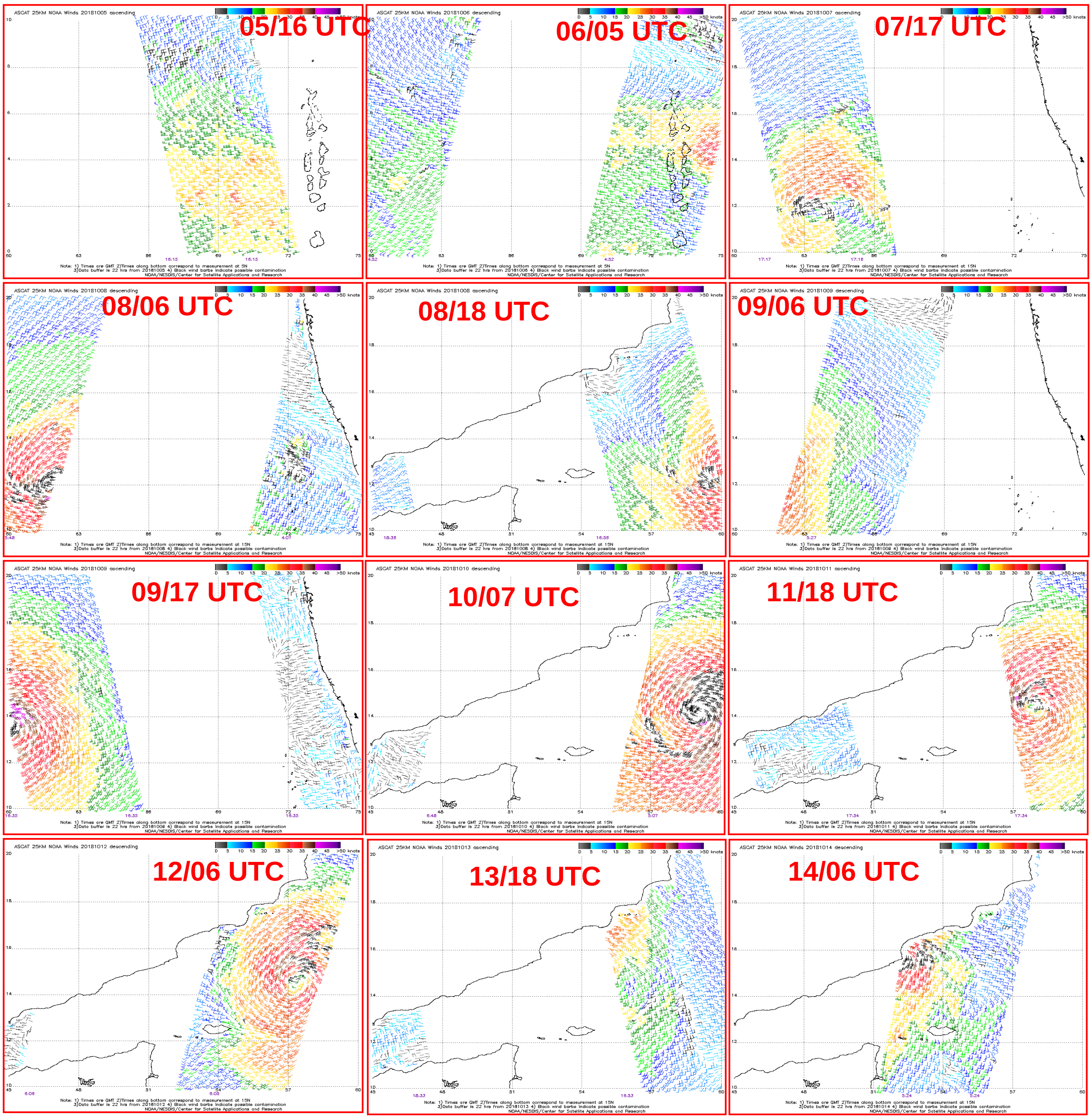


Fig. 2.11.6(f): ASCAT (Met-Op B) imageries during life cycle of ESCS Mekunu (06-15 October, 2018)

Typical imageries from polar satellite, SCATSAT are presented in Fig. 2.11.6 (g). SCATSAT passes are available twice a day at 0454 UTC and 1636 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations from both the satellites were very useful in determining the surface wind structure. Stronger winds were seen in northeast and southeast sectors. The imagery also indicated large scale cross equatorial flow, inflow of warm and moist air into the system centre from southeast sector. SCAT Sat imageries helped in determination of centre to a good extent. Intensity estimates beyond 50 kts cannot be done with the help of these imageries. The analysis of the matching index (MI) shows that it could not predict cyclogenesis till observation based on 0200 UTC of 8th Oct. while the system intensified into a CS at 0000 UTC of 8th Oct.

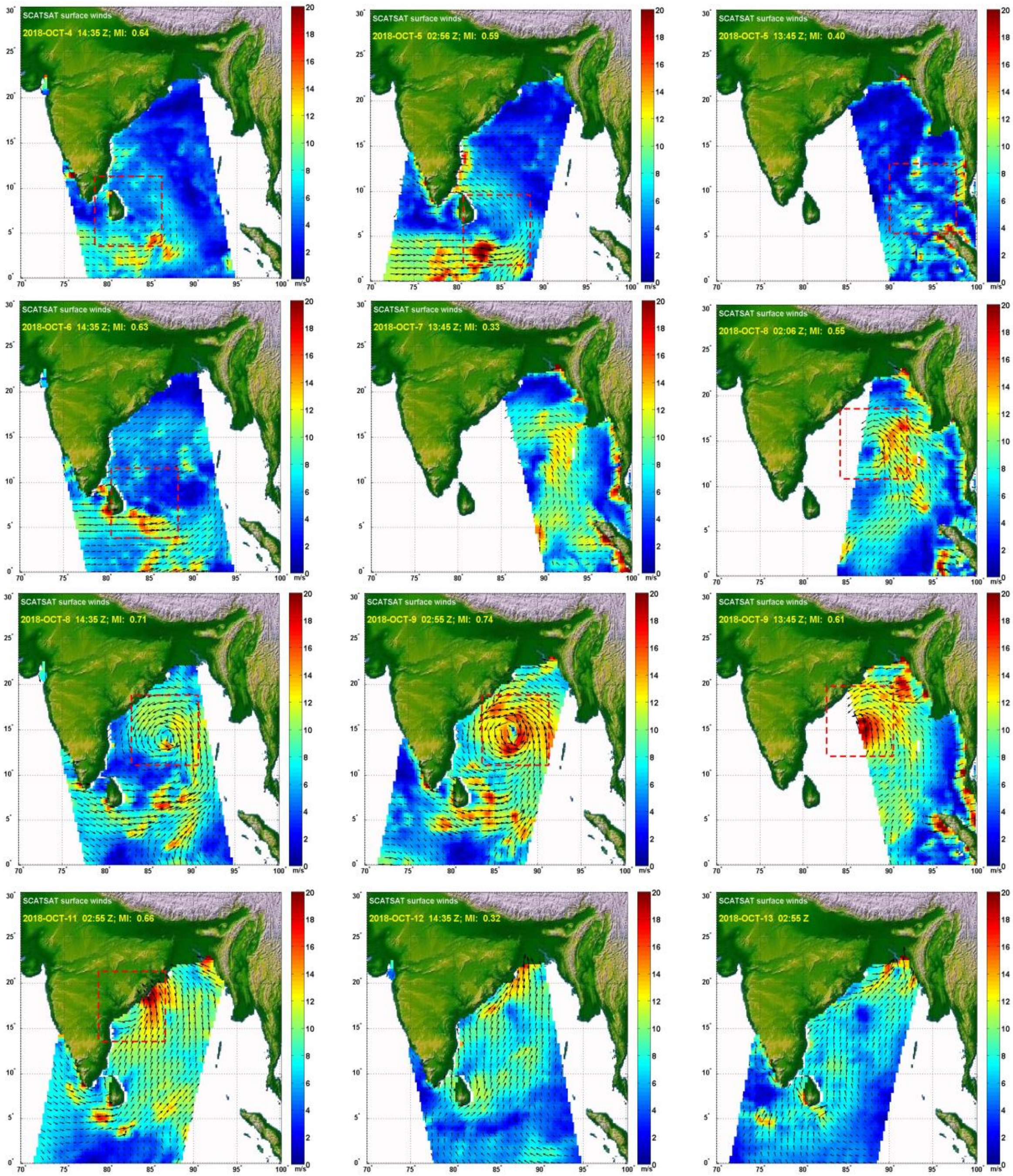


Fig. 2.11.6(g): SCATSAT imageries during life cycle of VSCS Luban (06-15 October, 2018)

2.11.5. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 6th to 15th October are presented in Fig. 2.11.7. Based on 0000 UTC observations of 6th, the model predicted a low pressure area over southeast and adjoining southwest AS. It indicated a cyclonic circulation over southeast AS extending upto 500 hPa level.

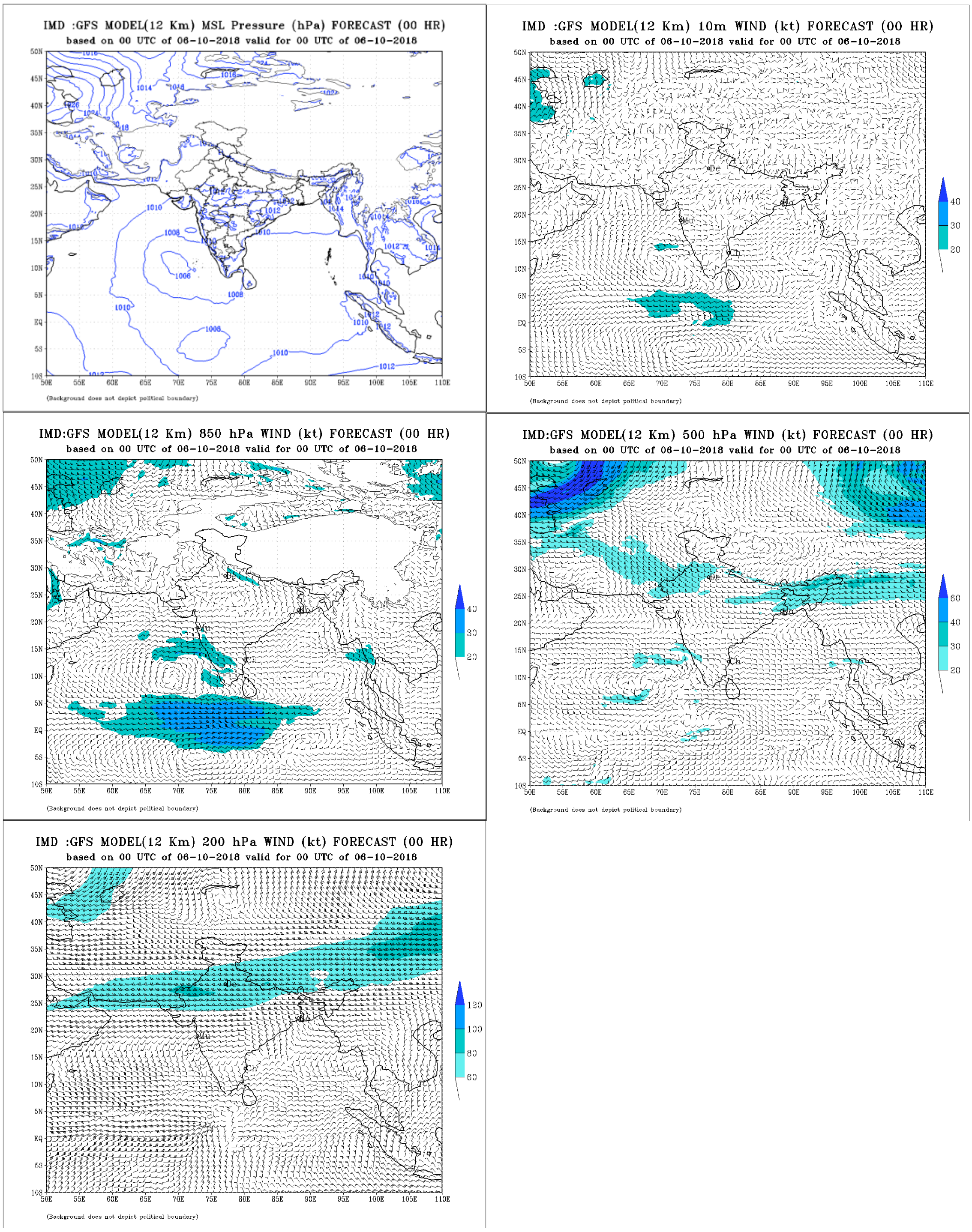


Fig. 2.11.7 (i): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 6th October 2018.

Analysis based on 0000 UTC of 7th Oct., predicted intensification of system into a depression over southeast AS. Vertically the system extended upto 500 hPa levels.

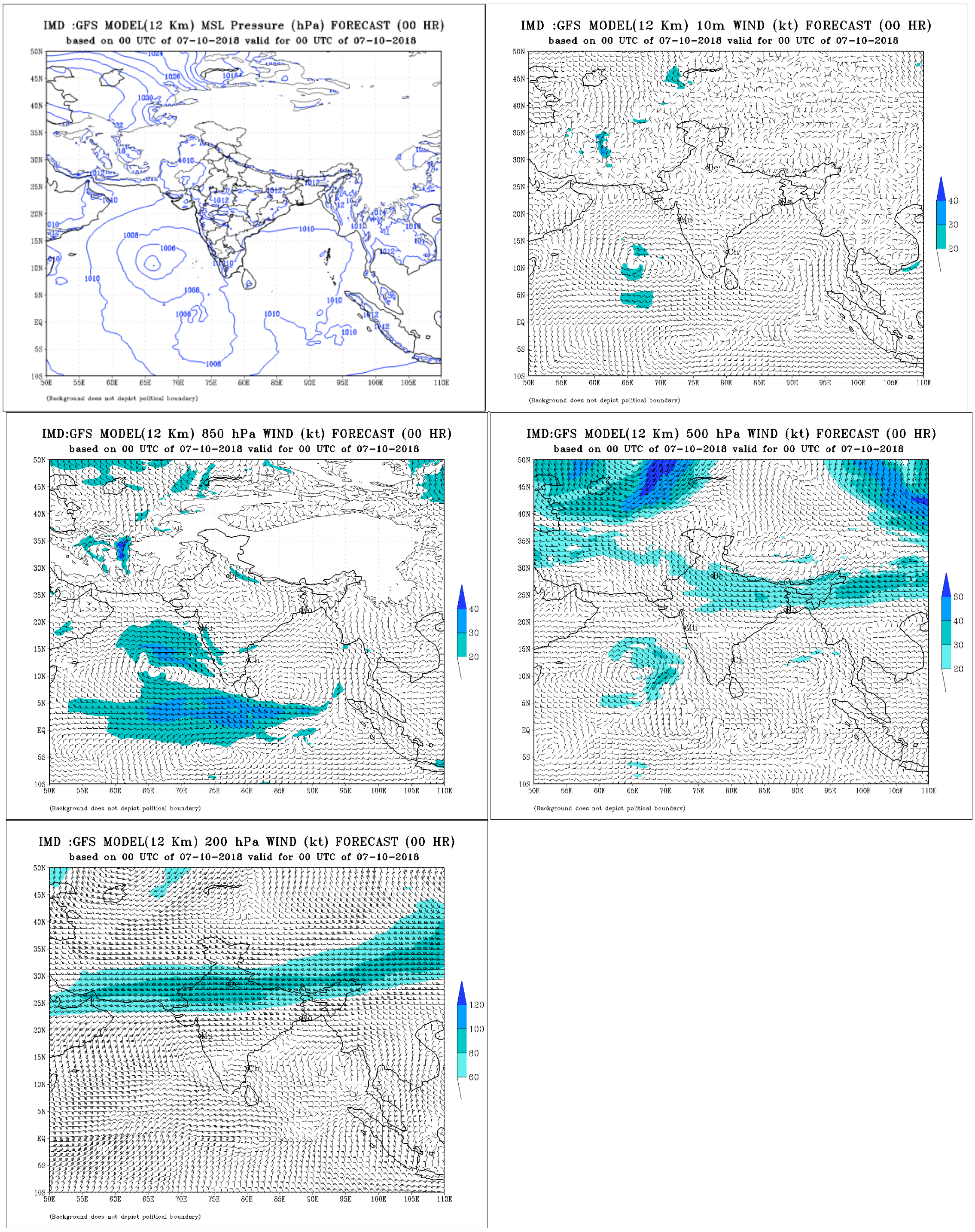


Fig. 2.11.7 (ii): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 7th October 2018.

Analysis based on 0000 UTC of 8th Oct. predicted northwards movement and further intensification of system into a cylonic storm over southeast AS. The circulation extended upto 500 hpa levels.

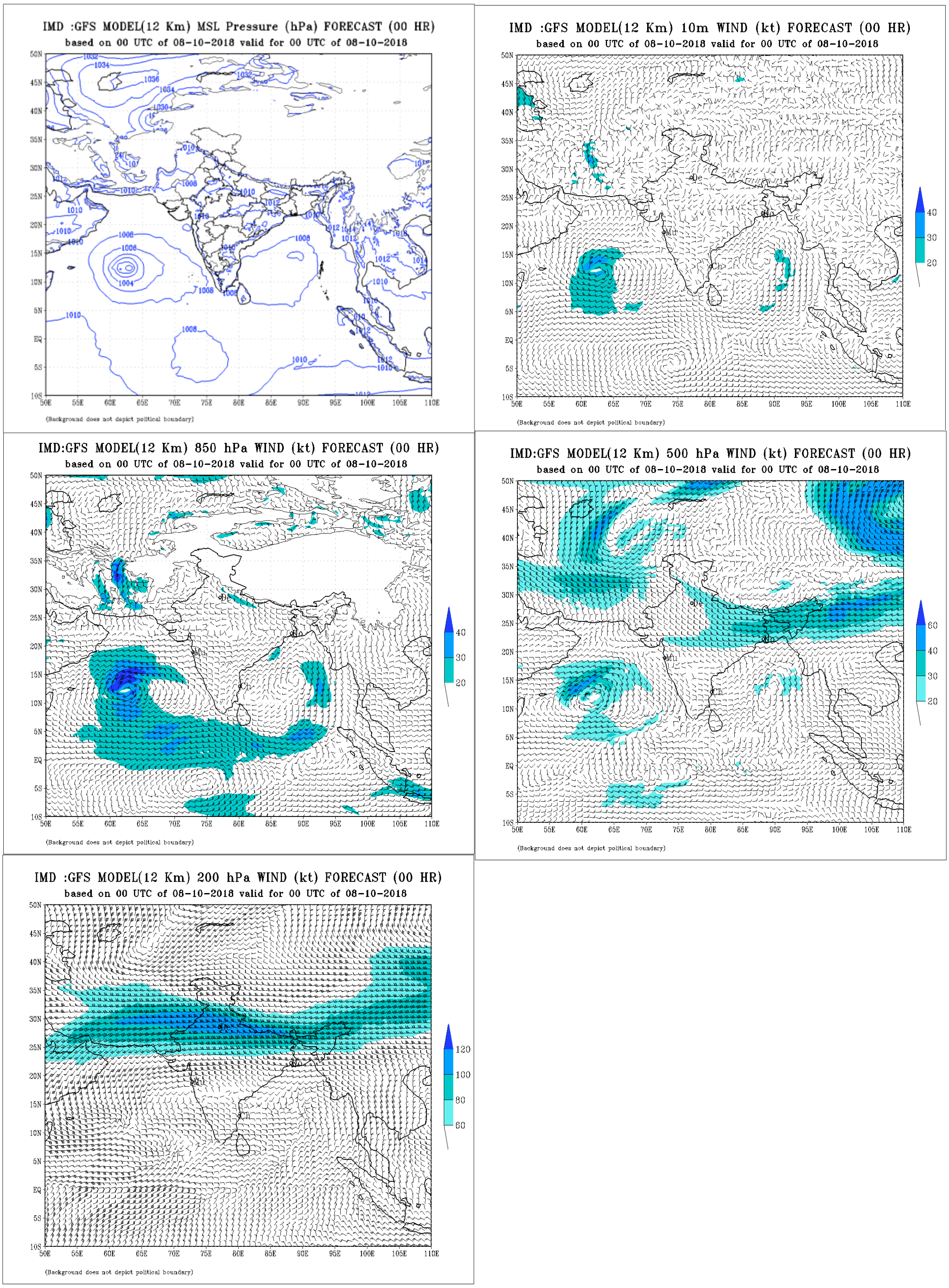


Fig. 2.11.7 (iii): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 8th October 2018.

Initial conditions based on 0000 UTC of 9th Oct. indicated further intensification of the system into a severe cyclonic storm (SCS) to the east of Socotra Islands.

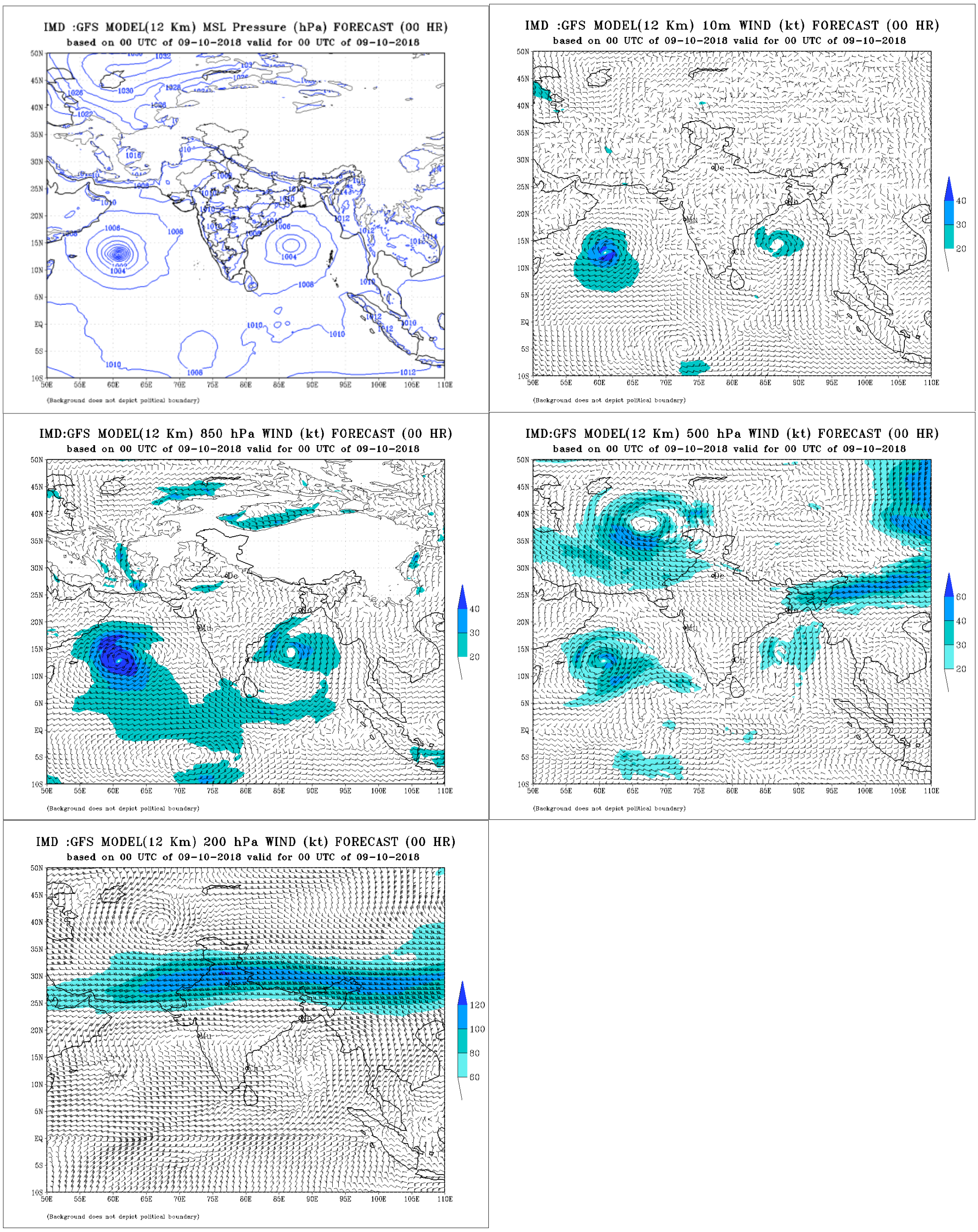


Fig. 2.11.7 (iv): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 9th October 2018.

Analysis based on 0000 UTC of 10th Oct. indicated further intensification into VSCS and movement towards Yemen coast.

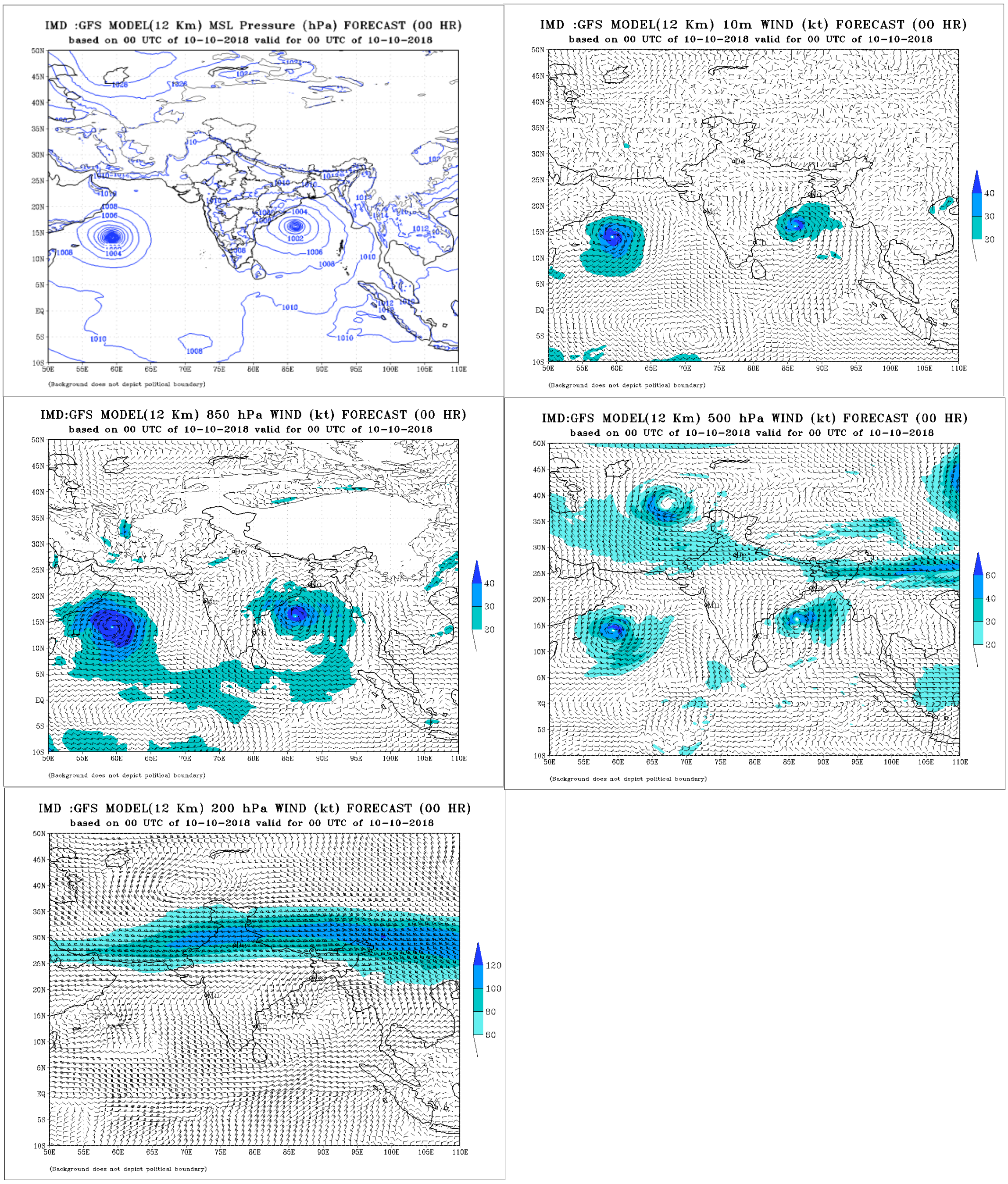


Fig. 2.11.7(v): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th October 2018.

The initial conditions based on 0000 UTC of 11th indicated the system maintaining the intensity of VSCS.

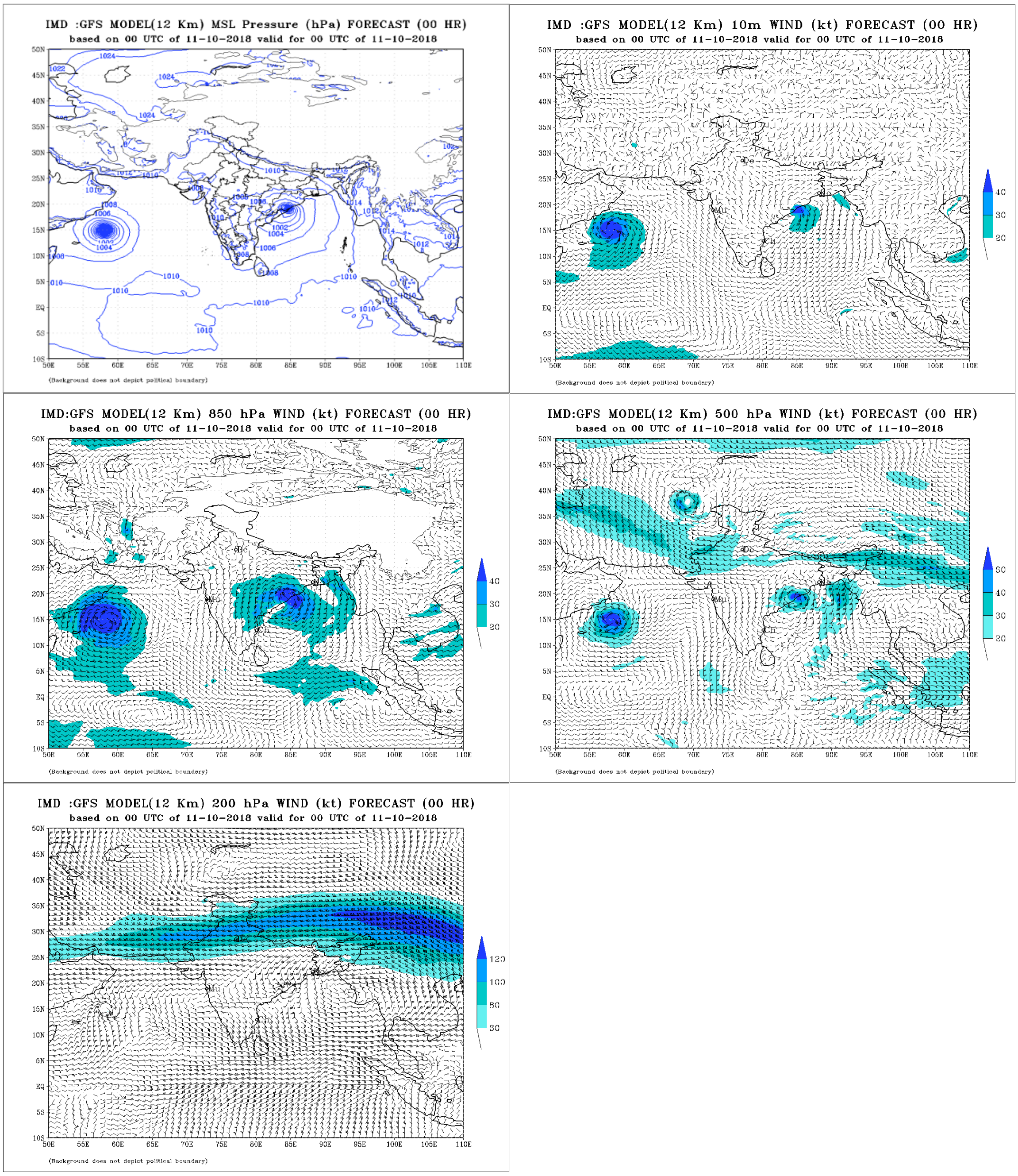


Fig. 2.11.7(vi): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th October 2018.

The initial conditions based on 0000 UTC of 12th indicated the system maintaining the intensity of VSCS, but with slightly weakening trend.

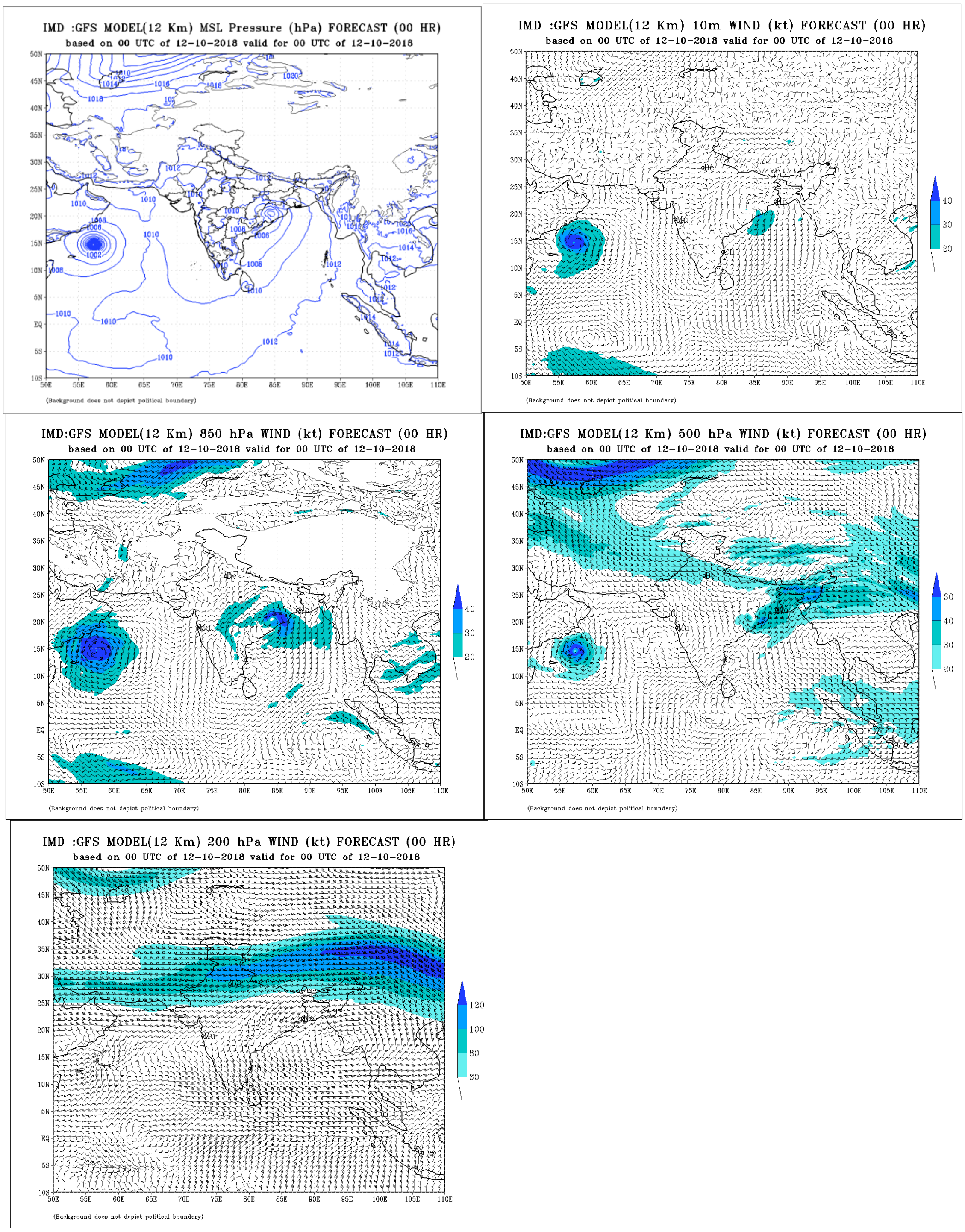


Fig. 2.11.7 (vii): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 12th October 2018.

The initial conditions based on 0000 UTC of 13th indicated weakening of the system into SCS.

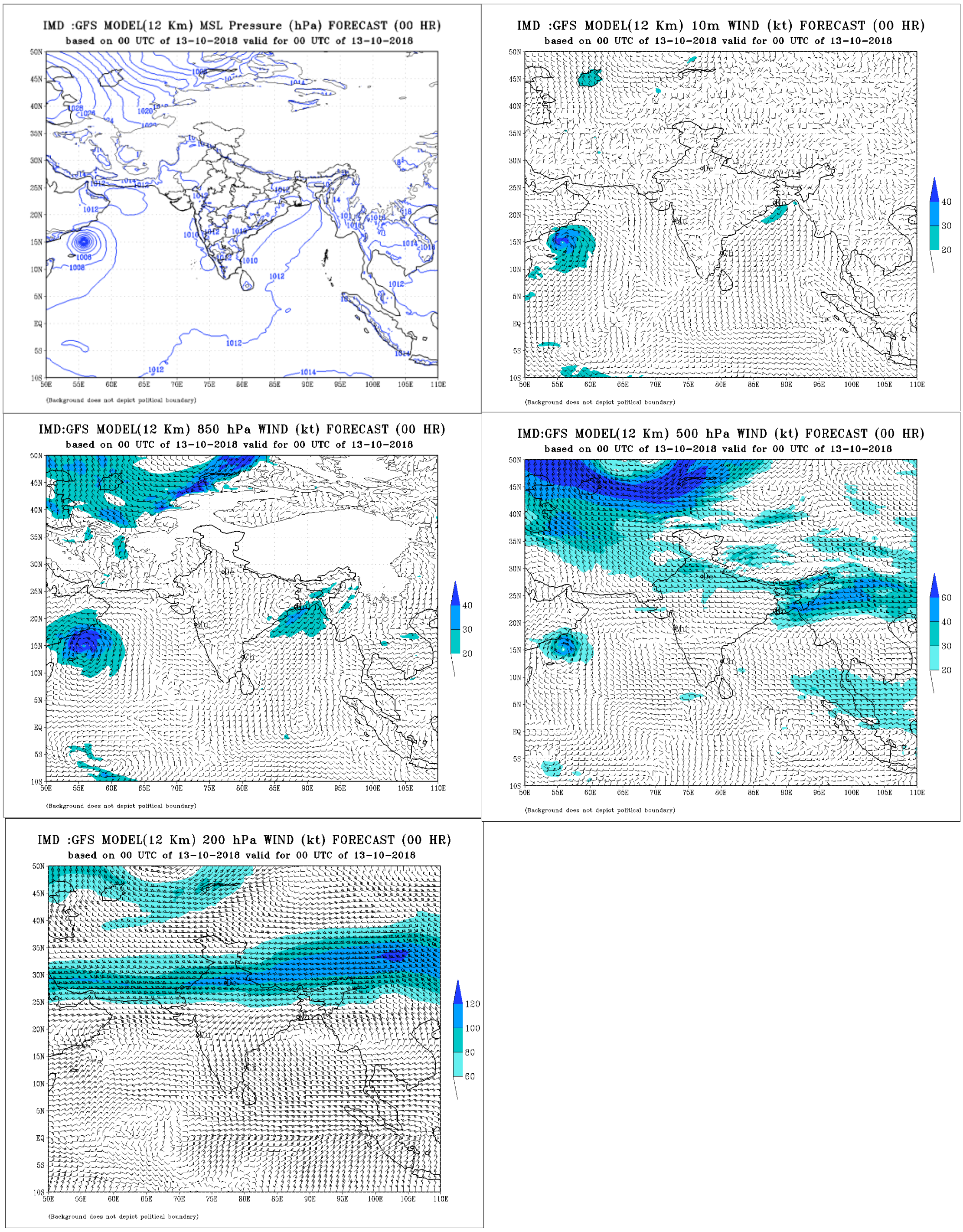


Fig. 2.11.7(viii): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th October 2018.

The initial conditions based on 0000 UTC of 14th indicated further weakening of the system into CS.

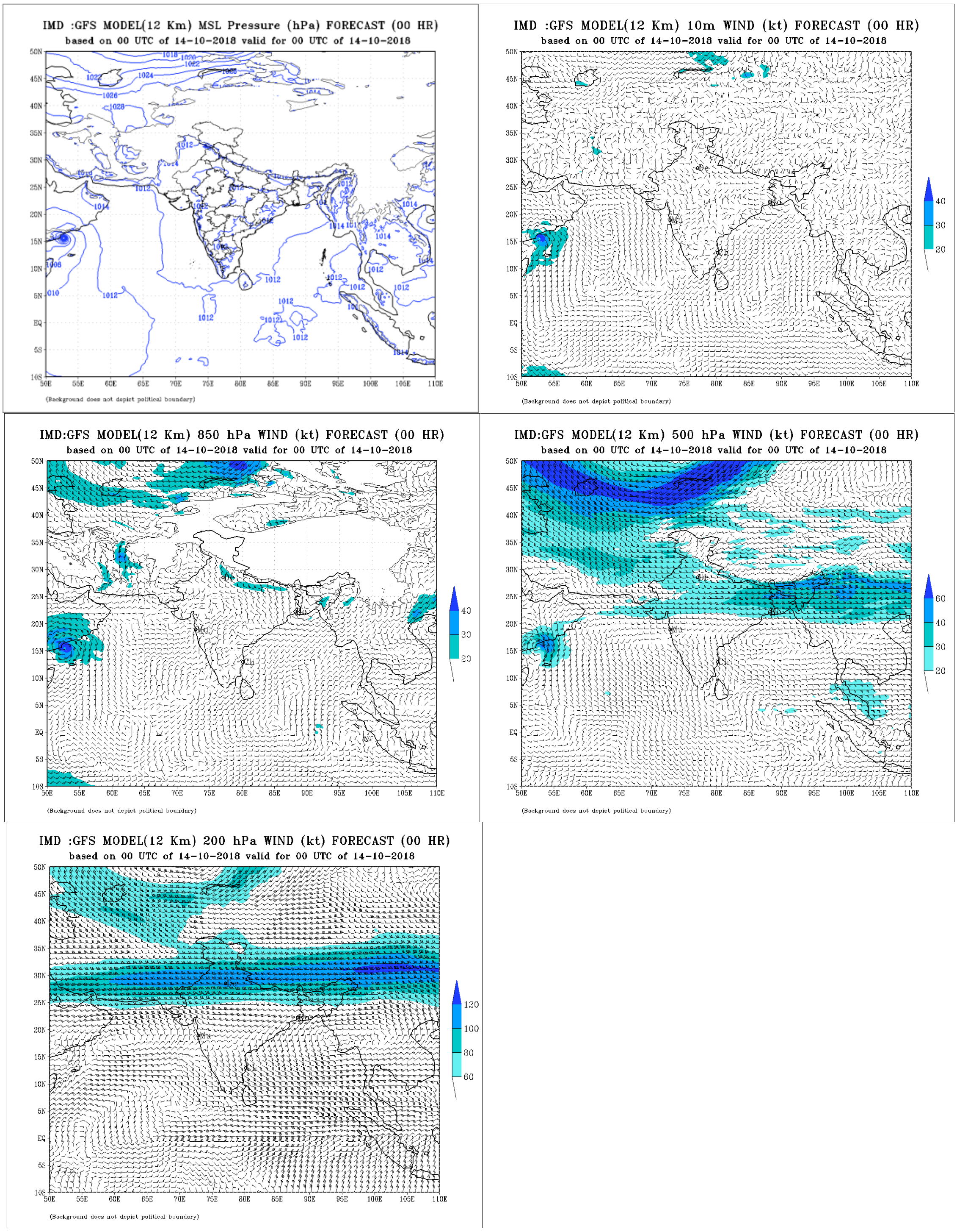


Fig. 2.11.7(ix): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th October 2018.

The initial conditions based on 0000 UTC of 15th indicated weakening of the system over Yemen and adjoining Gulf of Aden.

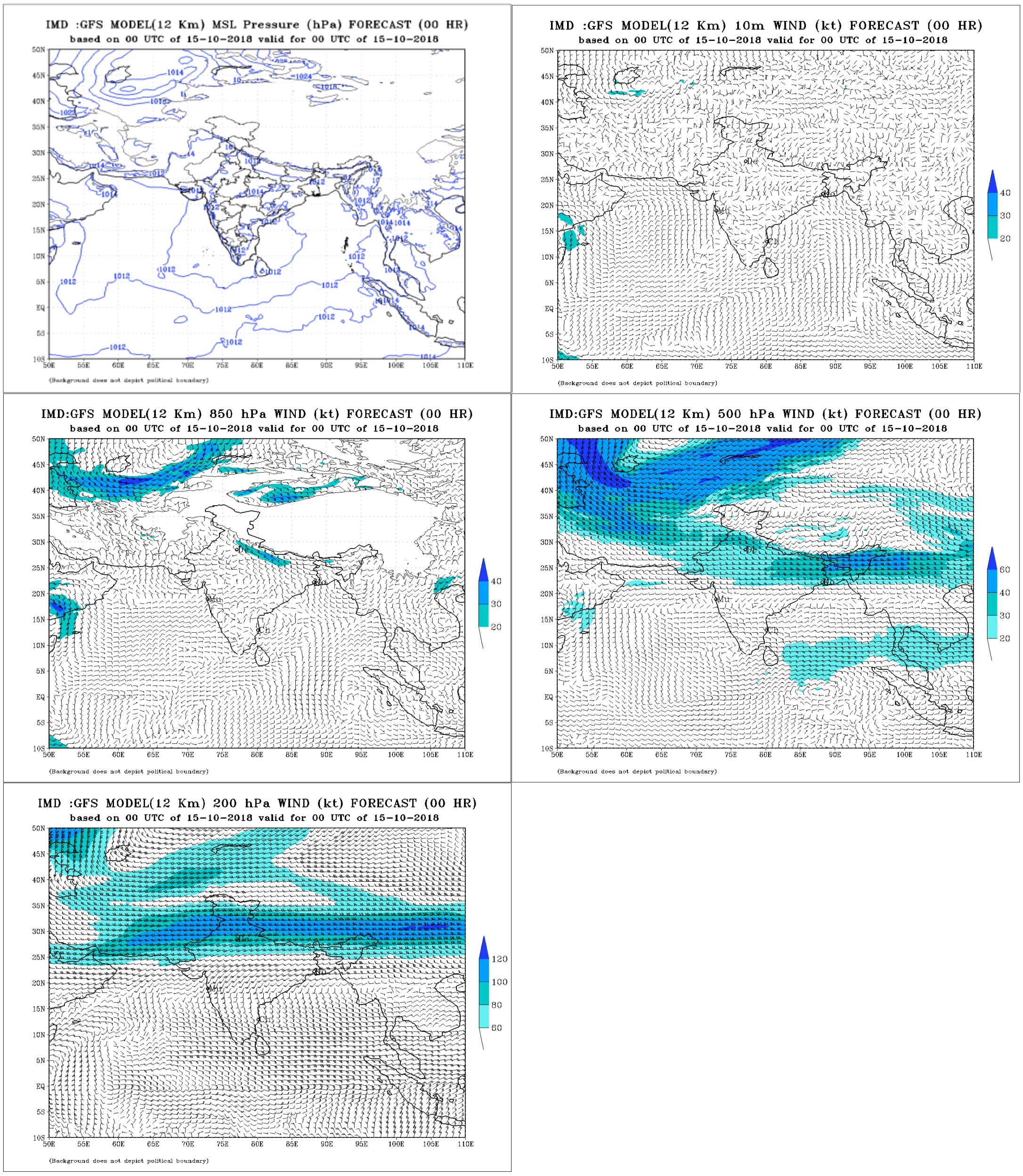


Fig. 2.11.7(x): IMD GFS (T1534) mean sea level pressure (MSLP) and winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th October 2018.

Hence to conclude, to a large extent IMD GFS could simulate the genesis, intensification, movement and weakening of the system. However, during landfall it predicted west-southwestward movement against actual northwestward movement of the system.

2.11.5.1. Thermodynamical features based on HWRF model for weakening of the system before landfall.

The diagnostic products from IMD HWRF Model are presented in Fig. 2.11.8 (i-iii). The SST forecast based on 0000 UTC of 10th upto 96 hours is presented in Fig. 2.11.8 (i). The 96 hr. forecast indicated weakening of SST on 14th near Yemen coast.

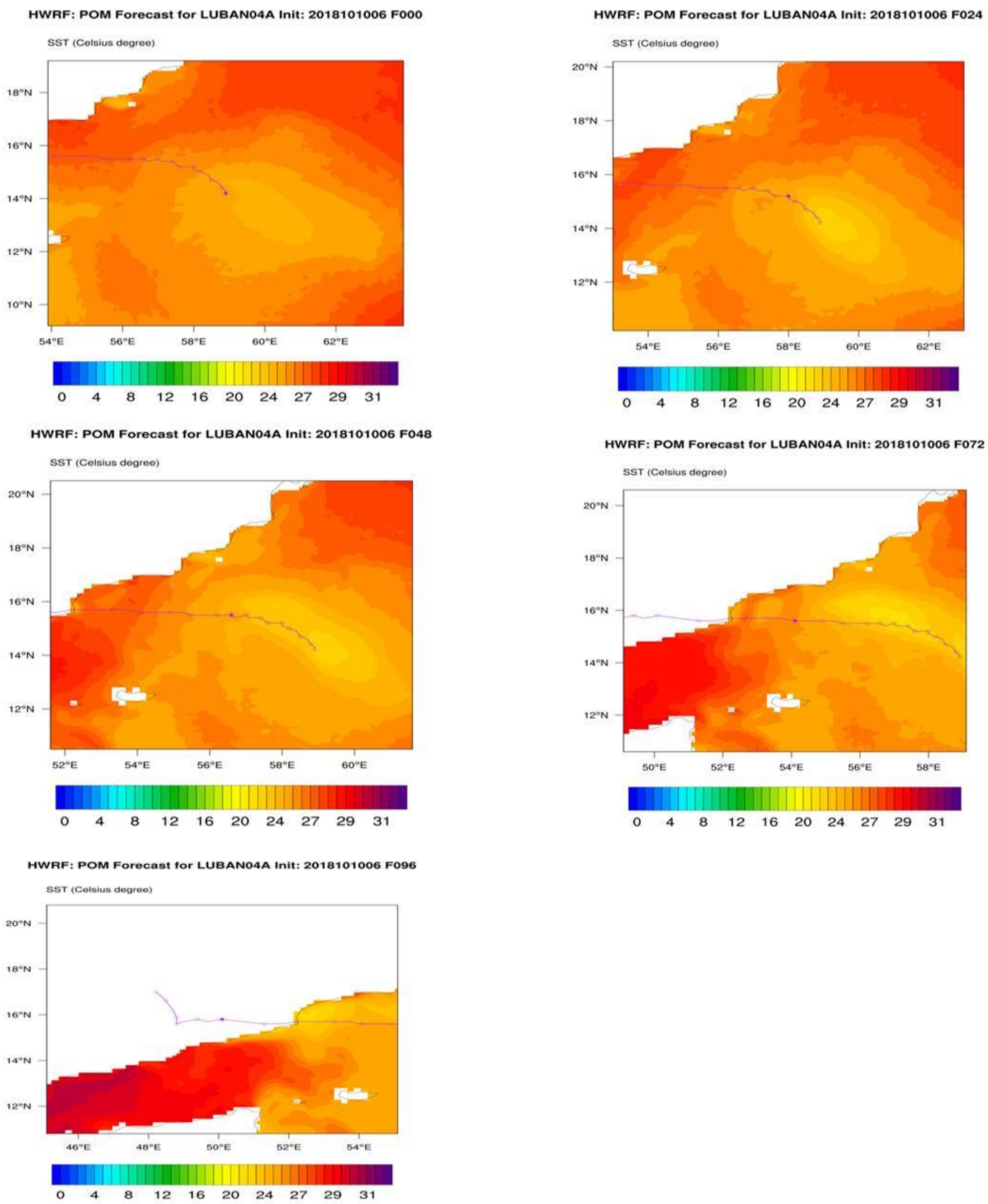


Fig. 2.11.8 (i): IMD HWRF forecast of SST for next 96 hours based on 0000 UTC of 10th October.

The wind shear between 200-850 hPa levels is presented in Fig. 2.11.8 (ii). It indicated high wind shear towards Oman and adjoining Yemen coast on 13 and 14 Oct.

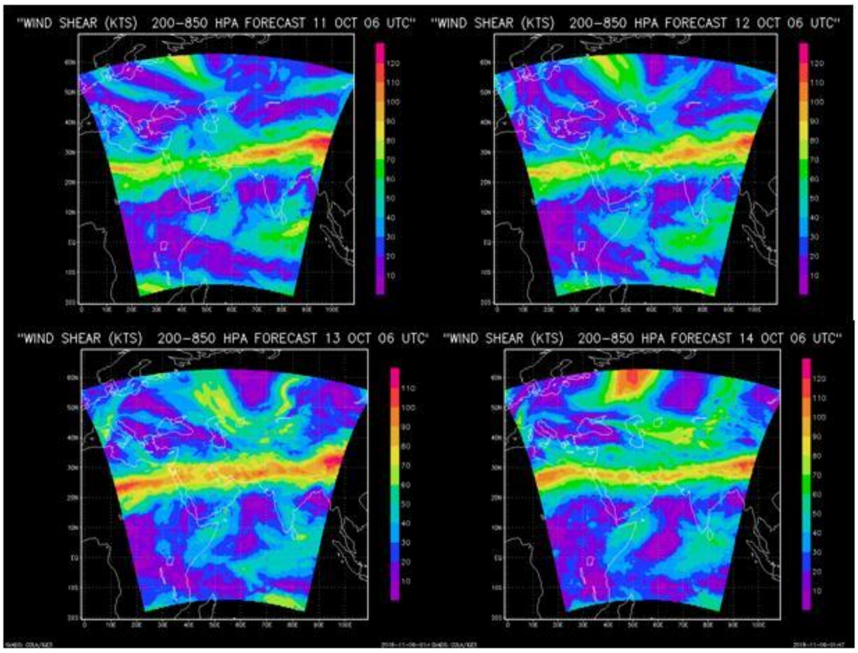


Fig. 8(ii): IMD HWRF forecast of wind shear for next 96 hours based on 0000 UTC of 10th October.

The relative humidity at 500 hPa level is presented in Fig. 2.11.8(iii). The humidity pattern in middle and upper indicated weakening of the system on 13th and 14th.

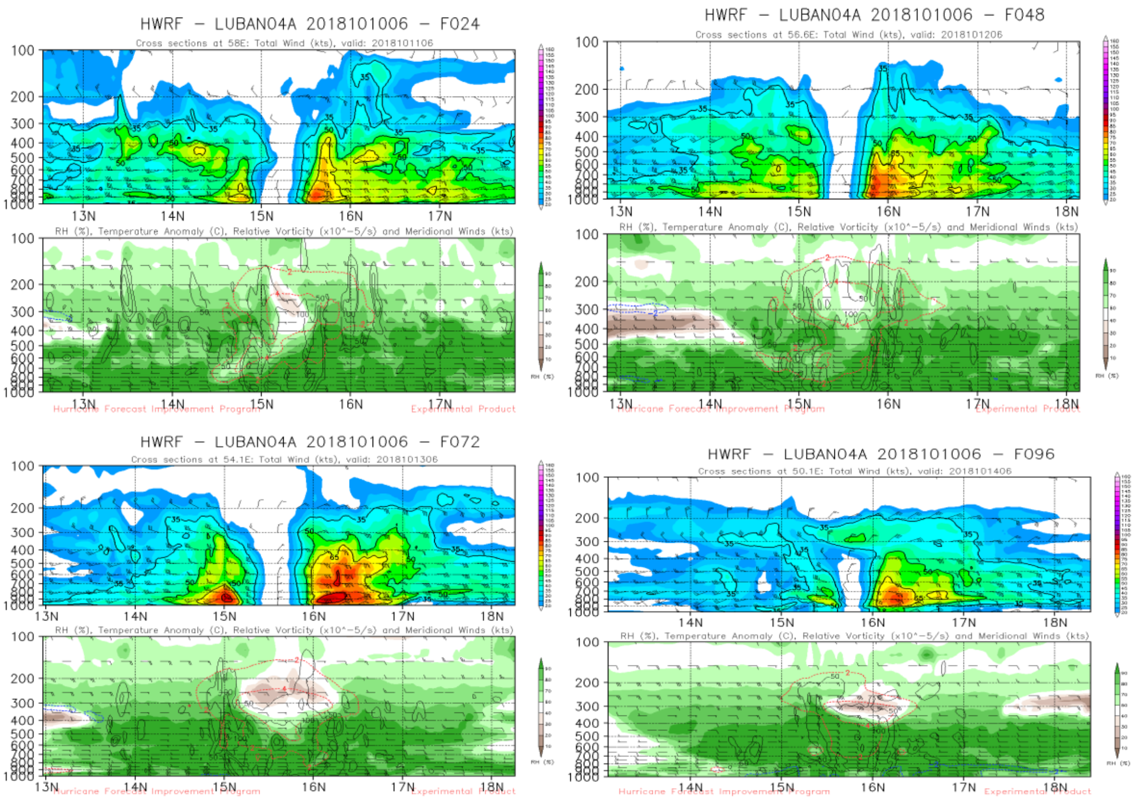


Fig. 2.11.8(iii): IMD HWRF forecast of wind, relative humidity and temperature for next 96 hours based on 0000 UTC of 10th October.

2.11.6. Realized Weather:

2.11.6.1 Rainfall:

IMD-NCMRWF merged rainfall plots (Fig. 2.11.9) indicate that the system caused heavy to very rainfall (8-16cm) over coastal areas of south Oman at a few places on 13th, 4-8 cm rainfall over coastal areas of Yemen on 14th and over interior parts of Yemen and Saudi Arabia on 15th.

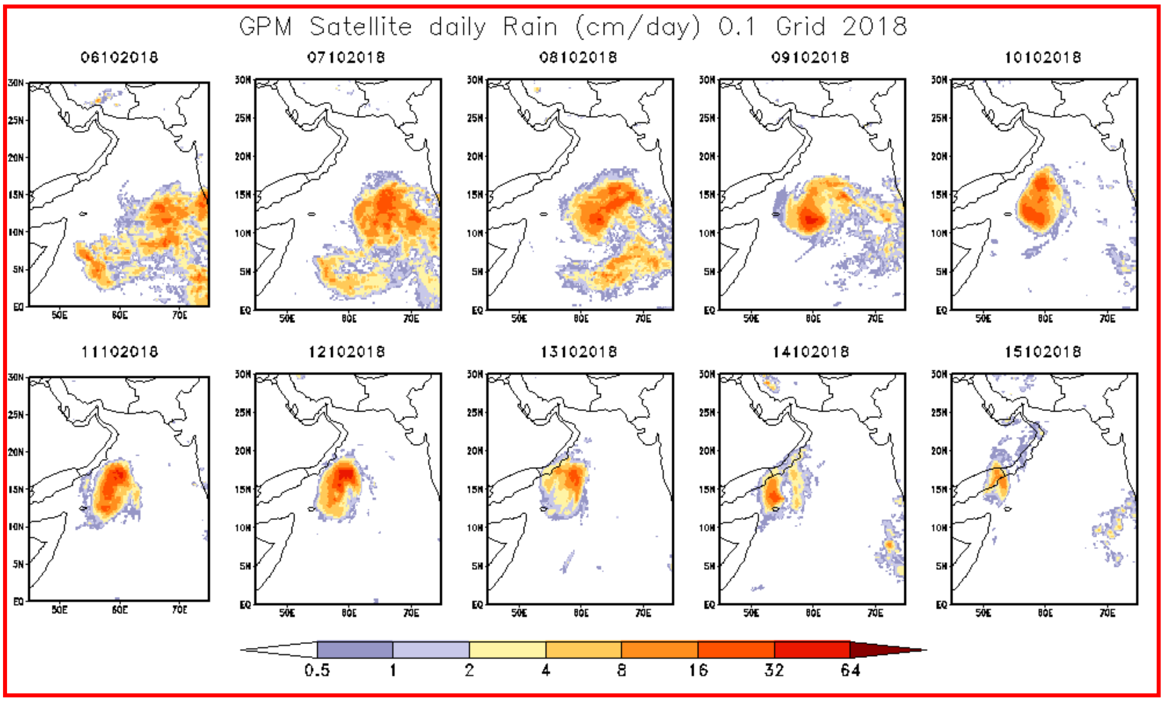


Fig. 2.11.9: IMD-NCMRWF GPM merged gauge rainfall during 06-15 October and 7 days average rainfall (cm/day)

Realised weather over Yemen:

Al- Ghaidah (41398) : Rainfall (290mm), Wind 50kt.(45 gusting to 55kt),
Muklla (41443): Rainfall (56.5mm), Wind 20kt.
Socotra (41494): Rainfall (40mm), Wind 26kt.

Realised weather over Oman:
The highest amount of rainfall in Dhofar during 4pm on October 13 to 8am on October 14 was recorded in Dalkout (14.5 cm) followed by Salalah (13.8 cm), Rakhiout (13.3 cm), Mirbat (3.8 cm), Shaleem and Al Halaniyat Island (3.2 cm), Sadah (2.4 cm), Taqah (1.3 cm), Thumrait (1.1 cm) and Al Mazyouna (1.0 cm). The highest amount of rainfall recorded in Al Wusta was 1.1 cm in the Wilayat of Al Jaser, 9.0 cm in Mahout and 6.0 cm in Haima.

2.11.7. Damage due to VSCS Luban

Damage over India:
No casualties were reported from any Indian state due to VSCS, Luban.
Damage over Oman and Yemen: 14 persons lost their lives in Yemen due to floods in association with VSCS Luban. A few damage photographs are shown in Fig. 2.11.10.

Fig. 2.11.10. Flooding in Qishn district in Al Mahrah Governorate and damaged houses in Al Masilah district in Al Mahrah Governorate (Source: https://reliefweb.int/sites/reliefweb.int/files/resources/Cyclone%20Luabn%20Flash%20Update%203.pdf)

2.12. Very Severe Cyclonic Storm "Titli" over Eastcentral Bay of Bengal (08-13 October 2018)

2.12.1. Introduction

Very Severe Cyclonic Storm (VSCS) Titli originated from a low pressure area (LPA) which formed over southeast Bay of Bengal (BoB) and adjoining north Andaman Sea in the morning (0830 IST) of 7th October. It lay as a well marked low pressure area (WML) over the same region in the same evening (1730 IST). Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the morning (0830 IST) of 8th October. Moving nearly west-northwestwards, it intensified into a deep depression (DD) over eastcentral BoB in the mid-night (2330 IST) of 8th October and further into a cyclonic storm (CS) **"Titli**" around noon (1130 IST) of 9th October. It then moved northwestwards and intensified, into a severe cyclonic storm (SCS) in the early hours (0230 IST) of 10th . It then moved north-northwestwards and further intensified into a very severe cyclonic storm (VSCS) around noon (1130 IST) of 10th. It crossed north Andhra Pradesh and south Odisha coasts near Palasa (18.8^{0}N/84.5^{0}E) to the southwest of Gopalpur during 0430-0530 IST of 11th as a VSCS with the wind speed of 140-150 gusting to 165 kmph. Moving further west-northwestwards, it weakened into an SCS around noon (1130 IST) of 11th and a CS in the same evening (1730 IST). Under the influence of southwesterly winds at middle and upper tropospheric levels, the system recurved northeastwards from 11th evening. It weakened into a DD over south Odisha in the mid-night (2330 IST) of 11th. It further weakened into a D in the afternoon (1430 IST) of 12th, into a WML over Gangetic West Bengal and adjoining Bangladesh & north BoB in the early hours (0530 IST) of 13th and into an LPA over the same region in the morning (0830 IST) of 13th.

The best track parameters of the system are presented in **Table 2.12.1**.

The salient features of the system were as follows:

- Titli was the most destructive cyclonic storm to strike Indian coast during 2018.
- The genesis of VSCS, Titli over Bay of Bengal took place 45 hours after the genesis of VSCS, Luban over Arabian Sea. It was one of the rarest of rare events that simultaneously two VSCSs developed over Arabian Sea and Bay of Bengal.
- Considering the data during satellite era (1961 onwards), simultaneous occurrence of such two VSCSs last occurred in November 1977, viz. (i) Bay of Bengal Super Cyclonic Storm (14-20 Nov., 1977) which crossed Andhra Pradesh coast near Chirala on 19th Nov. and (ii) Bay of Bengal VSCS (09-23rd Nov., 1977) which crossed Tamil Nadu coast close to south of Nagapattinam on 12th Nov. and then emerged into Arabian Sea, made a looping track, intensified into an SCS, weakened thereafter and crossed Karnataka coast to the north of Mangalore on 29th Nov. as a depression.
- The system exhibited rapid intensification during 10th Oct with increase in maximum sustained wind speed from 50 knots at 0230 IST to 80 knots at 1200 UTC.
- The peak maximum sustained surface wind speed (MSW) of the cyclone was 140-150 kmph gusting to 165 kmph (80 knots) during 1200 UTC of 10th to 0000 UTC of 11th Oct. The lowest estimated central pressure was 972 hPa 1200 UTC of 10th to 0000 UTC of 11th Oct.
- The VSCS crossed north Andhra Pradesh and south Odisha coast near Palasa (Srikakulam district) to the southwest of Gopalpur with the same intensity during 0430-0530 IST of 11th Oct. 2018.

- The system maintained the cyclonic storm intensity for 15 hours even after landfall during 0000 UTC to 1500 UTC of 11^{th}.
- The life period (D to D) of the system was 117 hours (4 days & 21 hours) against long period average (LPA) (1990-2013) of 114 hours for VSCS category over Bay of Bengal during post monsoon season.
- It moved slower, as the 12 hour average translational speed of the cyclone was 12.1 kmph against LPA (1990-2013) of 14.3 kmph for VSCS category over north Indian Ocean.
- The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 6.25 $X10^2$ knots, 3.85 X 10^4 $knots^2$ and 2.55 $X10^6$ $knots^3$ respectively.
- The track and intensity of VSCS, Titli was largely analogous to that of the VSCS over the Bay of Bengal during 15-19 Oct. 1999, which crossed Odisha coast with a wind speed of 98 knots (180 kmph) in the early morning of 18^{th} October 1999 and recurved northeastwards across Odisha. While Titli recurved after landfall, the VSCS of October 1999 recurved during the landfall period.
- While there was loss of about 198 human lives due to VSCS of 1999, it is about 89 due to VSCS Titli and associated floods in 2018.

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. The observed track of the system during **08-13 October** is presented in **Fig. 2.12.1** The best track parameters of the system are presented in Table **2.12.1.**

2.12.2. Monitoring of VSCS, 'TITLI'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it"s genesis as low pressure area over BoB from 5^{th} October onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations, Doppler Weather Radar (DWR) Visakhapatnam and Gopalpur and available ships & buoy observations in the region. Various national and international numerical weather prediction 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 including Bangladesh, Myanmar, Sri Lanka, National & State Disaster Management Agencies, general public and media since inception of the system over BOB. Typical satellite and radar imageries are presented in **Fig. 2.12.5** respectively.

2.12.3. Brief life history

2.12.3.1. Genesis

At 0300 UTC, the Madden Julian Oscillation (MJO) index lay in phase 1 with amplitude more than 1. Considering the environmental conditions, the sea surface temperature (SST) was 29-30^0C over most parts of eastcentral Bay of Bengal (BoB) and Andaman Sea becoming 30-31^0C over westcentral and northwest BoB. The tropical cyclone heat potential (TCHP) was about 60-80 KJ/cm^2 over major parts of south & central BoB becoming less than 40 KJ/cm^2 over north BoB. Low level relative vorticity was about 70 $x10^{-5}$ sec^{-1} over Andaman Sea. The vorticity zone was extending upto 500 hPa level. The lower level convergence was about 10 $x10^{-5}sec^{-1}$ over north Andaman Sea. The upper level divergence was about 10 x 10^{-5} sec^{-1} over north Andaman Sea. The vertical wind shear was low to moderate (5-15 kt) over south & central BoB and adjoining Andaman Sea. The animation of total precipitable water imageries (TPW) indicated the warm and moist air advection to the core of the system. The upper tropospheric ridge ran along 16^0N. The middle and upper tropospheric winds were southeasterly indicating northwestward movement of the system. Under these conditions and under the influence of a cyclonic circulation over north Andaman Sea and adjoining southeast BoB, an **LPA** formed over southeast BoB and adjoining north Andaman Sea at 0300 UTC of 7th October, 2018. Similar favourable conditions continued and the LPA over southeast BoB and adjoining north Andaman Sea lay as a WML over the same region at 0900 UTC of 7^{th} October.

At 0300 UTC of 8^{th}, the MJO lay in phase 1 with amplitude more than 1. The genesis potential parameter (GPP) indicated potential zone of cyclogenesis developing over eastcentral BoB on 8th. Similar sea conditions prevailed. The low level relative vorticity was about 70 $x10^{-5}$ sec^{-1} over Andaman Sea. Extending upto 500 hPa level. The lower level convergence increased and was about 20 $x10^{-5}sec^{-1}$ over eastcentral BoB to the northeast of system centre. The upper level divergence also increased significantly and was about 30 $x10^{-5}sec^{-1}$ over eastcentral BoB. The vertical wind shear was low to moderate (5-15 kt) over south & central BoB and adjoining Andaman Sea. The animation of total precipitable water imageries indicated the warm and moist air advection to the core of the system. The upper tropospheric ridge ran along 16^0N. The middle and upper tropospheric winds were southeasterly indicating northwestward movement of the system. Under these circumstances the WML over southeast and adjoining eastcentral BoB concentrated into a **depression** over eastcentral BoB near 14.0°N/88.8°E.

2.12.3.2. Intensification and movement

At 1800 UTC of 8^{th}, similar MJO and sea conditions prevailed. The low level relative vorticity increased becoming about 100 $x10^{-5}sec^{-1}$ to the west of the system center and extended upto 500 hpa level. The lower level convergence was about 10 $x10^{-5}sec^{-1}$ around the system centre. The upper level divergence was about 20 x 10^{-5} sec^{-1} around the system center. The vertical wind shear was low to moderate (10-15 kt) around the system center. Warm and moist air advection was taking place into the core of the system. The upper tropospheric ridge ran along 16^0N. The middle and upper tropospheric winds were southeasterly indicating northwestward movement of the system. Under these conditions, the depression over eastcentral BoB moved further west-northwestwards and intensified into a **deep depression** (DD) near latitude 14.5°N/87.6°E.

At 0600 UTC of 9^{th}, similar MJO conditions prevailed. The SST increased and was about 30-31^0C over westcentral BoB. THE TCHP was
The GPP indicated intensification of potential zone for intensification over westcentral BoB on 10^{th}. The low level relative vorticity increased and was about 150 $x10^{-5}$ sec^{-1} to the west of the system center and extended upto 500 hPa level. The lower level convergence increased and was about 20 $x10^{-5}$ sec^{-1} around the system centre. The upper level divergence also increased and was about 30 $x10^{-5}$ sec^{-1} around the system center. The vertical wind shear was low to moderate (10-15 kt) to the northwest of the system centre . The animation of TPW imageries indicated the warm and moist air advection to the core of the system. The upper tropospheric ridge ran along 16^0N. The middle and upper tropospheric winds were southeasterly indicating northwestward movement of the system. Under these conditions the DD over westcentral BoB moved west-northwestwards and intensified into a **cyclonic storm** (CS) „Titli‟ over westcentral BoB near 14.8°N/86.7°E.

At 2100 UTC of 9th, the MJO was in phase 1 with amplitude greater than 1. The SST increased and was about 30-31^{0}C over westcentral BoB. The TCHP was 60-80 KJ/cm^{2} over major parts of south & central BoB. The low level relative vorticity now increased and was about 250 x10^{-5} sec^{-1} around the system extending upto 200 hpa level. The lower level convergence was about 20 x10^{-5} sec^{-1} around the system centre. The upper level divergence was about 30 x10^{-5} sec^{-1} around the system center. The vertical wind shear was low to moderate (10-15 kt) to the northwest of the system centre. The animation of total precipitable water imageries indicated the warm and moist air advection to the core of the system. The upper tropospheric ridge ran along 16^{0}N. The middle and upper tropospheric winds were southeasterly indicating northwestward movement of the system. Under these conditions the CS „Titli" over westcentral BoB intensified into a **severe cyclonic storm** (SCS) near latitude 15.7°N/85.8°E

At 0600 UTC of 10th, similar MJO and sea conditions prevailed. The low level relative vorticity was about 250 x10^{-5} sec^{-1} around the system extending upto 200 hpa level. The lower level convergence increased and was about 30 x10^{-5} sec^{-1} around the system centre. The upper level divergence increased and was about 40 x10^{-5} sec^{-1} around the system center. The vertical wind shear was low (05-10 kt) to the northwest of the system centre. The animation of total precipitable water imageries indicated the warm and moist air advection to the core of the system. The upper tropospheric ridge ran along 18^{0}N. The middle and upper tropospheric winds were southeasterly indicating northwestward movement of the system. Under these conditions the SCS „Titli" over westcentral BoB intensified into a **very severe cyclonic storm** (VSCS) near latitude 17.0°N/85.6°E. favourable conditions continued and the system further intensified gradually reaching peak intensity of 80 kts at 1200 UTC of 10th near 17.5°N/85.3°E. The system maintained its peak intensity till 2100 UTC of same day and crossed north Andhra Pradesh and south Odisha coasts near 18.8^{0}N/84.5^{0}E during 2300 UTC of 10th and 0000 UTC of 11th with peak intensity. Thereafter, the system started weakening but maintained it"s intensity of VSCS for next 6 hours because of low vertical wind shear.

At 0600 UTC of 11th, MJO lay in phase 2 with amplitude more than 1. The low level relative vorticity was about 250 x10^{-5} sec^{-1} around the system extending upto 200 hpa level. The lower level convergence decreased and was about 10-15 x10^{-5} sec^{-1} around the system centre. The upper level divergence decreased and was about 20 x10^{-5} sec^{-1} around the system center. The vertical wind shear was low (05 kt) around and to the east of the system centre. There was cold and dry air advection to the core of the system from northwest. The upper tropospheric ridge ran along 20^{0}N. The middle and upper tropospheric winds were southwesterly indicating northeastward movement of the system. Under these conditions the VSCS „Titli" over south Odisha weakened into an **SCS** over south Odisha near 19.3^{0}N/83.8^{0}E.

Thereafter, due to land interactions, cold and dry air advection into the core of system and gradual decrease in the intensity of environmental parameters favourable for cyclogenesis, the system weakened gradually into a CS at 1200 UTC of 11th near 19.9^{0}N/83.7^{0}E, a **DD** at 1800 UTC of 11th near 20.3^{0}N/84.3^{0}E. From 1500 UTC of 11th, the system exhibited northeastwards movement under the influence of southwesterly middle and upper tropospheric winds and the ridge was located at 18^{0}N. Even after landfall for 15 hours the system maintained cyclonic storm intensity (≥34 kts) over land. Thereafter, it weakened into a **D** at 0900 UTC of 12th near 20.9^{0}N/85.5^{0}E over Odisha and into a **WML** at 0000 UTC of 13th over Gangetic West Bengal and adjoining Bangladesh & north BoB and into an **LPA** over the same region at 0300 UTC of 13th.

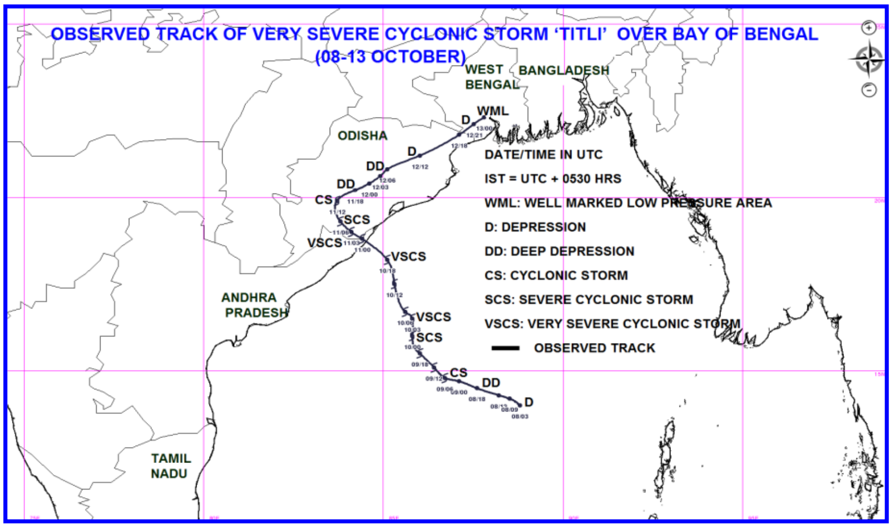


Fig. 2.12.1. Observed track of VSCS TITLI (08- 13 October, 2018) over eastcentral Bay of Bengal.

Table 2.12.1: Best track positions and other parameters of the Very Severe Cyclonic Storm, 'Titli' over eastcentral Bay of Bengal during 08-13 October, 2018

Date	Time (UTC)	Centre lat.^{0} N/ long. ^{0} E		C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
08/10/2018	0300	14.0	88.8	1.5	1002	25	3	**D**
	0600	14.0	88.8	1.5	1002	25	4	D
	1200	14.3	88.2	1.5	1002	25	4	D
	1800	14.5	87.6	2.0	1000	30	5	**DD**
09/10/2018	0000	14.7	87.1	2.0	1000	30	5	DD
	0300	14.7	86.9	2.0	999	30	6	DD
	0600	14.8	86.7	2.5	998	35	7	**CS**
	0900	14.9	86.6	2.5	997	35	7	CS
	1200	15.1	86.4	2.5	996	40	8	CS
	1500	15.3	86.2	2.5	995	40	9	CS
	1800	15.5	86.0	3.0	996	45	10	CS
	2100	15.7	85.8	3.0	994	50	12	**SCS**
10/10/2018	0000	16.0	85.8	3.5	990	55	16	SCS
	0300	16.5	85.8	3.5	988	60	18	SCS
	0600	17.0	85.6	4.0	982	70	24	**VSCS**
	0900	17.3	85.4	4.5	976	75	28	VSCS
	1200	17.5	85.3	4.5	972	80	32	VSCS
	1500	17.7	85.2	4.5	972	80	32	VSCS
	1800	18.2	85.1	4.5	972	80	32	VSCS
	2100	18.6	84.7	4.5	972	80	32	VSCS
		Crossed north Andhra Pradesh and south Odisha coasts near 18.8^{0}N/84.5^{0}E during 2300 UTC of 10th and -0000 UTC of 11th						
11/10/2018	0000	18.8	84.4	-	972	80	32	VSCS

	0300	19.0	84.1	-	985	65	21	VSCS
	0600	19.3	83.8	-	988	60	18	**SCS**
	0900	19.6	83.8	-	994	50	12	SCS
	1200	19.9	83.7	-	996	45	10	**CS**
	1500	20.1	84.0	-	998	40	8	CS
	1800	20.3	84.3	-	999	30	6	**DD**
12/10/2018	0000	20.5	84.7	-	1000	30	6	DD
	0300	20.6	84.9	-	1001	30	5	DD
	0600	20.8	85.2	-	1001	30	5	DD
	0900	20.9	85.5	-	1002	25	4	**D**
	1200	21.2	86.1	-	1002	25	4	D
	1800	21.9	87.2	-	1003	25	4	D
	2100	22.1	87.5	-	1004	20	3	D
13/10/2018	0000	**Weakened into a well-marked low pressure area over Gangetic West Bengal and adjoining Bangladesh and North Bay of Bengal.**						

The total precipitable water imageries (TPW) during 9th-12th October are presented in **Fig. 2.12.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system till 11th from southeast sector. From 11th afternoon onwards, the warm moist air advection into the core decreased significantly and cold and dry air advection into the core started increasing from northwest.

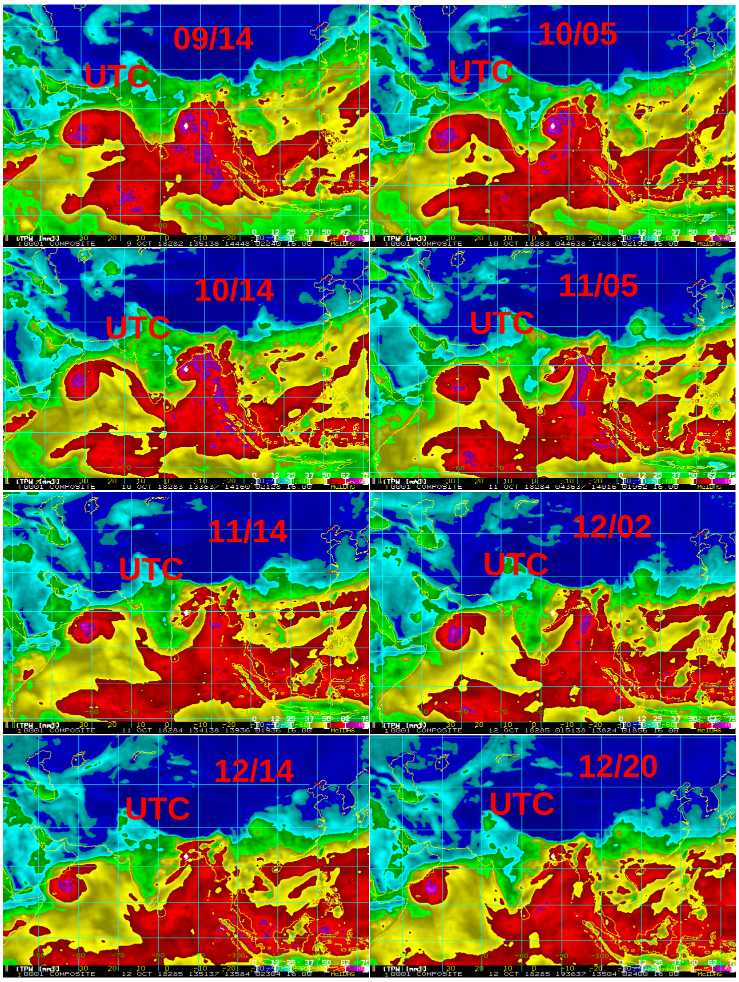


Fig. 2.12.2: Total Precipitable Water Imageries during 09-12 October, 2018

The mean wind shear and wind speed in middle and deep layer around the system centre is presented in **Fig. 2.12.3**. The wind shear between lower to upper tropospheric levels around the system centre increased from 5 to 15 kt from 0000 UTC of 9th to 0300 UTC of 11th. It then increased gradually to 2o kt till 0300 UTC of 12th. Thereafter, it increased significantly to 30 kts by 1200 UTC of 12th. The direction of wind shear between lower to upper tropospheric levels was nearly north-northeasterly upto 1200 UTC of 11th, it then became east-northeasterly. The wind shear between lower to middle tropospheric levels around the system was gradually increased from 2 to 10 kt from 0000 UTC of 9th to 0000 UTC of 10th, thereafter decreased to almost 2 kt around 0300 UTC of 11th and increased to 20 kt around 1200 UTC of 12th. For this layer, the direction of wind shear was northerly upto 1200 UTC of 10th, thereafter it gradually became east-northeasterly. Hence the direction as well as the speed of shear was favourable for intensification of the system.

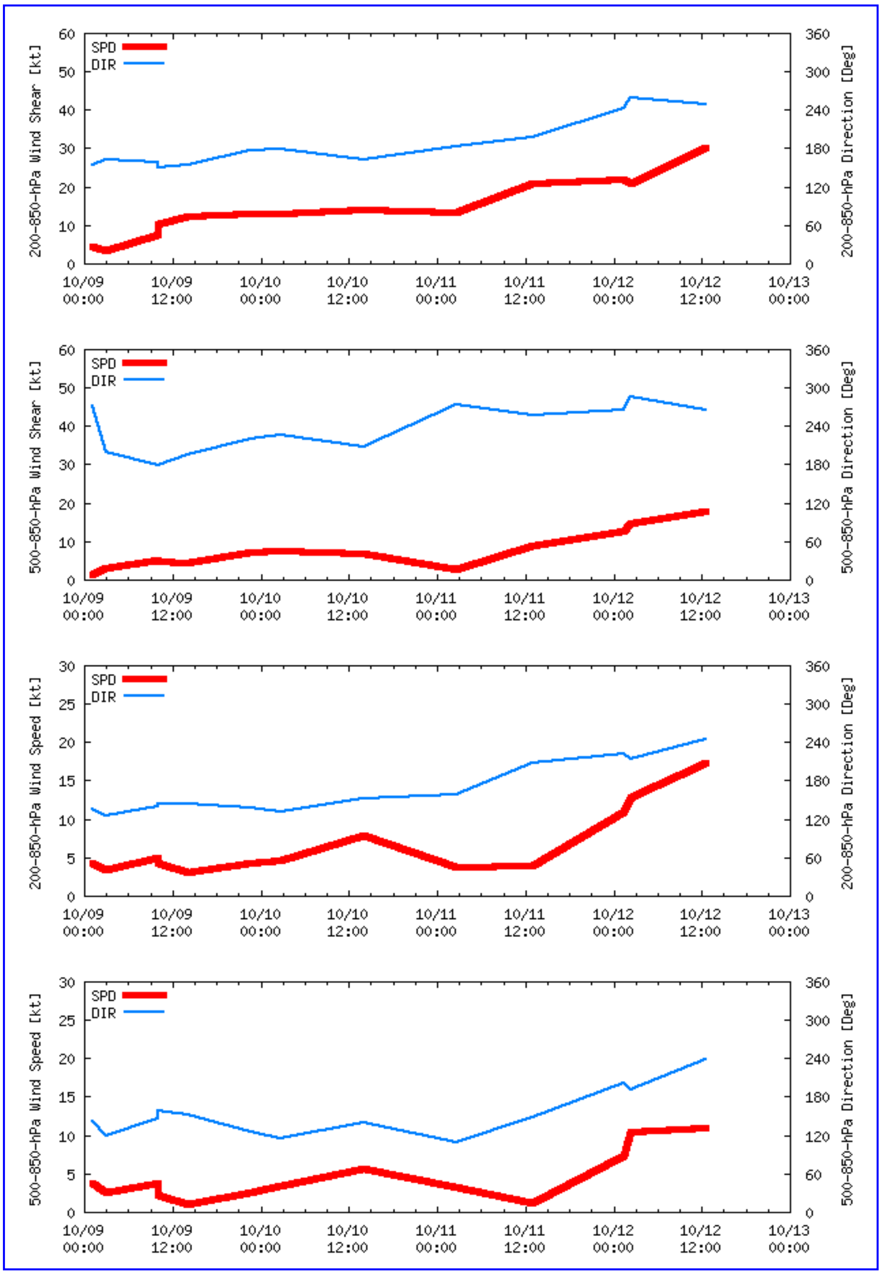


Fig. 2.12.3 **Wind shear and wind speed in the middle and deep layer around the system during 09nd to 13th October 2018.**

2.12.3.3 Movement

From **Fig. 2.12.3**, the mean deep layer winds between 200-850 hPa levels steered the system northwestwards till 0300 UTC of 11th with direction gradually becoming northeastwards from 1200 UTC of 11th onwards. The mean wind speed of deep layers was 5-7 knots upto 1200 UTC of 11th, thereafter it increased sharply becoming 13knots by 1200 UTC of 12th. The six hourly movement of VSCS Titli is presented in **Fig. 2.12.4 (a)**. The six hourly average translational speed of the cyclone was about 12.7 kmph and hence was slow moving in nature. The system had a track length of about 1450 km during its life period.

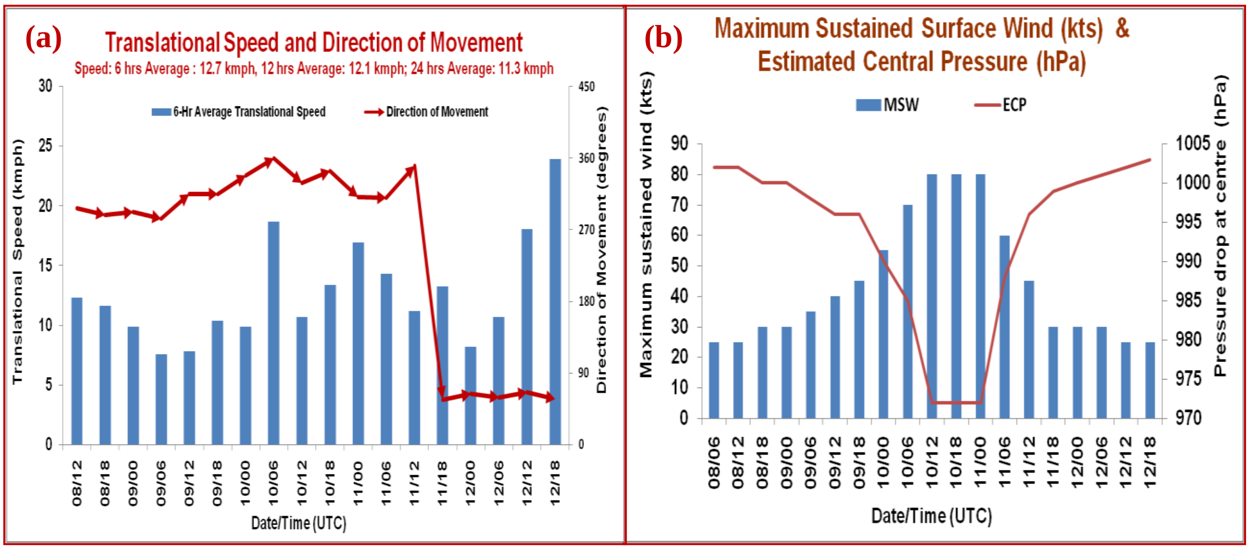


Fig. 2.12.4: (a) Translational speed & direction of movement and (b) Maximum sustained surface winds (kts) & Estimated Central Pressure

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

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig. 2.12.4 (b)**. The lowest estimated central pressure (ECP) had been 972 hPa during 1200 of 10th to 0000 UTC of 11th. The ECP gradually decreased from 1002 hPa at 0300 UTC of 8th to 996 hPa at 1200 UTC of 9th. Thereafter, there was sharp fall from 996 hPa at 1800 UTC of 9th to 972 hPa at 1200 UTC 10th. Thereafter, it remained constant at 972 hPa till 0000 UTC of 11th. Thereafter, there was sharp rise in ECP from 972 hPa (at 0000 UTC of 11th) to 996 hPa at 1200 UTC of 11th. Thereafter it increased gradually to 1003 hPa at 1800 UTC of 12th. Similarly, in the wind field it is seen that the maximum sustained surface wind speed (MSW) had been 80 kts during 1200 of 10th to 0000 UTC of 11th. The MSW gradually increased from 1002 hPa 25 kts at 0300 UTC of 8th to 40 kts at 1200 UTC of 9th. Thereafter, there was sharp rise from 45 kts at 1800 UTC of 9th to 80 kts at 1200 UTC 10th. Thereafter, it remained constant at 80 kts till 0000 UTC of 11th. Thereafter, there was sharp fall in MSW from 80 kts at 0000 UTC of 11th to 45 kts at 1200 UTC of 11th. Thereafter it decreased gradually to 25 kts at 1800 UTC of 12th. There was rapid intensification during

0000 UTC of 9th to 0000 UTC of 11th, when there was an increase in wind speed by 25 knots or more in past 24 hours.

2.12.5. Features observed through satellite

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

At 0300 UTC of 7th, the intensity of the system was T 1.0. Broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 9.0°N & 16.0° N and longitude 88.0°E & 97.0°E. At 0900 UTC of 7th, the intensity of the system was T 1.0. Broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 9.0° N & 17.0° N and longitude 88.0° E & 96.0° E. At 0300 UTC of 8th, there was organization of cloud mass and the system was assigned intensity as T 1.5. Broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 13.2° N & 17.0° N and longitude 87.0°E & 95.0°E. At 1800 UTC of 8th, intensity of the system was T 2.0. Broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 6.0°N & 20.5°N and longitude 83.5°E & 96.5°E. At 0600 UTC of 9th, intensity of the system was T 2.0. Broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 10.0°N & 18.0°N and longitude 83.0°E & 90.0°E. At 0000 UTC of 10th, intensity of the system was T 3.5. Broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 13.5°N & 21.0°N and longitude 81.5°E & 90.0°E. The ragged eye developed at 0300 UTC of 10th October with a diameter of about 25 km. Gradually, it became a clear eye at 1200 UTC of 10th with eye diameter decreasing to 18 km. Eye disappeared around 1500 UTC and reappeared at 1600 UTC of 10th. Thereafter, eye was visible till 0100 UTC of 11th. At the time of landfall eye diameter was around 24 km with eye temperature of -320C. The eye region was the warmest during 0900 to 1200 UTC of 10th with temperature of -140C. According to satellite imagery and eye characteristics, the intensity may be maximum during 0900-1200 UTC of 10th with the smallest and warmest eye. At 0600 UTC of 11th, broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 16.0°N & 21.0°N, west of longitude 87.0°E. At 1800 UTC of 11th, broken low and medium clouds with embedded intense to very intense convection lay over area between latitude 16.0°N & 22.0°N, west of longitude 87.0°E. At 0900 UTC of 12th, broken low and medium clouds with embedded intense to very intense convection lay over Odisha and neighbourhood between latitude 19.00N & 22.50N and longitude 82.5E & 87.0E.

2.12.5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.12.5 (a-d)**.

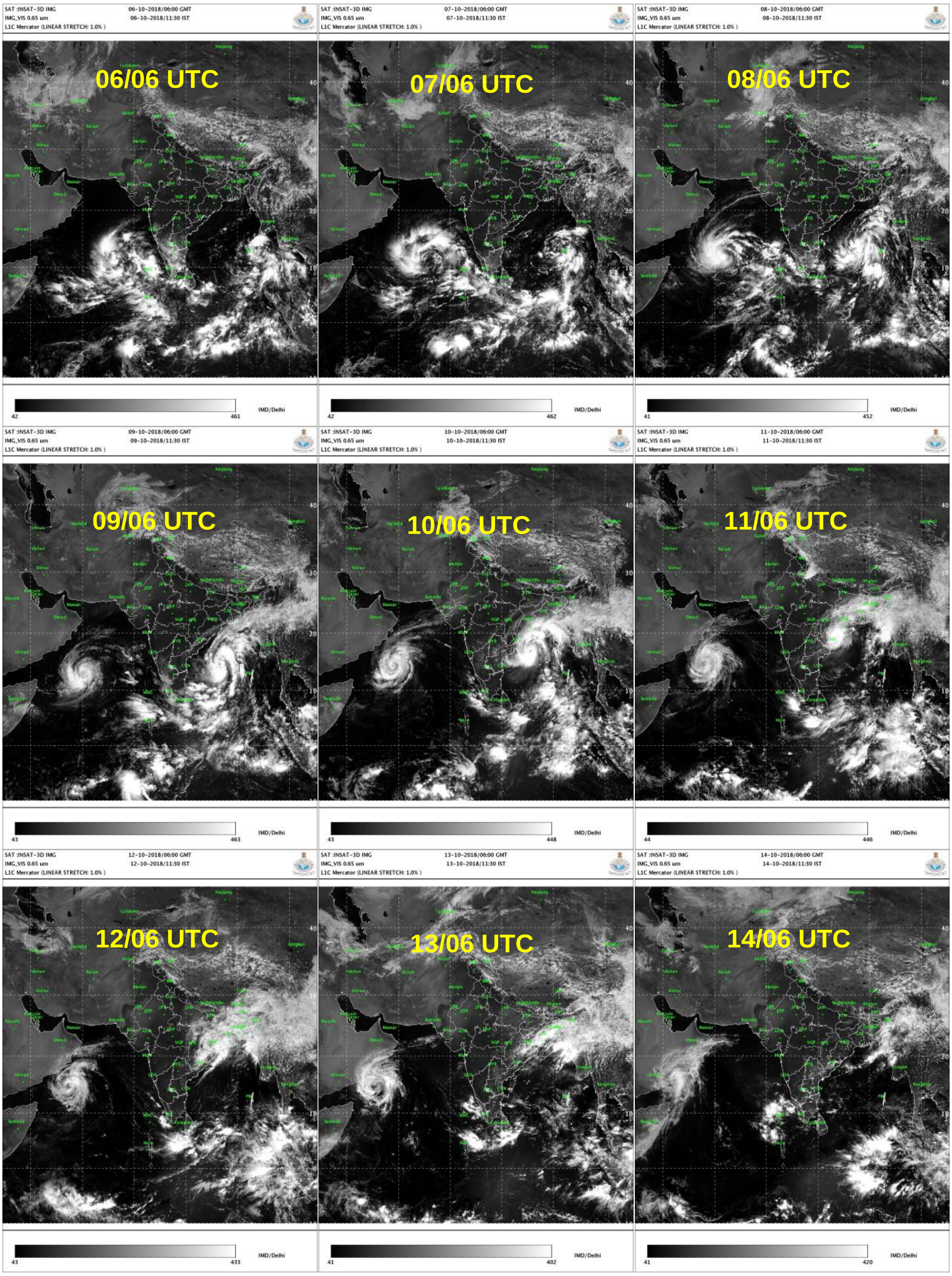


Fig. 2.12.5a: INSAT-3D visible imageries during life cycle of VSCS Titli (08-13 October, 2018)

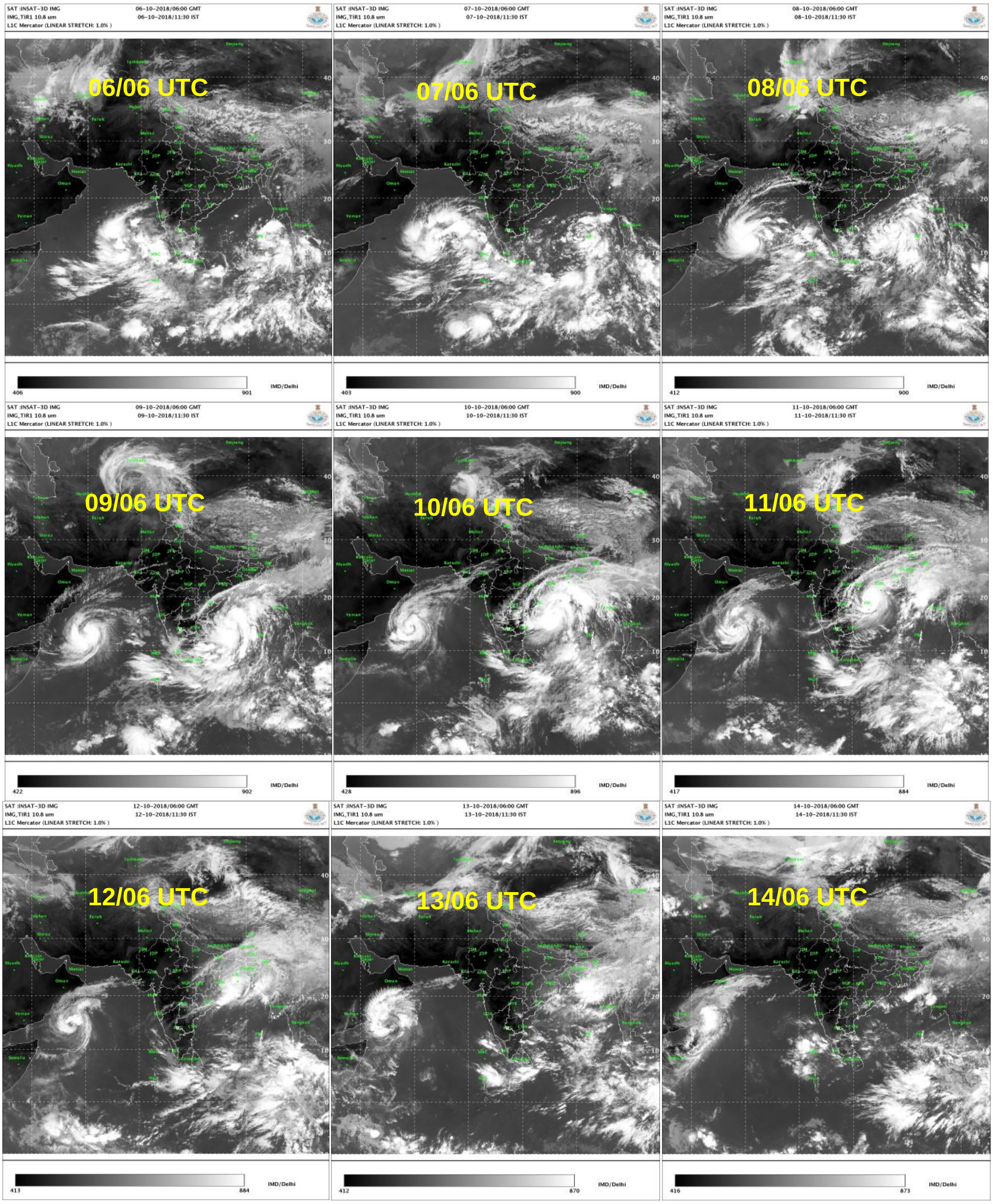


Fig. 2.12.5b: INSAT-3D IR imageries during life cycle of VSCS Titli (08-13 October, 2018)

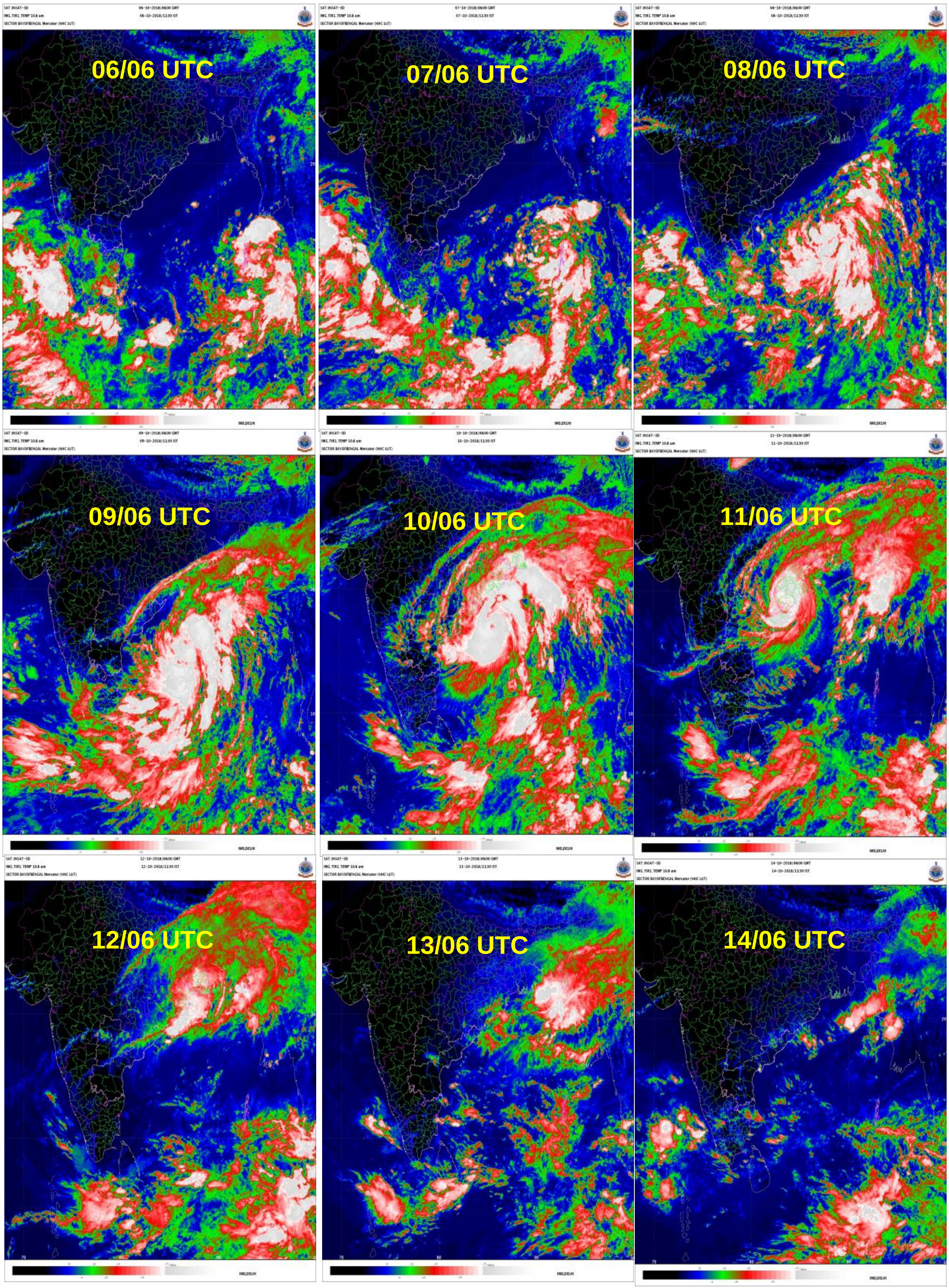


Fig. 2.12.5c: INSAT-3D enhanced colored imageries during life cycle of VSCS Titli (08-13 October, 2018)

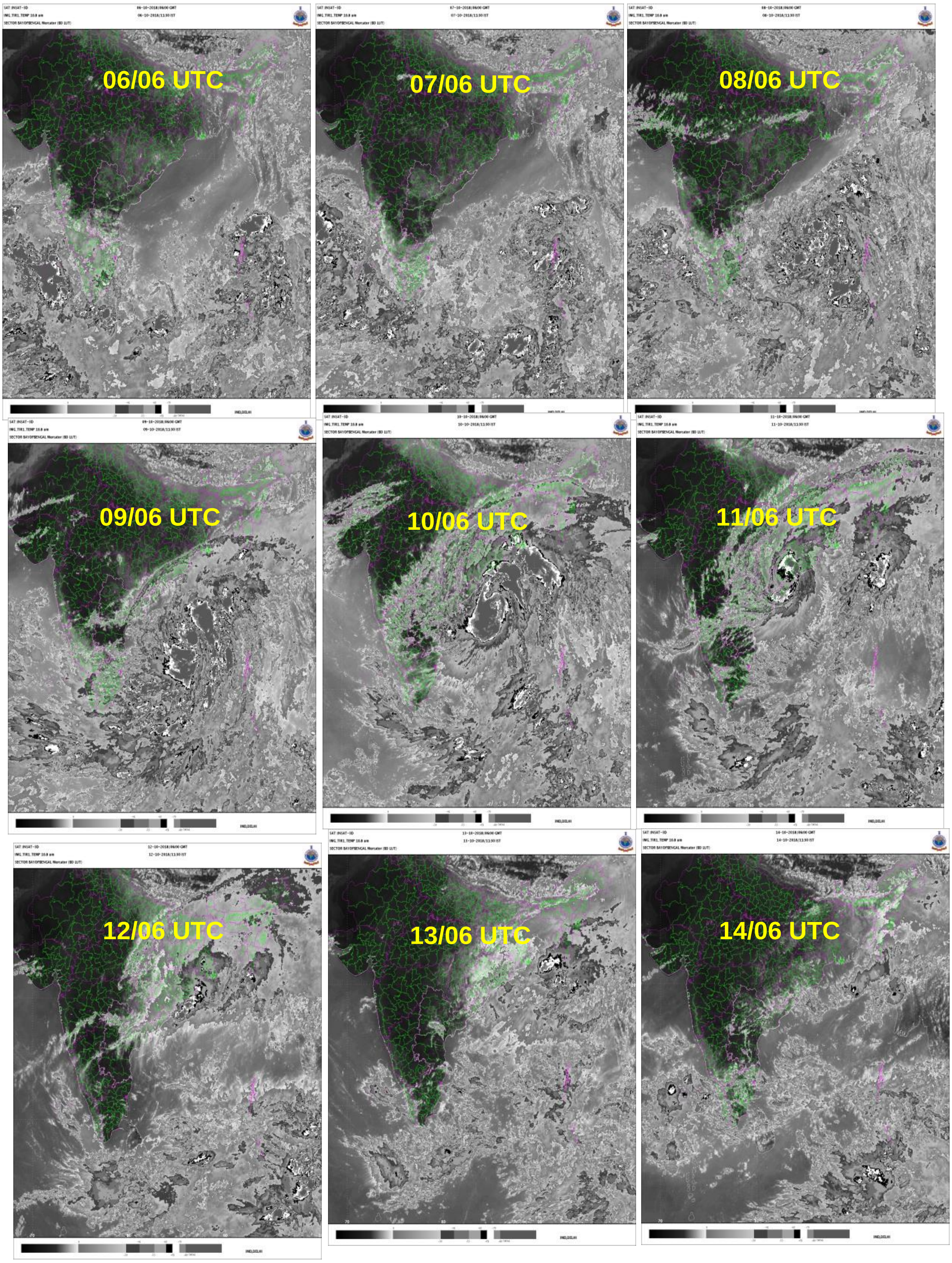


Fig. 2.12.5d: INSAT-3D cloud top brightness imageries during life cycle of VSCS Titli (08-13 October, 2018)

2.12.5.2. Radar Imageries:

The system came under Radar surveillance from the morning of 10th . Eye was visible in DWR Visakhapatnam since 0830 UTC of 10th. Diameter of eye was in the range 40-50 km during 0830 UTC to 2130 UTC of 10th. Thereafter, it started decreasing from 2200 UTC of 10th, becoming the least about 12km around 0100 UTC of 11th. The eye closed at 0200 UTC of 11th. As per observations from DWR Gopalpur, eye was not visible from 0300 UTC of 11th . After landfall, the system was captured by DWR Gopalpur till it‟s weakening. Typical radar imagaries from DWR Visakhapatnam & Gopalpur are presented in Fig. 2.12.5(e-f)

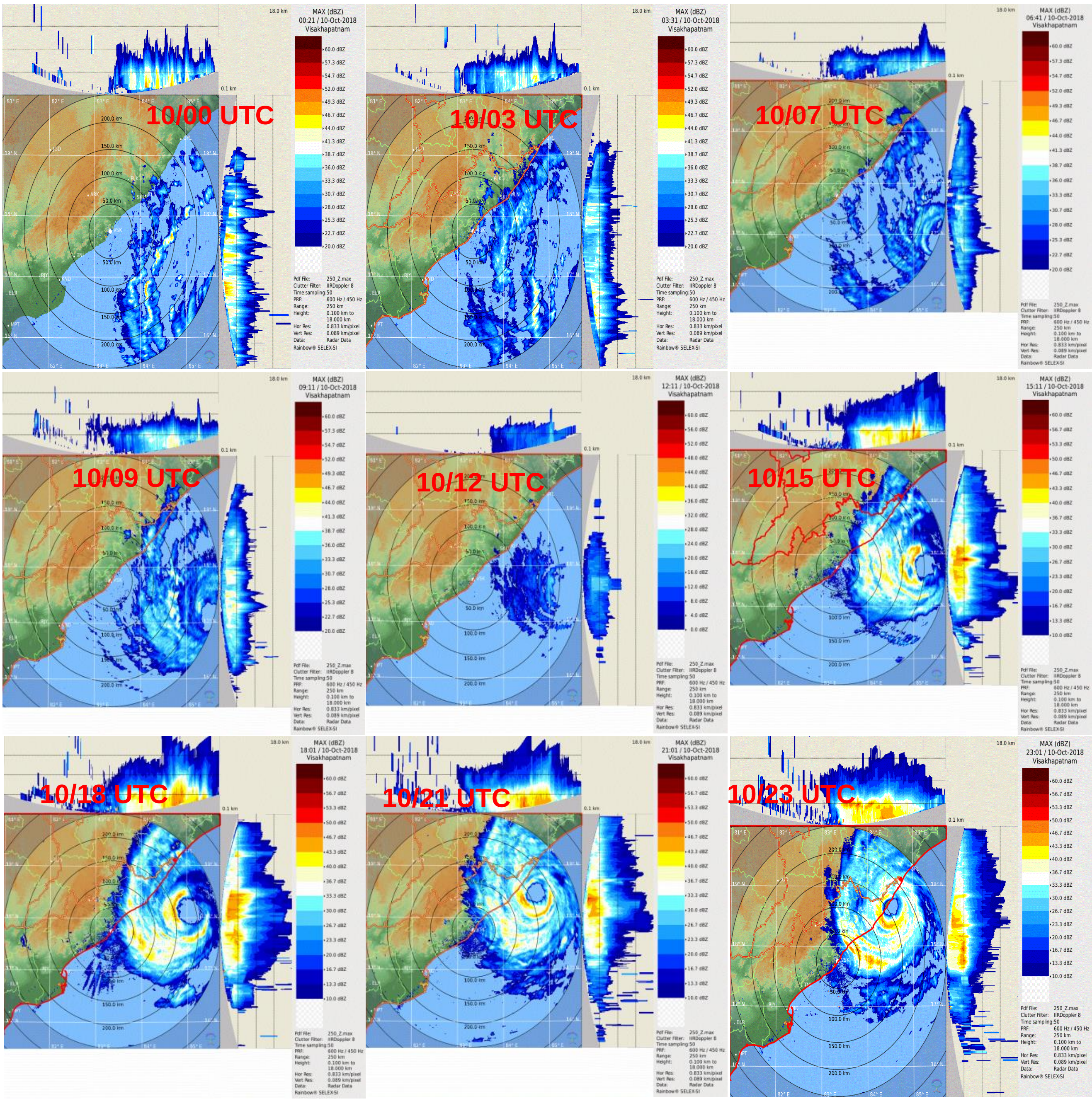


Fig. 2.12.5e: Visakhapatnam **radar imageries of VSCS Titli during 0000-2300 UTC of 10th**

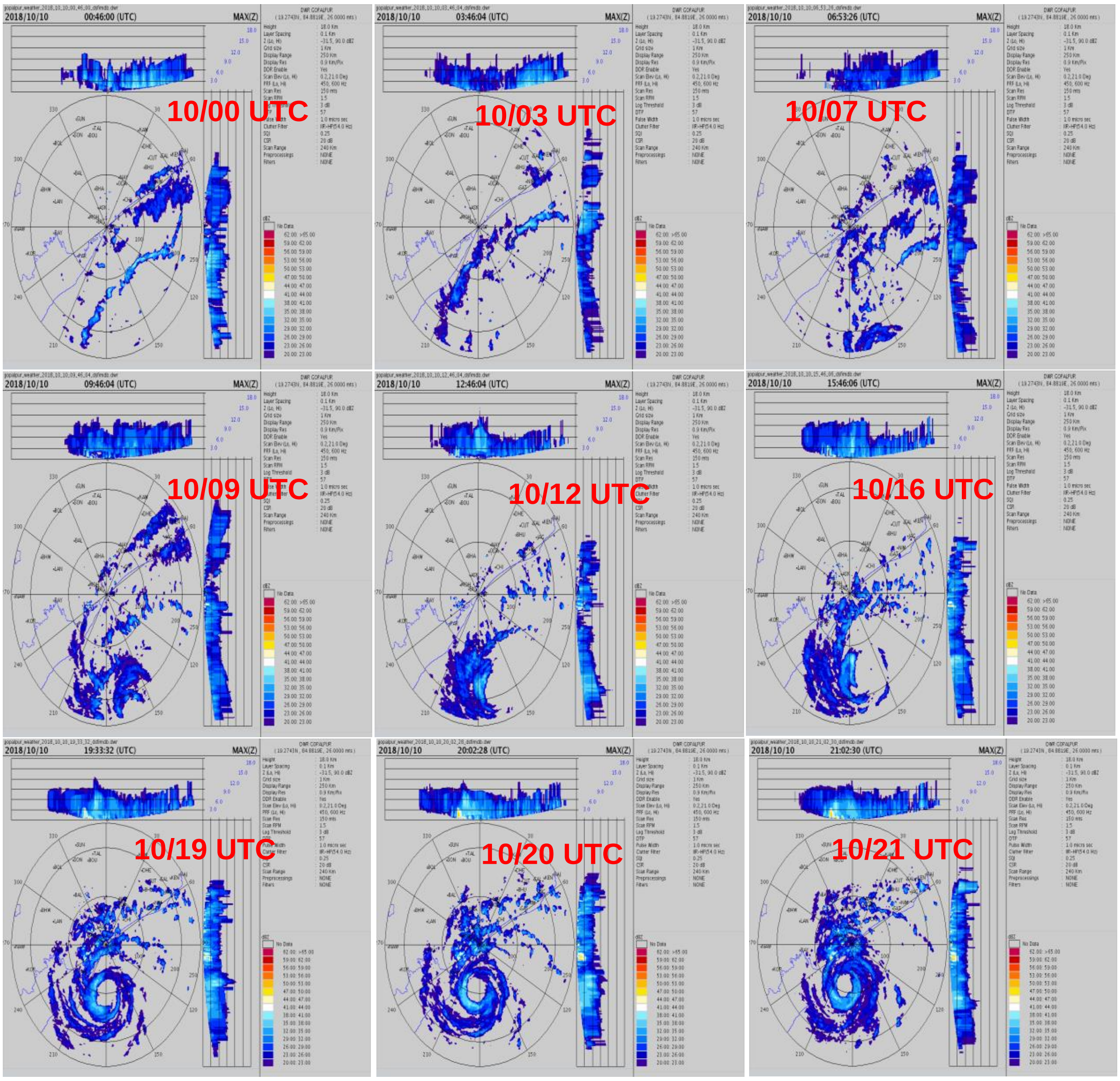


Fig. 2.12.5f: Gopalpur radar imageries of VSCS Titli during 0000-2100 UTC of 10th.

2.12.5.3. Microwave Imageries:

Microwave imageries from polar orbiting satellites F-15, F-16, F-18, GCOM W1, GPM 89, NOAA-19 were utilised for determining the centre and area of intense convection. Typical microwave imageries during the life cycle of ESCS Mekunu are presented in **Fig. 2.12.5(g).**

When the system was over sea, imageries from ASCAT were also utilized for determination of centre, intensity and wind distribution around the centre of the system. Typical ASCAT imageries from Metop-B are presented in Fig. 2.12.5(g).

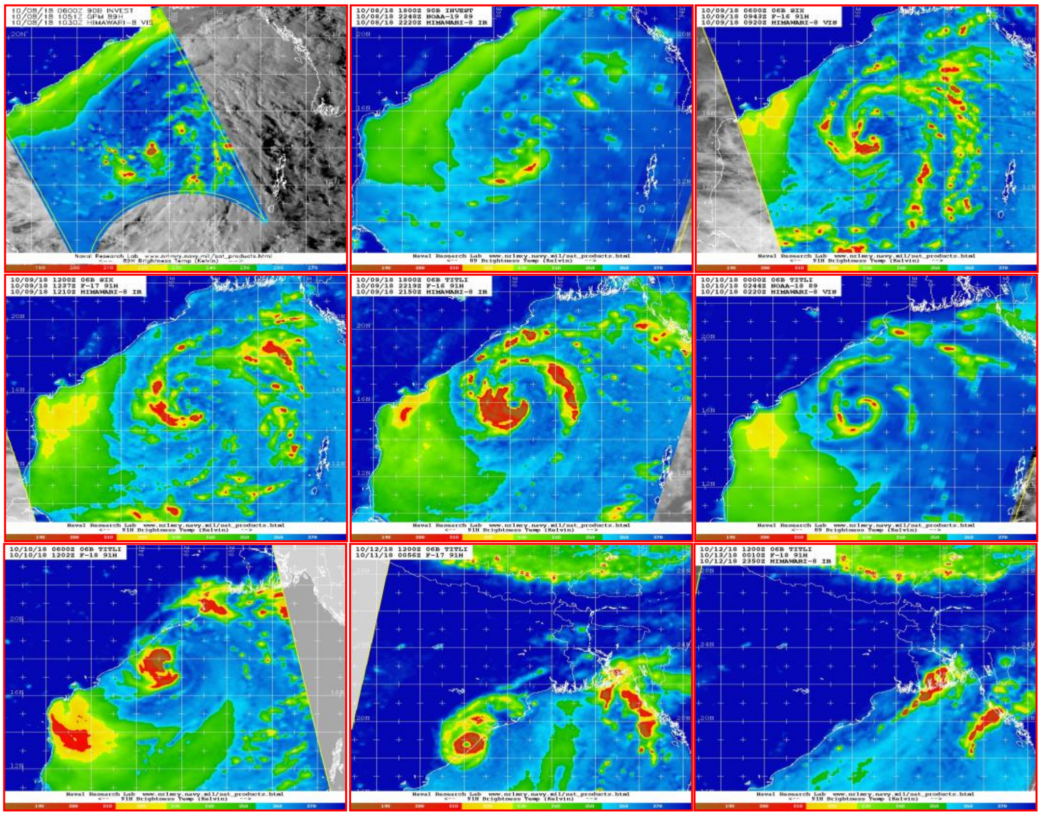


Fig. 2.12.5g: Microwave imageries during life cycle of VSCS Titli (08-13 October, 2018)

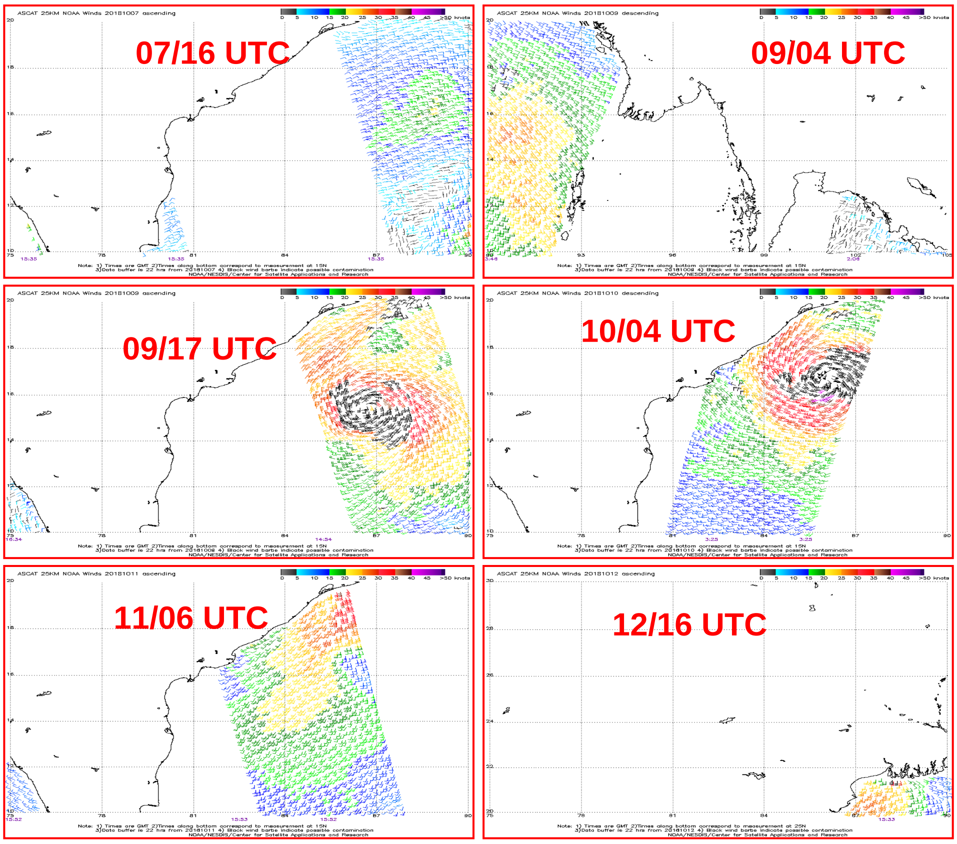


Fig. 2.12.5(h): ASCAT (Met-Op B) imageries during life cycle of VSCS Titli (08-13 October, 2018)

Typical imageries from polar satellite, SCATSAT are presented in Fig. 2.12.5 (i). SCATSAT passes are available twice a day at around 0300 UTC and 1500 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. These imageries helped in determination of centre to a good extent. Intensity estimates beyond 60 kts cannot be done with the help of these imageries. The matching index MI>0.6 represents cyclogenesis. The M.I. during 8th to 11th indicated cyclogenesis. However, the imageries on 4th and 6th also indicated MI>0.6, which was a false alarm.

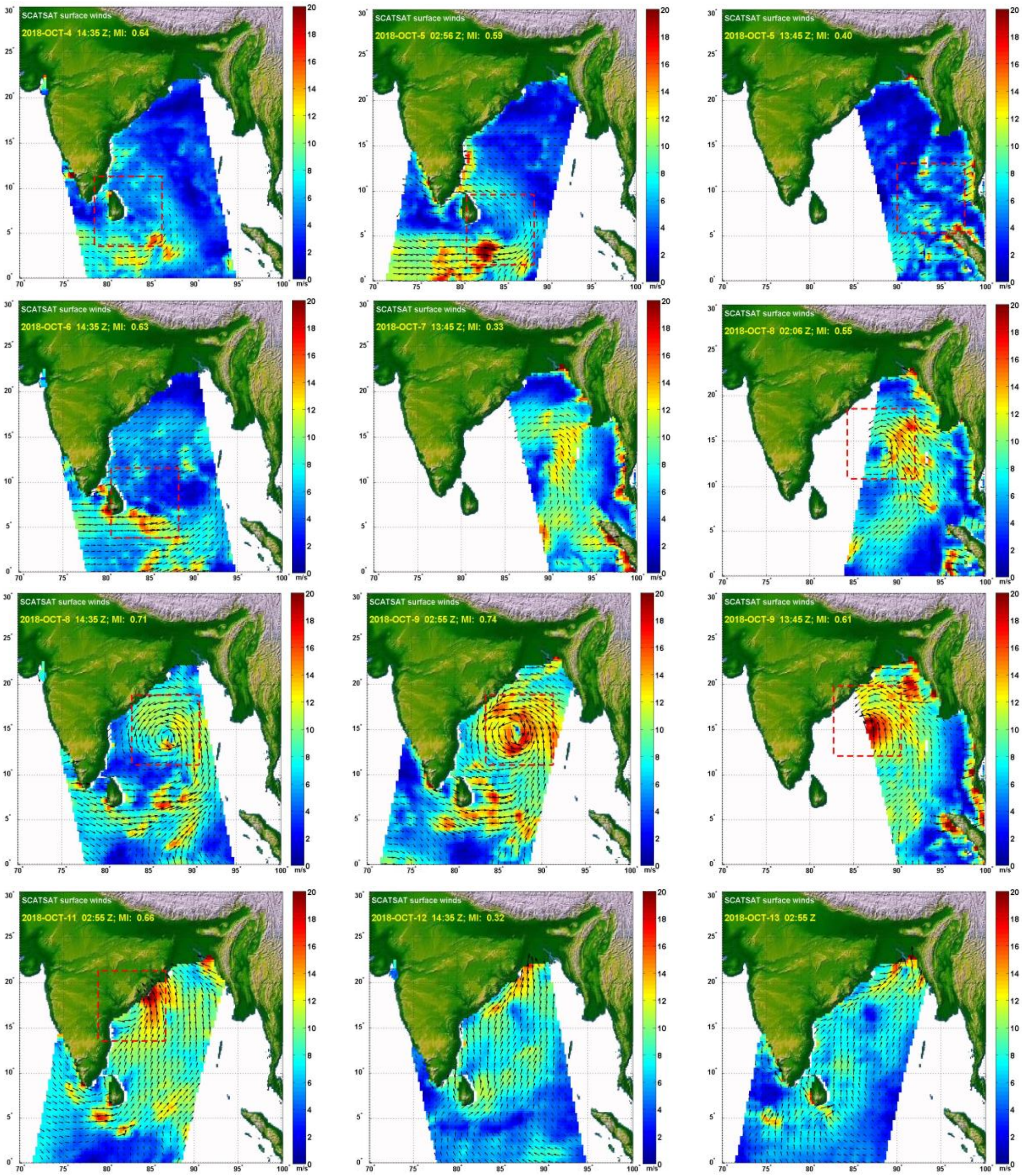


Fig. 2.12.5(i): SCAT SAT imageries during life cycle of VSCS Titli (08-13 October, 2018)

2.12.6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 7th to 13th October are presented in Fig. 2.12.6. GFS (T1534). Based on 0000 UTC observations of 7th, the model could not pick up the signatures of low pressure area over southeast Bob and adjoining Andaman Sea. It indicated a cyclonic circulation over southwest BoB at 10 m level.

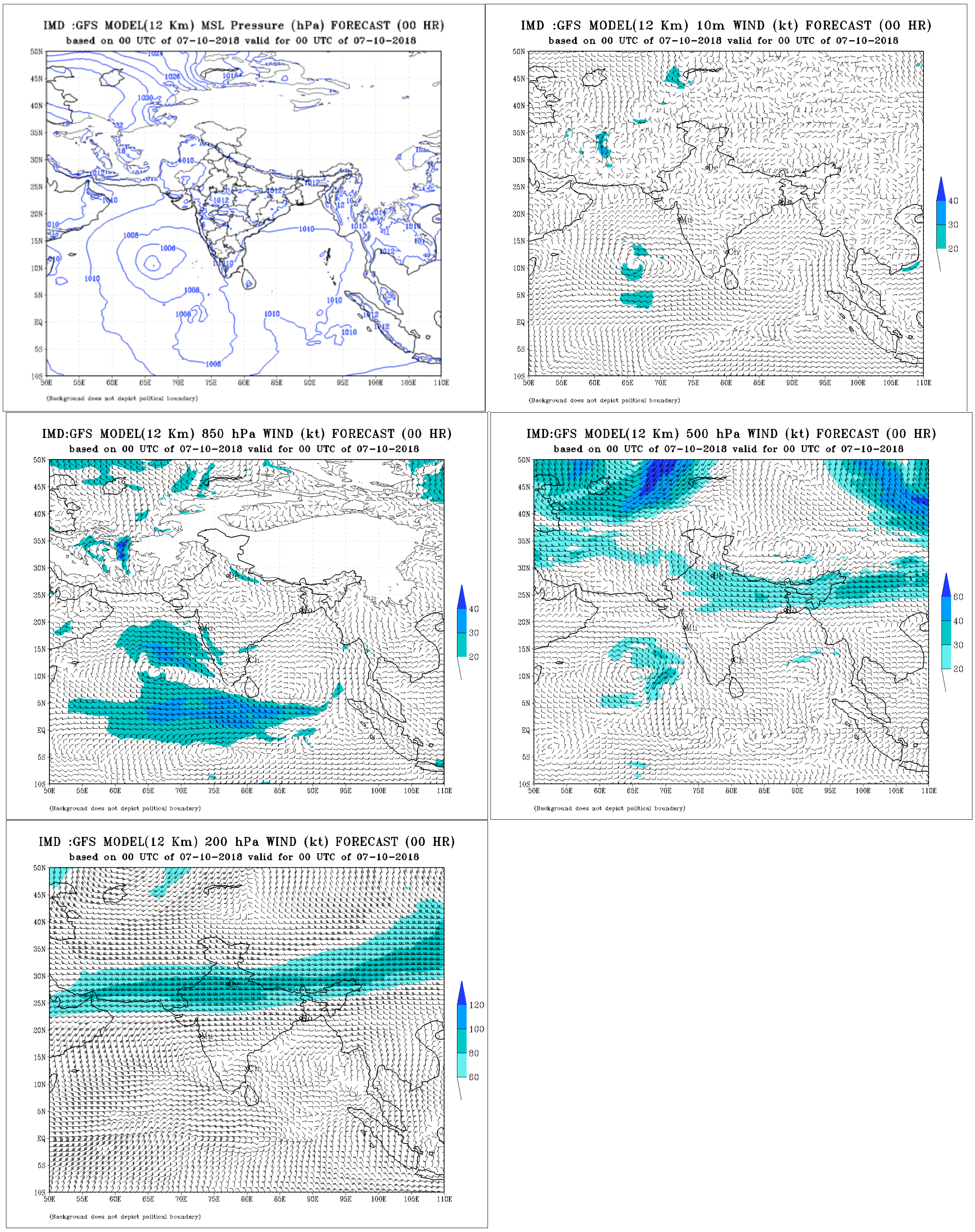


Fig. 2.12.6 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 7th October

Analysis based on 0000 UTC of 8th October, indicated an LPA over eastcentral BoB Vertically the system extended upto 500 hPa level.

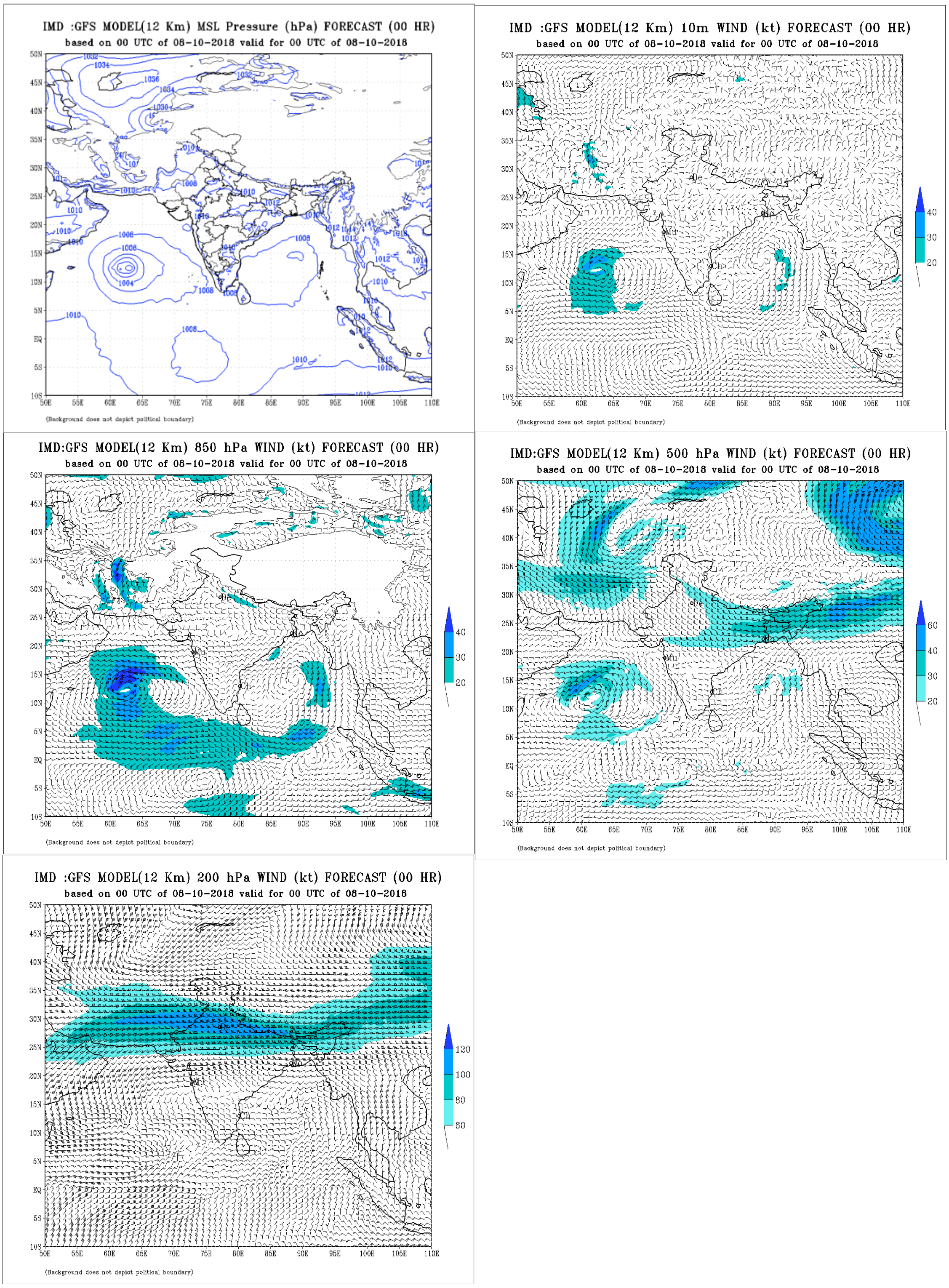


Fig. 2.12.6 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 8th October

Analysis based on 0000 UTC of 9th October indicated a DD over eastcentral BoB. The circulation extended upto 500 hpa levels. The position and intensity was correctly picked up by the model.

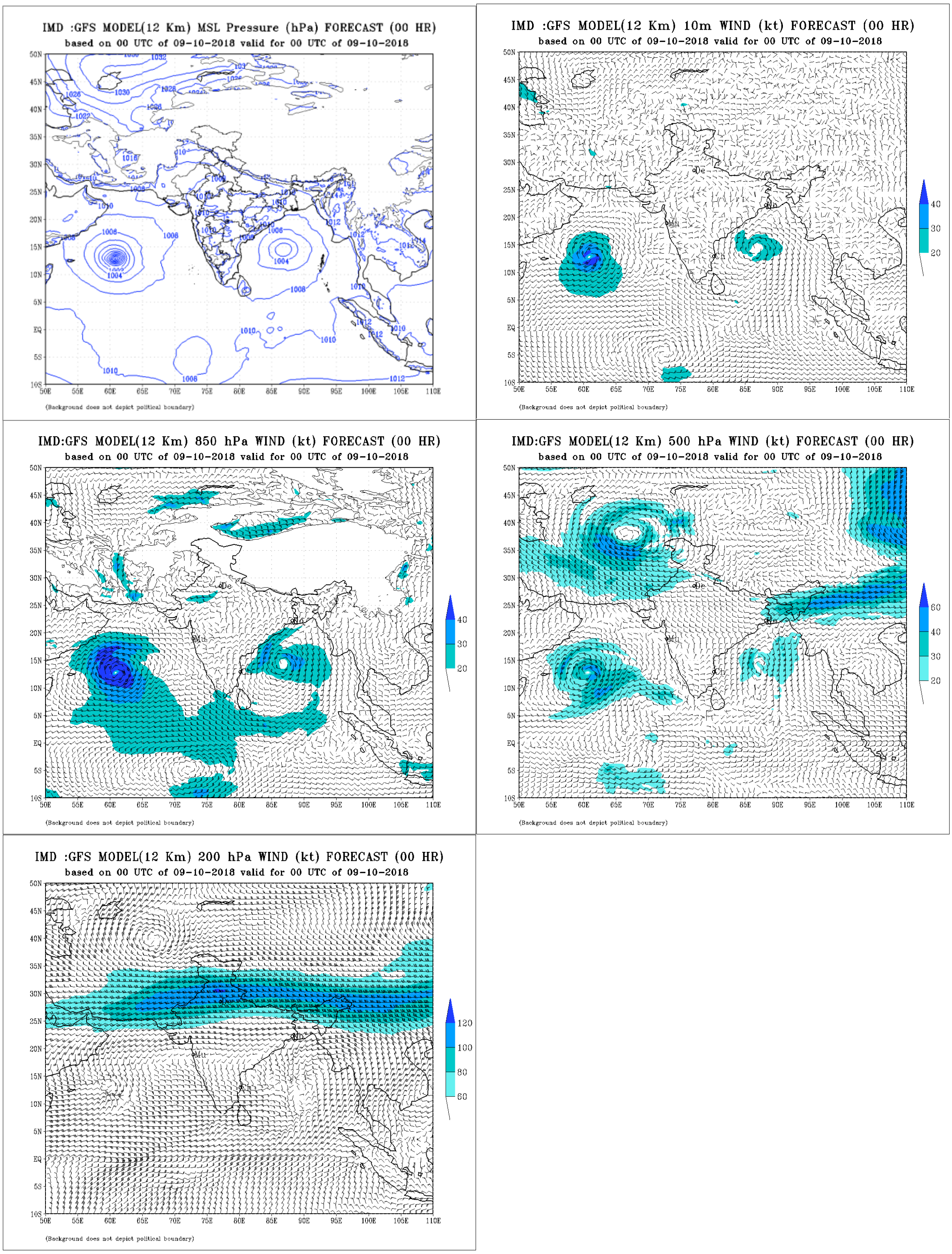


Fig. 2.12.6 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 9th October

Initial conditions based on 0000 UTC of 10th October indicated intensification of the system into an SCS and the system lay over westcentral BoB. Vertically the circulation extended upto 500 hPa levels. The intensity and location was correctly picked by the model.

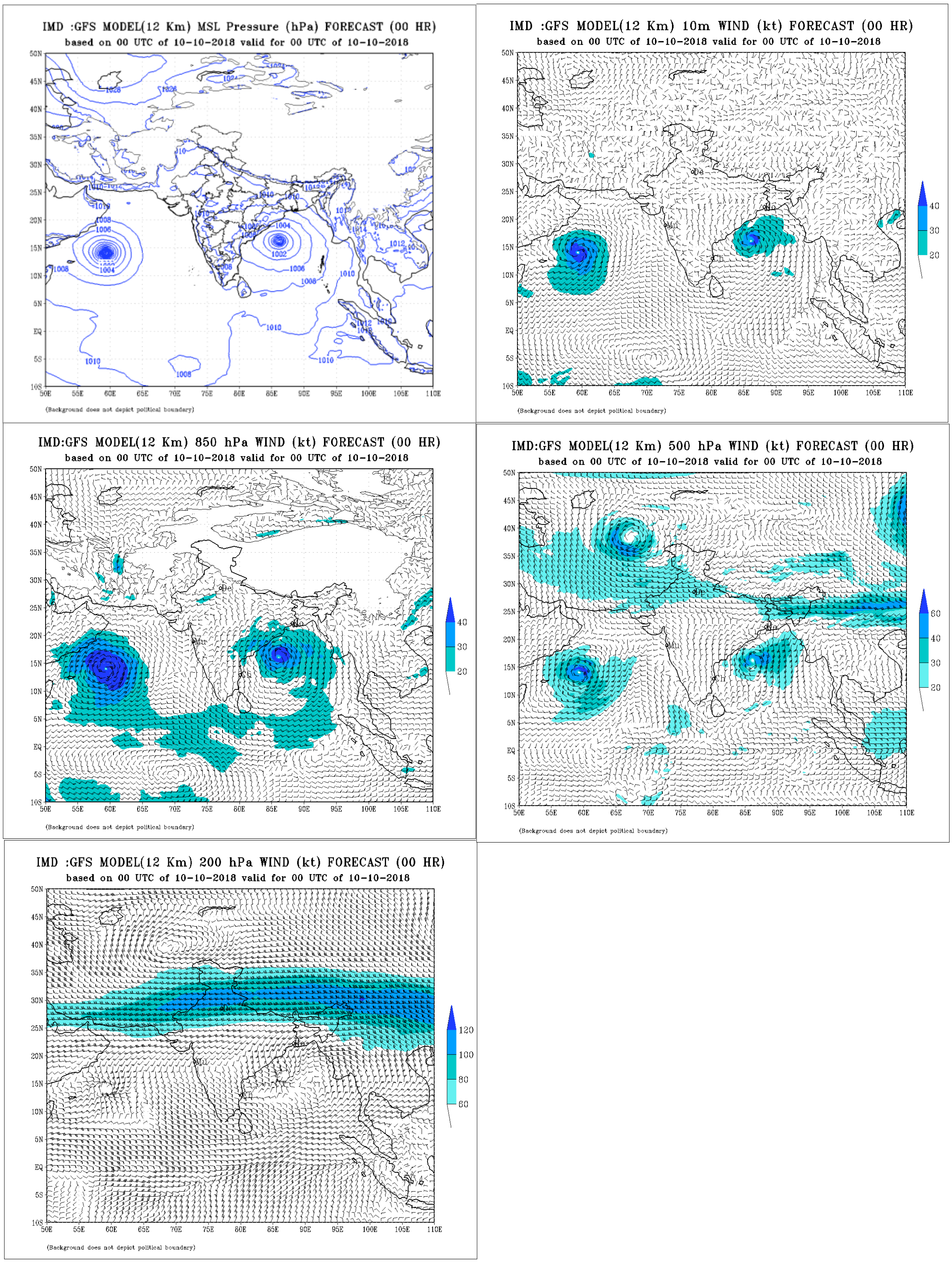


Fig. 2.12.6 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th October

Analysis based on 0000 UTC of 11th October indicated the system crossing north Andhra Pradesh and adjoining south Odisha coasts as a VSCS prior to 0000 UTC of 11th. The model could pick up landfall point, time and intensity correctly.

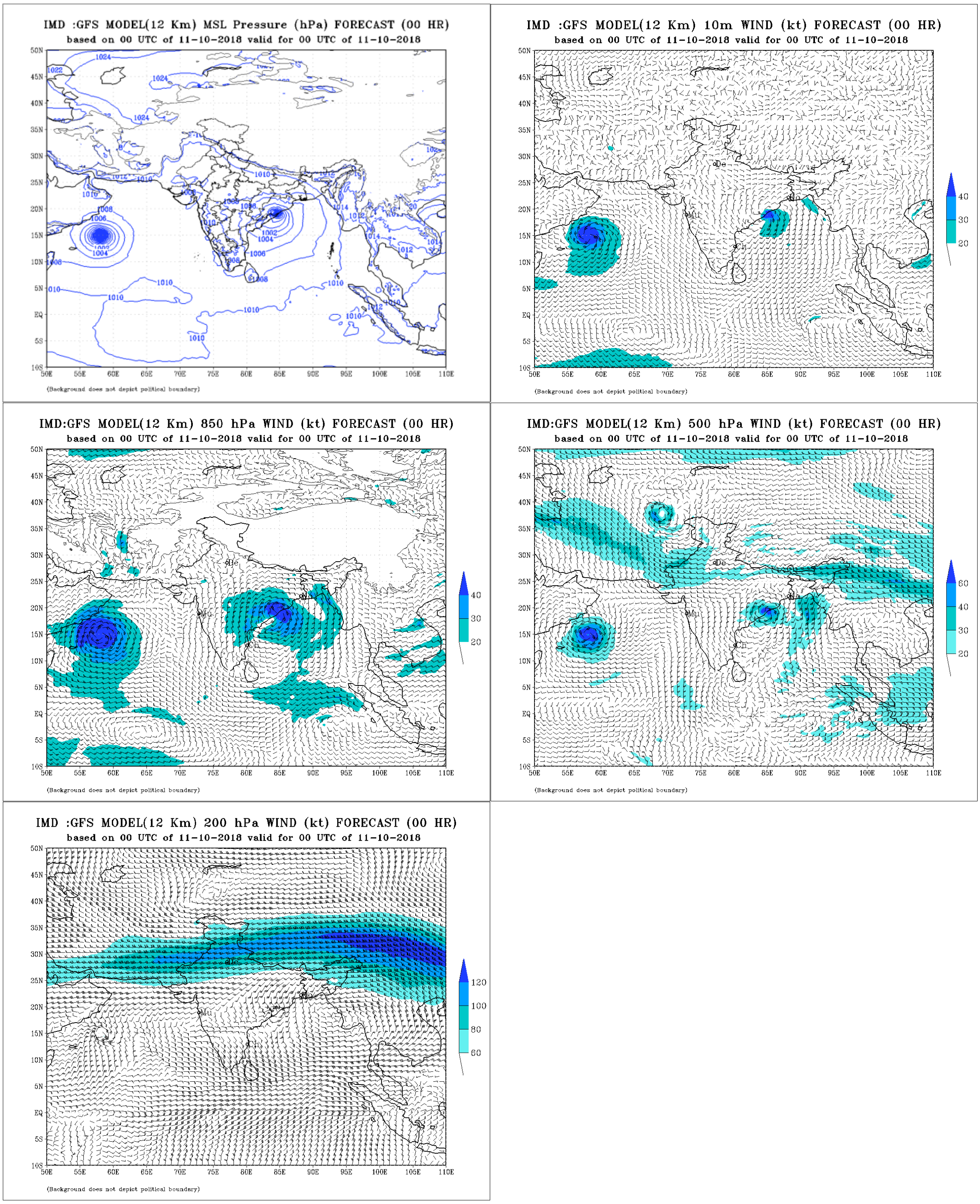


Fig. 2.12.6 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th October

The initial conditions based on 0000 UTC of 12th indicated weakening of the system into a deep depression over south Odisha. The model picked up the intensity and location intensity correctly.

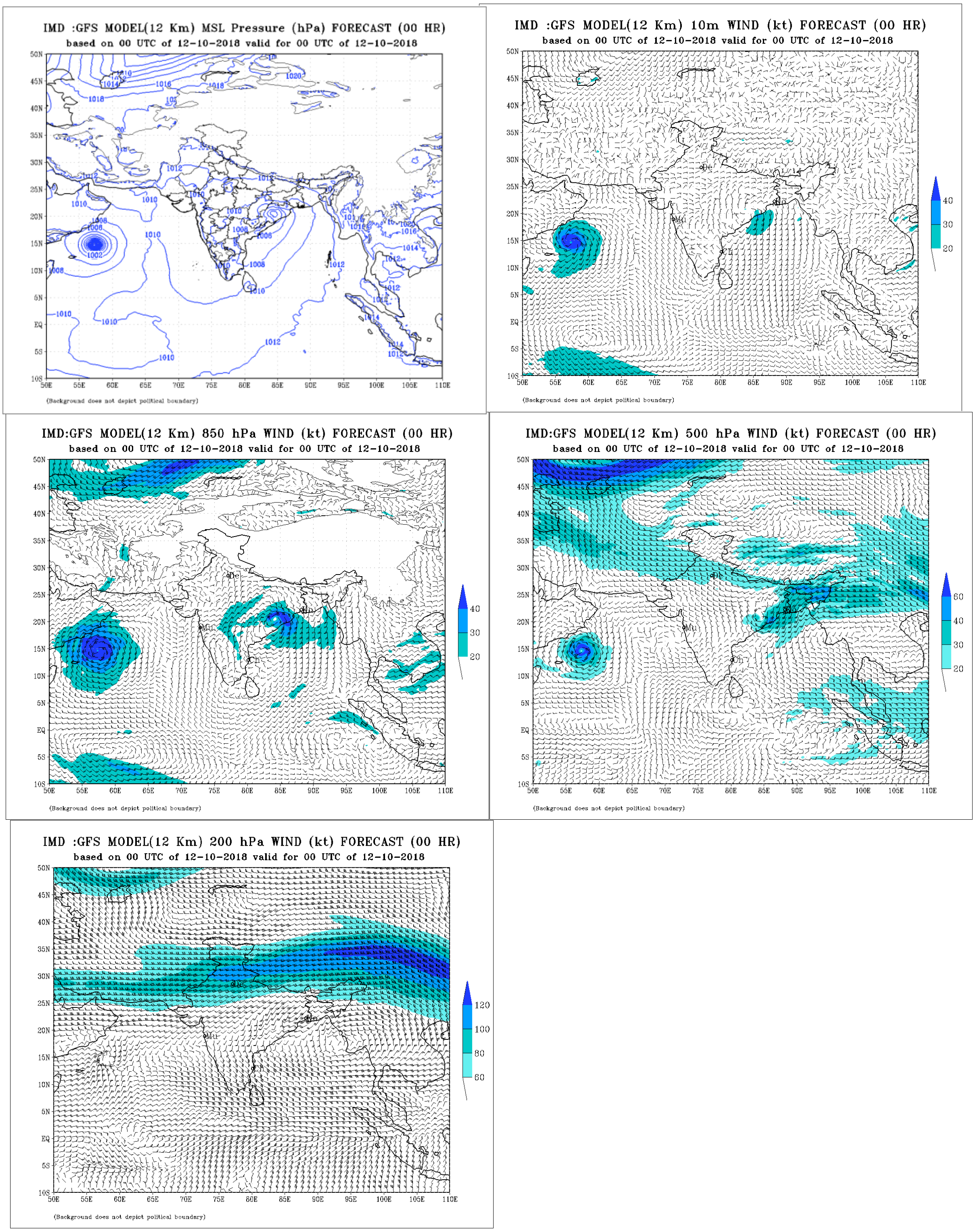


Fig. 2.12.6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 12th October

Based on initial conditions of 0000 UTC of 13th, the model indicated cyclonic circulation over Gangetic West Bengal and adjoining north BoB. At 0000 UTC of 13th, the system weakened into a WML over Gangetic West Bengal and adjoining Bangladesh & north BoB. Thus IMD GFS could predict the track, intensity and landfall of the system correctly.

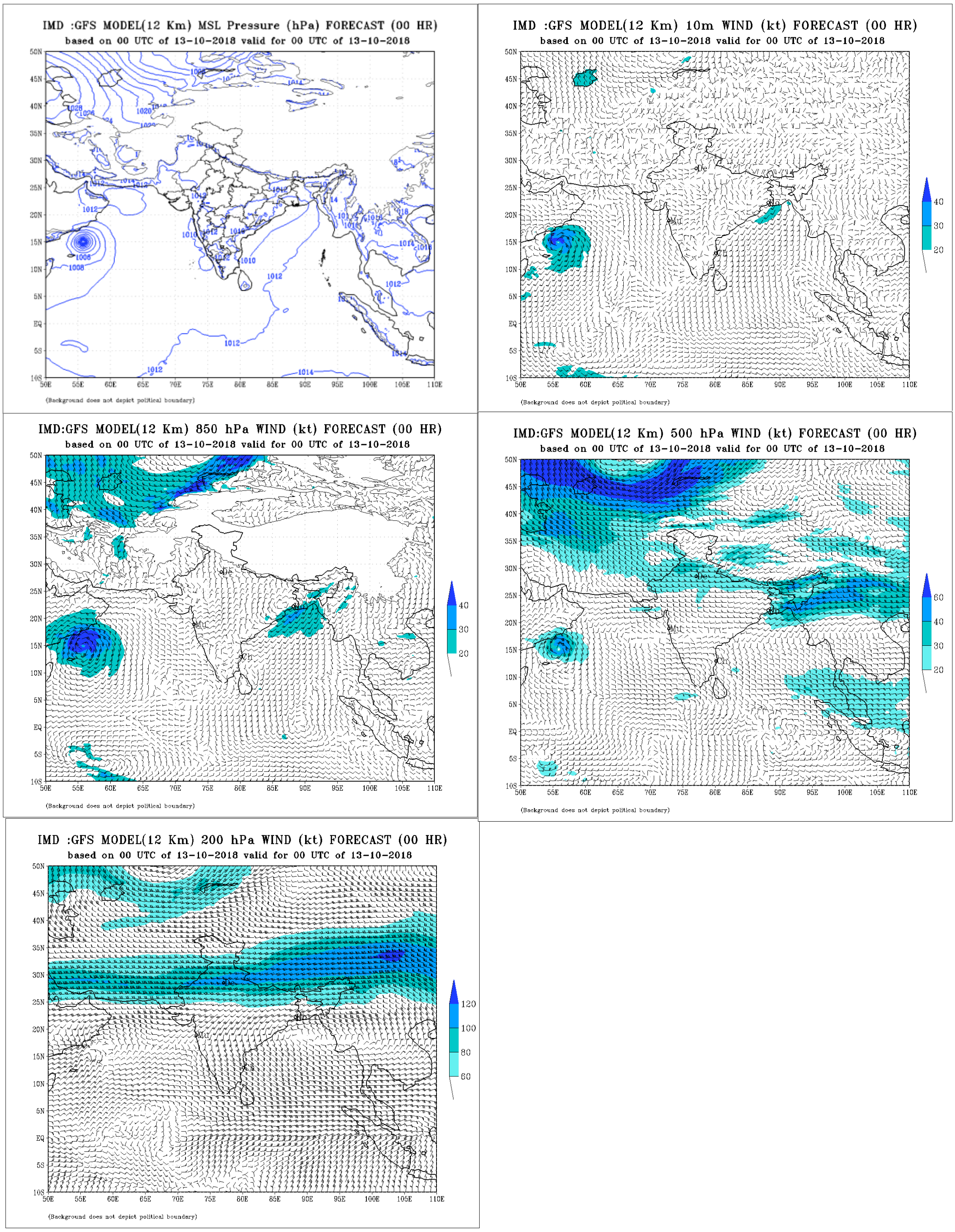


Fig. 2.12.6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th October

2.12.7. Realized Weather:

2.12.7.1 Rainfall:

Rainfall associated with VSCS titli based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 2.12.7**.

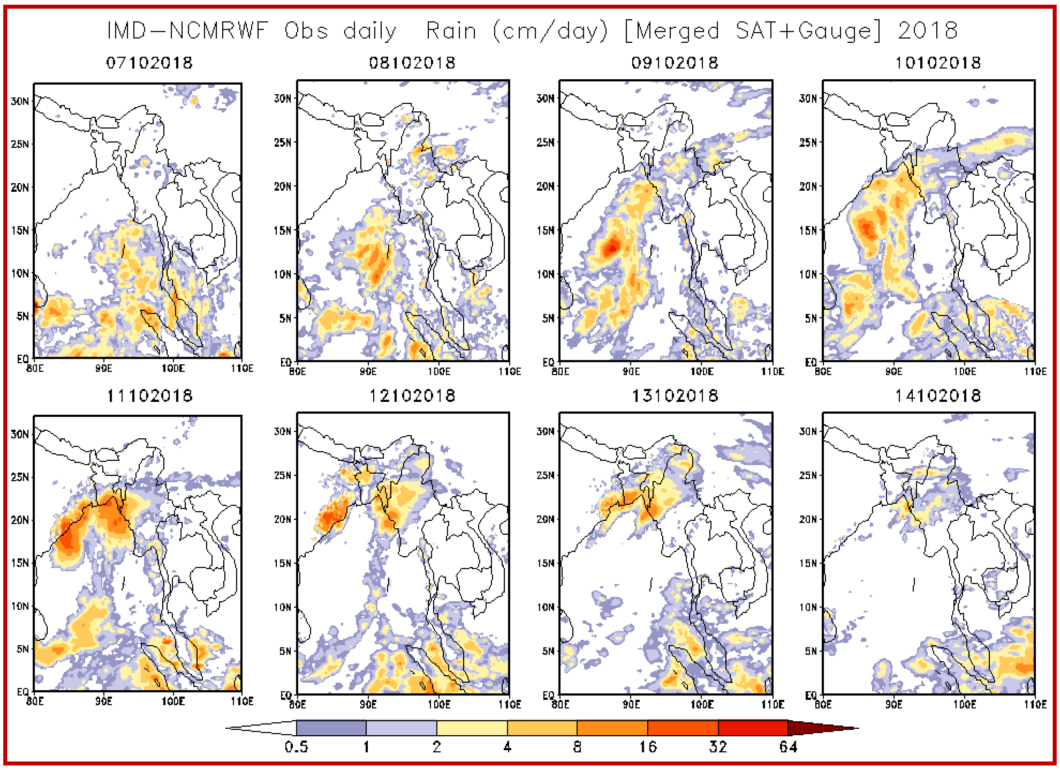


Fig. 2.12.7: IMD-NCMRWF GPM merged gauge rainfall during 07th October– 13th October and 7 days average rainfall (cm/day)

It indicates that the system caused rainfall at most places with heavy to very rainfall at isolated places over southeast BoB and adjoining north Andaman Sea on 7th, heavy to very rainfall at a few places over southeast BoB on 8th, heavy rainfall at most places over southwest BoB upto northeast BoB with extremely heavy falls at isolated places over eastcentral BoB on 9th & 10th, rainfall at most places with heavy to very heavy rainfall at many places over coastal Odisha, Gangetic west Bengal and adjoining north BoB upto Assam with extremely heavy falls at isolated places over coastal Odisha on 11th, heavy to very falls at a few places with extremely heavy falls over coastal Odisha & heavy to very falls at most places over Assam on 12th and heavy to very falls at many places over Gangetic West Bengal upto Assam, Meghalaya, Manipur, Mizoram on 13th. The rainfall was higher in the right forward sector of the cyclone during and after the landfall.

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

11th October

Odisha:- Mahendragarh-23, R.Udaigiri & Mohana-22 each, Purushottampur-21, Rajghat-17, Nuagada -16, Aska-15, Bhograi, Digapahandi, Balikuda-14 each, Chhatrapur, Ranpur, Raghunathpur & Sorada-13 each, Kendrapara, Nilgiri, Nh5 Gobindpur, Balasore, Kantapada-12 each, Kaptipada, Soro, Marsaghai , Chandikhol , Paradeep & Binjharpur -11 each, Alipingal, Jagatsinghpur Aws, Basudevpur, Gop, Korei & Gopalpur-10 each, Tikabali,

Bhanjnagar, Jaipur, Kujanga , Madhabarida, Odagaon , Betanati , Remuna , Belaguntha , Tirtol , Pattamundai, Bhadrak, Niali -9 each, Raikia , Kakatpur, Nimpara, G Udayagiri , Puri, Nischintakoili , Pipili, Astaranga , Tangi, Jaleswar-8 each, Banpur, Jagannath Prasad , Krishnaprasad, Narsinghpur, Balimundali, Derabis , Banki , Akhuapada, Salepur , Bari , Balipatna , Jajpur, Bhubaneswar , Nayagarh, Jenapur, Garadapur -7 each,
Gangetic West Bengal:- Digha-14, Contai-10,
Coastal Andhra Pradesh: Itchpuram-24, Tekkali-23 and Palasa-20 and Kalingapatnam-9.

12th October
Coastal Andhra Pradesh: Pathapatnam-14, Veeraghattam, Ichchapuram, Kurupam-11 each, Tekkali-10, Balajipeta-9, Mandasa, Komarada & Sompeta & Palakonda-8 each, Palasa & Jiyyamma Valasa-7 each,
Odisha: G Udayagiri-35, Kantapada-32, Raikia & Banki-28, Mohana-24, Sorada, Phiringia-23 each, Ranpur-22, Baliguda-21, Harabhanga, K Nuagaon, Phulbani, Daspalla-20 each, Puri, Satyabadi, Tigiria, Baripada, Jagatsinghpur & Niali-19 each, Bolagarh-18, Jaipur, Gania & Banpur-17 each, Tikarpara, Athgarh & Nimpara-16 each, Odagaon, Narsinghpur, Bhanjnagar, Barmul, R.Udaigiri, Nayagarh, Jajpur & Balipatna-15 each, Tangi, Kotagarh, Krishnaprasad, Garadapur & Cuttack-14 each, Salepur, Alipingal & Mahanga-13 each, Parjang, Madhabarida, Talcher, Jagannath Prasad, Gop, Ambadola, Kashinagar, Pipili & Kendrapara-12 each, Gudari, Balimundali, Mundali, Korei, Samakhunta, Marsaghai, Hindol, Madanpur & Rampur-11 each, Lanjigarh, Binjharpur, Nilgiri, Dhenkanal, Bari, Sukinda, Khandapara, Kotraguda, Tirtol, Danagadi, Gunupur, Derabis & Bhubaneswar -10 each, Brahmagiri, Banarpal, Jenapur, Naraj, Bonth, Rajkishorenagar, Angul & Tihidi-9 each, Muniguda, Dhamnagar, Chandanpur, Akhuapada, Rajkanika, Berhampur, Kantamal, Bhadrak, Raghunathpur, Bhuban & Astaranga-8 each, Purushottampur, Chendipada, Chandikhol, Balikuda, Altuma Cwc, Harichandanpur, Khairamal, Athmalik, Narla, Boudhgarh, Rayagada, Bangiriposi, Soro, Sonepur, Bhawanipatna, Nawana, Pattamundai, Saintala, Chandbali, Ghatagaon, Kamakhyanagar, Anandpur & Basudevpur-7 each.
Gangetic West Bengal:
Murarai-7.
Assam, Meghalaya, Mizoram and Tripura:
Moderate rainfall upto 5 cm at many places
13th October
Assam & Meghalaya: Karimganj and B P Ghat-8 each,
Nagaland, Manipur, Mizoram & Tripura: Serchip-8,
Gangetic West Bengal: Digha-15, Contai-13, Kalaikunda-10,
Odisha:- Betanati Arg-16, Kaptipada, Rajghat & Bhograi-13 each, Danagadi, Dhamnagar, Balimundali, Tihidi & Bonth-11 each, Jaleswar & Remuna -10 each, Thakurmunda & Karanjia-9 each, Jajpur, Samakhunta, Bangiriposi, Mahanga, Anandpur, Bari & Balasore, NH5 Gobindpur & Chandanpur-8 each, Baripada, Nilgiri, Udala, Sukinda, Ghatagaon, Jamsolaghat-7 each
14th October
Assam & Meghalaya: Cherrapunji-9, Cherrapunji (RKM)-8,

2.12.8. Damage due to VSCS Titli

As per report by media and post cyclone survey team, IMD about 77 people lost their lives in Odisha and 8 deaths were reported from Andhra Pradesh due to VSCS Titli.

Fig. **2.12.8a** : Uprooted Peepal Tree at Khajuru, Andhra Pradesh

Fig. **2.12.8b** : Uprooted Palm Tree at Khajuru, Andhra Pradesh

Fig. **2.12.8c** : Uprooted coconut trees in Baruva village, AP

Fig. **2.12.8d** : Casuarina Jhau tree twisted and broken by gale wind in Baruva village, AP

2.13. Very Severe Cyclonic Storm "Gaja" over southeast Bay of Bengal (10-19 November 2018)

2.13.1 Introduction

Very Severe Cyclonic Storm (VSCS) Gaja originated from a low pressure area (LPA) which formed over Gulf of Thailand and adjoining Malay Peninsula in the morning (0830 IST) of 8th November. It lay as a well marked low pressure area (WML) over north Andaman Sea and neighbourhood in the evening (1730 IST) of 9th November. Under favourable environmental conditions, it concentrated into a Depression (D) over southeast BoB in the morning (0830 IST) of 10th November. Moving west-northwestwards, it intensified into a deep depression (DD) over southeast & adjoining central BoB in the same evening (1730 IST). Moving further west-northwestwards, it intensified into cyclonic storm (CS) "Gaja" over eastcentral and adjoining westcentral & southeast BoB in the early morning (0530 IST) of 11th November, 2018. It then moved nearly westwards till early morning (0530 IST) of 12th. Thereafter it recurved south-southwestwards and followed an anticlockwise looping track till 13th morning. It then moved west-southwestwards and intensified, into a Severe Cyclonic Storm (SCS) over southwest BoB in the morning (0830 IST) of 15th November and into a very severe cyclonic storm in the same night (2030 IST). Moving further west-southwestwards it crossed Tamilnadu & Puducherry coast between Nagapattinam and Vedaranniyam near latitude 10.45˚N and longitude 79.8°E with wind speed of 130 kmph gusting to 145 kmph during 0030 to 0230 hours IST of 16th November. Thereafter, it moved nearly westwards, and weakened rapidly into an VSCS in the early morning (0530 IST), a CS in the morning (0830 IST) and into a DD over interior Tamil Nadu in the forenoon (1130 IST) of 16th November. It then moved west-southwestwards and weakened into a D in the same evening (1730 IST) over central Kerala. Moving nearly westwards, it emerged into southeast Arabian Sea (AS) in the same midnight (2330 IST). Moving nearly westwards, it intensified into a DD over southeast AS in the early morning (0530 IST) of 17th November. Thereafter, it moved nearly west-northwestwards and crossed Lakshadweep Islands in the 17th afternoon (1400-1700 hrs IST) as a deep depression. It continued to move west-northwestwards and weakened into a D over southeast AS around noon (1130 IST) of 19th & into a WML over southwest & adjoining southeast AS in the same midnight (2330 IST). It lay as a low pressure area over southwest Arabian Sea on 21st and became less marked over the same region on 22nd. The observed track of the system during 10th-19th November is presented in Fig.2.13.1. The best track parameters of the system are presented in Table 2.13.1.

The salient features of the system are as follows.

i. VSCS Gaja was the sixth cyclone over north Indian Ocean during 2018 against the normal frequency of about 4.5 cyclones per year during the satellite era (1961 onwards).
ii. It was the first ever looping track cyclone over the Bay of Bengal after 1996.
iii. The system had one of the longest track length equal to 3418 km.
iv. Despite unfavorable environmental conditions, the system intensified into a VSCS just prior to landfall near to coast.
v. The very severe cyclonic storm intensity of the system was short lived (about 3 hrs). The peak maximum sustained surface wind speed (MSW) of the cyclone was 130 kmph gusting to 145 kmph during 1800 to 2100 UTC of 1^{5th}. The lowest estimated central pressure was 975 hPa with pressure drop of about 31 hPa.

vi. The life period (D to D) of the system was 219 hours (9 days and 3 hours) against long period average (LPA) (1990-2013) of 98 hours for VSCS category over Bay of Bengal during post monsoon season.
vii. It moved with normal speed, as the 12 hour average translational speed of the cyclone was 14.6 kmph against LPA (1990-2013) of 14.7 kmph for VSCS category over north Bay of Bengal.
viii. The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 9.4 $X10^2$ knots, 4.35X 10^4 $knots^2$ and $2.1X10^6$ $knots^3$ 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.

2.13.2. Monitoring of VSCS, 'GAJA'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to its genesis as low pressure area over BoB from 7th November onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations, Doppler Weather Radar (DWR) Karaikal, Chennai, Thiruvananthapuram and Kochi along with available ships & buoy observations in the region. Various national and international numerical weather prediction 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 including Bangladesh, Myanmar, Sri Lanka, Maldives National & State Disaster Management Agencies, general public and media since inception of the system over BOB. The system came under Radar surveillance from morning of 15th.

2.13.3. Brief life history

2.13.3.1. Genesis

VSCS Gaja originated from an **LPA** which formed over Gulf of Thailand and adjoining Malay Peninsula at **0300 UTC of 8th November.** At 0300 UTC of 8th November, the Madden Julian Oscillation (MJO) index lay in phase 3 with amplitude less than 1. It was expected to remain in phase 3 & 4 during next 4 days with amplitude less than 1. Hence MJO phase was expected to support enhancement of convective activity over south BoB & adjoining areas during next 4 days. The environmental conditions like sea surface temperature (28-29^{0}C), lower level convergence ($20x10^{-5}$ $second^{-1}$), lower level vorticity ($100x10^{-6}$ $second^{-1}$), upper level divergence ($15x10^{-5}$ $second^{-1}$) and vertical wind shear (10-15 knots) were also favoring intensification of LPA after its emergence into Andaman Sea. The upper tropospheric ridge ran along 12°N and under its influence the system was expected to move west-northwestwards after its emergence into Andaman Sea. Similar conditions prevailed and the system lay as a **WML** over north Andaman Sea and neighborhood at **1200 UTC of 9th November**.

At **0300 UTC of 10th**, the MJO index lay in phase 4 with amplitude close to 1. MJO phase and amplitude were supporting enhancement of convective activity over south BoB & adjoining areas. The SST was 28-29^{0}C over southeast BoB and adjoining north Andaman Sea. TCHP was 50-80 KJ/cm^2 over southeast BoB. The lower level vorticity was $50x10^{-6}$ $second^{-1}$, lower level convergence was $5\text{-}10x10^{-5}$ $second^{-1}$, upper level divergence was $10x10^{-5}$ $second^{-1}$ and low level vertical wind shear was low to moderate (5-15 kt). The upper tropospheric ridge ran along 14°N. Under these supportive conditions, the system intensified into a **depression** over central parts of Andaman Sea near 11.7°N/92.5°E.

2.13.3.2. Intensification and movement

At 1200 UTC of 10th, the MJO index lay in phase 4 with amplitude close to 1. Similar sea conditions prevailed. The lower level convergence increased and was of the order of 10-15x10-5 second-1, the lower level vorticity also increased and was of order 100x10-6 second-1 to the south of the system centre, the upper level divergence also increased and was of the order 30x10-5 second-1 around the system centre and vertical wind shear was low (5-10 knots) around the system centre. The total precipitable water vapour (TPW) imagery indicated warm air advection into the core of the system. Under these conditions, the system intensified into a deep depression over southeast & adjoining central BoB near 12.6°N/90.8°E. The upper tropospheric ridge ran along 14°N and favoured west-northwestward movement of the system.

At 0000 UTC of 11th, similar thermo-environmental conditions and MJO phase continued. TPW imagery indicated warm air advection into the core from the southeast sector. Under these conditions the system intensified into a cyclonic storm “Gaja” over eastcentral and adjoining westcentral & southeast BoB near latitude 13.4°N/89.3°E. The upper tropospheric ridge ran along 16°N favoring west-northwestward movement of the system during next 36 hours. The system however, moved nearly westwards till early morning (0000 UTC) of 12th. Thereafter, it recurved south-southwestwards and followed an anticlockwise looping track till 13th morning. It then moved west-southwestwards and intensified, into a VSCS over southwest BoB in the morning (0300 UTC) of 15th November.
At 0300 UTC of 15th, the MJO lay in phase 5 with amplitude close to 1. It was forecast to remain in phase 5 for next 48 hours with amplitude less than 1. MJO phase was favoring intensification of system during next 48 hours. The SST was around 28-29°C and TCHP is 50-80 KJ/cm2 around the system centre. It is less than 50 KJ/cm2 over western parts of southwest BoB north Tamil Nadu coast. The lower level convergence was of the order 10-15 x10-5 second-1 to the southeast of the system centre. The lower level vorticity increased and was of the order of 150x10-6 second-1 around the system centre. The upper level divergence was of the order of 20-30x10-5 second-1 around the system centre. The vertical wind shear was low to moderate (10-15 knots) over the system centre and also along the forecast track. The TPW imagery indicated warm air advection from the southeast sector into the core of the system centre and advection of cold & dry air near north Tamil Nadu and Andhra Pradesh coasts. The poleward outflow was favouring upper air divergence. Under these favourable conditions, the system intensified into an VSCS over southwest BoB near 11.3°N/82.6°E. Upper level ridge ran along 13°N and two anticyclonic circulations were lying to the east and west of the system centre. The system moved west-southwestwards under the influence of the anticyclone to the west (Arabian Sea) of the system and continued to move west-southwestwards till landfall.

At 1500 UTC of 15th, the SST was around 28-29°C and TCHP was 50-80 KJ/cm2 around the system Centre. It was less than 50 KJ/cm2 over western parts of southwest BoB off north Tamil Nadu coast. The lower level convergence was of the order 20-30 x10-5 second-1 to the southeast of the system centre. The low level vorticity was of the order of 150x10-6 second-1 around the system centre. The upper level divergence was of the order of 30x10-5 second-1 around the system centre. The vertical wind shear was low to moderate (10-15 knots) over the system centre and also along the forecast track. TPW imagery indicated warm air advection into the core from the southeast sector. The poleward outflow was favoring increase in divergence. Under these conditions, the system intensified into a VSCS over southwest BoB near 10.6°N/80.7°E. Upper level ridge ran along latitude 13°N in association with the anticyclonic circulation to the east and west of the system centre. Under the influence of anticyclone to the west (Arabian Sea) of the system centre, it moved west-southwestwards and crossed Tamil Nadu and Puducherry coasts between Nagapattinam & Vedaranniyam near 10.450N/79.80E during 1900 to 2100 UTC. The system maintained its peak intensity for 6 hours during 1500 UTC of 15th to 0000 UTC of 16th.

At 0000 UTC of 16th, the lower level convergence was of the order 30 x10-5 second-1, the lower level vorticity was of the order of 150x10-6 second-1 and the upper level divergence was of the order of 20x10-5 second-1 around the system centre. The vertical wind shear was low to moderate (5-10 knots) over the system centre and also along the forecast track. However, there was cut-off of moisture supply and thus, the system weakened into an VSCS over coastal Tamil Nadu 10.4°N/79.2°E. The upper tropospheric ridge ran along lat 14°N in association with the anticyclonic circulation to the west of the system centre. Under its influence, the system moved nearly westwards. Similar conditions prevailed and the system moving westwards weakened into a CS over coastal Tamil Nadu near 10.4°N/78.5°E and into a DD over interior Tamil Nadu near 10.5°N/77.6°E.

At 1200 UTC of 16th, there was further disorganization of cloud mass and weakening of environmental features with the lower level convergence of order 20x10-5 second-1 to southwest of the system centre, the lower level vorticity of the order 100x10-6 second-1 over the system centre and the upper level divergence of order 10x10-5 second-1 around the system centre. The vertical wind shear was low (5-10 knots) around the system centre. Under these conditions, the system weakened into a D near 10.1°N/76.4°E. The upper tropospheric ridge ran along 15°N and under it's influence, the system moved nearly westwards and emerged into southeast Arabian Sea at 0000 UTC of 17th.

At 0000 UTC of 17th, the system was over southeast Arabian Sea near 9.8°N/74.3°E as a depression. At that time, the SST was 29-30°C and TCHP was 50-80 KJ/cm2 over southeast Arabian Sea. The lower level convergence was of the order of 10-15x10-5 second-1 to the southwest of the system centre, the lower level vorticity was around 80-100x10-6 second-1 and the upper level divergence was around 10 x 10-5 second-1 around the system centre. The vertical wind shear was low (5-10 knots) around the system centre. The upper tropospheric ridge runs along 13°N and thus favored nearly westward movement of the system across southeast Arabian Sea.

At 0600 UTC of 19th, similar sea conditions prevailed. However, the TCHP was becoming less than 50 KJ/ cm2 to the west of 65°E. The lower level convergence was about 5x10-5 second-1, the lower level vorticity was of the order 100x10-6 second-1, the upper level divergence was 10-20x10-5 second-1 and vertical wind shear was low to moderate (5-15 knots) around the system centre. The TPW imagery was indicating dry air incursion from the western sector up to southern sector and decrease in warm moist air advection from the southeast into the system center. Water vapour imagery also indicated dry mid-level atmosphere. Under these conditions, there was no further intensification of the system. The system continued to move nearly westwards and weakened into a WML over southwest & adjoining southeast Arabian Sea at 1800 UTC of 19th.

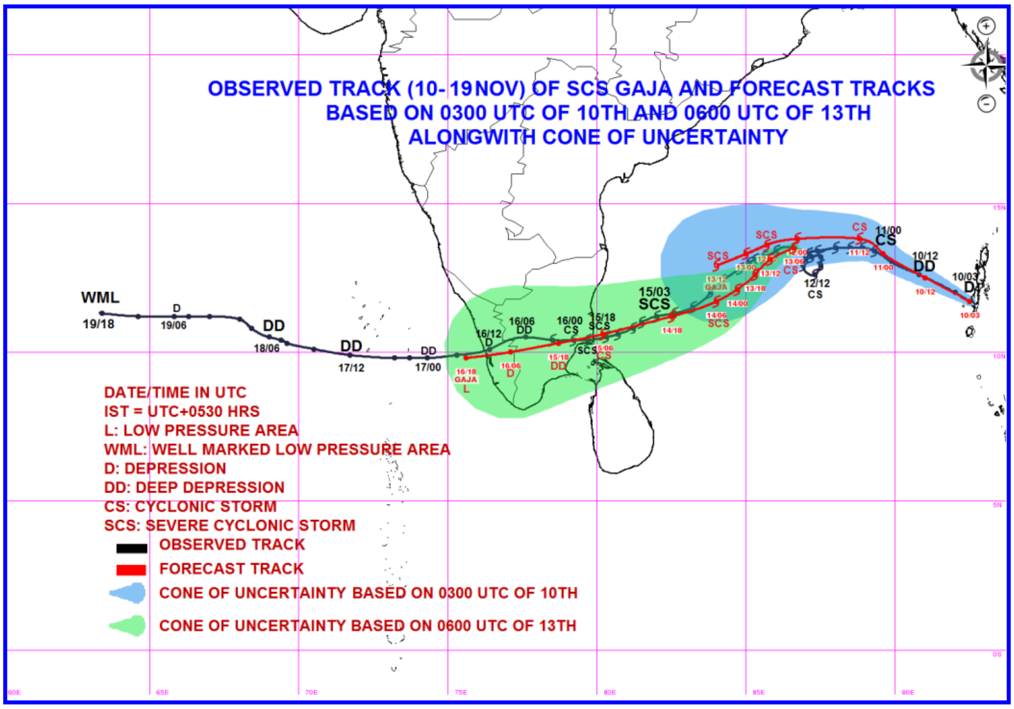


Fig.2.13.1 Observed track of VSCS GAJA (10-19 November, 2018) over southeast Bay of Bengal.

Table 2.13.1: Best track positions and other parameters of the Very Severe Cyclonic Storm "Gaja" over Bay of Bengal during 10th – 19th November

Date	Date/Time (UTC)	Centre lat.⁰ N/ long. ⁰ E		C.I. NO.	Estimated Maximum Sustained Surface Wind (kt)	Estimated Central Pressure (hPa)	Estimated Pressure drop at the Centre (hPa)	Grade
10/11/2018	0300	11.7	92.5	1.5	25	1003	3	**D**
	600	12	92	1.5	25	1002	4	D
	1200	12.6	90.8	2	30	1001	5	**DD**
	1800	13	89.9	2	30	1000	6	DD
11/11/2018	0000	13.4	89.3	2.5	35	999	7	**CS**
	0300	13.5	88.9	2.5	35	999	7	CS
	0600	13.5	88.5	2.5	40	998	8	CS
	0900	13.5	88.2	2.5	40	998	8	**CS**
	1200	13.5	88	2.5	40	998	8	CS
	1500	13.5	87.7	2.5	40	998	8	CS
	1800	13.4	87.4	2.5	40	998	8	CS
	2100	13.5	87.2	2.5	40	998	8	CS
12/11/2018	0000	13.3	87.1	2.5	40	998	8	CS
	0300	13.1	87	2.5	40	998	8	CS
	0600	12.9	86.9	2.5	40	998	8	CS
	0900	12.9	86.9	2.5	40	998	8	CS

	1200	12.6	87.3	2.5	40	998	8	CS
	1500	12.9	87.5	2.5	40	998	8	CS
	1800	13.2	87.5	2.5	45	996	8	CS
	2100	13.2	87.3	2.5	45	996	8	CS
13/11/2018	0000	13.2	87.2	2.5	40	998	8	CS
	0300	13.3	87.1	2.5	40	998	8	CS
	0600	13.5	86.6	2.5	40	998	8	CS
	0900	13.4	86.4	2.5	40	998	8	CS
	1200	13.4	86	2.5	40	998	8	CS
	1500	13.2	85.8	2.5	40	998	8	CS
	1800	13.2	85.6	2.5	40	998	8	CS
	2100	13.1	85.5	2.5	40	998	8	CS
14/11/2018	0000	13.1	85.3	2.5	40	998	8	CS
	0300	13	85.1	2.5	40	998	8	CS
	0600	12.8	84.8	2.5	45	996	10	CS
	0900	12.6	84.6	2.5	45	996	10	CS
	1200	12.4	84.2	2.5	45	996	10	CS
	1500	12.2	84.2	2.5	45	996	10	CS
	1800	12	83.8	2.5	45	996	10	CS
	2100	11.8	83.4	2.5	45	996	10	CS
15/11/2018	0000	11.5	83.2	2.5	45	996	10	CS
	0300	11.3	82.6	3	50	994	12	**SCS**
	0600	11.2	82	3.5	55	990	15	SCS
	0900	11	81.5	3.5	55	989	16	SCS
	1200	10.8	81.2	3.5	60	988	18	SCS
	1500	10.6	80.7	4	65	984	21	VSCS
	1800	10.5	80.3	4	70	976	30	VSCS
		Crossed Tamil Nadu and Puducherry coasts between Nagapattinam & Vedaranniyam near 10.45^{0}N and 79.8^{0}E during 1900 to 2100 UTC						
	2100	10.4	79.7	-	70	976	30	VSCS
16/11/2018	0000	10.4	79.2	-	55	990	15	**SCS**
	0300	10.4	78.5	-	45	996	10	CS
	0600	10.5	77.6	-	30	1000	6	**DD**
	1200	10.1	76.4	1.5	25	1002	4	**D**
	1800	9.9	75.3	1.5	25	1002	4	D
17/11/2018	0000	9.8	74.3	2	30	1003	5	**DD**
	0300	9.8	73.7	2	30	1003	5	DD
	0600	9.8	73.2	2	30	1003	5	DD
	1200	9.9	71.7	2	30	1003	5	DD
	1800	10.1	70.5	2	30	1003	5	DD
18/11/2018	0000	10.3	69.6	2	30	1003	5	DD
	0300	10.4	69.4	2	30	1003	5	DD
	0600	10.5	69	2	30	1003	5	DD
	1200	10.7	68.5	2	30	1003	5	DD

	1800	10.8	67.5	2	30	1003	5	DD
19/11/2018	0000	11	66.6	2	30	1003	5	DD
	0300	11.1	66.3	2	30	1003	5	DD
	0600	11.2	65.8	1.5	25	1004	4	D
	1200	11.2	65	1.5	25	1004	4	**D**
	1800	**Weakened into a well marked low pressure area over southwest & adjoining southeast Arabian Sea**						

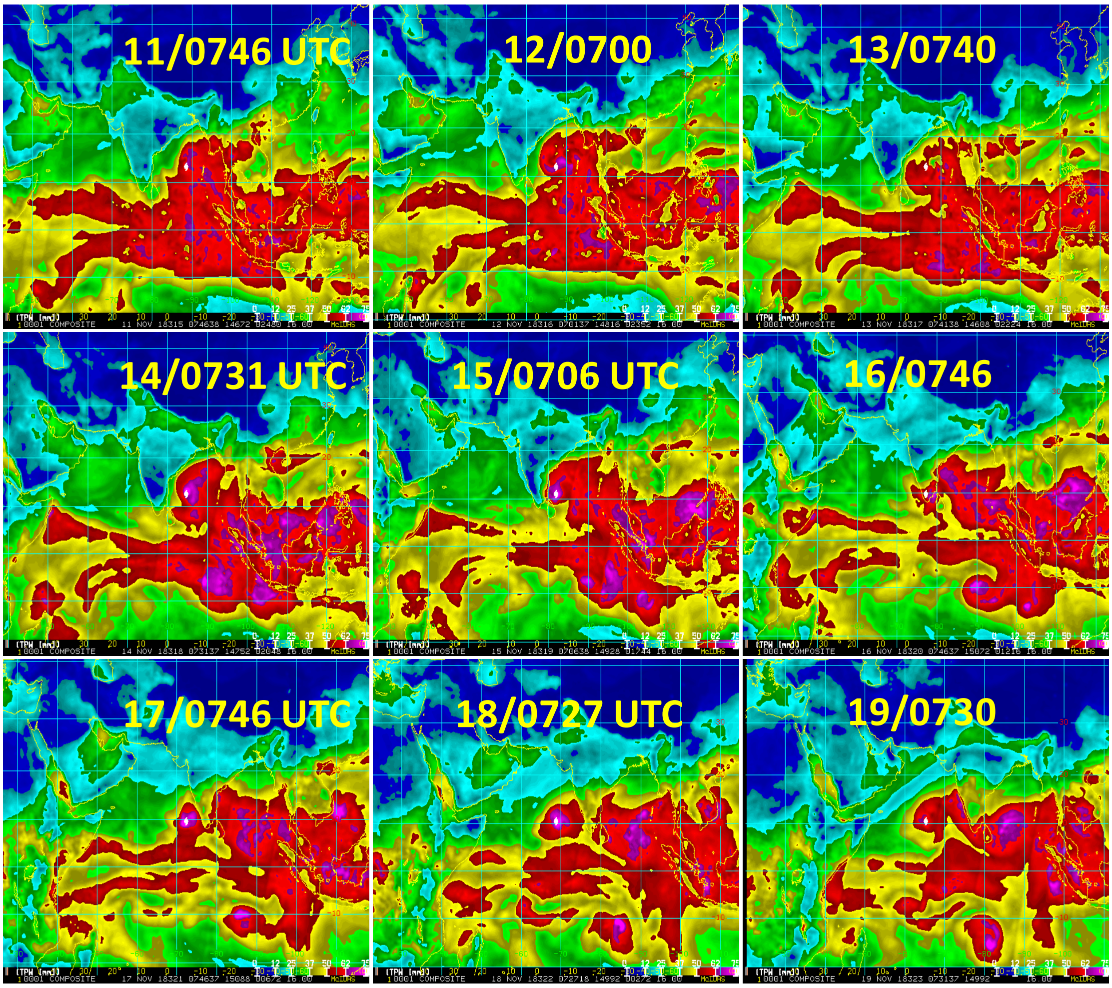


Fig. 2.13.2: Total Precipitable Water Imageries during 11-19 November, 2018

The total precipitable water imageries (TPW) during 11th-19th November are presented in **Fig.2.13.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the core of system till 15th November. Thereafter, cold dry air prevailed over north TamilNadu and adjoining Andhra Pradesh. The system was over land during this period and experienced decrease in its intensity. It emerged into AS at 1200 UTC of 16th as a depression. Thereafter, there was warm moist air advection into the core leading to its intensification into a DD at 0000 UTC of 17th. At 0600 UTC of 19th, there was significant decrease in warm moist air advection into the core of system, leading to weakening of the system.

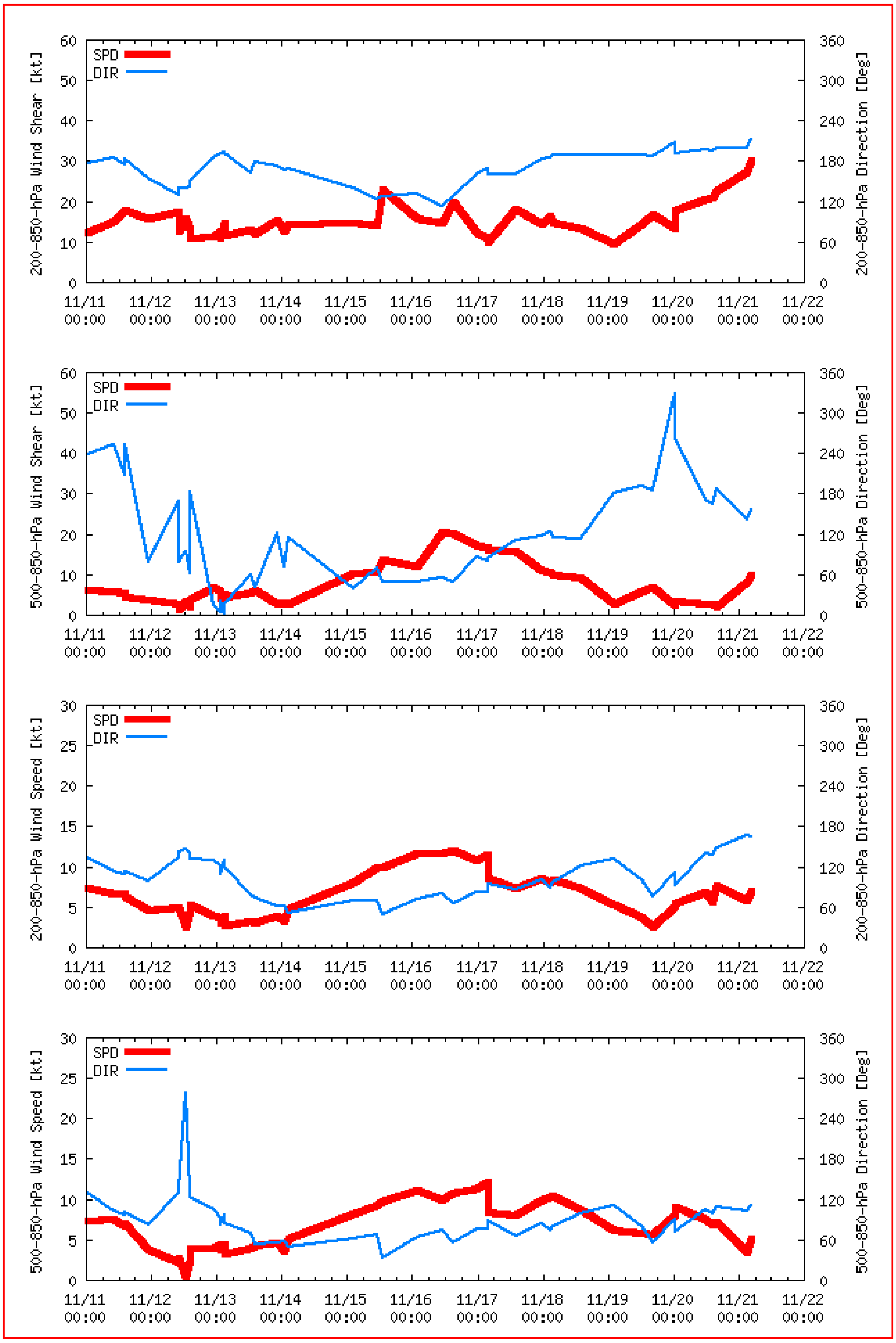


Fig. 2.13.3 Wind shear and wind speed in the middle and deep layer around the system during 11th to 22nd november 2018.

The mean wind speed in middle and deep layer around the system centre is presented in **Fig. 2.13.3**. The wind shear between middle to lower tropospheric levels around the system centre was less than 10 kts till 0000 UTC of 14th and around 15kts till 0000 UTC of 16th. Thereafter, it increased becoming 25 kts at 0600 UTC of 16th. Thereafter, it decreased becoming less than 5 kts till 19th November. The wind shear between upper to lower tropospheric levels was around 15 kts upto 0600 UTC of 15th. It increased slightly upto becoming around 20 kts upto 0600 UTC of 16th. Thereafter, it decreased becoming around 10 kts till 0000 UTC of 19th. Thus, the wind shear between middle to lower tropospheric levels better represents the strengthening/weakening of the system.

2.13.3.3 Movement

From **Fig. 2.13.3**, comparing the mean flow pattern between the mean deep layer winds between 200-850 hPa levels and 500-850 hPa levels, it is seen that the flow between 500-850 hPa levels could detect the looping of the system on 12th & 13th with very slow speed becoming stationary during 12th. The mean winds between 500-850 hPa levels steered the system west-southwestwards initially during 11th-12th with a speed of 10 knots or less. Thereafter, the system followed a looping track during 12th-13th and moved with an average speed less than 5 knots. Thereafter, it moved west-southwestwards till 0000UTC of 15th and nearly westwards thereafter and an increase in wind speed. The six hourly movement of VSCS Gaja is presented in **Fig. 2.13.4 (a)**. The six hourly average translational speed of the cyclone was about 10.5 kmph and hence was slow moving in nature. The system had a track length of about 3418 km during its life period.

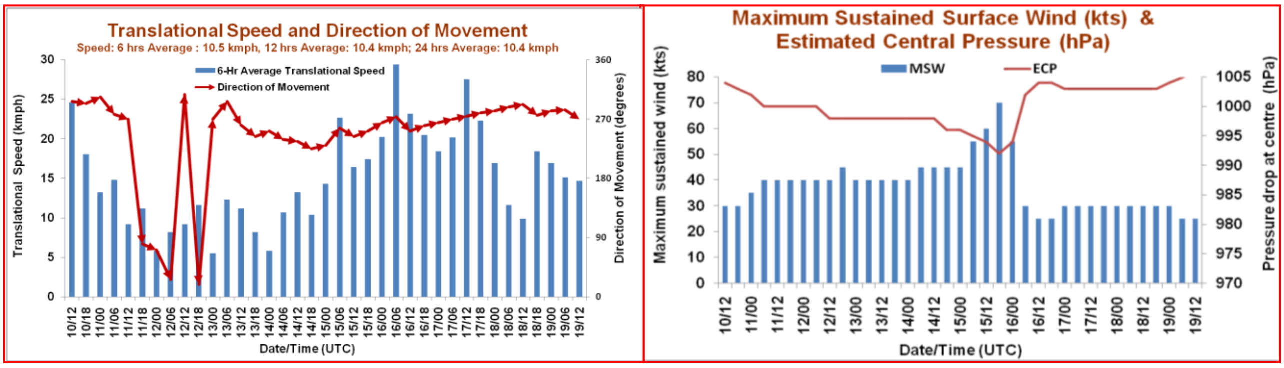


Fig. 2.13.4 (a): Six hourly average translational speed (kmph) and direction of movement in association with VSCS Gaja and (b) Lowest estimated central pressure and the maximum sustained wind speed

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

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig. 2.13.4 (b)**. The lowest estimated central pressure (ECP) had been 992 hPa at 1800 UTC of 15th. The ECP gradually decreased from 1004 hPa at 1200 UTC of 10th to 992 hPa at 1800 UTC of 15th. Thereafter, there was gradual rise in pressure to 994 hPa at 0000 UTC of 16th. It then increased suddenly to 1002 hPa (at 0600 UTC of 16th) indicating rapid weakening of the system during 0000 to 0600 UTC of 16th. Thereafter it increased gradually to 1006 hPa at 1200 UTC of 19th indicating slow weakening of the system during 0600 UTC of 16th to 1200 UTC of 19th. Similarly, in the wind field it is seen that the maximum sustained wind speed (MSW) had been 70 kts at 1800 UTC of 15th. The MSW gradually increased becoming 35 kts at 0000 UTC of 11th. The system maintained MSW of 40-45 kts till 0000 UTC of 15th. There was rapid intensification of the system during 0000 to 1800 UTC of 15th and the system attained its peak intensity of 70 kts at 1800 UTC of 15th. Thereafter, there was rapid weakening of the system till 0600 UTC of 16th (MSW becoming 30 kts). Thereafter it maintained the intensity of depression/deep depression till 1200 UTC of 19th.

2.13.5. Features observed through satellite

At 0300 UTC of 10th, the intensity of the system was characterized by T1.5. Banding features were not clear. Broken low and medium clouds with embedded intense to very intense convection lay over Andaman Sea and adjoining eastcentral BoB. Minimum cloud top temperature (CTT) was minus 93°C. At 1200 UTC of 10th, the system showed curved band pattern. The convective clouds were higher in northern sector. The intensity of the system was T 2.0. Broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 11.5°N & 16.0°N and longitude 88.5°E to 93.5°E & northwest Andaman Sea. Minimum CTT was minus 93°C. At 0000 UTC of 11th, the system showed central dense overcast (CDO) pattern. The convective clouds were higher in northern sector. The intensity of the system was T 2.5. Broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 13.0°N & 19.0°N and longitude 86.5°E & 95.0°E and northwest Andaman Sea. Minimum cloud top temperature is minus 93°C. At 0300 UTC of 15th, cloud imagery indicated improvement in organization of cloud mass with bands wrapping tightly around the centre from northwest and northeast sectors resulting in curved band pattern. The intensity of the system was T 3.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 10.5°N & 13.0°N and longitude 81.0°E & 84.0°E. Minimum CTT was minus 86°C. At 1500 UTC of 15th, there was further improvement in clouds organisation with bands wrapping tightly around the centre in curved band pattern. The intensity of the system was T 3.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over Bob between latitude 9.5°N & 12.5°N and longitude 79.5°E to 82.5°E. Minimum CTT was minus 93°C. At 0000 UTC of 16th, due to land interactions there was disorganization of cloud mass. Entire cloud mass was sheared to the northwest of system centre. Broken low and medium clouds with embedded intense to very intense convection lay between latitude 9.5°N & 12.5°N and west of longitude 81.5°E, Palk Strait, Tamilnadu and south Kerala. Minimum CTT was -89°C. At 0300 UTC of 16th, the system was over land. More clouds were seen in the southern sector. Broken low and medium clouds with embedded intense to very intense convection lay between latitude 7.5°N & 12.5°N and longitude 76.5°E & 80.5°E. Minimum CTT was -83°C. At 0000 UT of 17th, the system emerged over southeast Arabian Sea. Curved band features were observed and the system wrapped 0.4 on $\log_{10}$ spiral. Broken low and medium clouds with embedded intense to very intense convection lay between latitude 7.5°N & 12.5°N and longitude 71.5°E and 76.0°E. The minimum CTT was minus 93°C. At 0600 UTC of 19th, there was further disorganization of cloud mass. Shear pattern was observed. The cloud mass was sheared to the west of system centre. The intensity of the system was C.I.1.5. Broken low and medium clouds with embedded intense to very intense convection lay over Arabian Sea between latitude 8.5°N to 14.5°N and longitude 64.0°E to 66.0°E. The minimum cloud top temperature is minus 93°C.

2.13.5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig.2.13.5 (a-d)**.

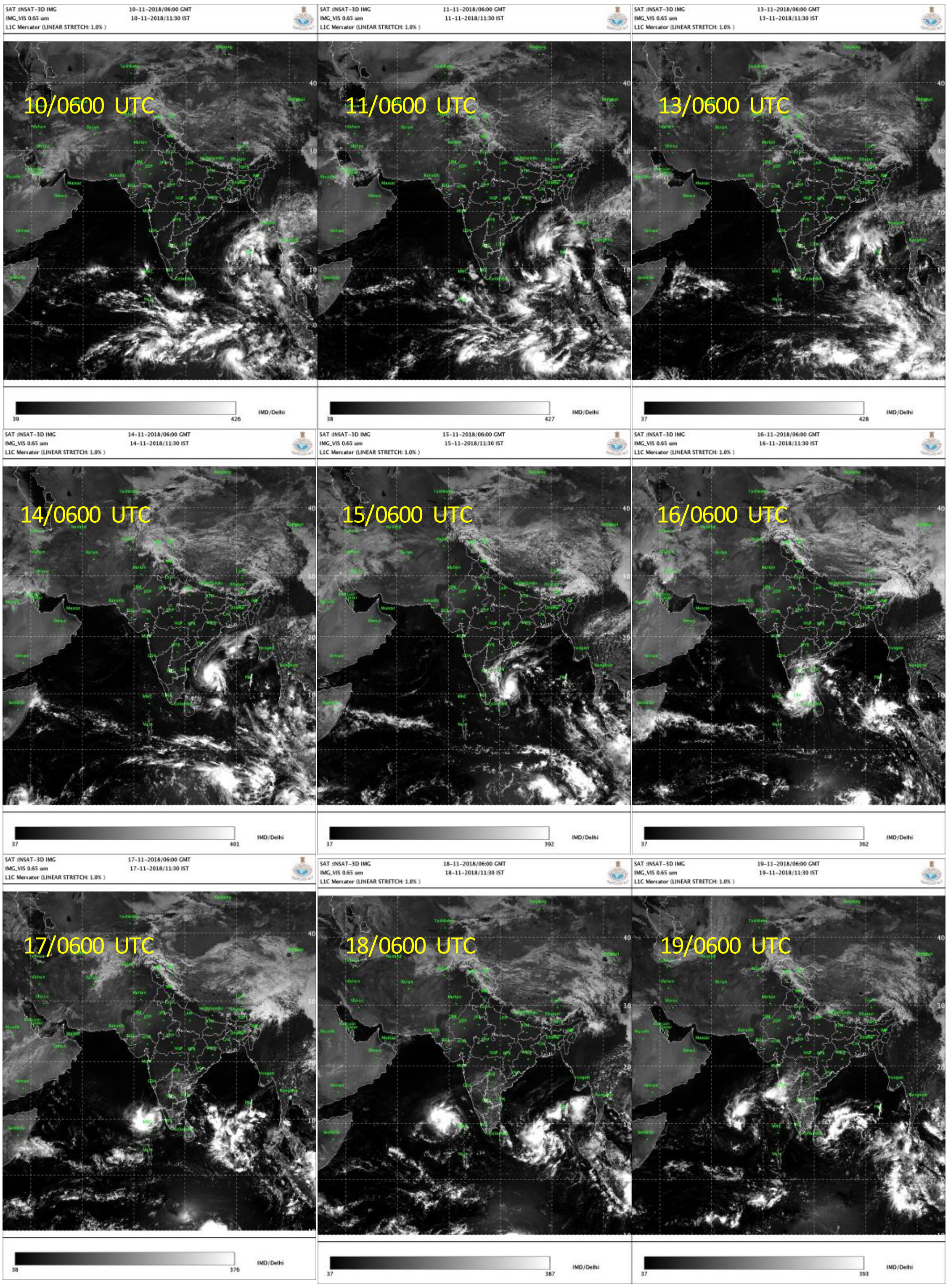


Fig. 2.13.5a: INSAT-3D visible imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

Intensity estimation using Dvorak's technique suggested that the system attained the intensity of **T 1.5** at 1200 UTC of 21st. The convection over south AS further organised and indicated curved banding features from northwest to southeast sector across southwest sector. Minimum cloud top temperature was -93^{0}C. At 0300 UTC of 22nd, the convection further organized and the system attained the intensity

of **T2.0**. The convection showed curved banding features from northeast to southwest sector across northwest sector. Minimum CTT was -93^{0}C.

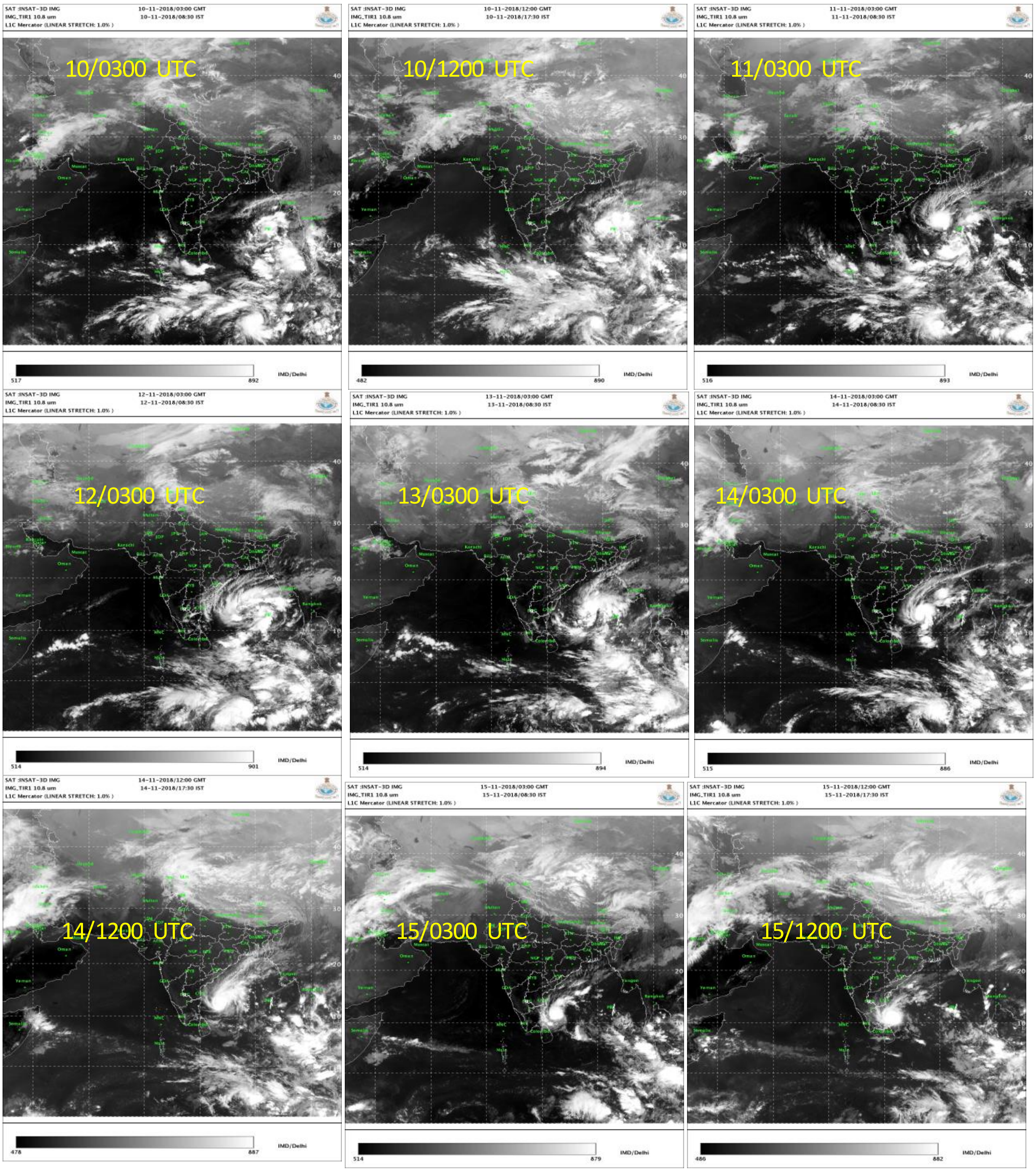


Fig. 2.13.5b: INSAT-3D IR imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

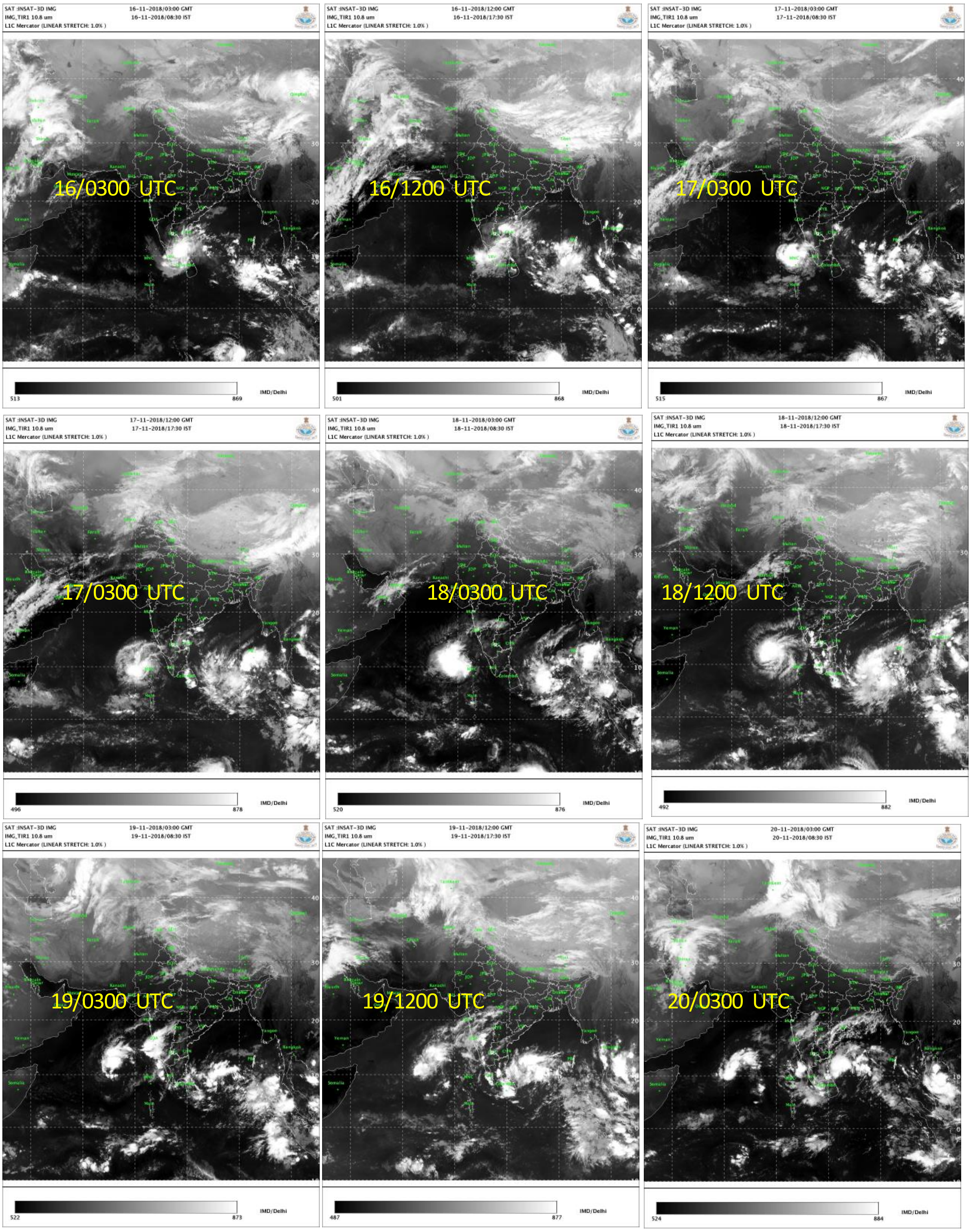


Fig. 2.13.5b(cont.): INSAT-3D IR imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

At 1200 UTC of 22nd, the system attained the intensity **T 2.5**. The cloud pattern indicated banding features from northeast to southwest sector across northwest sector. The intensity of the system was **T3.5**. The convection showed curved banding features from northeast to southwest sector across northwest sector. At 0900 UTC of 23rd, the system attained the intensity **T 4.0**. The convection increased over western and southern sector. With the consolidation of central dense overcast, satellite imagery indicated appearance of eye. It indicated intensification of the system. Minimum CTT was -93^{0}C. At 0300 UTC of 24th, the system further intensified and attained the intensity **T4.5**. The convection showed central dense overcast pattern with well defined spiral bands. Minimum CTT was -93^{0}C.

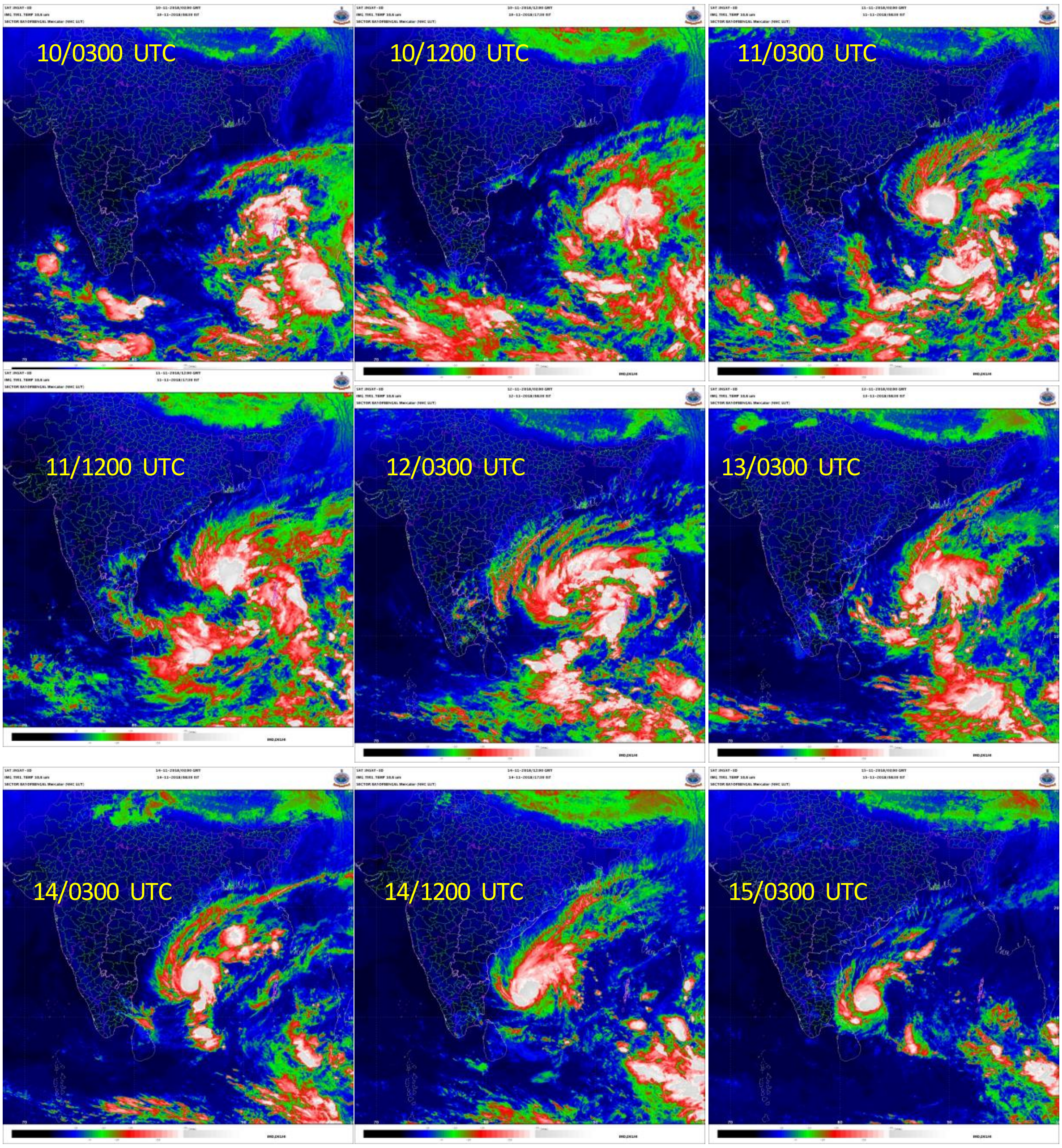


Fig. 2.13.5c: INSAT-3D enhanced colored imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

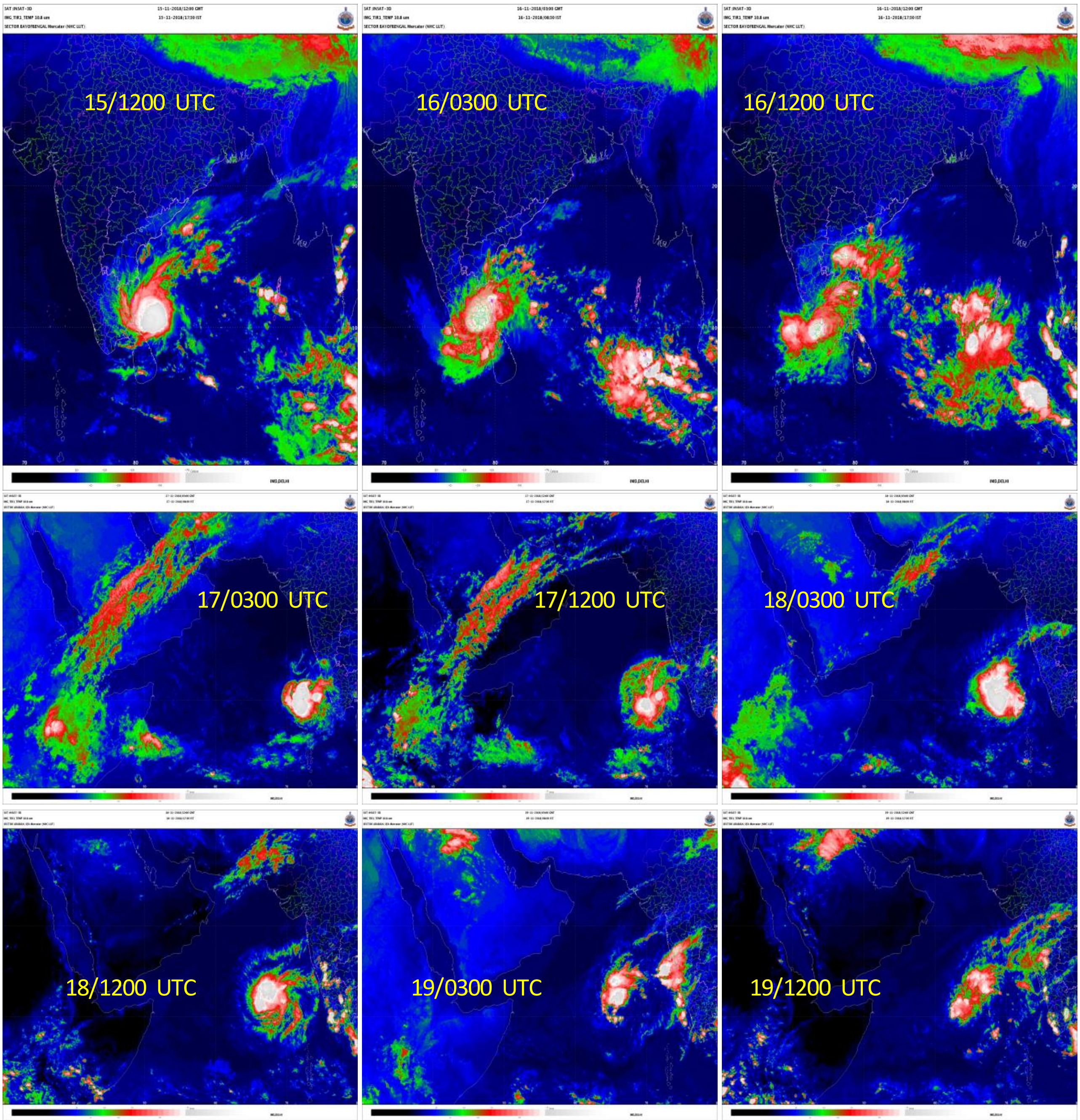


Fig. 2.13.5c(cotd): INSAT-3D enhanced colored imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

At 0300 UTC of 25th, the intensity of the system was **T 5.0**. The convection showed central dense overcast pattern with spiral bands. Associated broken low and medium clouds with embedded intense to very intense convection lay over westcentral and adjoining southwest AS between latitude 10.5^{0}N & 18.5^{0}N and longitude 51.0^{0}E to 58.0^{0}E. At 1800 UTC of 25th, the intensity of the system was **T 5.5**. The clouds got organized further and showed eye pattern. At 1800 UTC of 25th, the intensity of the system was T 5.5. The clouds got organized further and showed eye pattern. The system crossed Oman coast close to Salalah around 1900 UTC of 25th.

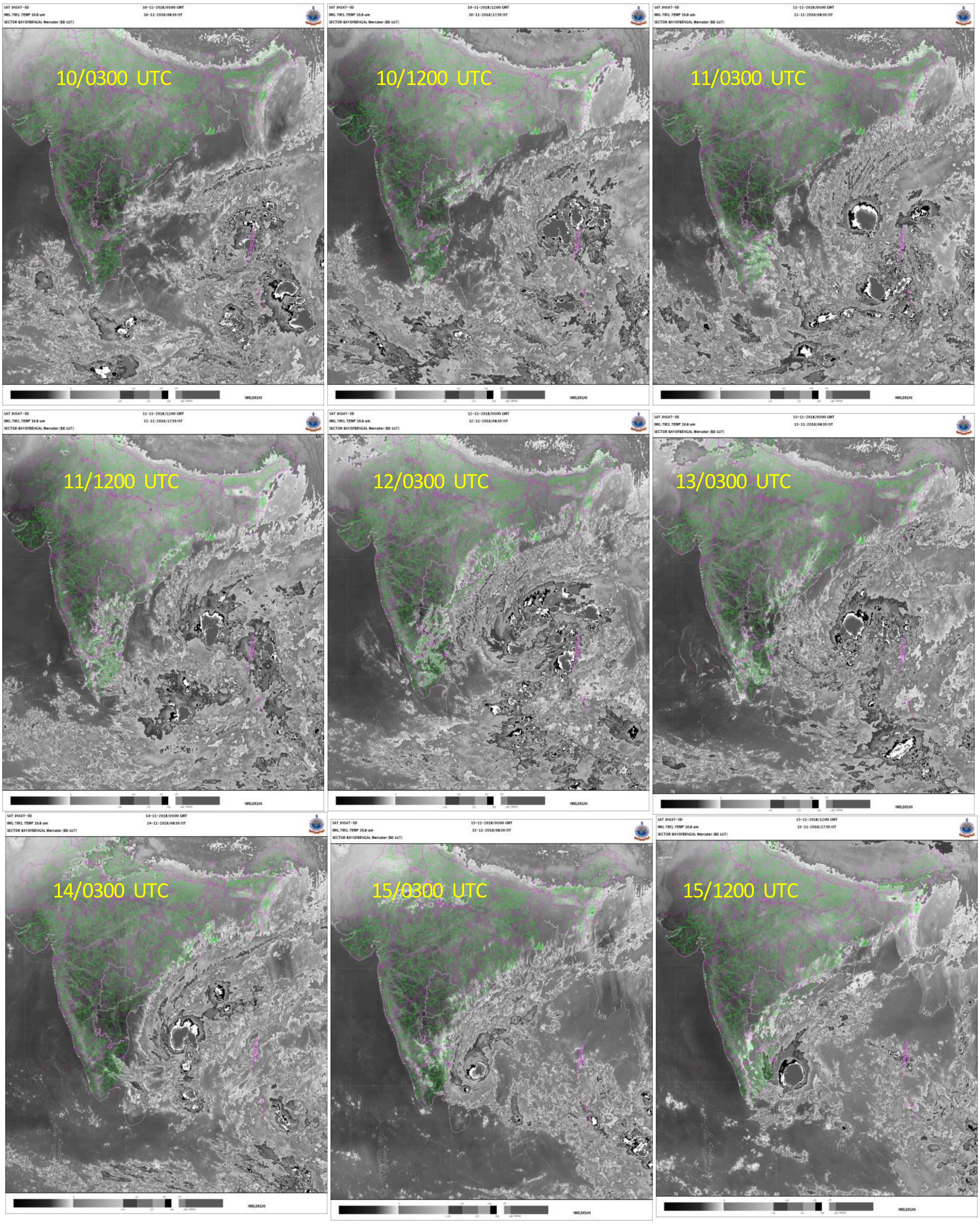


Fig. 2.13.5d: INSAT-3D cloud top brightness imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

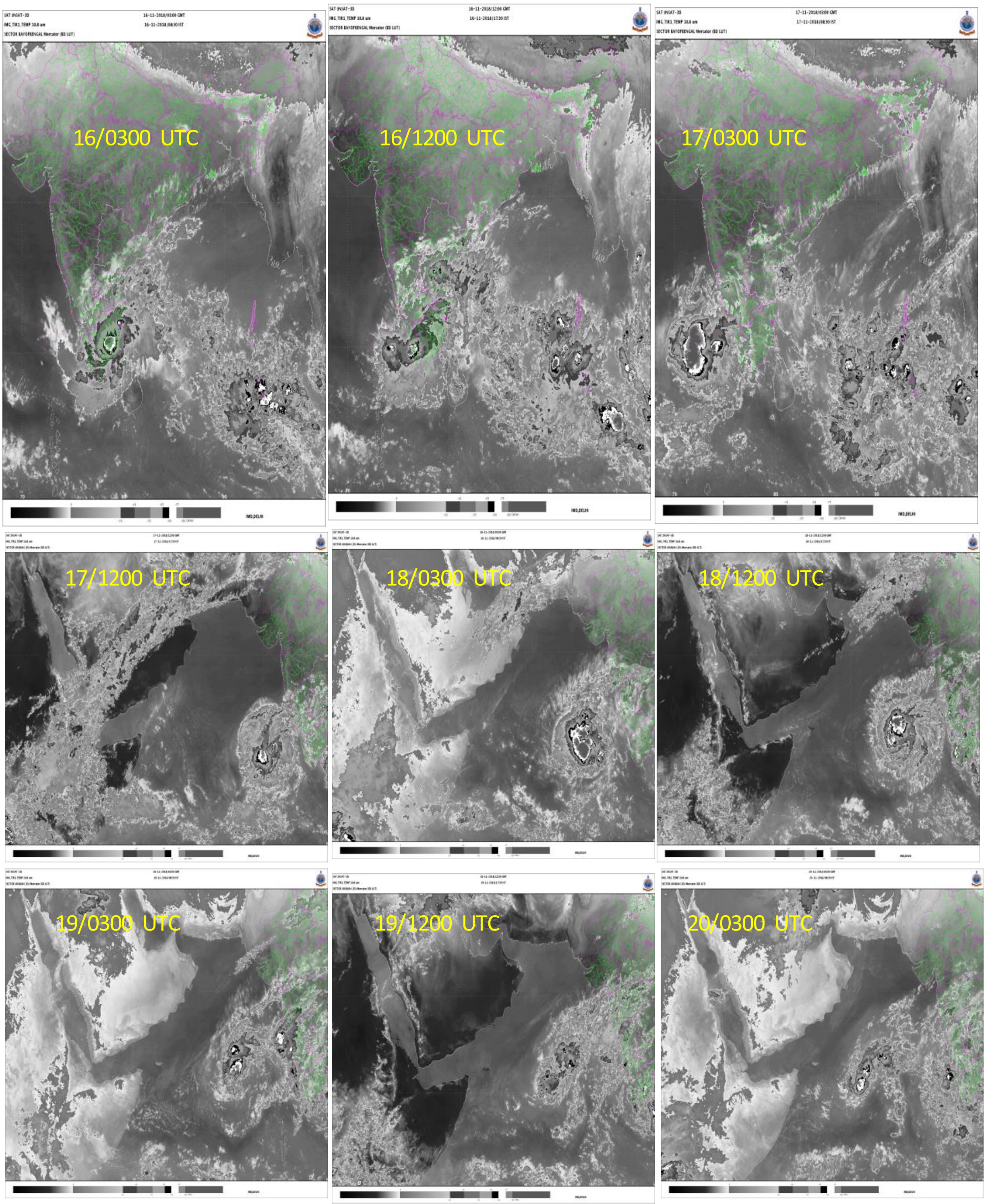


Fig. 2.13.5d(Cont): INSAT-3D cloud top brightness imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

2.13.5.2. Radar Imageries:

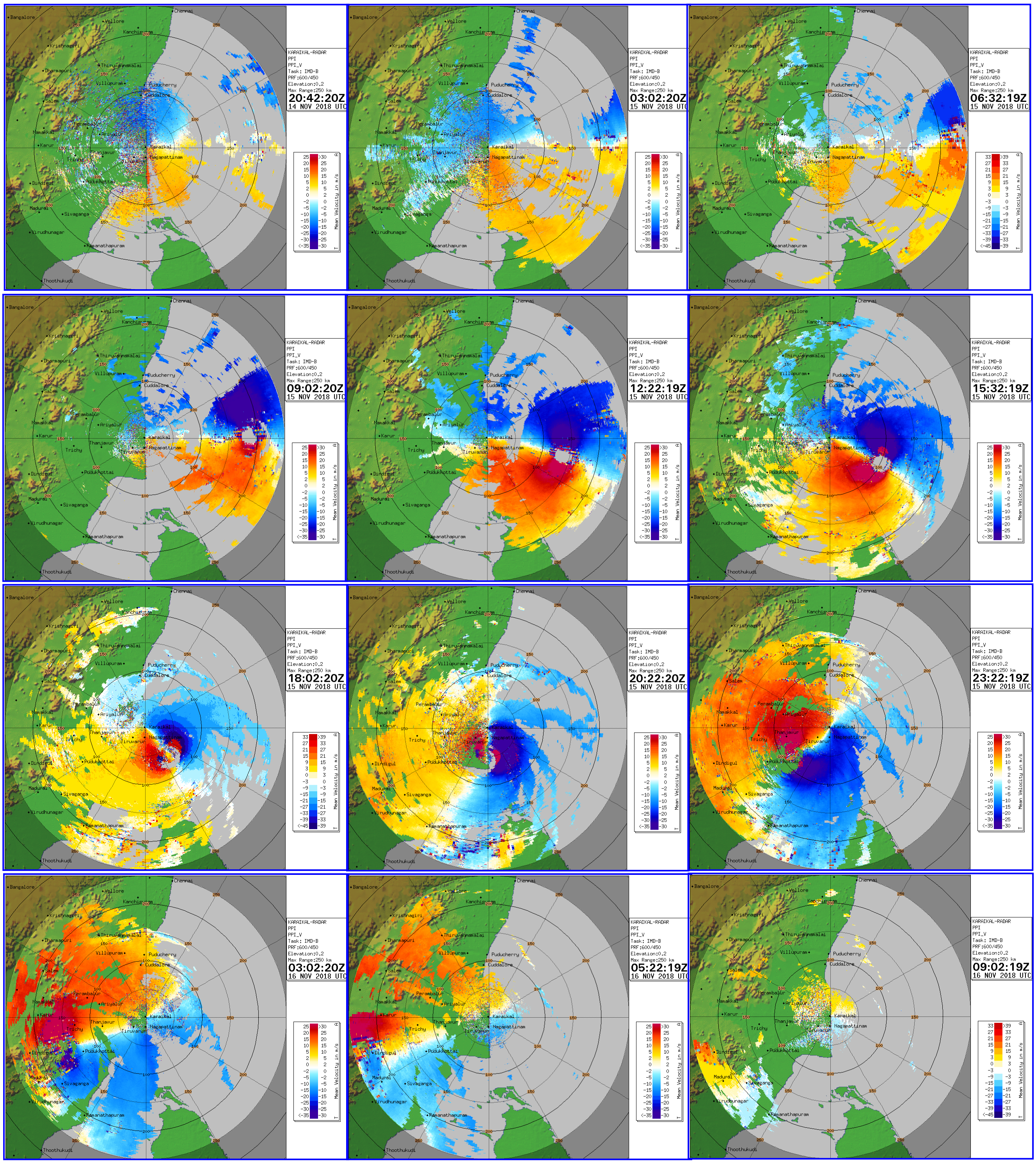


Fig. 2.13.5e: Karaikal radar imageries (14th – 16th November, 2018)of VSCS Gaja

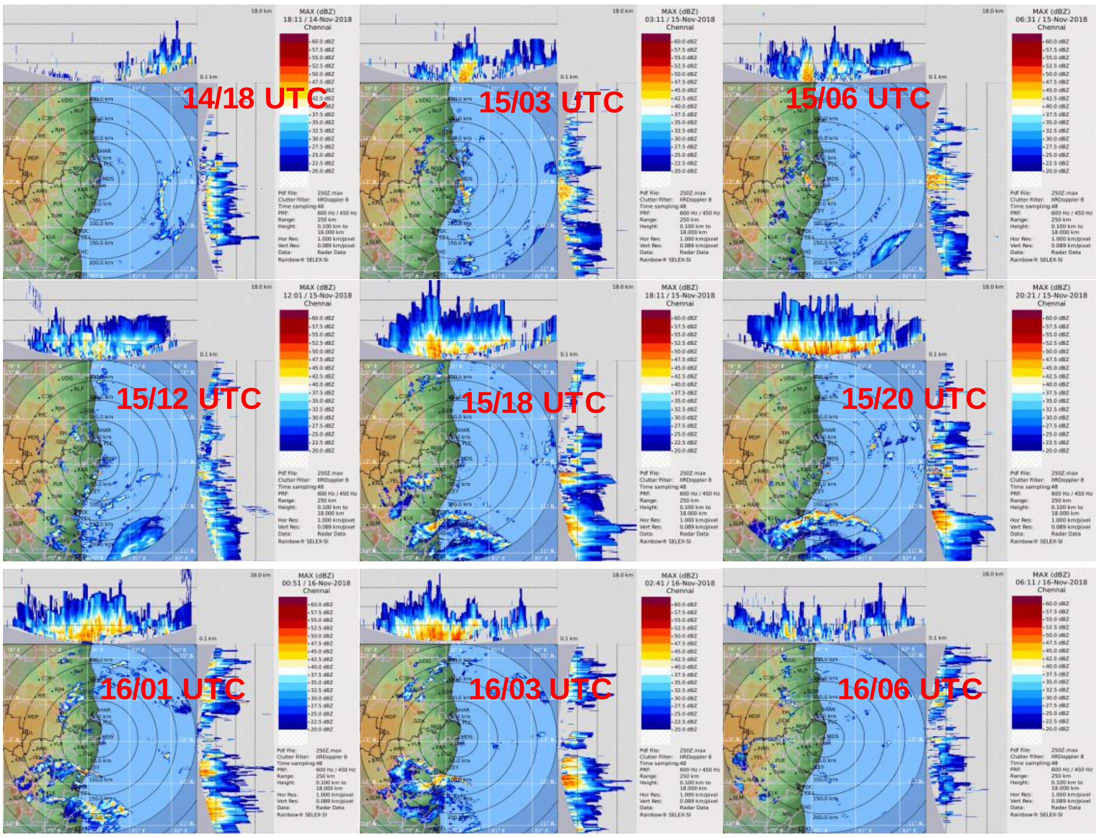


Fig. 2.13.5f: Chennai radar imageries (14th – 16th November, 2018) of VSCS Gaja

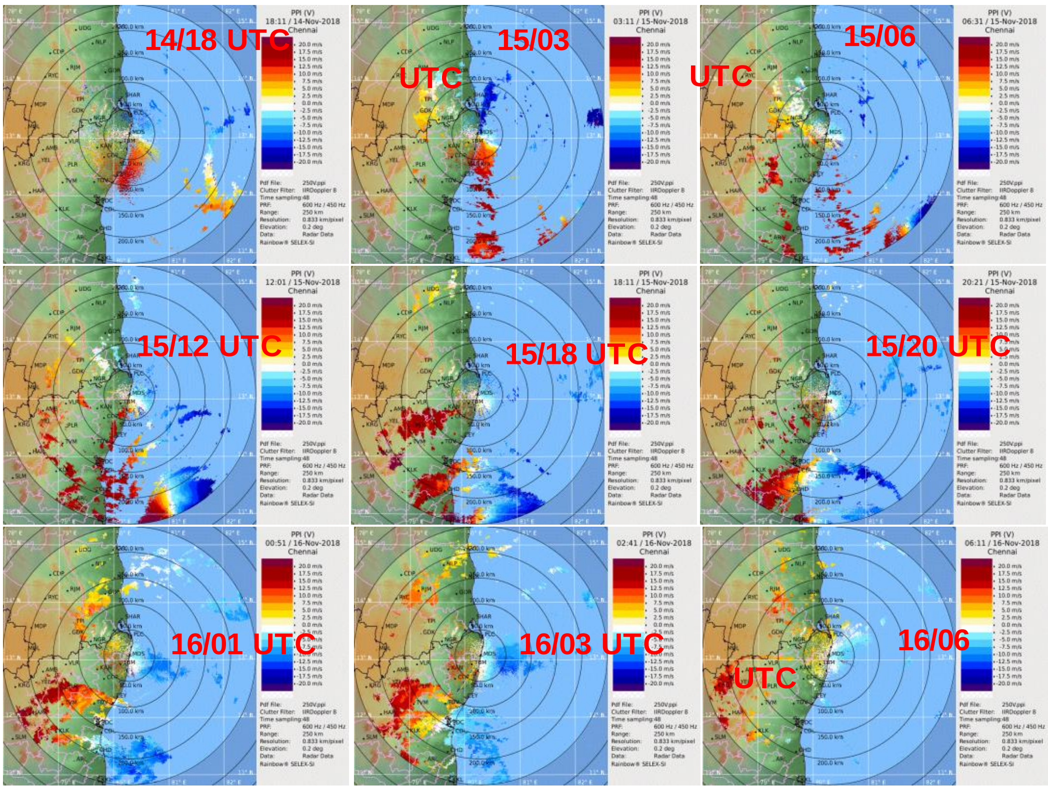


Fig. 2.13.5g: Chennai radar imageries (14th – 16th November, 2018) of VSCS Gaja

2.13.5.3. Microwave Imageries:

Microwave imageries from polar orbiting satellites F-15, F-16, F-18, GCOM W1, GPM 89, NOAA-19 were utilised for determining the centre and area of intense convection. Typical microwave imageries during the life cycle of VSCS Gaja are presented in **Fig. 2.13.5(h).**

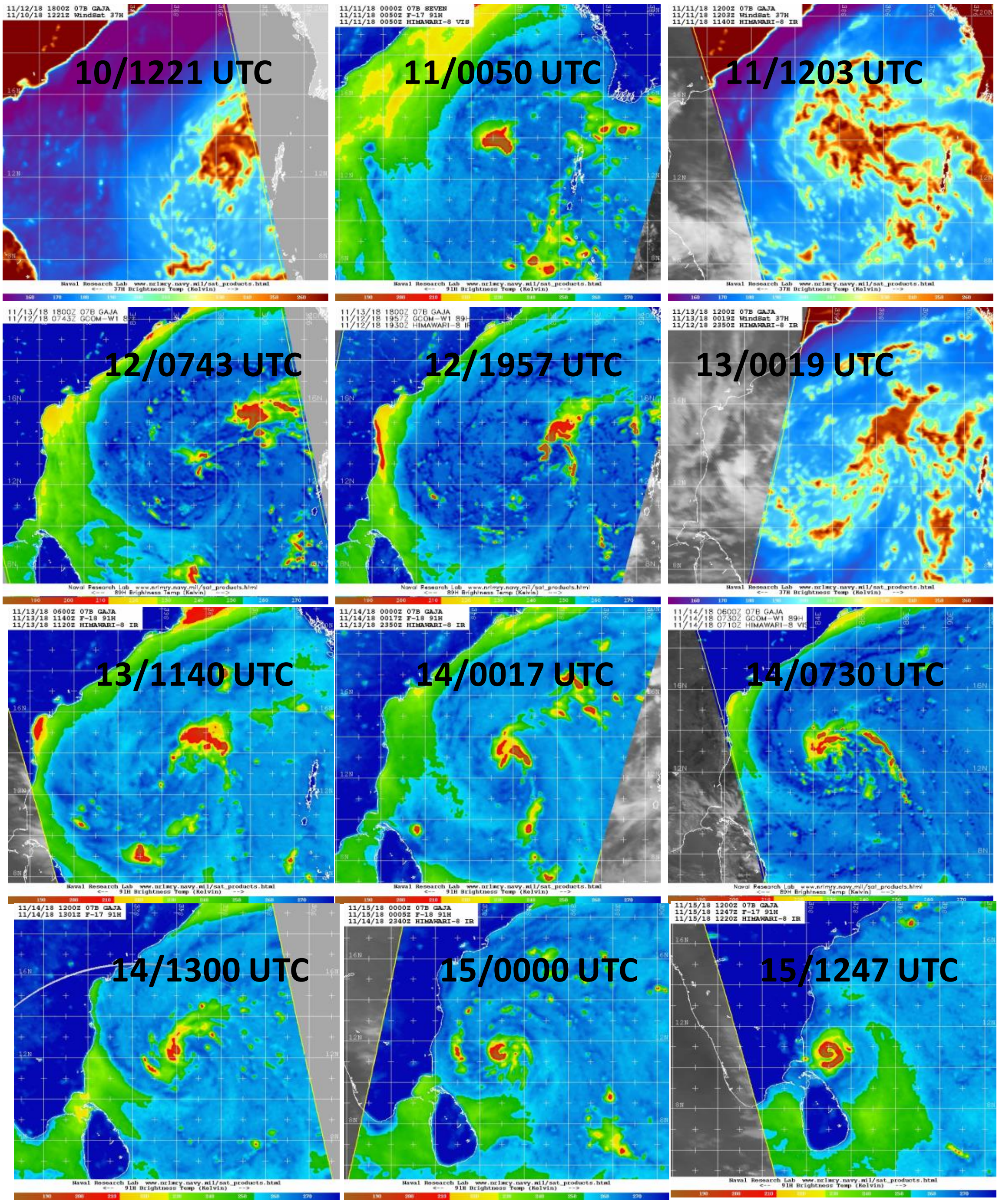


Fig. 2.13.5h: Microwave imageries during life cycle VSCS Gaja (10th – 19th November, 2018)

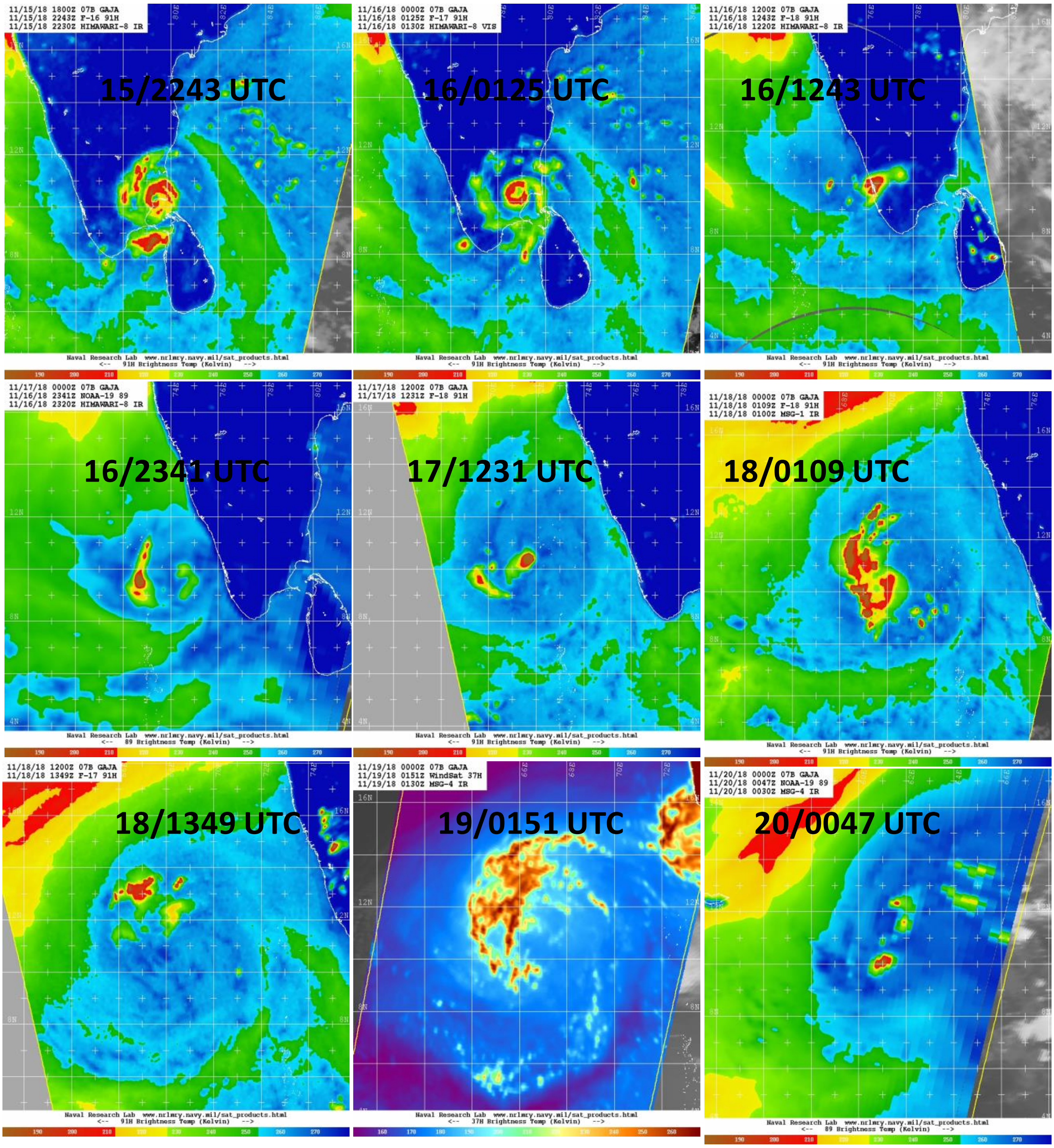


Fig. 2.13.5e(contd.): Microwave imageries during life cycle VSCS Gaja (10th – 19th November, 2018)

When the system was over sea, imageries from ASCAT were also utilized for determination of centre, intensity and wind distribution around the centre of the system. Typical ASCAT imageries from Metop-B are presented in Fig. 5.13.5(i).

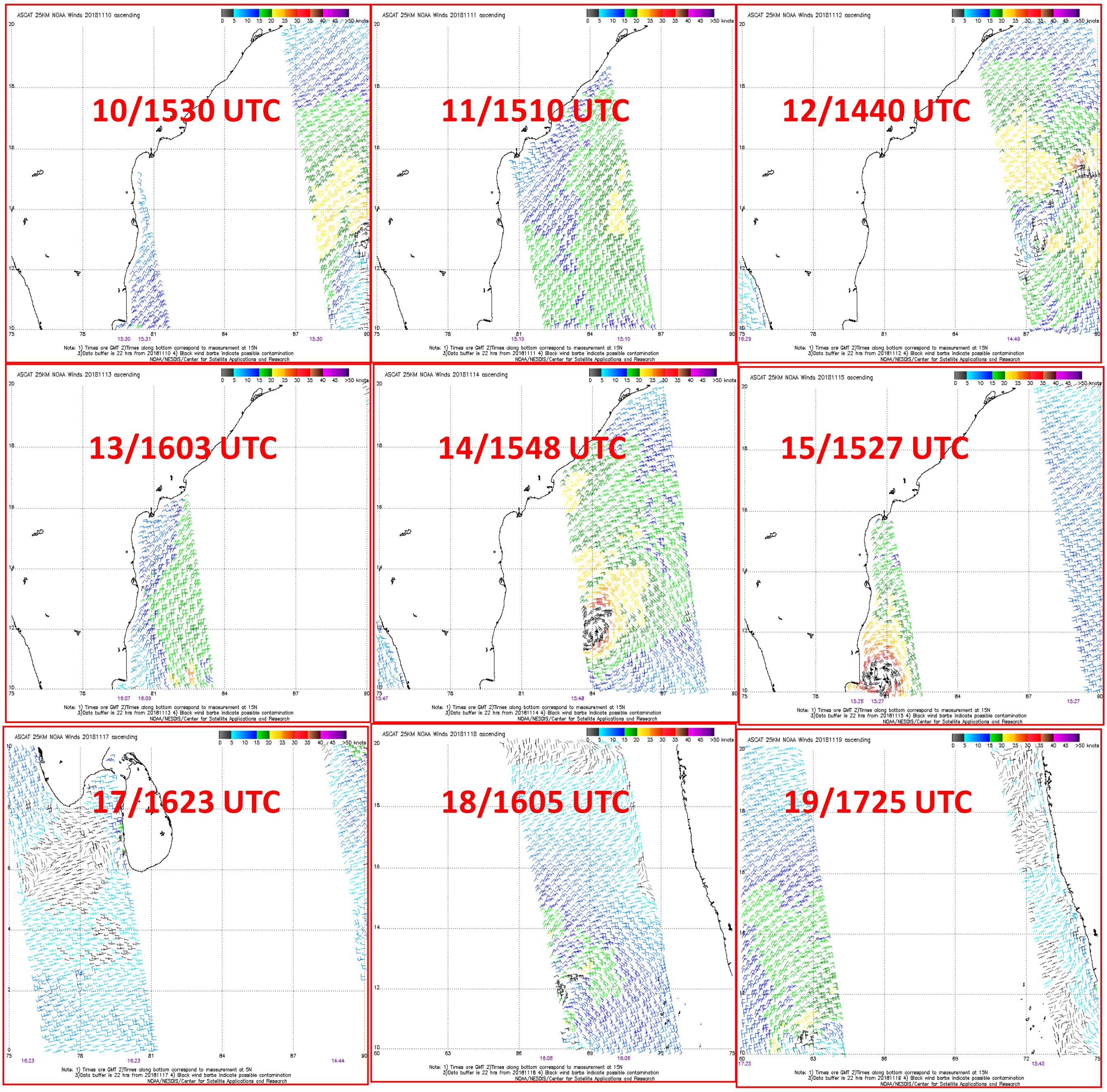


Fig. 2.13.5(i): ASCAT (Met-Op B) imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

Typical imageries from polar satellite, SCATSAT are presented in Fig.2.13.5 (g). SCATSAT passes are available twice a day at 0454 UTC and 1636 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 1636 UTC of 21st indicated cyclonic circulation over southwest Arabian Sea. Stronger winds were seen in northern sector. The imagery also indicated large scale cross equatorial flow, inflow of warm and moist air into the system centre from southeast sector. At 0454 UTC of 22nd May, the area of strong winds extended to southwest sector. At 1636 UTC of 23rd, stronger winds were seen in the northwest sector. At 0454 UTC of 24th, the centre was seen near 13.5N/56E, warm and moist air advection from southwest to northwest sector was seen. The estimated intensity was more than 60 kts. The maximum size in the southern sector was also due to higher southwesterly winds in the region. On 25th and 26th stronger winds were seen in the northeast sector. SCAT Sat imageries helped in determination of centre to a good extent. Intensity estimates beyond 60 kts cannot be done with the help of these imageries.

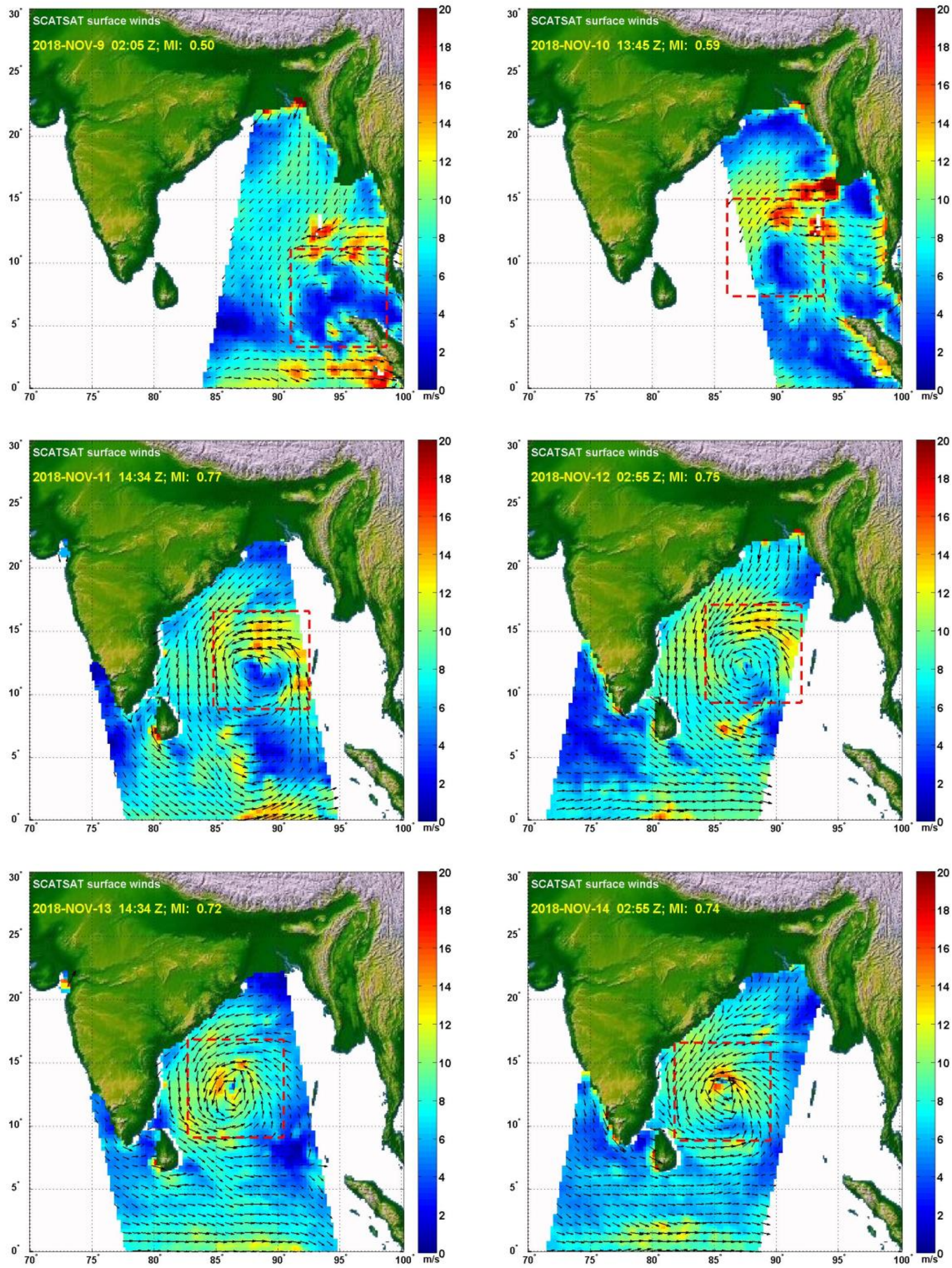


Fig. 2.13.5(j): SCATSAT imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

2.13.6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 10th to 19th November are presented in Fig. 2.13.6. Based on 0000 UTC observations of 10th, the model predicted a depression over southeast and BoB an adjoining north Andaman Sea. The circulation was extending upto 850 hPa level. Upper tropospheric ridge was seen along 14^0N. The centre, intensity and ridge were correctly captured.

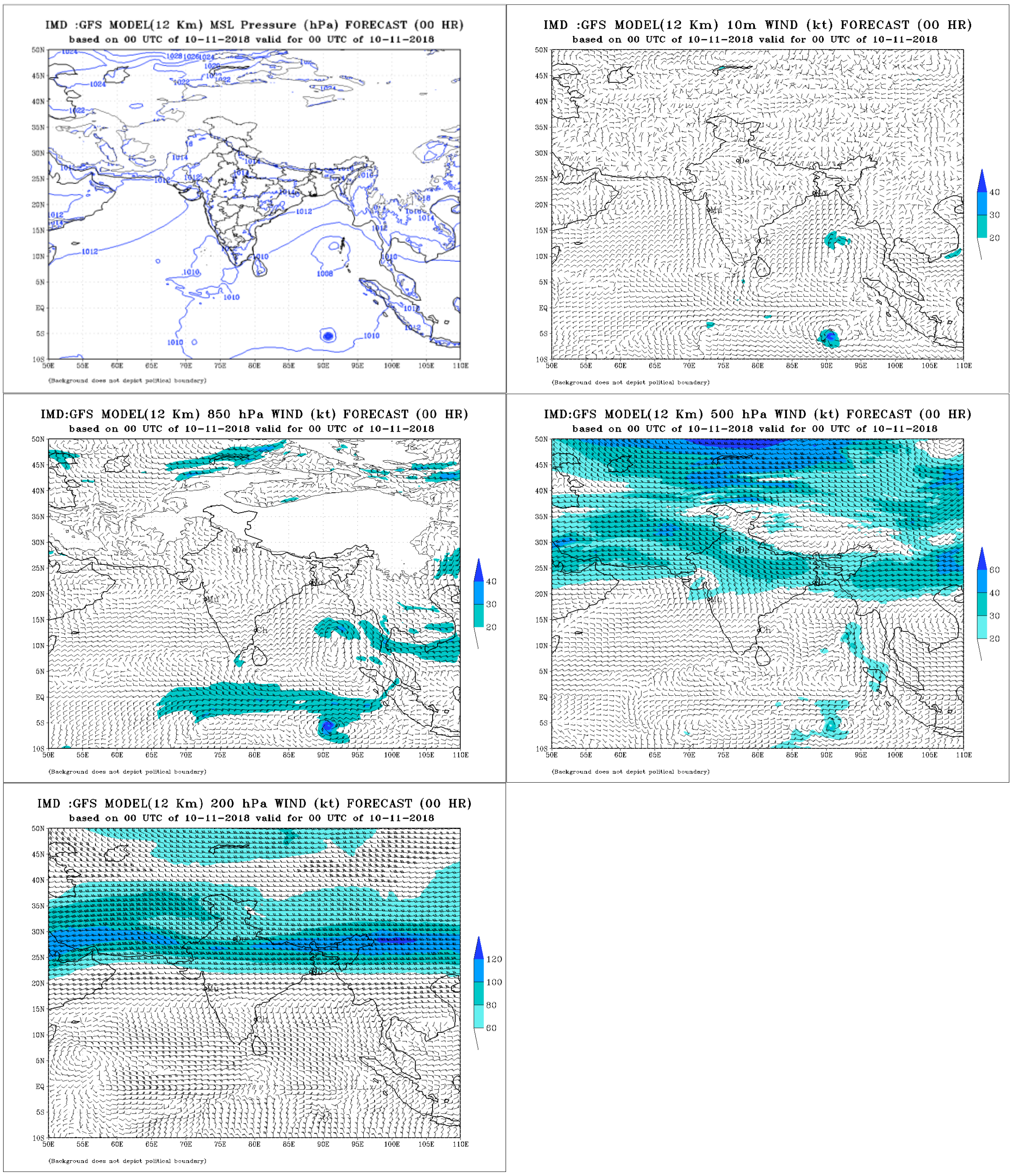


Fig. 2.13.6 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th November

Analysis based on 0000 UTC of 11th November, predicted slight weakening of system. Vertically the system extended upto 850 hPa levels. However, the system intensified into a deep depression at 1200 UTC of 10th.

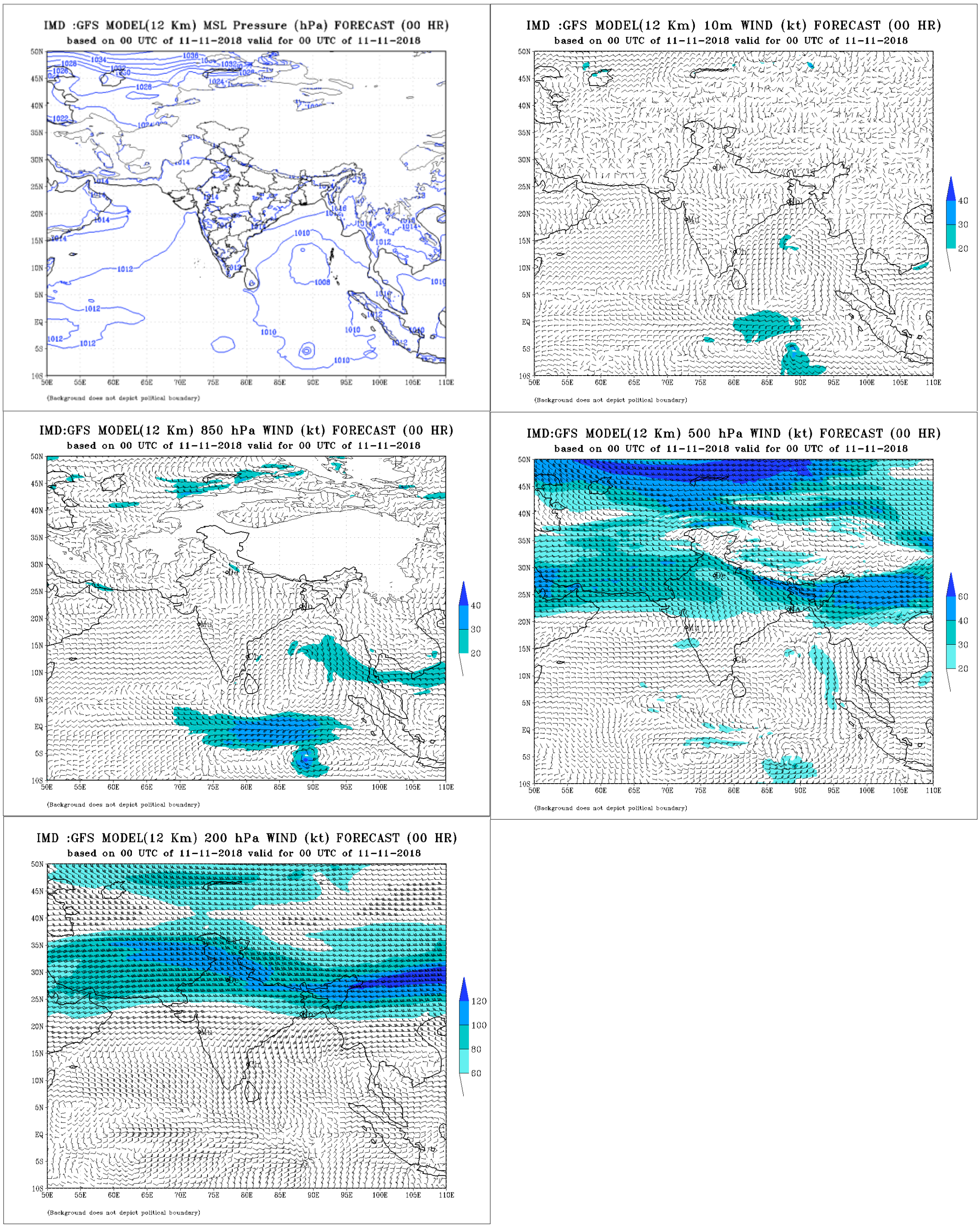


Fig. 2.13.6 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th November

Analysis based on 0000 UTC of 12th November predicted intensification of the system into a deep depression over westcentral BoB. The circulation extended upto 500 hpa levels. However, the system attained the cyclonic storm intensity at 0000 UTC of 11th. But GFS could capture the centre of the system correctly.

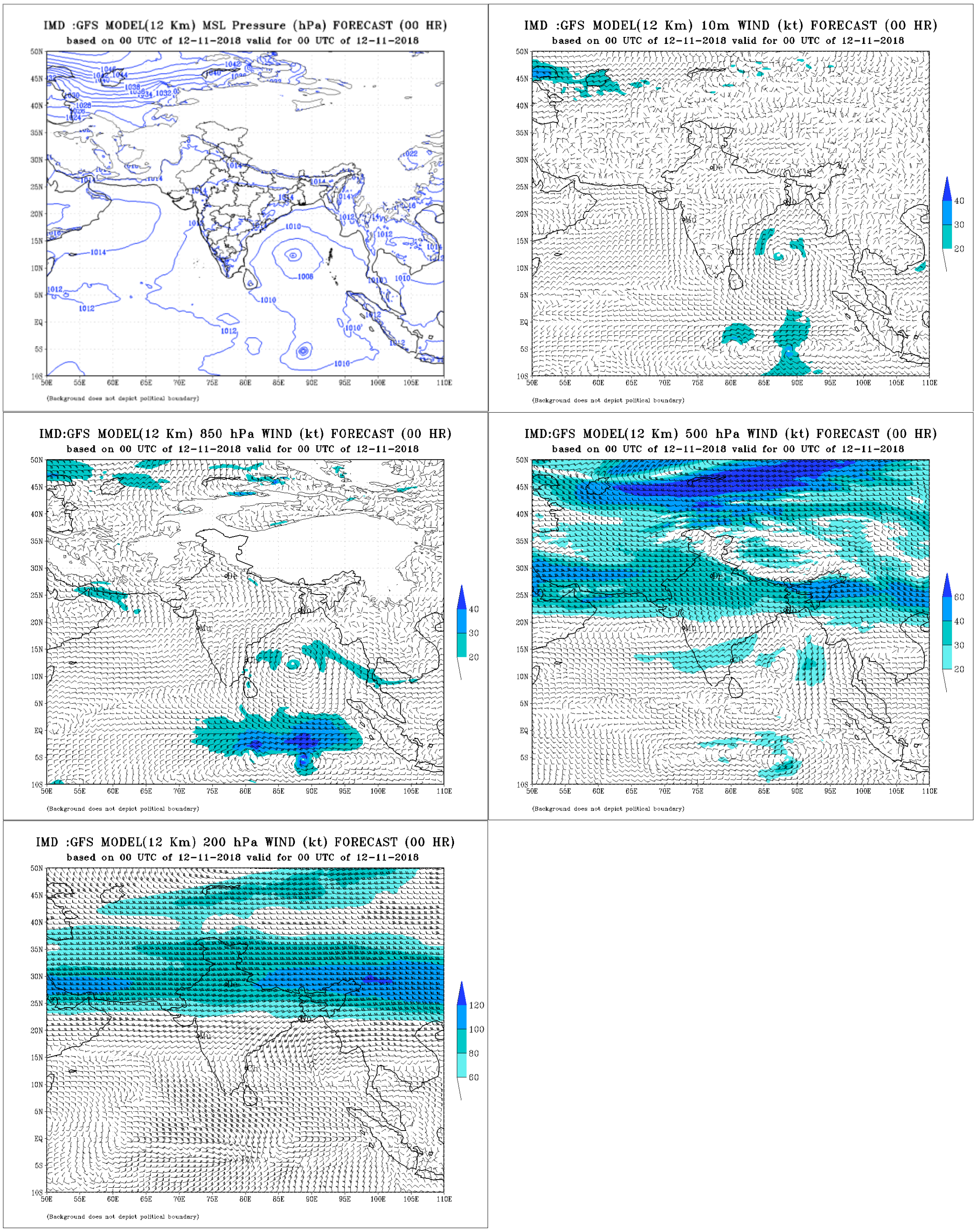


Fig. 2.13.6 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 12th November

Initial conditions based on 0000 UTC of 13th November indicated weakening of the system into a depression near 13.5N/87.5E. Vertically the system extension was seen upto 850 hPa level. IMD GFS could capture the location correctly, but underestimated the intensity of the system. The system had the intensity of cyclonic storm at 0000 UTC of 13th.

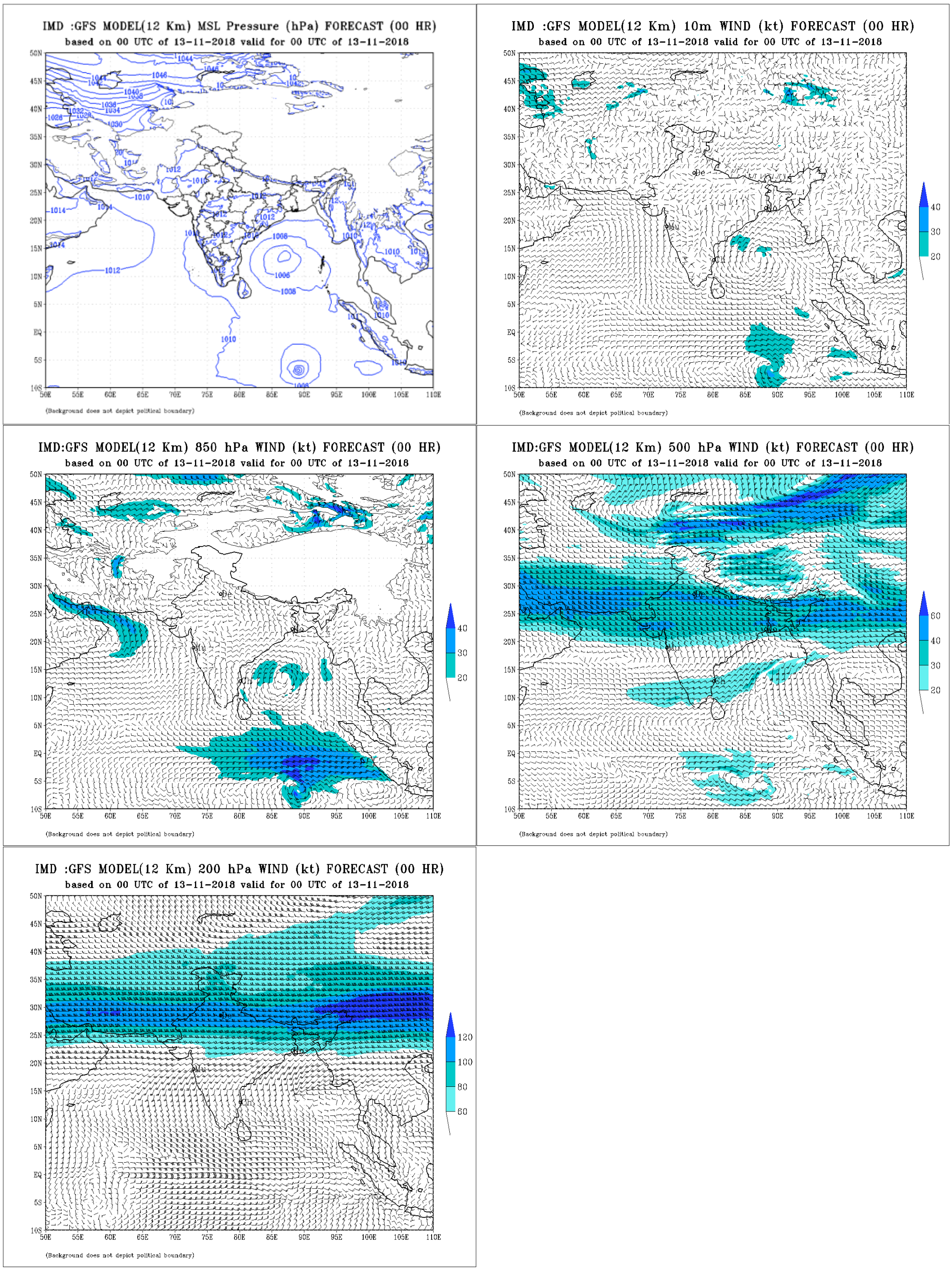


Fig. 2.13.6 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th November

Analysis based on 0000 UTC of 14th November indicated further weakening of the system into a WML over westcentral and adjoining southwest BoB near 12.5N/85.0E. The system was near 13.5N/85.3E as a cyclonic storm at 0000 UTC of 14th. Thus, IMD GFS could not capture the intensity correctly. Anticyclonic circulation over eastcentral AS and ridge around 15^{0}N were also seen in GFS analysis charts.

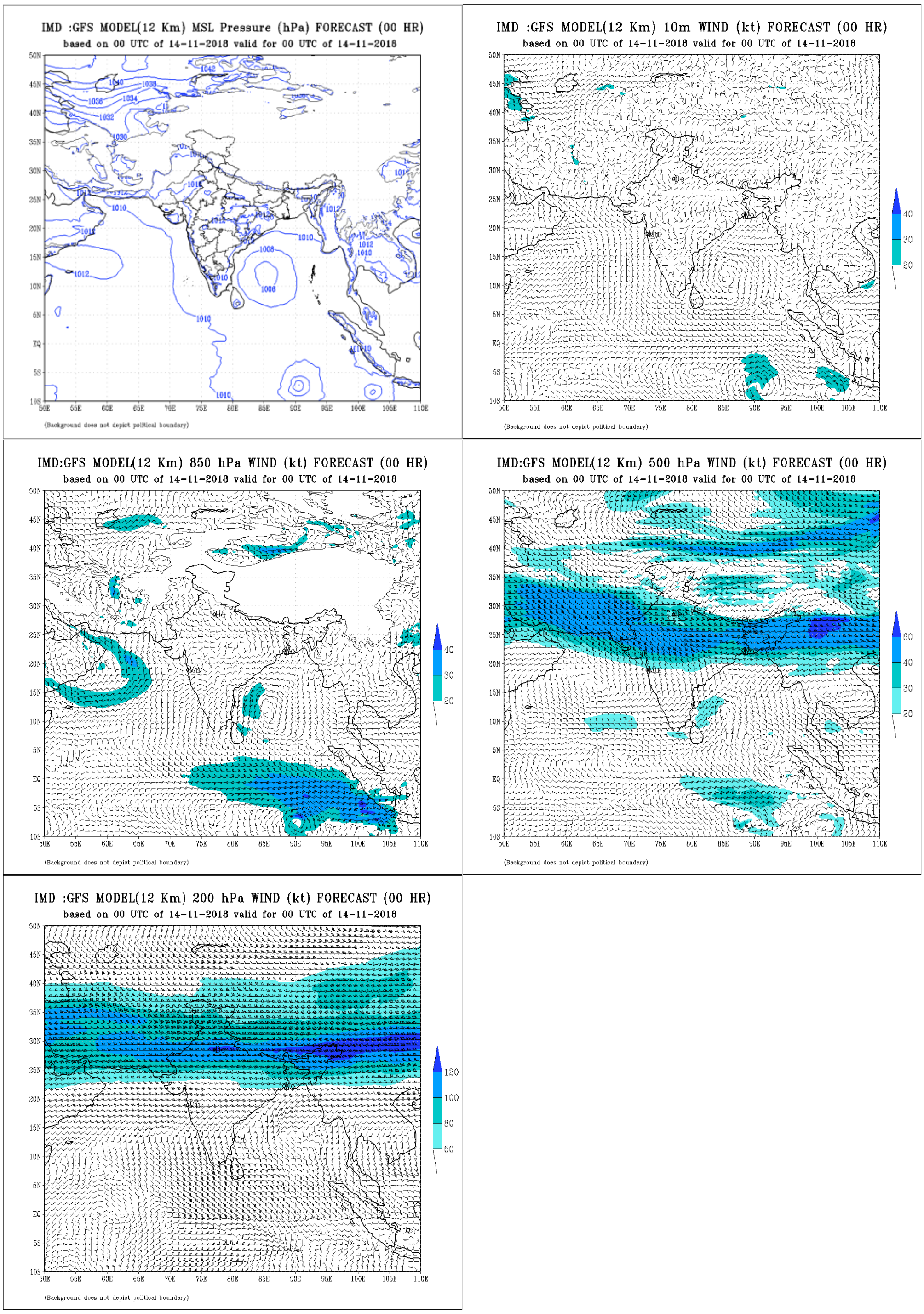


Fig. 2.13.6 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th November

The initial conditions based on 0000 UTC of 15th indicated intensification of the system into an VSCS over southwest BoB near 11.0N/83.0E. The movement and location was correctly captured. However, the intensity was overestimated. At 0000 UTC of 15th, the system lay over southwest BoB near 11.5N/83.2E as a cyclonic storm. The ridge and anticyclones to the west and east of system centre were also captured by GFS.

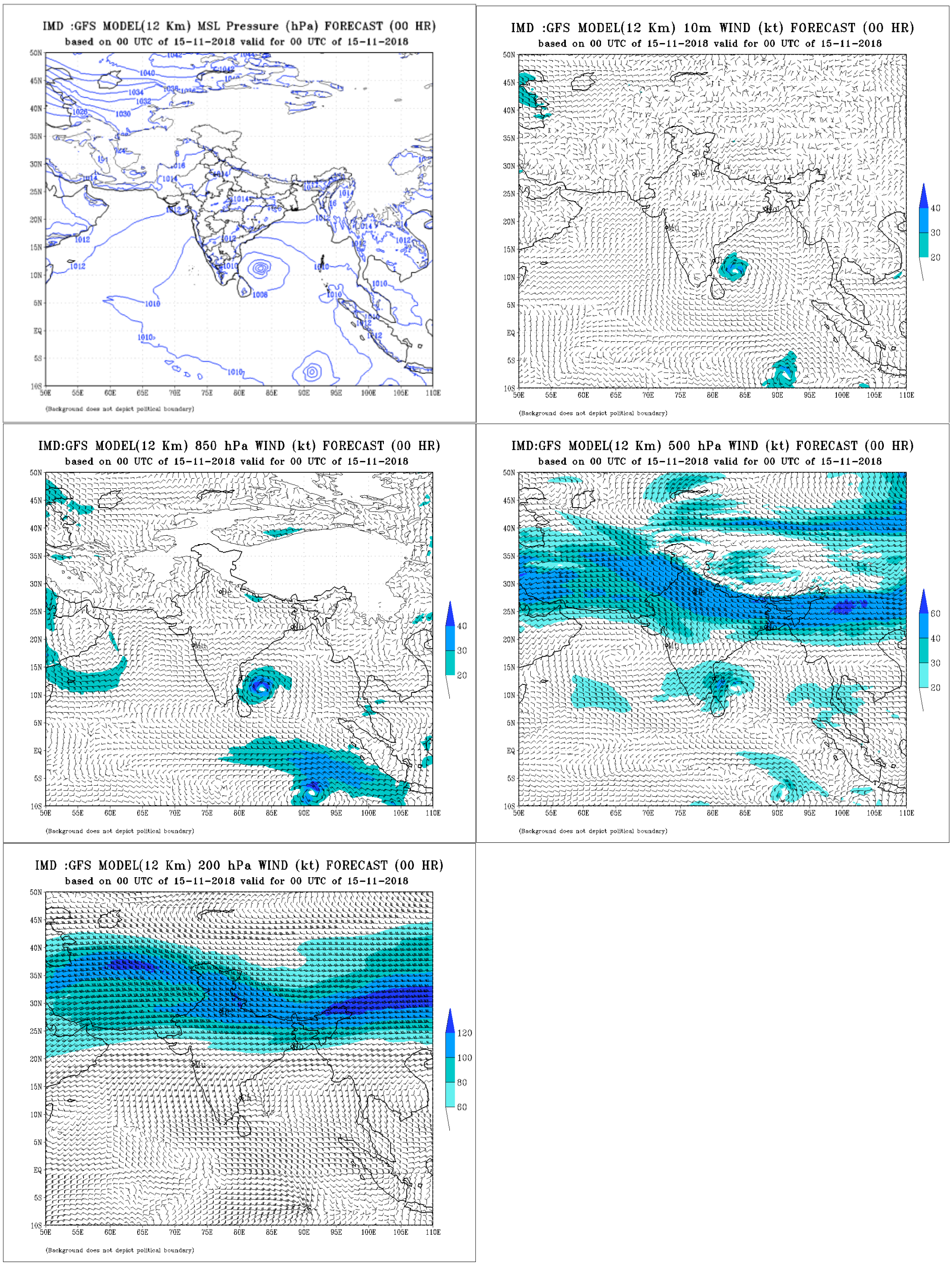


Fig. 2.13.6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th November

The initial conditions based on 0000 UTC of 16th indicated that the system crossed near 10.5N/79.5E around 2200 UTC of 15th as a VSCS. The landfall point & time and intensity were correctly predicted. The ridge and anticyclones to the west and east of system centre were also captured by GFS. The anticyclone to the west of system centre was also captured well that led to near westwards movement of the system. It also indicated that vertically the system extended upto 500 hPa level.

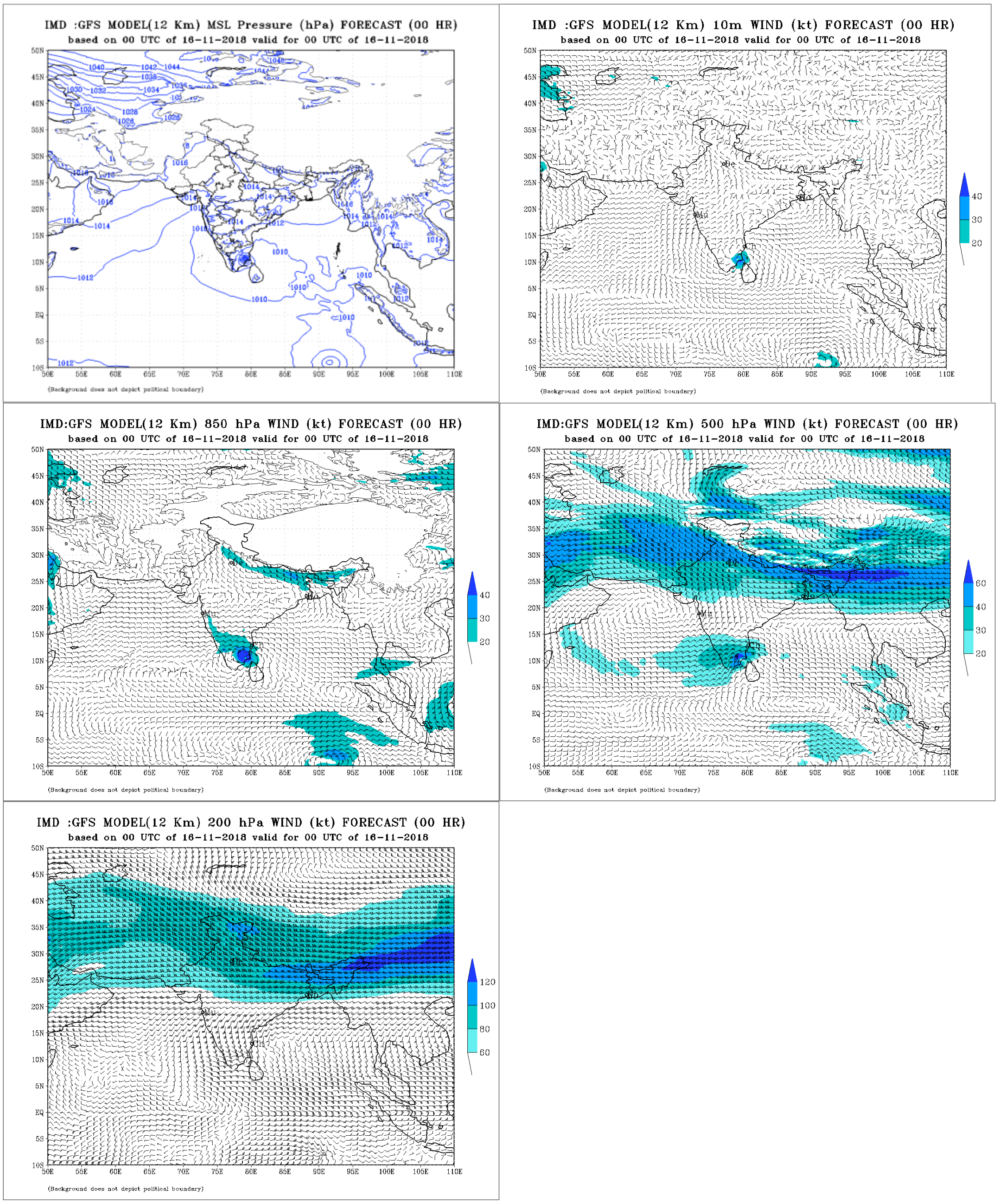


Fig. 2.13.6 (g): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th November

The initial conditions based on 0000 UTC of 17th captured the movement and location correctly. However, the intensity was underestimated. GFS indicated a depression over southeast AS near 10.0N/74.5E. However, at 0000 UTC of 17th, the system lay as a DD over southeast Arabian Sea near 9.8°N/74.3°E.

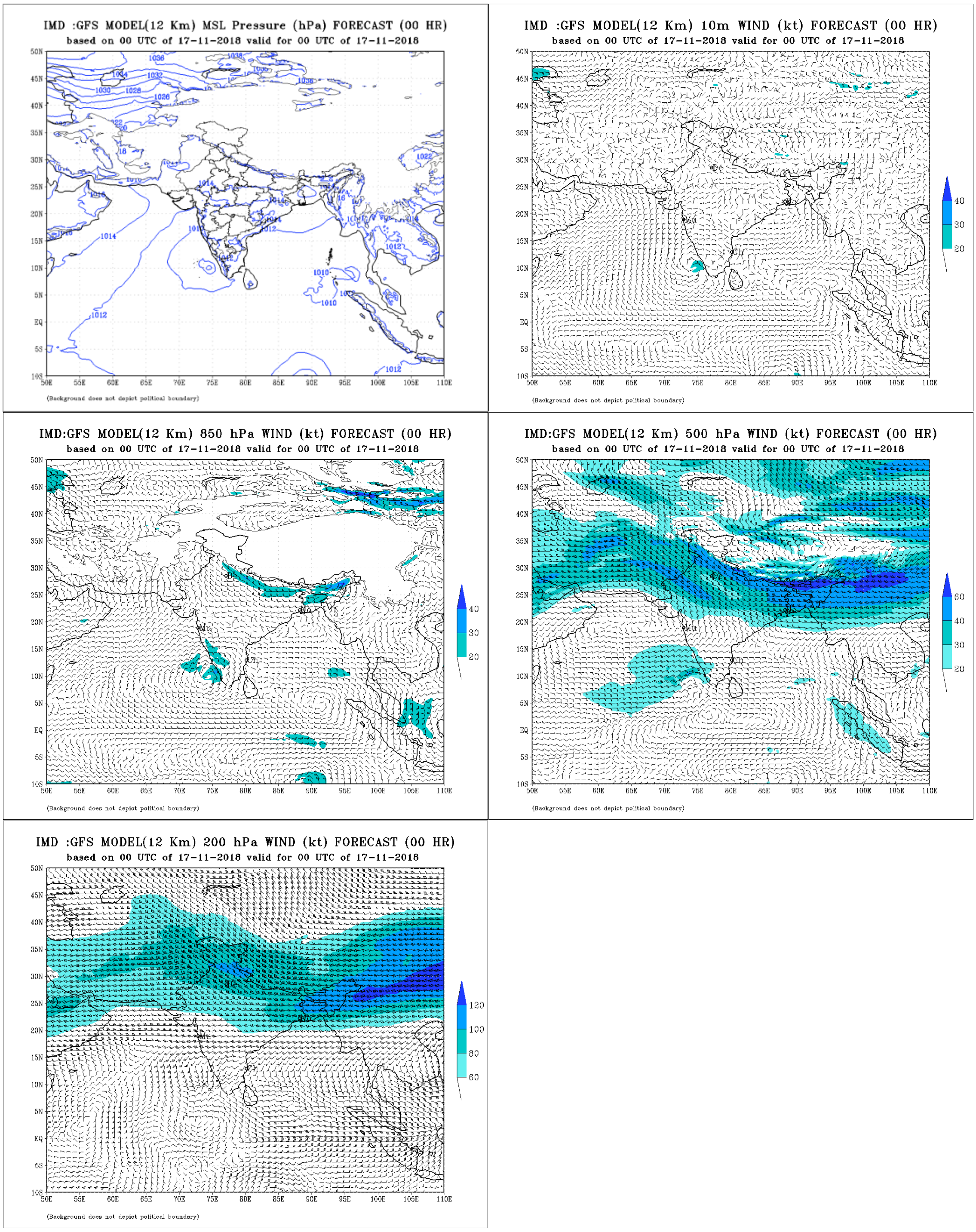


Fig. 2.13.6 (h): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th November

The initial conditions based on 0000 UTC of 18th captured the movement, location and intensity correctly. GFS predicted the system lay as a DD over southeast AS near 10.5N/69.5E. The best track parameters indicate that at 0000 UTC of 18th, the system lay as a DD over southeast Arabian Sea near 10.3°N/69.5°E.

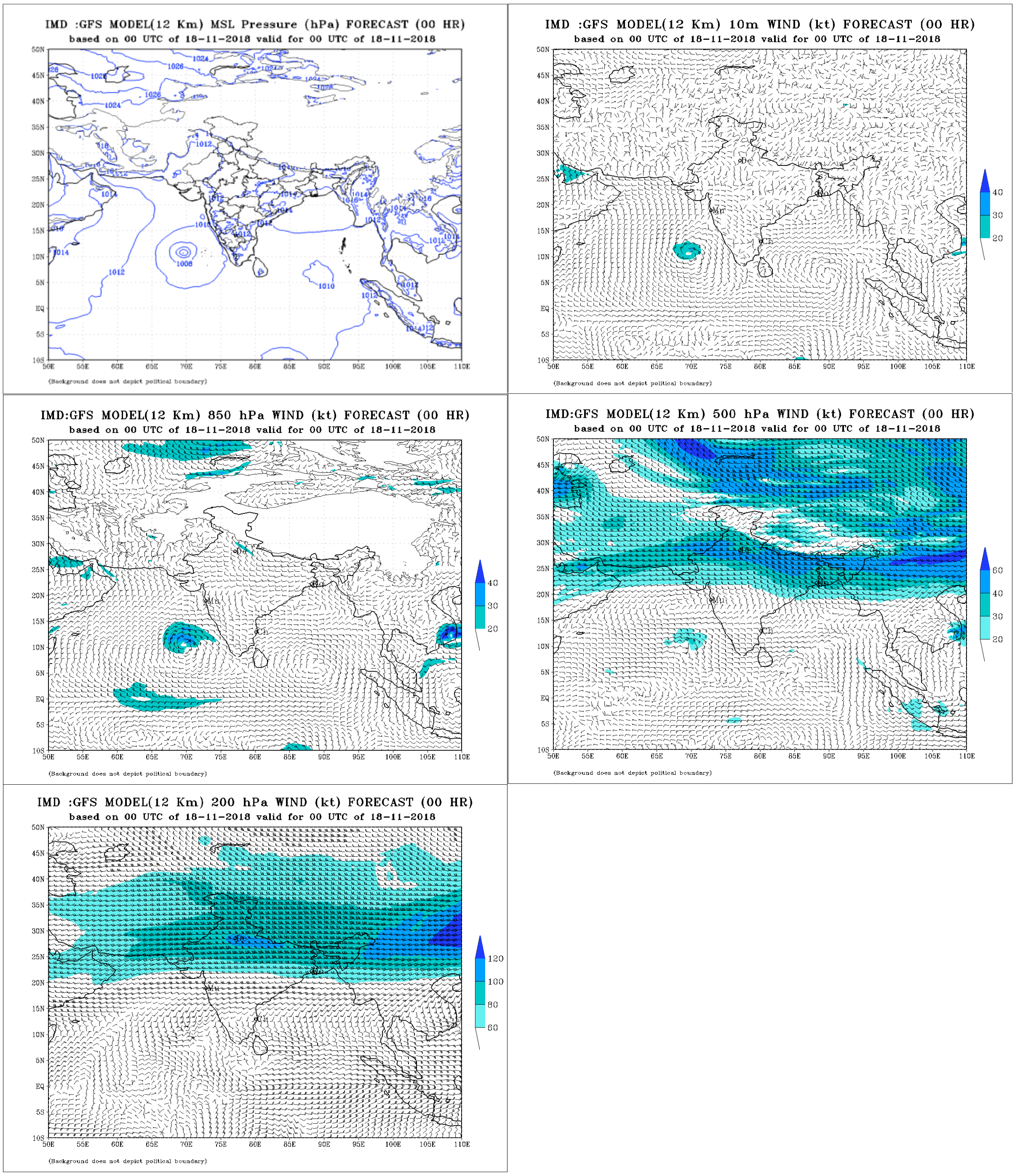


Fig. 2.13.6 (i): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th November

The initial conditions based on 0000 UTC of 19th indicated weakening of the system into a depression over southeast AS near 10.0N/66.5E. However, best track parameters indicate that the system retained it's intensity of DD and lay near 11.0N/66.0E.

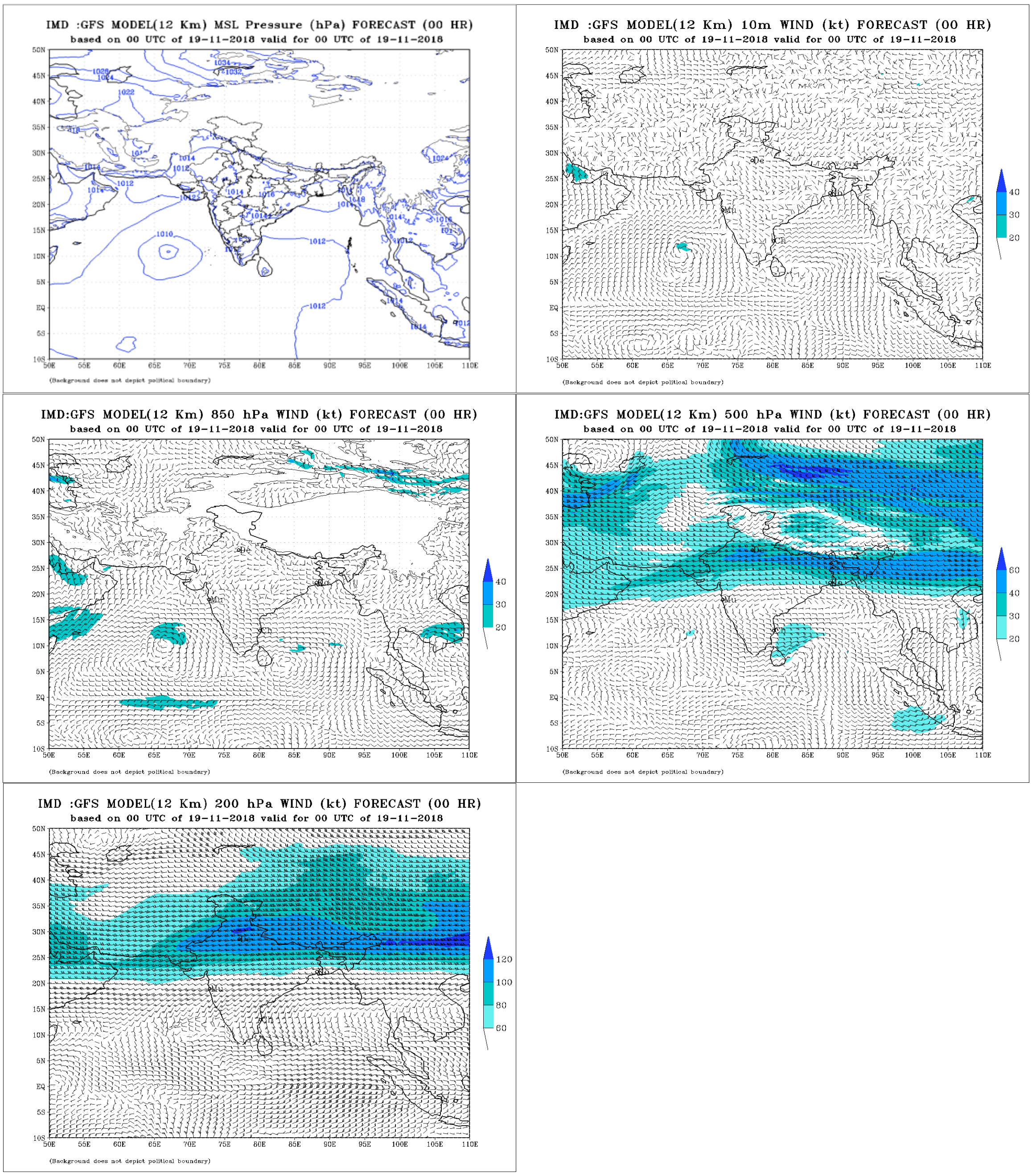


Fig. 2.13.6 (j): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th November

The initial conditions based on 0000 UTC of 20th indicated further weakening of the system into a WML over southwest AS near 10.5N/63.0E. The system weakened into a WML at 1800 UTC of 20th over southwest & adjoining southeast Arabian Sea.

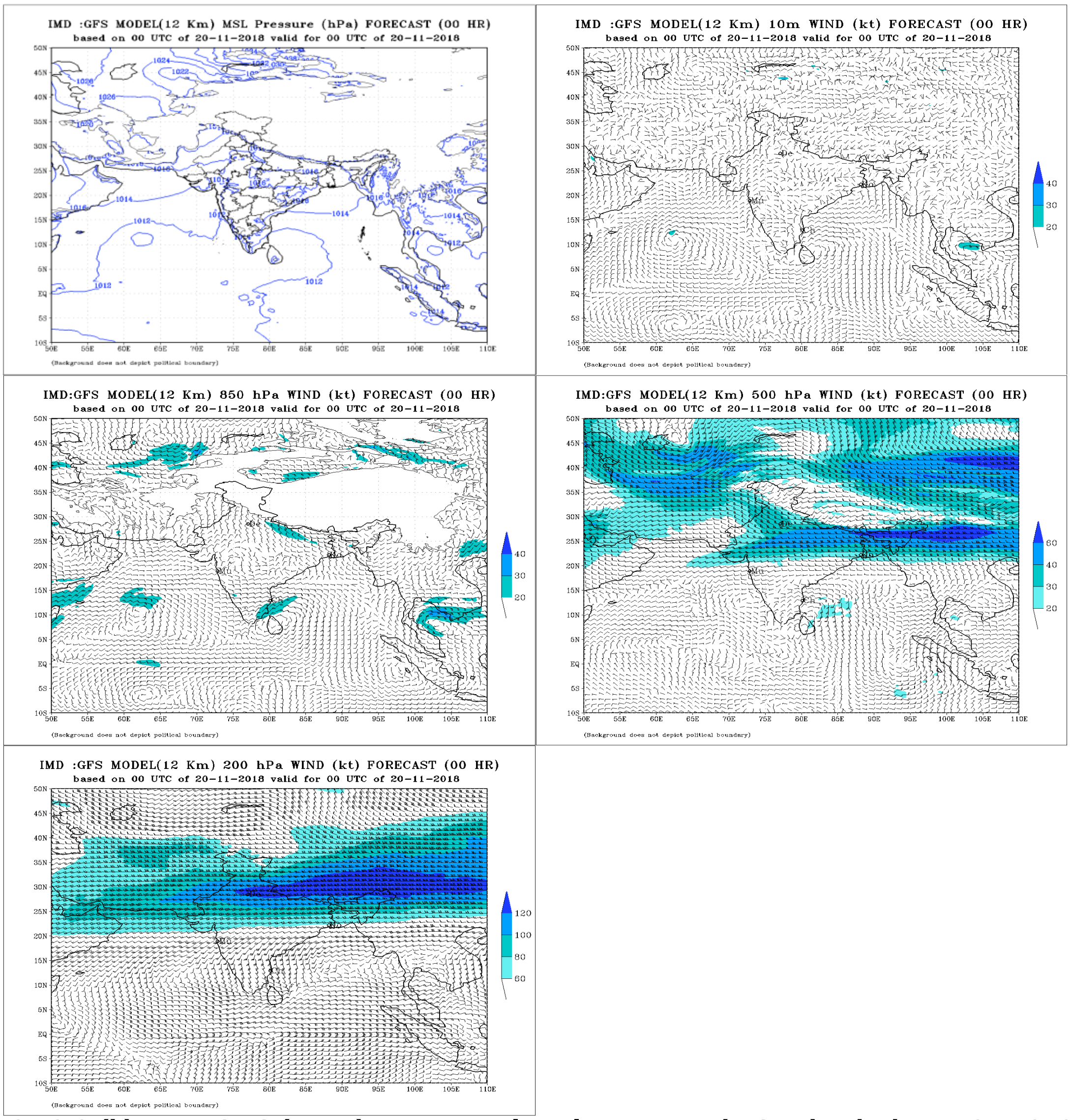


Fig. 2.13.6 (k): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th November

Hence to conclude, to a large extent IMD GFS could simulate the genesis, movement and landfall characteristics of the system. However, it could not consistently capture the intensity of the system correctly.

2.13.7. Realized Weather:

2.13.7.1 Rainfall:

Rainfall associated with VSCS Gaja based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 2.13.7**.

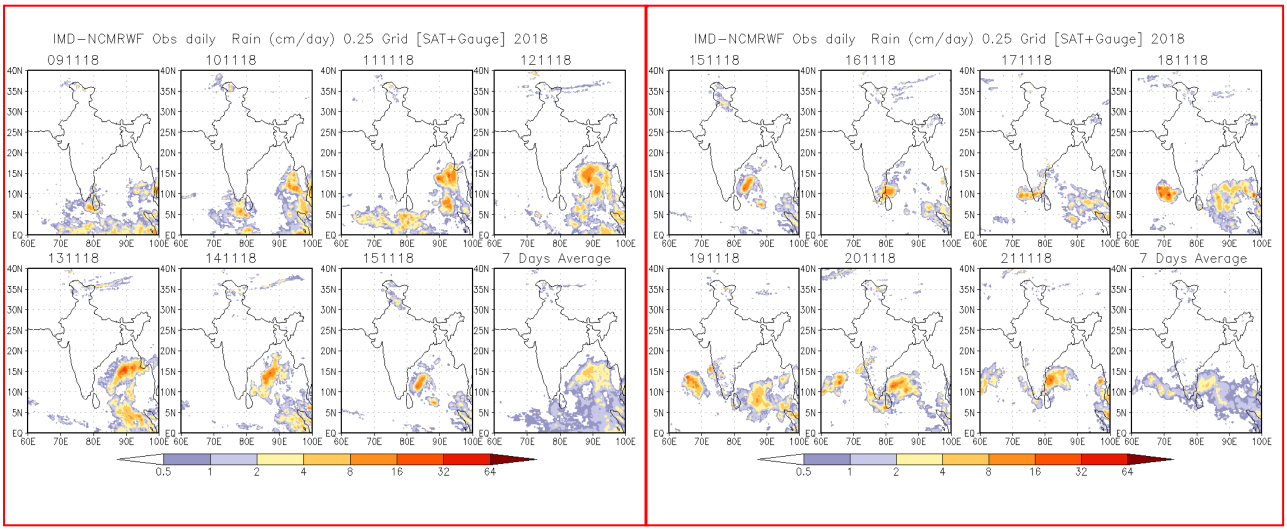


Fig. 2.13.7: IMD-NCMRWF merged satellite and rain gauge observed rainfall (cm/day) during 10-18 November in association with VSCS Gaja

Under the influence of the system, on 16th November, rainfall occurred at most places with heavy falls at a few places and very heavy falls at isolated places over Tamil Nadu. Moderate rainfall occurred over Kerala, south coastal Andhra Pradesh, Rayalaseema and south interior Karnataka. On 17th, rainfall occurred at most places with isolated heavy to very heavy rainfall over Kerala and Tamilnadu. Isolated extremely heavy rainfall also occurred over Kerala and isolated heavy rainfall over coastal Andhra Pradesh.

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

10 November 2018

Andaman & Nicobar Islands: Long Island-14, Maya Bandar-10, Port Blair-9

11 November 2018

Andaman & Nicobar Islands: Maya Bandar-7,

16 November:

Tamilnadu & Puducherry: Thiruthuraipoondi & Muthupet-17 each, Adirampatnam-16, Peravurani, Pattukottai & Neyveli-14 each, Virudachalam-12, Chengalpattu-11, Cuddalore-9, Madukkur, Arantangi & Vandavasi-8 each, and Srimushnam, Valinokkam, Nagercoil, Uthiramerur, Orthanad, Needamangalam, Thuckalay, Sethiathope, Pondicherry & Tozhudur-7 each

17 November:

Coastal Andhra Pradesh: Kandukur and Gudivada-7 each,

Telangana: Aswaraopeta-7,

Tamilnadu & Puducherry: Sivaganga-17, Kodaikanal-14, Thammampatty-10, Nilakottai, Illuppur, Periyakulam & Bodinaickanur-9 each, Tirupathur-8 and Chinnakalar, Vadipatti-7 each

Kerala: Kozha-28, Piravam-19, Thodupuzha-15, Cherthala & Munnar Kseb-12 each, Kumarakam-11, Idukki-10, Vaikom, & Myladumpara-9 each, Kottayam-8, Peermade -7

2.13.7.2. Wind

Atiramapattinam reported maximum wind speed of 117 kmph at 0330 hrs IST, Nagapattinam reported 100 kmph during 0230-0330 IST and Karaikal reported 92 kmph at 0130 IST of 16th. Estimated maximum wind speed at the time of landfall was 130 kmph gusting to 145 kmph.

2.13.7.3. Storm surge

Storm surge of about 1 metre above astronomical tide inundated low lying areas upto about 1 km from the coast near the landfall point.

2.13.8. Damage due to VSCS Gaja

As per media reports (Source: The News Minute dated the 21st November, 2018), about 46 people lost their lives as an aftermath of cyclonic storm Gaja. Tamil Nadu suffered loss of around 88,102 hectares of agriculture lands, 86702 electric poles, 841 transformers, 201 electricity substations and 4844 fishing boats. The impact of the cyclonic storm Gaja, particularly on perennial crops such as coconut in the Cauvery Delta region, appears insurmountable. Coconut farmers do not see light at the end of the tunnel at this juncture as more than 80 per cent of the trees, many over 20 years old, have fallen flat. (Source: Business Line dated 19 November, 2018). More than 80 per cent of the palms in the region were uprooted, affecting the livelihood of the small and marginal farmers. Around 75 lakh trees were damaged either fully or partially in the gale winds. Nagapattinam, Thanjavur, Tiruvarur, Pudukottai were the worst affected places in Tamil Nadu. Typical damage photographs are presented in **Fig. 2.13.8**.

Fig.2.13.8 (a): Coconut trees felled by cyclone Gaja in Peruvurani area in the Thanjavur district (Business Line 19.11.2018 and The News Minute 18.11.2018)

Fig. 2.13.8 (b): Damaged Poles and felled Trees in Tamil Nadu (India Today 16.11.2018 and Deccan Chronicle 24.11.2018)

Fig. 2.13.8 (c): Damaged beaches and boats in Tamil Nadu (Hindustan Times 16.11.2018 and The Economic Times 18.11.2018)

Fig. 2.13.8 (d): Damaged Karaikudi Tollways and blocked roads in Tamil Nadu (The Indian Express 15.11.2018)

Fig.2.13.8 (e): Flooded streets in Tamil Nadu and NDRF team clearing the debris (The Times of India 17.11.2018)

2.14. Severe Cyclonic Storm "PHETHAI" over southeast Bay of Bengal (13-18 December 2018)

2.14.1. Introduction

The Severe Cyclonic Storm (SCS) Phethai originated from a low pressure area (LPA) which formed over Equatorial Indian Ocean (EIO) and adjoining central parts of south Bay of Bengal (BoB) in the evening (1730 IST) of 9th December. It lay as a well-marked low pressure area (WML) over central parts of south BoB and adjoining EIO in the morning (0830 IST) of 11th December. Under favorable environmental conditions, it concentrated into a Depression (D) over southeast BoB in the early morning (0530 IST) of 13th December. Moving north-northwestwards, it intensified into a deep depression (DD) over southeast BoB in the same mid-night (2330 IST) of 13th December. It intensified into a cyclonic storm (CS) **"Phethai**" (Pronounced as Pay-ti) in the evening (1730 IST) of 15th December and into a severe cyclonic storm (SCS) in the afternoon of 16th December. It maintained its intensity of SCS till early morning (0530 IST) of 17th December and weakened into a CS in the same morning (0830 IST). Continuing to move north-northwestwards and then northwards it crossed Andhra Pradesh coast near 16.55^0N and 82.25^0E (close to south of Yanam and 40 km south of Kakinada) during 17th afternoon (1330-1430 IST) as a cyclonic storm with maximum sustained wind speed of 75-85 kmph gusting to 95 kmph. After landfall, it moved north-northeastwards and weakened rapidly into a deep depression over westcentral BoB off Kakinada coast in the evening (1730 IST) of 17th December. Continuing to move north-northeastwards, it crossed again Andhra Pradesh coast close to Tuni during 1930-2030 IST and weakened into a depression over coastal Andhra Pradesh during same midnight (2330 IST). It further weakened into a WML over northwest and adjoining westcentral BoB & coastal Odisha in the early morning (0530 IST) and into a low pressure area over northwest BoB and adjoining Odisha in the morning (0830 IST) of 18th December.

2.14.2. Salient Features:

The salient features of the system were as follows:

- SCS Phethai was the seventh cyclone over north Indian Ocean during 2018 against normal frequency of about 4.5 cyclones per year during the satellite era (1961 onwards).
- Earlier such occurrence of 7 cyclones in a year was witnessed in 1985.
- It was a recurving cyclone with northeastward recurvature during and after the landfall.
- The track length of the system was 1525 km.
- The severe cyclonic storm intensity of the system was short lived (about 15 hrs).
- The system weakened slightly before landfall from the stage of SCS to CS.
- The peak maximum sustained surface wind speed (MSW) of the cyclone was 100-110 kmph gusting to 120 kmph (55 knots) during 1200 to 2100 UTC of 16th. The lowest estimated central pressure was 992 hPa during the same period with pressure drop of 15 hPa.
- The life period (D to D) of the system was 120 hours (5 days) against long period average (LPA) (1990-2013) of 98 hours for SCS category over Bay of Bengal during post monsoon season.

- It moved with normal speed, as the 12 hour average translational speed of the cyclone was 13.5 kmph against LPA (1990-2013) of 14.7 kmph for SCS category over north Bay of Bengal.
- The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 3.6 X102 knots, 1.67 X 104 knots2 and 0.79 X106 knots3 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.

2.14.3. Monitoring of SCS, 'PHETHAI'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to its genesis as low pressure area over BoB from 7th December onwards. The observed track of the cyclone over BoB during 13-18 December is shown in **Fig. 2.14.1**. The best track parameters of the systems are presented in **Table 2.14.1.**

The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations, Doppler Weather Radar (DWR) Visakhapatnam and Chennai and available ships & buoy observations in the region. The system came under Radar surveillance from the morning of 16th night. Various national and international numerical weather prediction 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 including Bangladesh, Myanmar, Sri Lanka, National & State Disaster Management Agencies, general public and media since inception of the system over BOB.

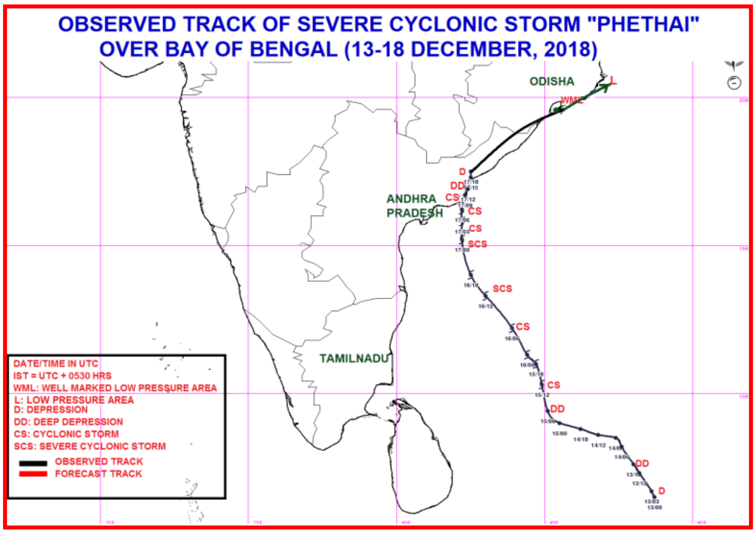


Fig. 2.14.1 Observed track of SCS PHETHAI (13-18 December, 2018) over Bay of Bengal

Table 2.14.1: Best track positions and other parameters of the Severe Cyclonic Storm, 'Phethai' over the southeast Bay of Bengal during 13-18 December, 2018

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
13/12/2018	0000	6.5	88.7	1.5	1004	25	3	**D**
	0300	6.7	88.6	1.5	1004	25	3	**D**
	0600	6.8	88.5	1.5	1003	25	4	D
	1200	7.3	88.2	1.5	1003	25	4	D
	1800	7.6	88.0	2.0	1002	30	5	**DD**
14/12/2018	0000	8.2	87.6	2.0	1002	30	5	DD
	0300	8.5	87.4	2.0	1002	30	5	DD
	0600	8.5	87.4	2.0	1002	30	5	DD
	1200	8.6	86.8	2.0	1002	30	5	DD
	1800	8.8	86.2	2.0	1002	30	5	DD
15/12/2018	0000	9.0	85.5	2.0	1002	30	5	DD
	0300	9.2	85.2	2.0	1001	30	6	DD
	0600	9.4	85.1	2.0	1001	30	6	DD
	1200	10.3	84.9	2.5	1000	35	7	**CS**
	1500	10.7	84.7	2.5	1000	35	7	CS
	1800	11.0	84.6	2.5	1000	35	7	CS
	2100	11.1	84.5	2.5	1000	35	7	CS
16/12/2018	0000	11.3	84.3	3.0	998	40	8	CS
	0300	11.8	84.1	3.0	996	45	10	CS
	0600	12.2	83.9	3.0	996	45	10	CS
	0900	12..6	83.6	3.0	994	50	13	**SCS**

	1200	13.3	83	3.5	992	55	15	**SCS**
	1500	13.8	82.7	3.5	992	55	15	**SCS**
	1800	14.0	82.5	3.5	992	55	15	**SCS**
	2100	14.5	82.2	3.5	992	55	15	**SCS**
	0000	15.2	82.2	3.0	994	50	13	**SCS**
	0300	15.8	82.2	3.0	997	45	10	**CS**
	0600	16.2	82.2	3.0	997	45	10	CS
		Crossed Andhra Pradesh coast near 16.55^{0}N and 82.25^{0}E 25 km south of Yanam and 40 km south of Kakinada during 0800 to 0900 UTC						
	0900	16.7	82.3	-	998	40	8	CS
	1200	16.9	82.4	2.0	1001	30	6	**DD**
		Crossed Andhra Pradesh coast close to TUNI during 1400 to 1500 UTC						
	1500	17.3	82.5	-	1004	30	5	DD
17/12/2018	1800	17.5	82.5	-	1006	25	3	D
18/12/2018	0000	**Weakened into a well marked low pressure area over northwest and adjoining west central Bay of Bengal and coastal Odisha.**						

2.14.4. Brief life history

2.14.4.1. Genesis

On 9th December, the Madden Julian Oscillation (MJO) index lay in phase 3 with amplitude more than 1. Forecast indicated that it would continue in same phase with amplitude greater than 1 for next 4 days. Thereafter it would move to phase 4 with amplitude remaining more than 1. Thus, MJO phase and amplitude were favourable for enhancement of convection over BoB region. Considering the environmental conditions, the sea surface temperature (SST) was 29-31˚C over southeast BoB and adjoining EIO region. It was decreasing slightly becoming 27-28˚C towards west of 82°E and north of 8˚N. The tropical cyclone heat Potential was more than 100 KJ/cm^2 over central parts of south BoB and adjoining EIO. It was around 60-80 KJ/cm^2 over major parts of south BoB and adjoining EIO. However, it was less than 40 KJ/cm^2 over western parts of BoB along the east coast of India and Sri Lanka. The low level relative vorticity was east-west oriented and was around 60-80 x10^{-6} sec^{-1} over southeast BoB and adjoining EIO and was extending upto 500 hpa level.

The lower level convergence and upper level divergence were about 15 $x10^{-5}$ sec^{-1} and 20 $x10^{-5}$ sec^{-1} over southeast BoB & adjoining EIO. The vertical wind shear was high (20-25 kt) over southeast BoB & adjoining EIO. The upper tropospheric ridge ran along 11°N.

Under the influence of these atmospheric & sea conditions and trough of low at mean sea level over EIO and adjoining central parts of south BoB, an LPA formed over the same region in the evening (1200 UTC) of 9^{th} December. The favourable conditions continued and it the system lay as a WML over central parts of south BoB and adjoining EIO in the morning (0300 UTC) of 11^{th} December.

At 0000 UTC of 13^{th} December, similar sea conditions prevailed. The atmospheric conditions further consolidated. The lower level convergence increased significantly and was around $50x10^{-5}$ $second^{-1}$, the lower level vorticity was $130x10^{-6}$ $second^{-1}$, upper level divergence was $60x10^{-5}$ $second^{-1}$ and low vertical wind shear was moderate (10-15 knots) around the system centre. The upper tropospheric ridge ran along 11°N. Under these favourable environmental conditions, the system concentrated into a depression (D) over southeast BoB near latitude 6.5°N and longitude 88.7 °E about 850 km east-southeast of Triconmalee in the early morning (0000 UTC) of 13th December.

2.14.4.2. Intensification and movement

Moving north-northwestwards, it intensified into a deep depression (DD) over southeast BoB in the same mid-night (1800 UTC) of 13th December. Considering the environmental conditions, the sea surface temperature (SST) was 29-30˚C over southeast BoB and adjoining areas. The TCHP was more than 100 KJ/cm^2 over central parts of south BoB and adjoining EIO. It was around 60-80 KJ/cm^2 over remaining parts of southeast BoB. However, it was less than 40 KJ/cm^2 over western parts of BoB along the east coast of India and Srilanka. The lower level convergence was $30x10^{-5}$ $second^{-1}$, lower level vorticity was$150x10^{-6}$ $second^{-1}$, upper level divergence was $40x10^{-5}$ $second^{-1}$ and low vertical wind shear was high (20-25 knots) over the system area and was increasing towards the northwest of the system area. The upper tropospheric ridge ran along 12°N. Under the influence of an anticyclone over southeast Asia, more northward component of movement was exhibited in movement.

At 1200 UTC of 15^{th}, the MJO index lay in Phase 4 with amplitude more than 1. The SST was 28-29˚C around the system area. The tropical cyclone heat potential was around 60-80 KJ/cm^2 over the system area. However, it is less than 40 KJ/cm^2 over western parts of BoB along the east coast of India. The lower level convergence was $60x10^{-5}$ $second^{-1}$ towards north-northwest of the system center. Lower level vorticity was $200x10^{-6}$ $second^{-1}$ around the system center. Upper level divergence was $20x10^{-5}$ $second^{-1}$ towards north-northwest of the system centre and vertical wind shear was moderate (15-20 knots) over the system area and was indicating increasing trend along the forecast track. The total precipitable water imagery indicated warm and moist air feeding into the core of the system from southeast sector and dry & cold air prevailed over peninsular India. The upper tropospheric ridge runs along 16°N. The system was guided by the anticyclone over southeast Asia. Under these conditions, the system intensified into cyclonic storm (CS) “Phethai” (Pronounced as Pay-ti) in the evening (1200 UTC) of 15th December and into a severe cyclonic storm (SCS) in the evening (1200 UTC) of 16th December. It maintained its intensity of SCS till early morning (0000 UTC) of 17th December.

At 0300 UTC of 17th, the SST was 28-29˚C around the system area. it is decreasing slightly becoming 26-28˚C towards westcentral BoB and along & off Andhra Pradesh coast. The tropical cyclone heat potential decreased and was around 35-50 KJ/cm^2 over the system area. However, it is less than 35 KJ/cm^2 over western parts of BoB along the east coast of India. The lower level convergence decreased significantly and was around 20x10^{-5} second^{-1} towards north-northeast of the system centre. The lower level vorticity was around 200x10^{-6} second^{-1} around the system center. The upper level divergence also decreased and was around 10x10-5 second^{-1} around the system center. The vertical wind shear increased over the system area and along the forecast track (around 20 knots). Wind shear tendency was positive over the system area as well as along the forecast track. The TPW imagery indicated warm and moist air feeding into the core of the system from north-northeast sector and dry & cold air prevailing over peninsular India. The upper tropospheric ridge ran along 17°N. An anticyclone lay over southeast Asia, and hence under it's influence, the system moved north-northeastwards as it approached the coast and weakened into a CS in the same morning (0300 UTC) of 17th. Moving nearly northwards, it crossed Andhra Pradesh coast near 16.55^{0}N and 82.25^{0}E 25 km south of Yanam and 40 km south of Kakinada during 0800 to 0900 UTC of 17th.

At 1200 UTC of 17th, the system emerged into westcentral Arabian Sea. The lower level convergence was 30x10^{-5} second^{-1} towards east of the system centre. Upper level divergence was 20x10^{-5} second^{-1} towards northeast of the system center. Lower level vorticity was 150x10^{-6} second^{-1} to the south of the system centre. The upper tropospheric ridge ran along 16°N. The system was guided by the anticyclone over southeast Asia and a deep trough in upper tropospheric westerlies to the west. Under the combined effect of anticyclone and above trough, the upper level winds increased over northeast coast of India leading to an increase in increase in wind shear over the region. There was lower SST over the region, lower ocean heat content, land interactions and high wind shear. Under these circumstances, the system weakened into a deep depression over westcentral BoB at 1200 UTC of 17th and moving nearly northwards crossed Andhra Pradesh coast close to TUNI during 1400 to 1500 UTC.

The unfavourable conditions continued and moving nearly northwards, it weakened into a depression at 1800 UTC of 17th over coastal Andhra Pradesh and into a well marked low pressure area over northwest and adjoining westcentral Bay of Bengal and coastal Odisha at 0000 UTCof 18th December.

The TPW imageries during 16-18 Dec. 2018 are presented in **Fig. 2.14.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system, till 16th December. However, as the system approached coast , there was land interaction and moisture supply also reduced relatively as evident from TPW imageries on 17th and 18th Dec . The TPW image also indicated cold air advection from central and peninsular India on 17th and 18th Dec helping in weakening of the system.

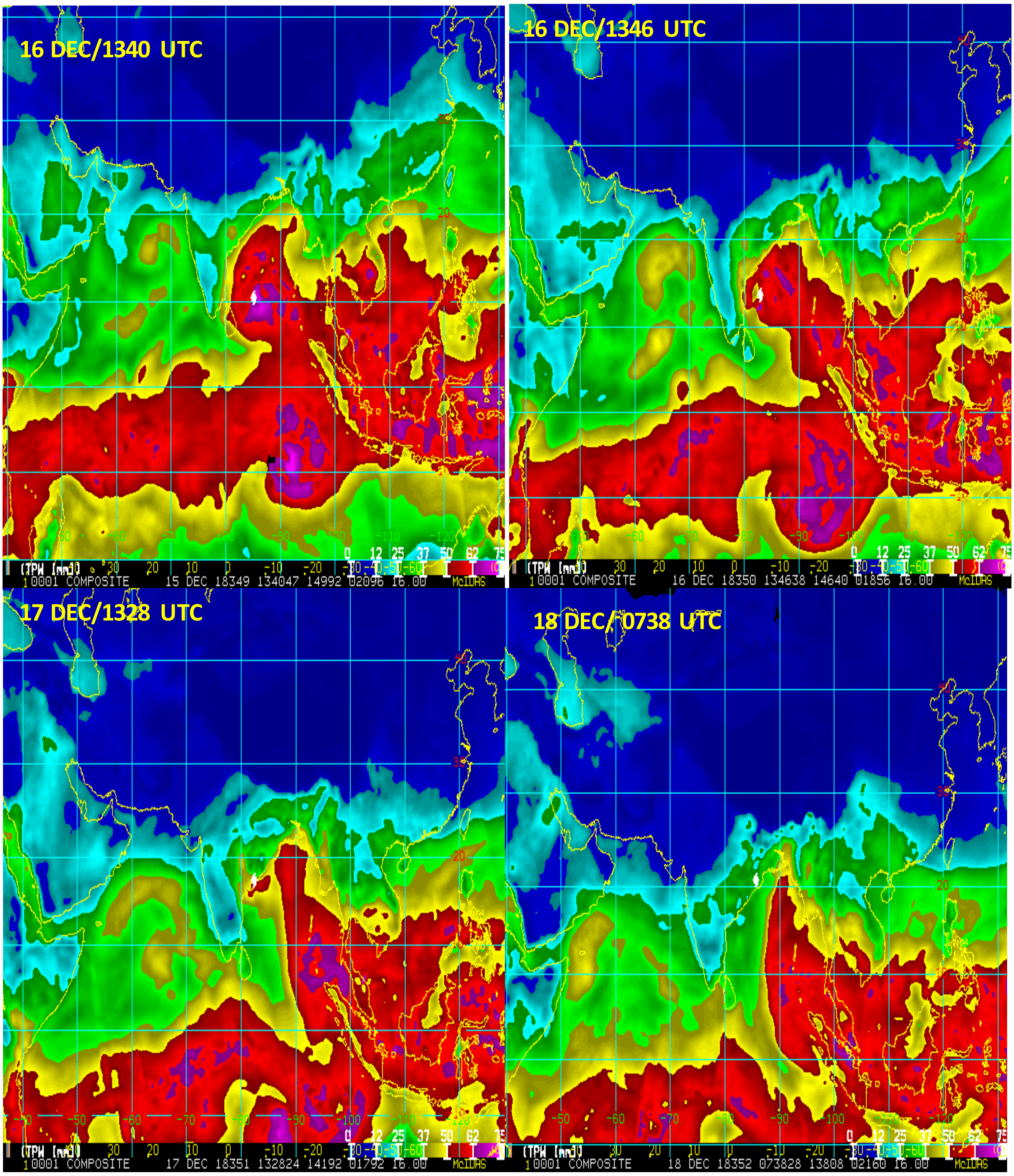


Fig. 2.14.2: Total Precipitable Water (TPW) imageries during 13-18 December, 2018

The wind speed in middle and deep layer around the system centre is presented in **Fig. 2.14.3**. The wind shear around the system between 200 & 850 hPa levels remained moderate (10-20 knots) till 0000 UTC of 17th December. Thereafter, it increased becoming high (20-30 knots) till dissipation as the system came under the combined influence of anticyclone over southeast Asia and a deep trough in upper tropospheric westerlies to the west of system centre. The direction of 200-850 hPa wind shear was northwesterly during the period. It caused the convective cloud mass to be sheared to the southeast of the system centre.

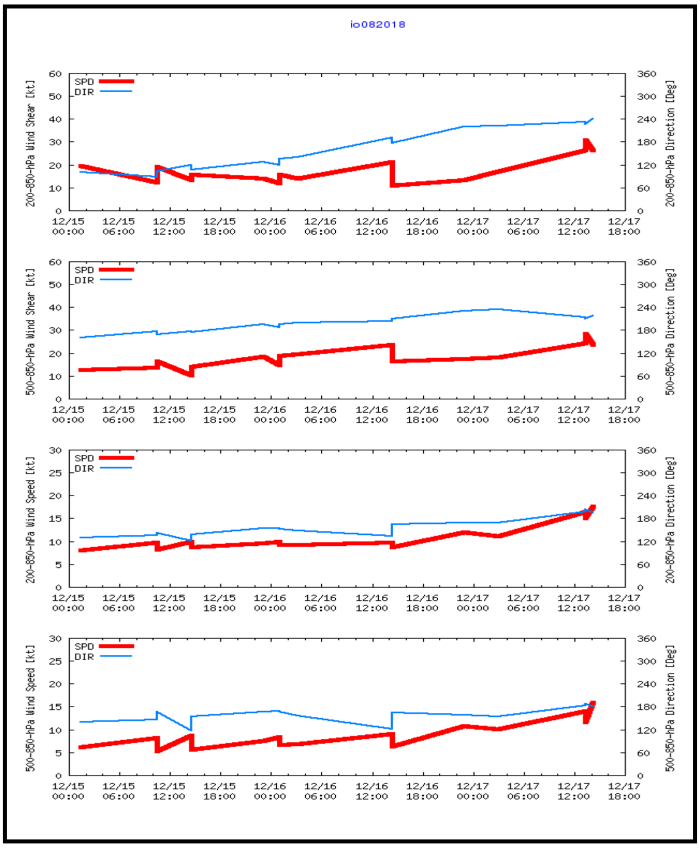


Fig. 2.14.3 Wind shear and wind speed in the middle and deep layer around the system during 13-18 December 2018.

From **Fig. 2.14.3**, it indicates that from the genesis stage, the mean deep layer winds between 200-850 hPa levels steered the system initially northwestwards till 00 UTC of 17th Dec and then northwards for 12 hours and then north-northeastwards. The twelve hourly movement of SCS Phethai is presented in **Fig. 2.14.4**. The 6 hourly average translational speed of the cyclone was about 13.4 kmph and hence the cyclone was moving slower against the normal speed of 14.7 kmph.

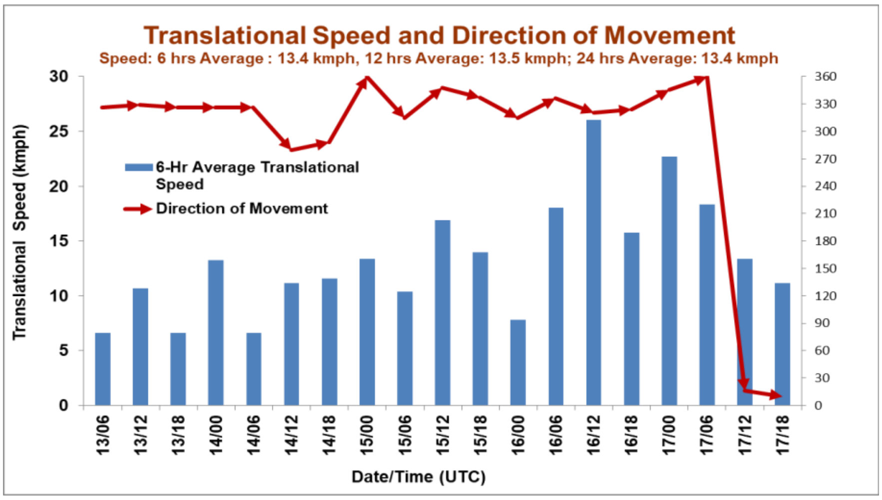


Fig. 2.14.4 Six hourly average translational speed (kmph) and direction of movement in association with SCS Phethai

2.14.4.3 Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig. 2.14.5**. The lowest estimated central pressure had been 992 hPa during 1200-2100 UTC of 16$^{th.}$ The estimated maximum sustained surface wind speed (MSW) was 55 knots during the same period with pressure drop of 15 hPa.. At the time of landfall, the ECP was 997 hPa and MSW was 45 knots (cyclonic storm). During second landfall near Tuni the ECP was 1001 hPa and MSW was 30 knots (Deep Depression).

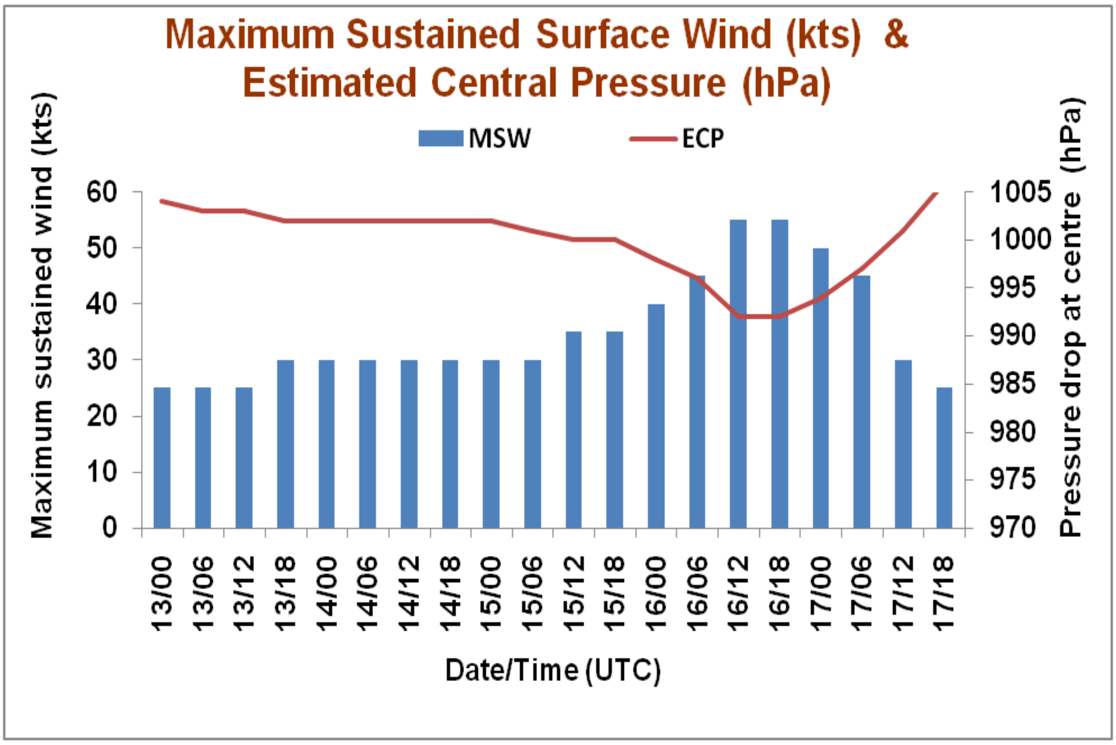


Fig. 2.14.5. Lowest estimated central pressure and the maximum sustained wind speed

2.14.5. Monitoring

2.14.5. 1. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of international geostationary satellites Meteosat-8 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig. 2.14.6(a-d)**. The system showed curved band pattern during genesis and groth stage upto the intensity of CS. It has central dense overcast (CDO) pattern during SCS stage. It showed sheared pattern after landfall .

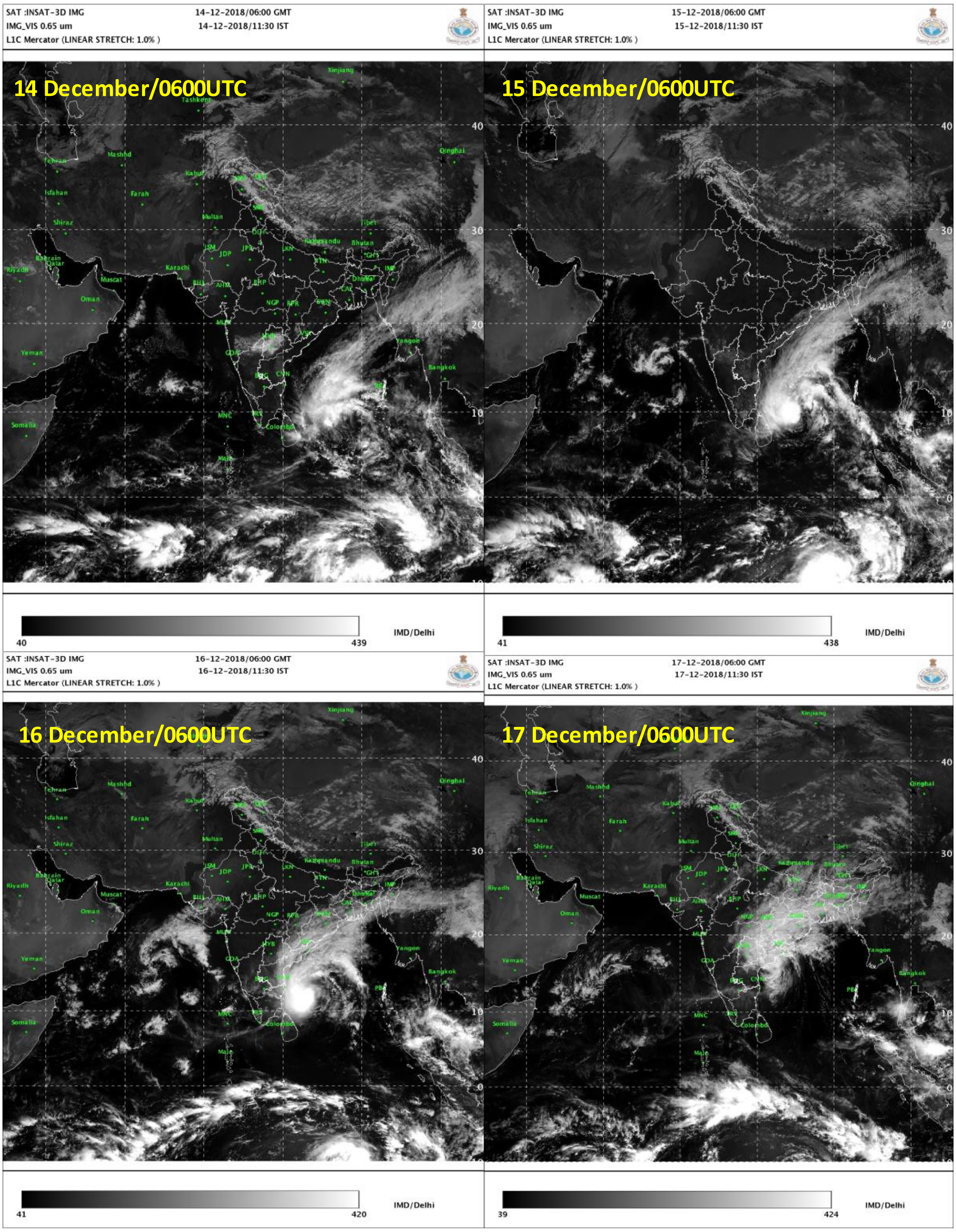


Fig. 2.14.6a: INSAT-3D visible imageries during life cycle of SCS PHETHAI (13-18 December, 2018

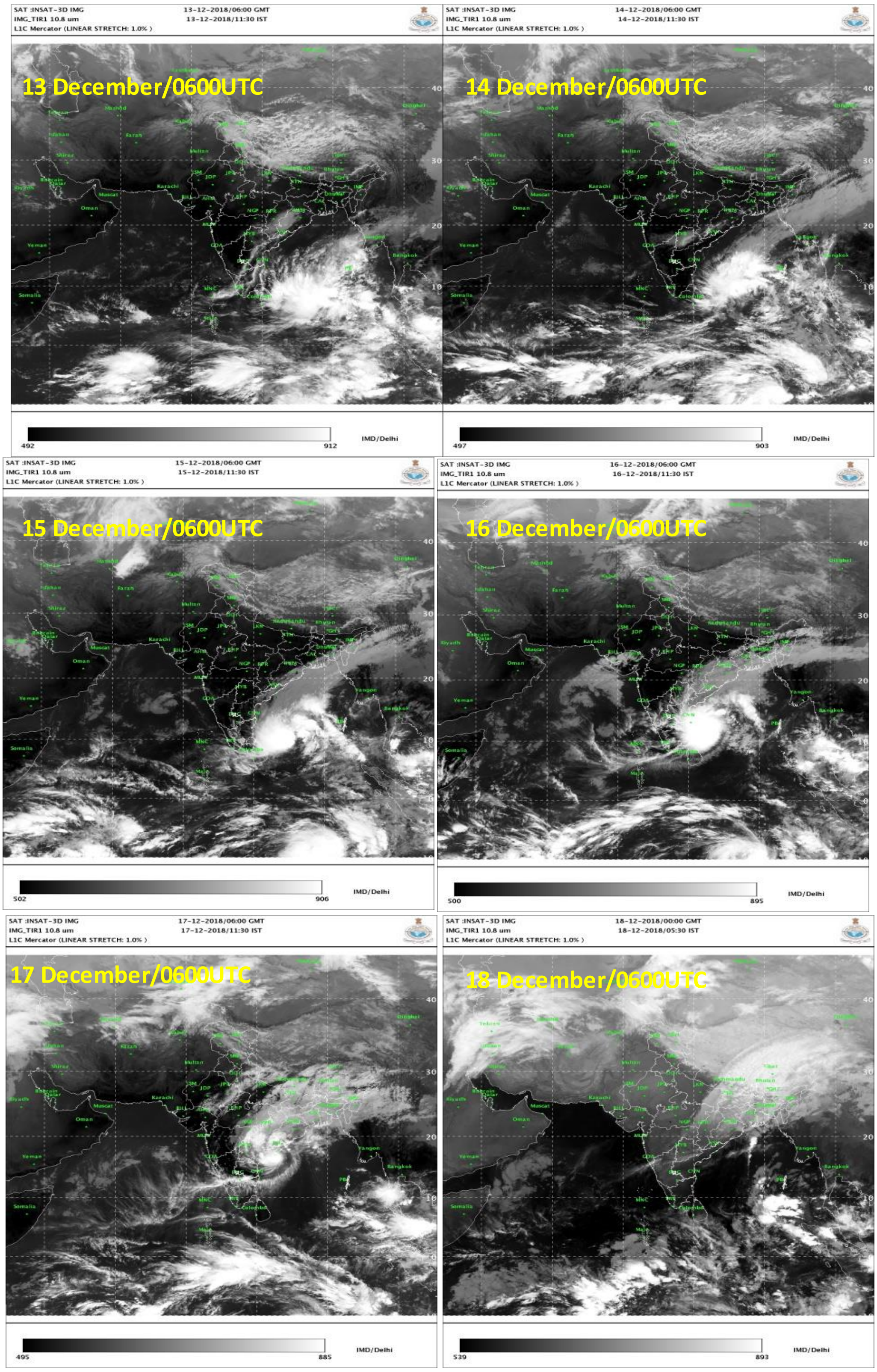


Fig. 2.14.6b: INSAT-3D IR imageries during life cycle of SCS PHETHAI (13-18 December, 2018)

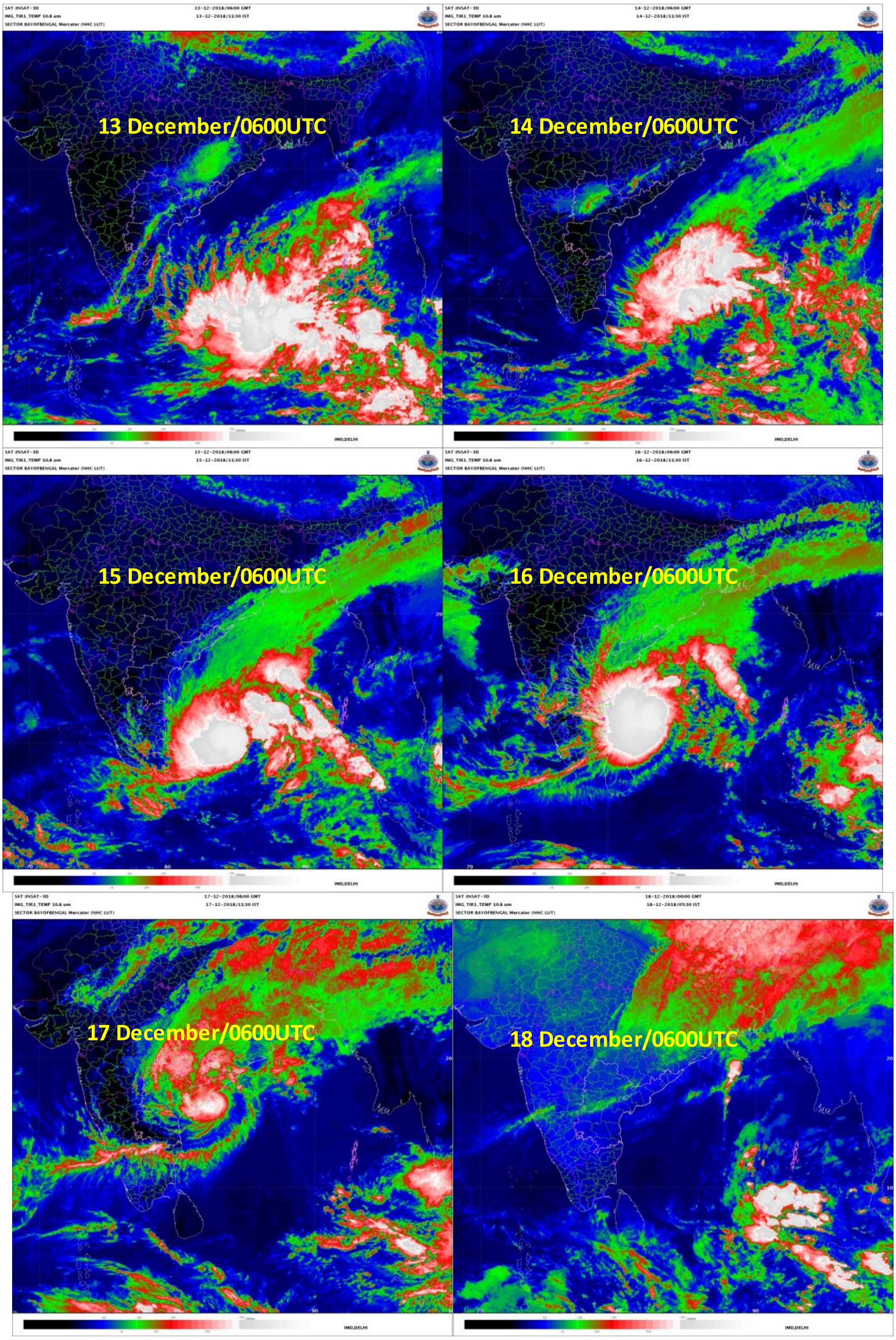


Fig. 2.14.6c: INSAT-3D enhanced colored imageries during life cycle of SCS DAYE (19-22 September, 2018)

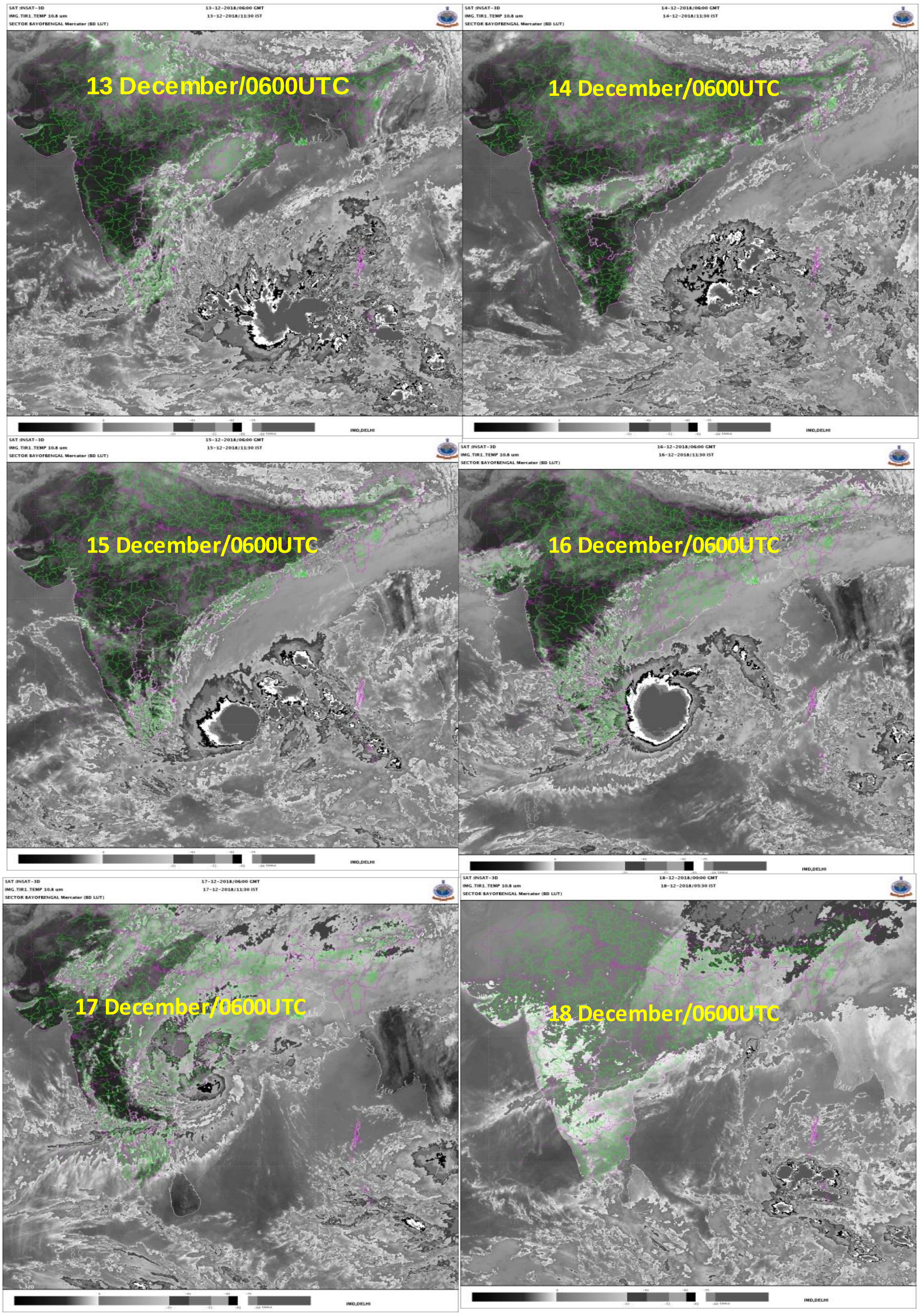


Fig. 2.14.6d: INSAT-3D cloud top brightness imageries during life cycle of SCS PHETHAI (13-18 December, 2018)

Typical SCATSAT imageries during 11-16 Dec. 2018 are presented in Fig. 2.14.6e**.**

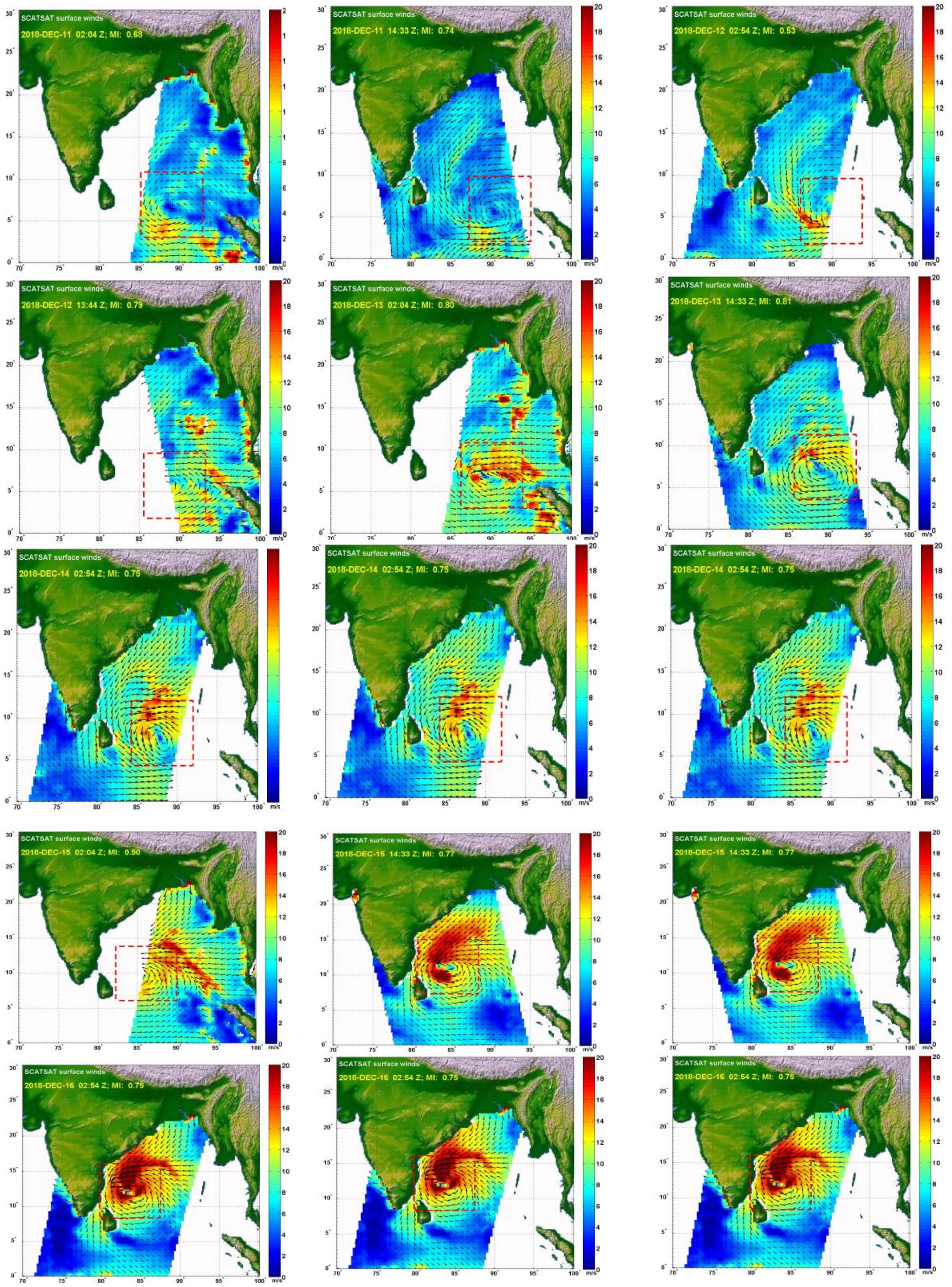


Fig. 2.14.6e: SCATSAT imageries during life cycle of SCS PHETHAI (13-18 December, 2018

Typical ASCAT and microwave imageries during life cycle of SCS Phethai are presented in Fig. 2.14.6f-g respectively.

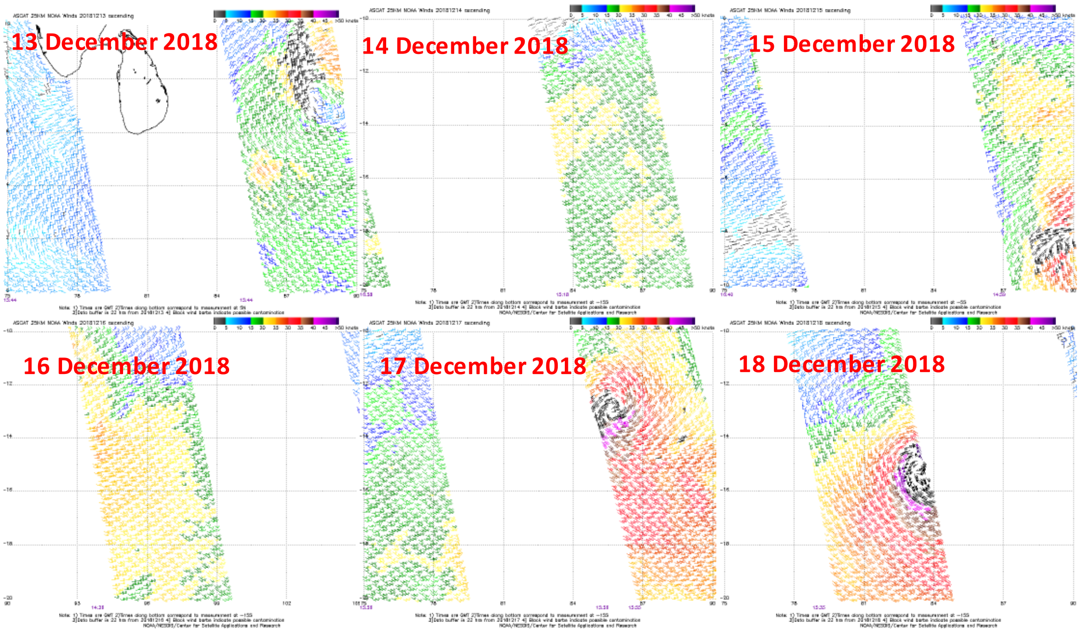


Fig. 2.14.6f: ASCAT imageries during life cycle of SCS PHETHAI (13-18 December, 2018

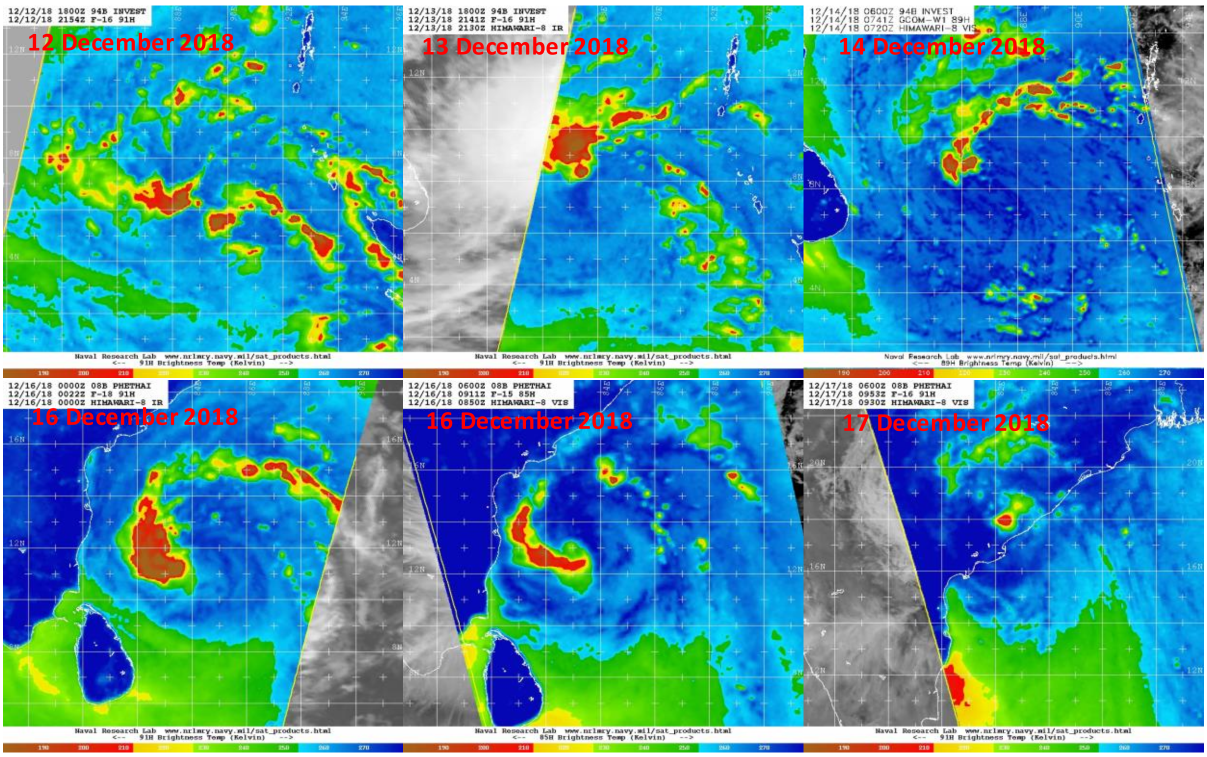


Fig. 2.14.6g: Microwave imageries during life cycle of SCS PHETHAI (13-18 December, 2018

2.14.5.2. Features observed through Radar

The system was captured by DWR Chennai, Machillipatnam and Visakhapatnam during 14th-17th Dec. Typical imageries from these radars are presented in 2.14.7(h-j).

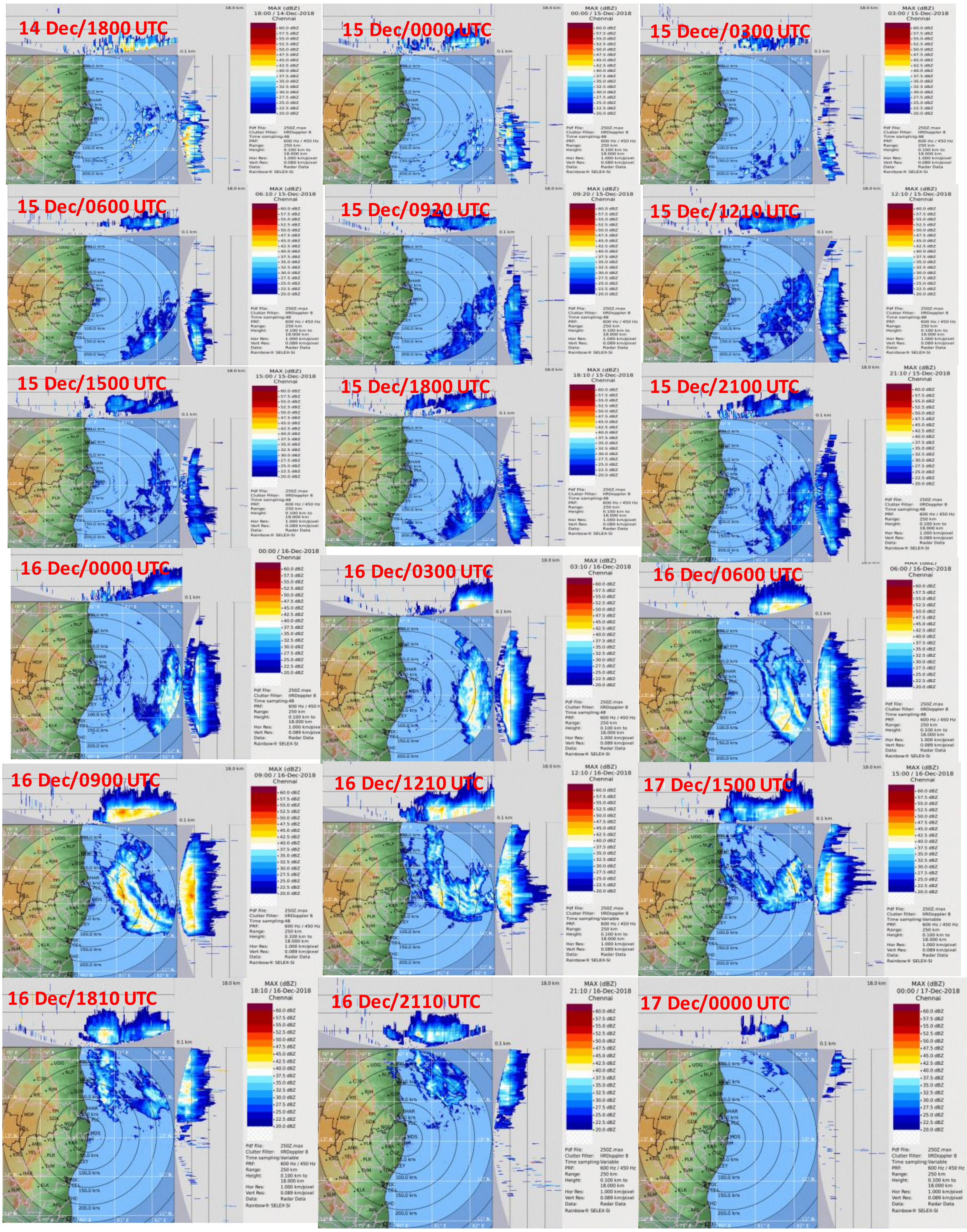


Fig. 2.14.7(h): Typical Radar imagery Max(dBZ) from DWR Chennai From 13-18 December, 2018.

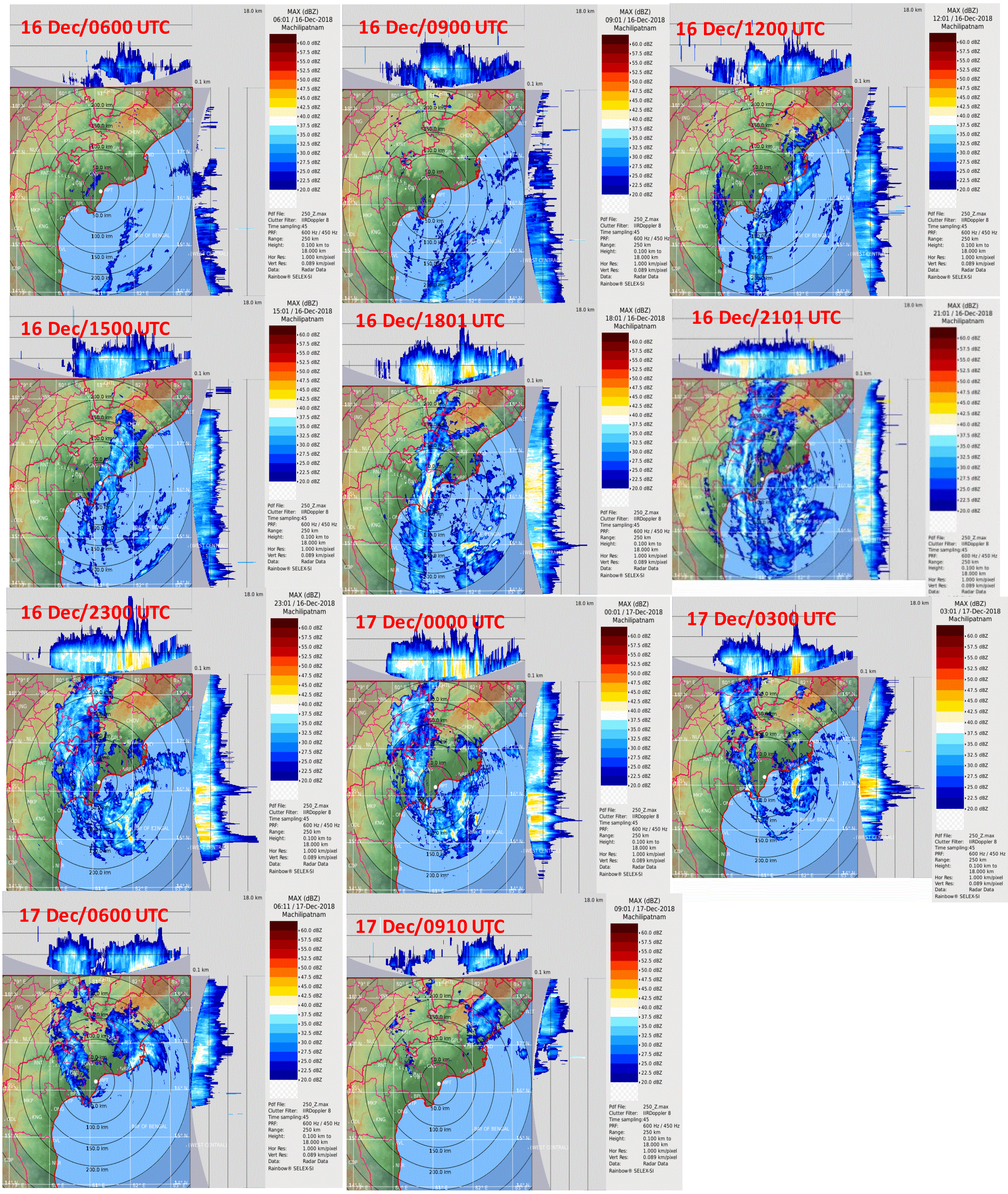


Fig. 2.14.7(i): Typical Radar imagery MAX-Z from DWR Machilipatnam From 13-18 Dec

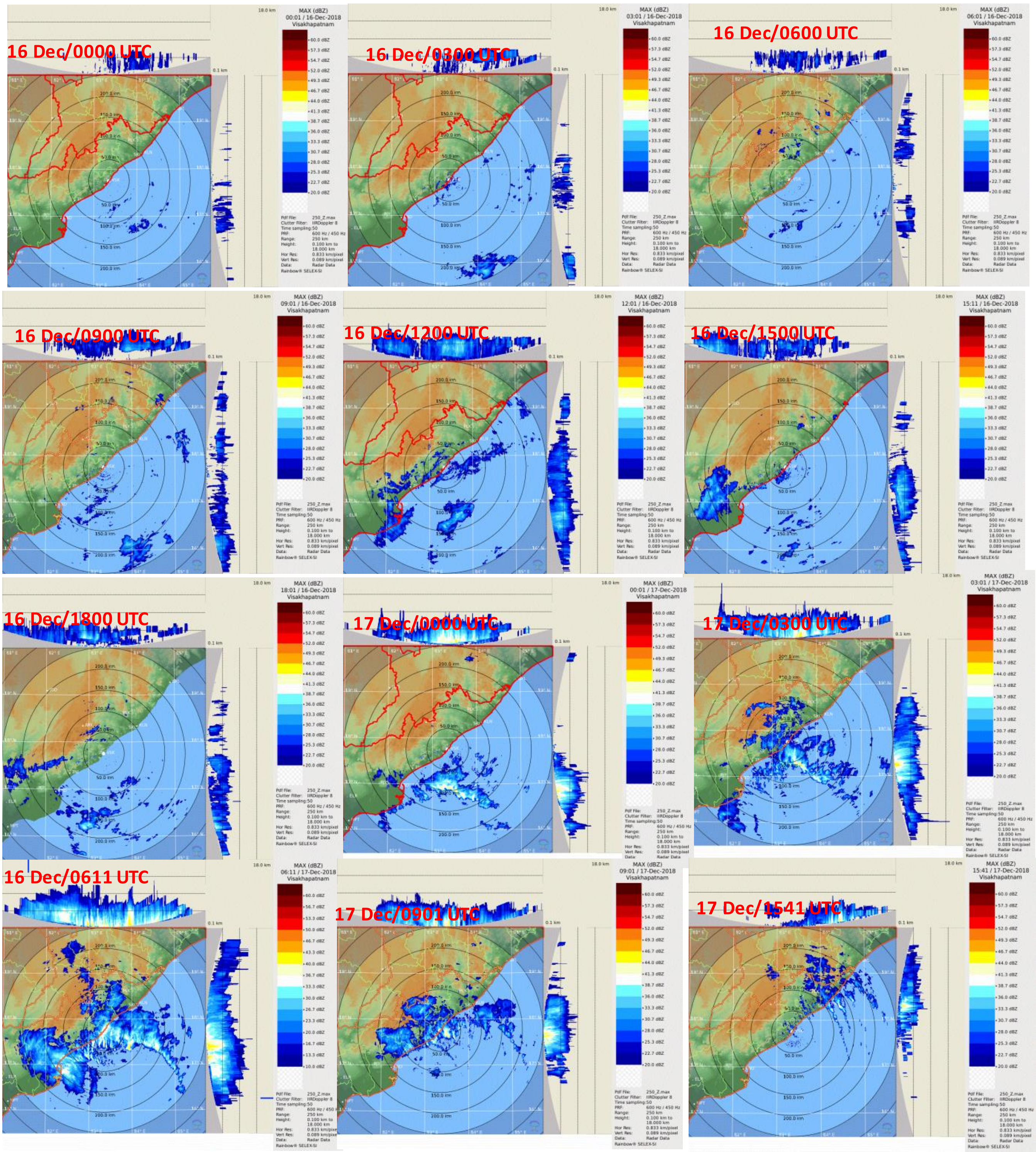


Fig. 2.14.7(j): Typical Radar imagery MAX-Z from DWR Visakhapatnam From 13-18 Dec

2.14.6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 19th-18th December are presented in Fig. 2.14.8. GFS (T1534). Analysis based on 0000 UTC of 13th to 18th December, indicates that the model could detect the genesis of the low pressure system and its track towards north Andhra Pradesh Coast. It could also detect the gradual intensification upto SCS and its weakening after the landfall.

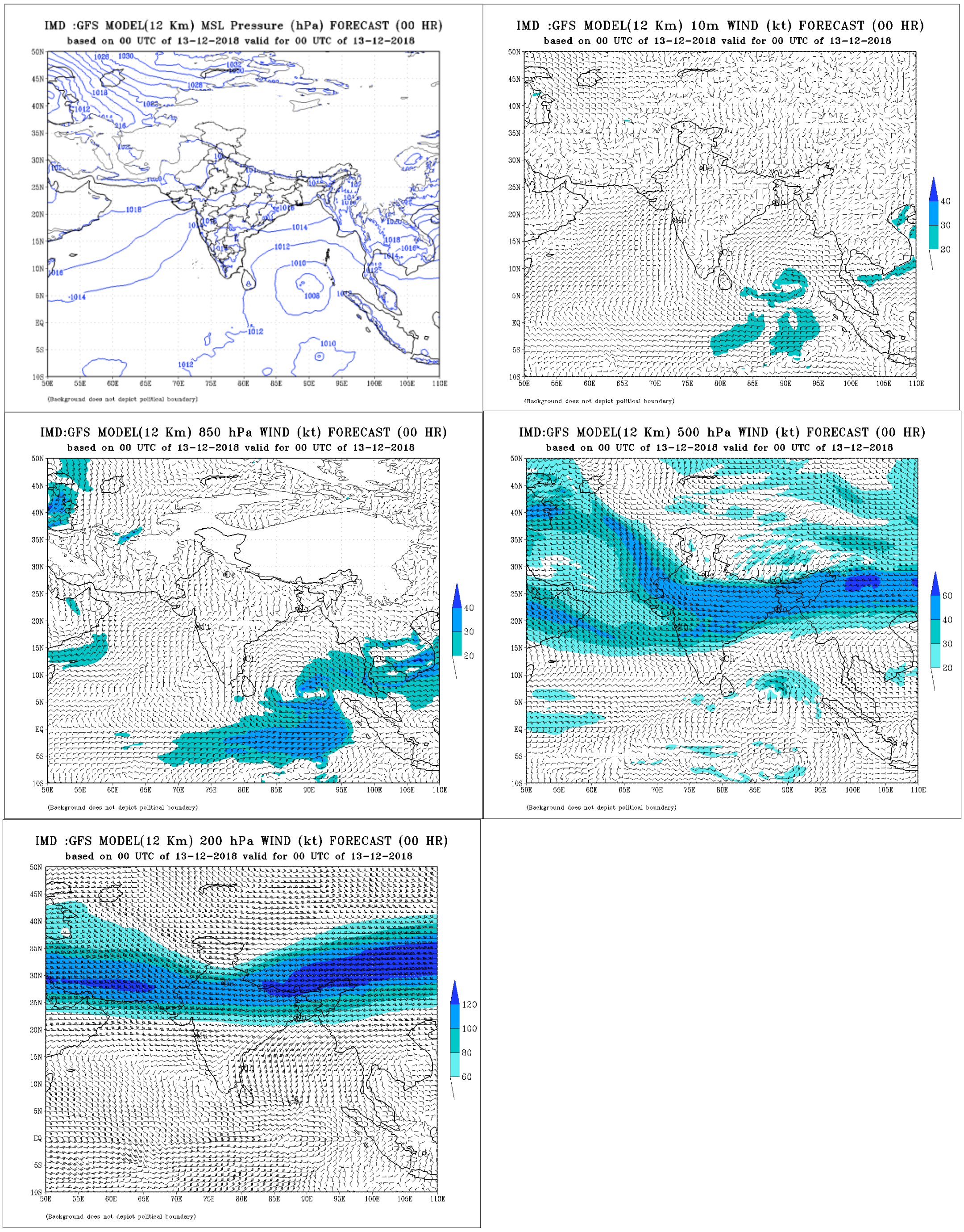


Fig. 2.14.8(a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th December 2018

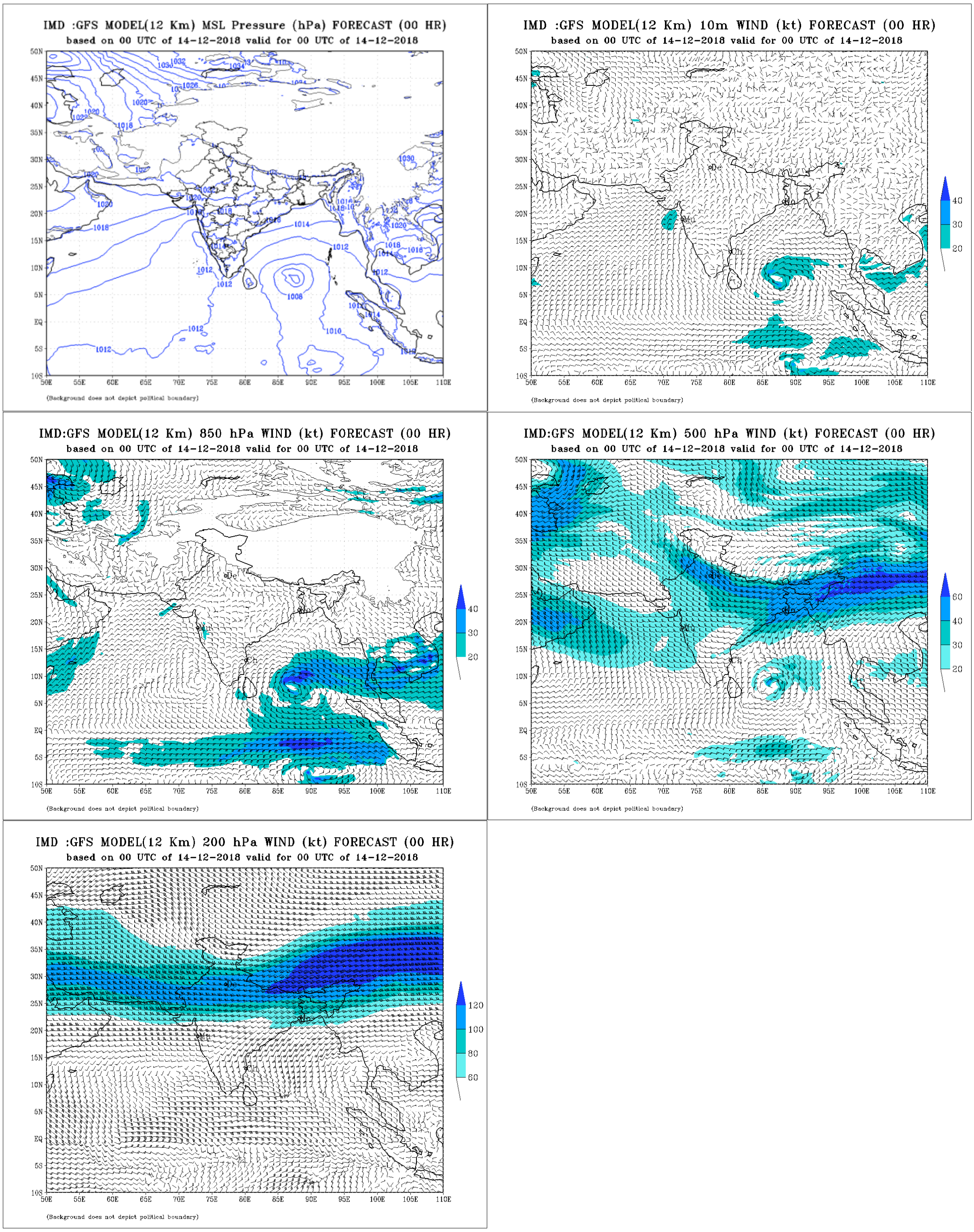


Fig. 2.14.8(b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th December 2018

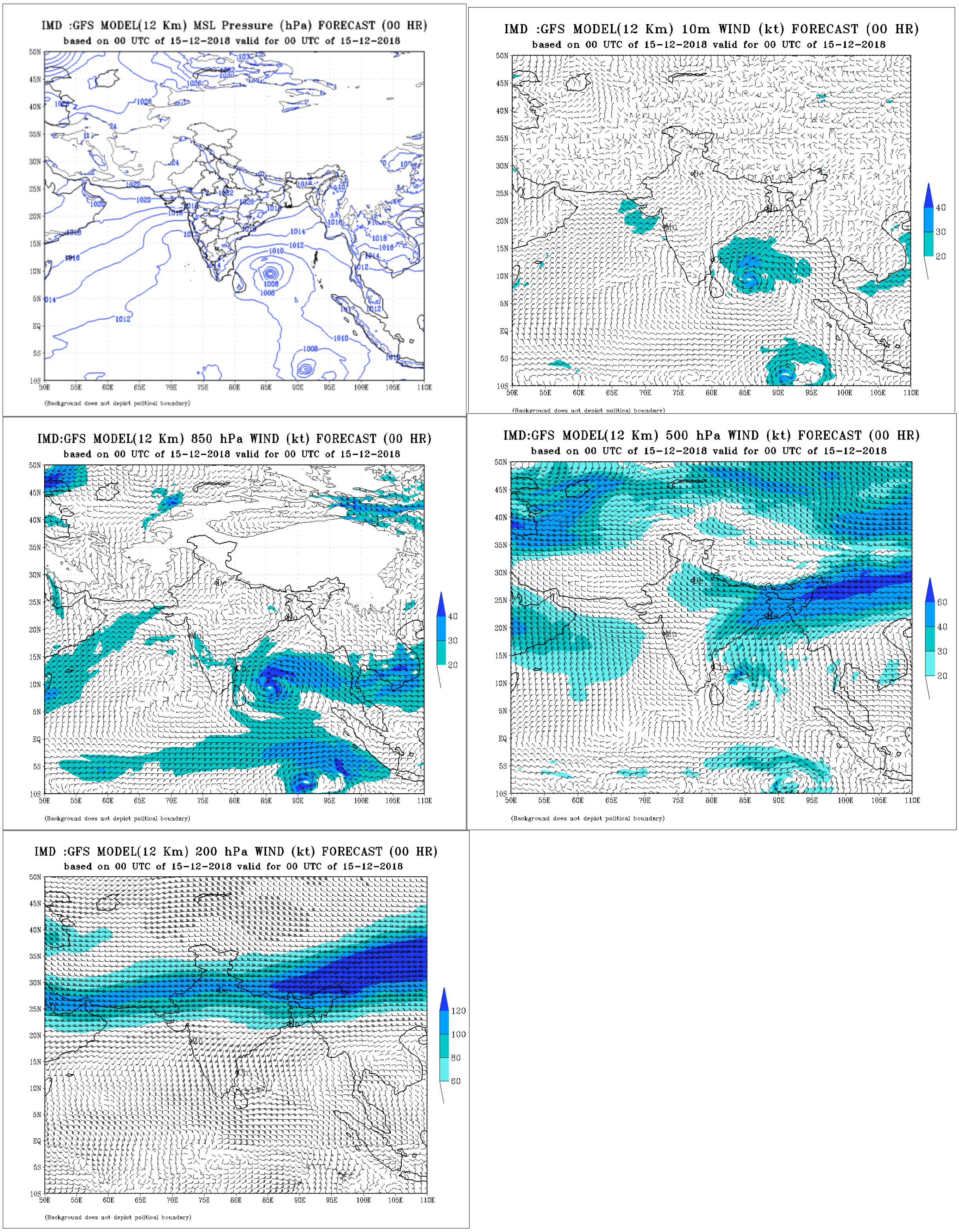


Fig. 2.14.8(c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th December 2018

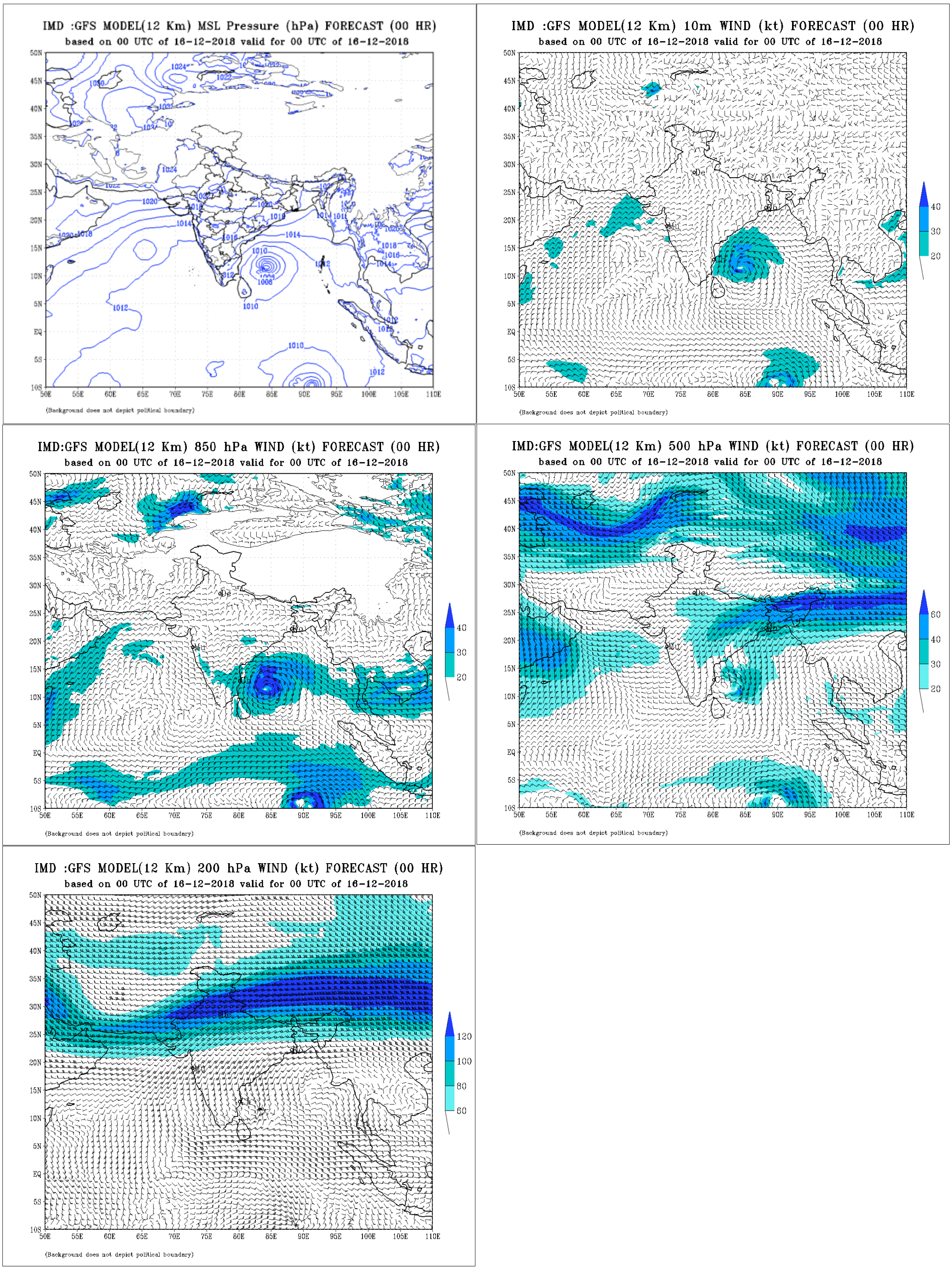


Fig. 2.14.8(d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th December 2018

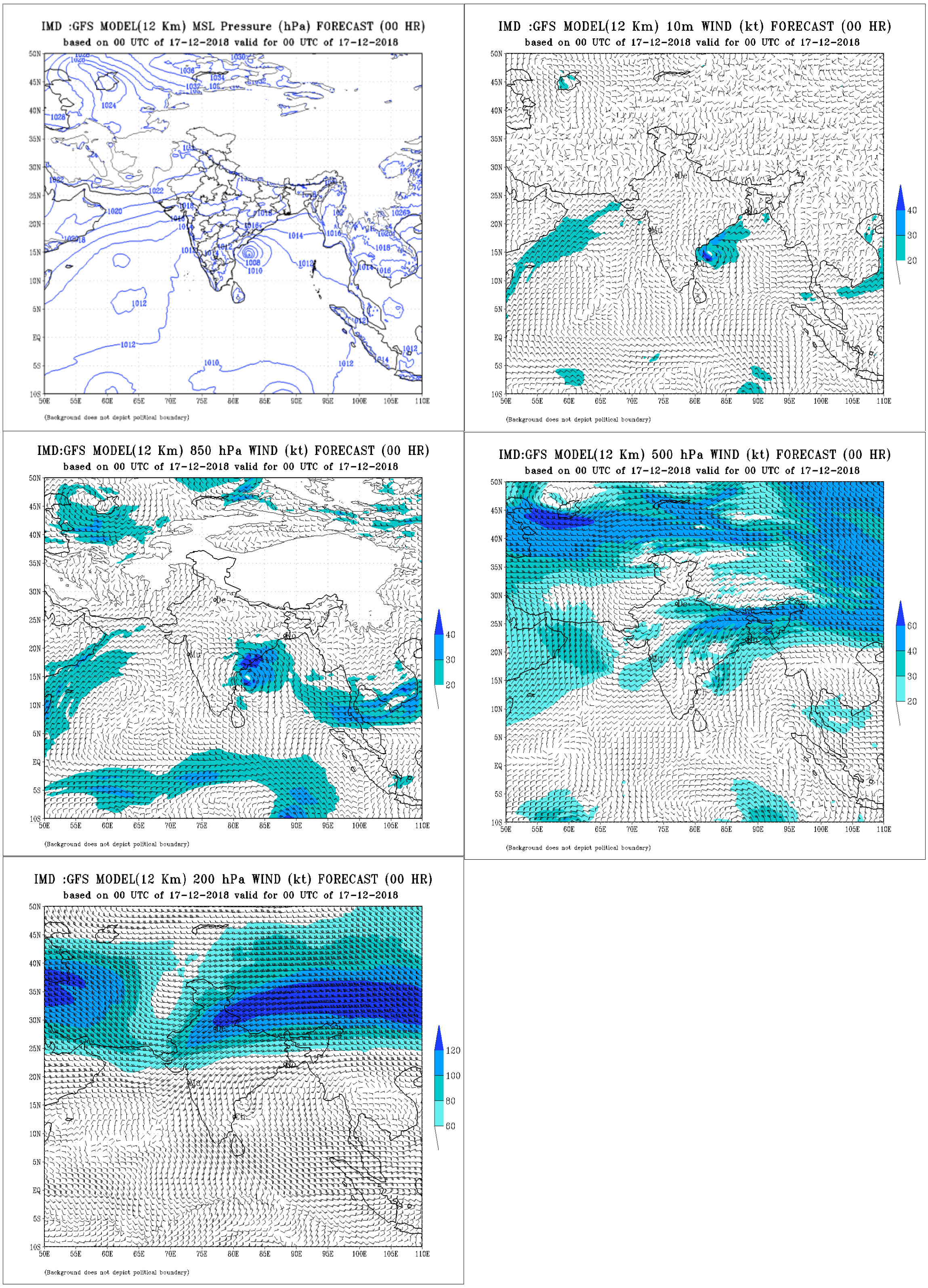


Fig. 2.14.8(e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th December 2018

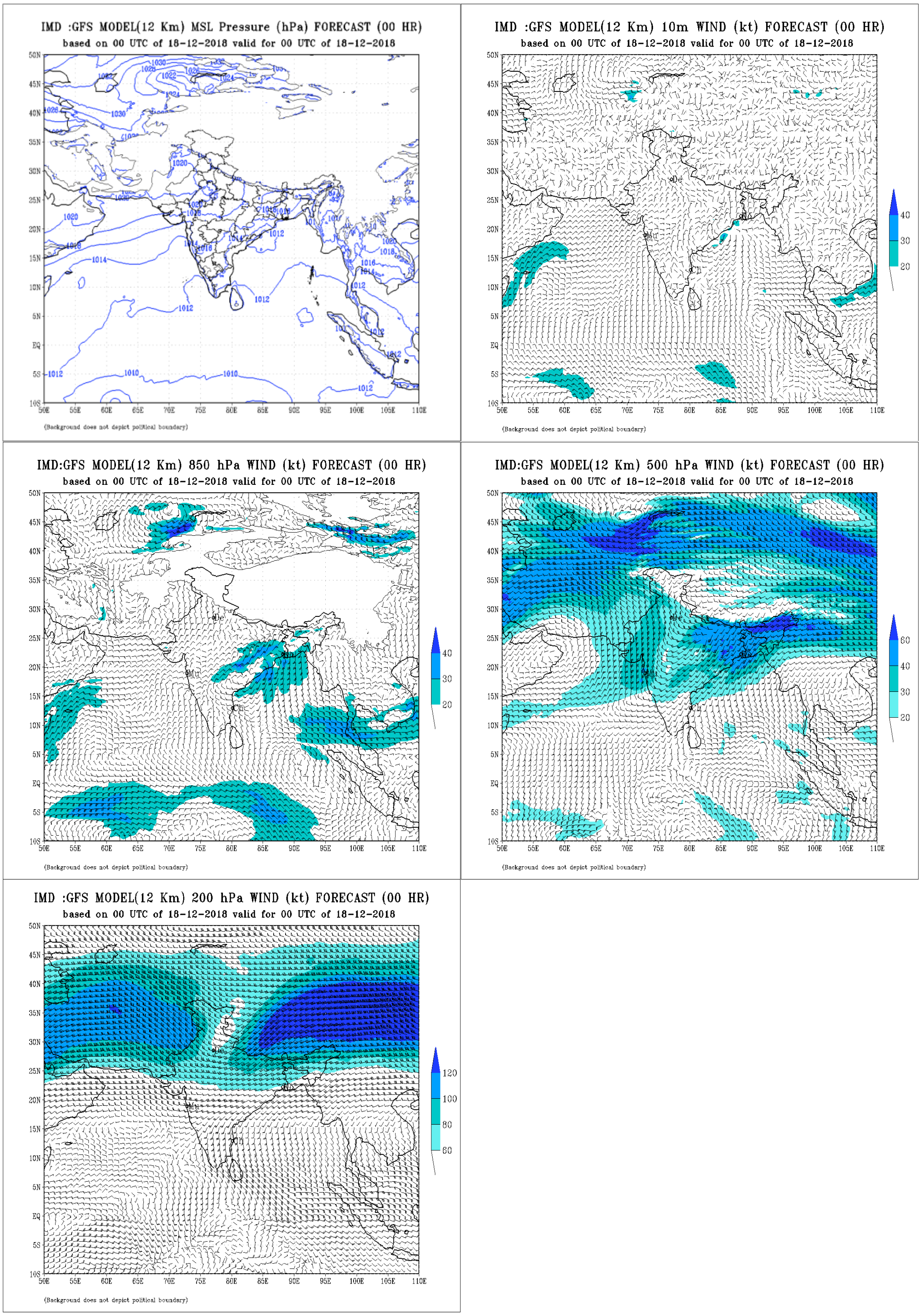


Fig. 2.14.8(f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th December 2018

2.14.7. Realized Weather:

Rainfall associated with SCS Phethai based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 2.14.9**.

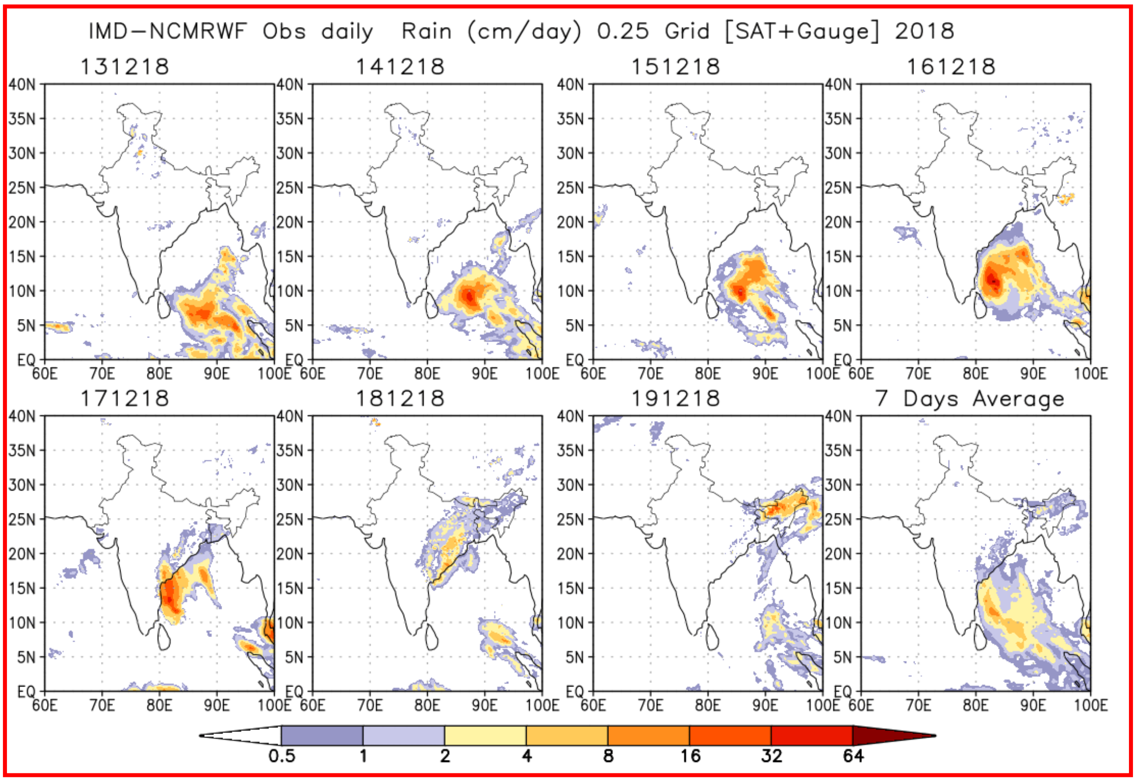


Fig. 2.14.9: IMD-NCMRWF merged satellite and rain gauge observed rainfall (cm/day) during 13-18 December in association with SCS PHETHAI.

It indicates that the system caused rainfall at most places with heavy to very rainfall at isolated places over central parts of south BoB during 13th-15th, over southwest BoB on 16th and over coastal Andhra Pradesh on 17th. On 18th, low to moderate rainfall activity was observed over coastal Andhra Pradesh and adjoining Odisha.

Heavy to very heavy rainfall occurred at isolated places over north coastal Andhra Pradesh and heavy rainfall at isolated places over Telangana in past 24 hours ending at 0830 hours IST of 17th December. Heavy to very heavy rainfall occurred at a few places over north coastal Andhra Pradesh and heavy rainfall at a few places over Odisha & isolated places over Jharkhand in past 24 hours ending at 0830 hours IST of 18th December.

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

17 December 2018

Coastal Andhra Pradesh: Vijayawada-13, Gudivada-10, Nuzvid, Avanigada & Vijayawada-9 each, Eluru-8 and Kaikalur, Chintalapudi, Repalle, Amalapuram & Tenali-7 each

Telangana: Aswaraopeta, Sathupalle & Aswaraopet-9 each, Mulakalapalle, Chandrugonda & Enkuru-8 each and Kothagudem, Julurpad, Manuguru, Palawancha & Burgampadu-7 each

18 December 2018

Coastal Andhra Pradesh: Ninnimamidivalasa-19, Ananthagiri-14, Pachipenta-18, Pachipenta-15, Kantakapalle-14, Araku Valley-13, Salur-13, Amalapuram-12, Bheemunipatnam-12, Visakhapatnam-11, Mentada-11, Bondapalle-11, Ranastalam-11, Gajapathinagaram, Kalingapatnam-10, Cheepurupalle, Merakamudidam, Therlam, Nellimarla, Garividi, Bobbili-9, Vizianagaram, Chodavaram-8, Pusapatirega, Seethanagaram, Kakinada, Gantyada, Chintapalle, Parvathipuram, Balajipeta, Paderu, Tuni, Garugubilli, Srungavarapukota-7 each

Odisha: Gurundia, Padampur, Kirmira -10, Bolangir, Lahunipara, Tensa, Nuagada, Banaigarh, Bamra, Rajgangpur & Jamankira-9 each, Deogaon, Kuchinda, Burla, Hirakud, Jhumpura, Joda, G Udayagiri, Reamal, Ambabhona, Pottangi, Lakhanpur, Binika, Bargarh, Panposh, Barpalli, Jharsuguda, Paikmal, Batli & Champua-8 each and Laikera, Sambalpur, Gaisilet, Ullunda, Paralakhemundi, Dunguripalli, Deogarh, Keonjhargarh, Rairakhol, Sonepur, Hemgiri, Bijepur, Atabira & Lanjigarh-7 each

Jharkhand: Jamshedpur-9 and Chakradharpur & Chaibasa-7 each

CHAPTER-III

Performance of operational NWP models for forecasting tropical cyclones over the North Indian Ocean during the year 2018

3.1. Introduction:

The performance of various NWP models run in IMD and NCMRWF with respect to cyclone forecasting over the north Indian Ocean are presented and discussed in this chapter. The results of forecast verification is presented for individual cyclones. Also the annual average errors of the models are calculated and analysed. The results are presented in the following sections.

3.2. Cyclonic Storm “Sagar” over Arabian Sea (16 – 21 May 2018)

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

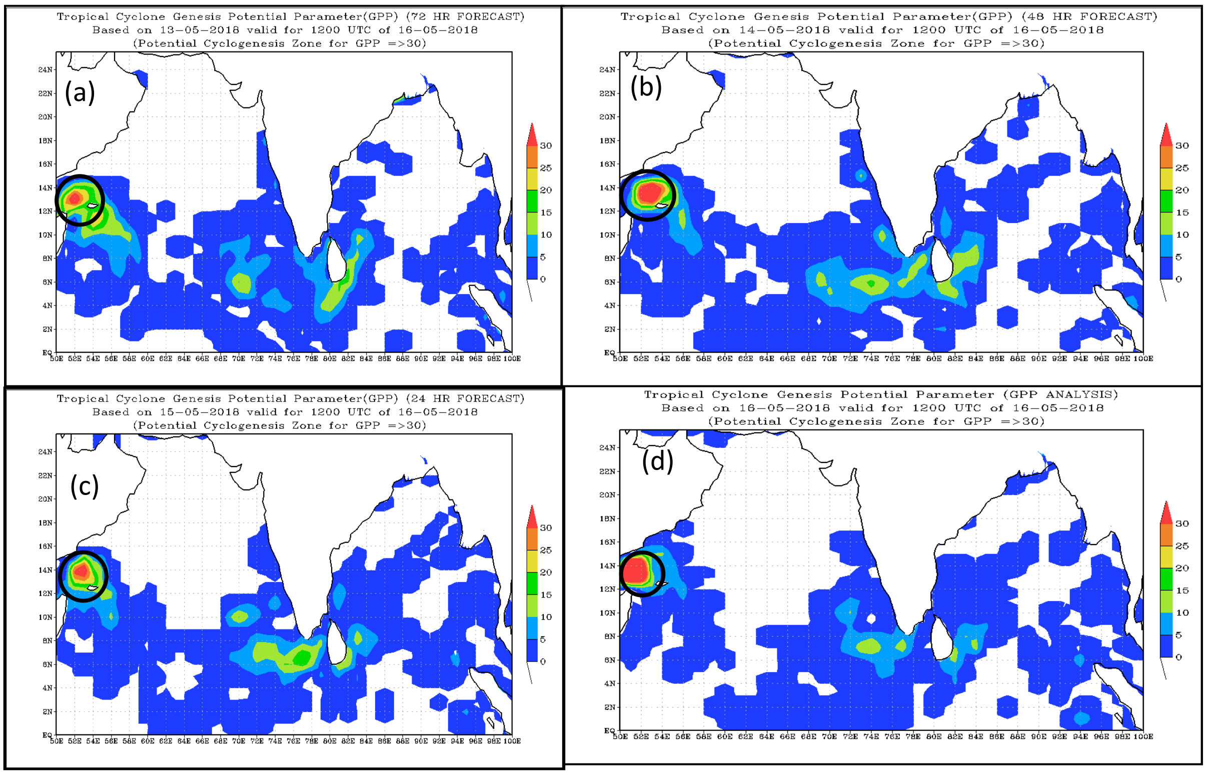


Fig.3.2.1(a-f): Predicted zone of cyclogenesis based on 0000 UTC of 13-16th May 2018.

The Genesis Potential Parameter forecast for 16th on 12 UTC of 13-16th May is presented in Fig. 3.2.1(a-f).

The model could predict cyclogenesis zone correctly about 72 hrs in advance. 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. Based on 0000 UTC of 15th May, the forecasts of GPP (**Fig. 3.2.2**) showed potential to intensify into a cyclone at 36 and 60 hrs lead period. Thus the model was not consistent in predicting the cyclogenesis. Similarly the model run at 0000 UTC of 16th May indicated potential for genesis at its 12 hr forecast only. Thus it could not predict the genesis of the system well.

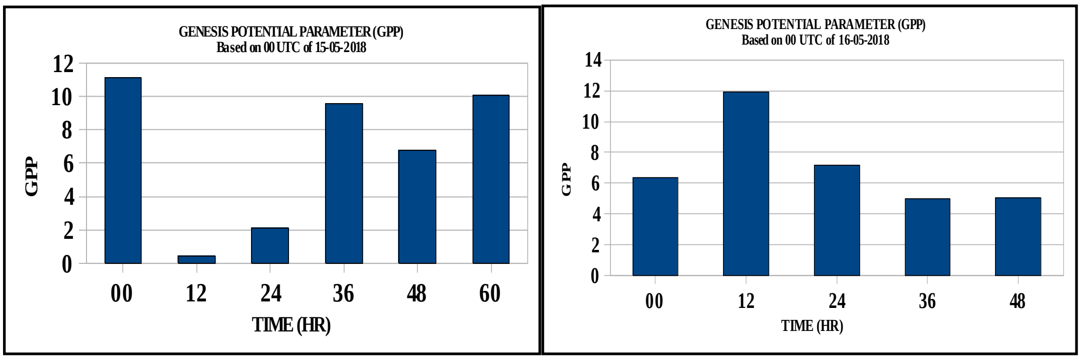


Fig. 3.2.2: Area average analysis and forecasts of GPP based on 0000 UTC of 15th and 16th May 2018

3.2.2 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.3.2.3**. Based on initial conditions of 0000 UTC of 17th May, most of the models indicated southwestward or west-southwestward movement. However a few models only predicted the landfall and the rest of

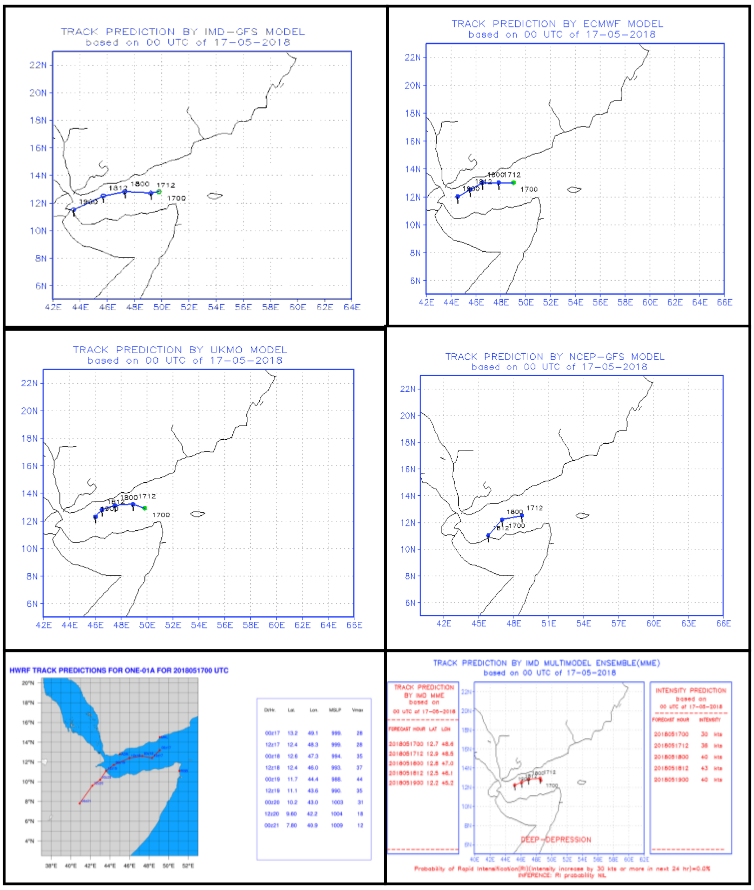


Fig. 3.2.3 (a): NWP model track forecast based on 0000 UTC of 17th May

the models weakened the system over Gulf of Aden. Based on the initial conditions of 0000 UTC of 18th May, the performance of ECMWF model was better than other in predicting the landfall.

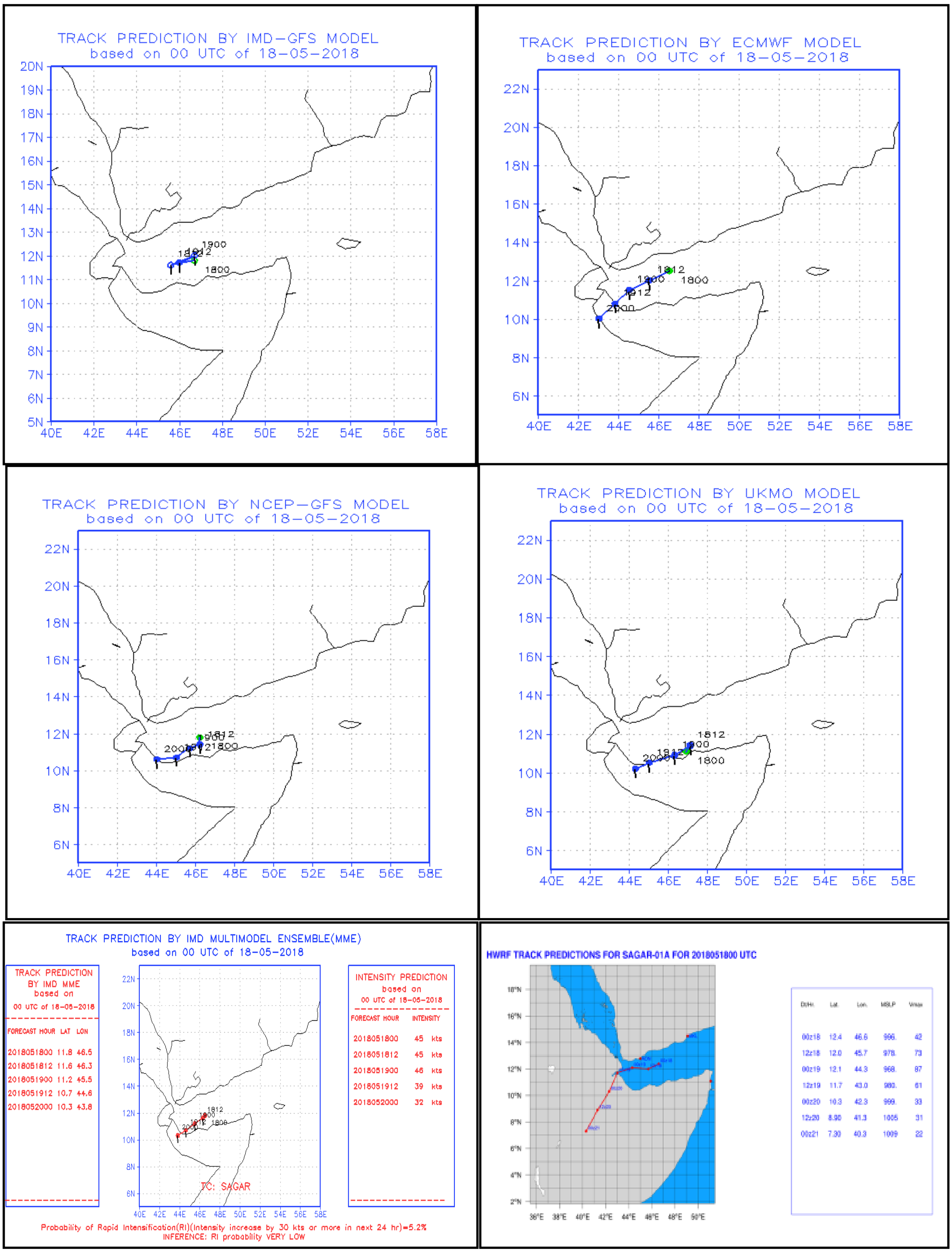


Fig. 3.2.3 (b): NWP model track forecast based on 0000 UTC of 18th May

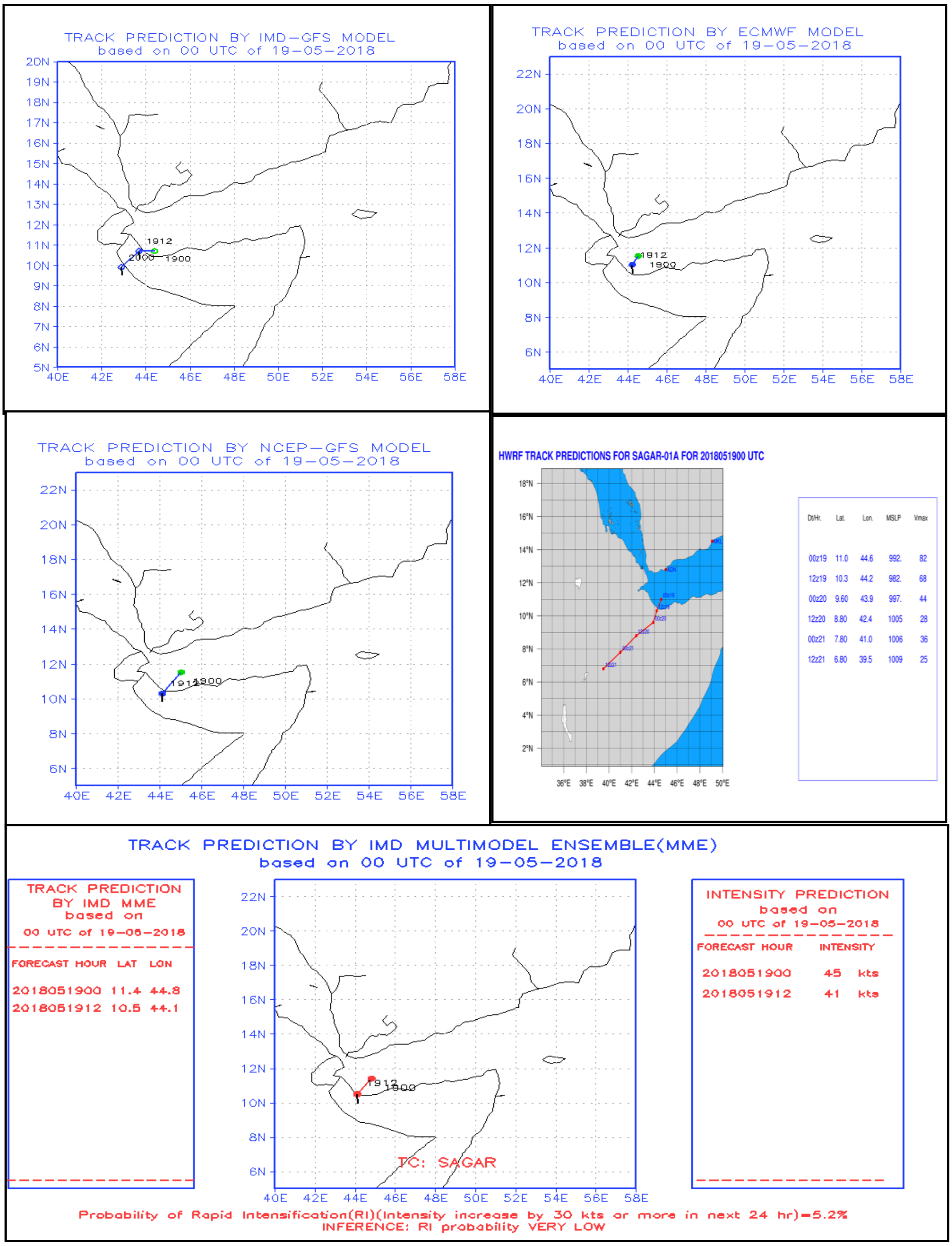


Fig. 3.2.3 (c): NWP model track forecast based on 0000 UTC of 19th May

3.2.3. 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 3.2.1**. The average cross track errors (CTE) and along track errors (ATE) are presented in Table **3.2.2(a-b).** From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of ECMWF model was minimum for 24 and 48 hr forecasts followed by MME. Above tables show that DPE was largely contributed by ATE, i.e. the errors in speed of movement of the storm.

Table 3.2.1. Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses) for CS, Sagar

Lead time →	12H	24H	36H	48H	60 H	72 H
IMD-GFS	68(6)	99(5)	154(4)	118(3)	-	-
NCEP-GFS	90(6)	144(5)	212(4)	175(2)	-	-
UKMO	119(4)	127(4)	153(3)	158(3)	-	-
ECMWF	47(6)	59(5)	123(4)	65(3)	-	-
IMD-HWRF	49(5)	106(5)	125(4)	129(3)	136(2)	25(1)
IMD-MME	55(6)	74(5)	170(4)	123(3)	-	-

Table 3.2.2(a). Average cross-track forecast errors (CTE) in km for CS, Sagar

Lead time →	12H	24H	36H	48H	60 H	72 H
IMD-GFS	37	37	68	77	-	-
NCEP-GFS	41	45	52	13	-	-
UKMO	65	52	66	46	-	-
ECMWF	26	51	85	48	-	-
IMD-HWRF	38	30	32	96	79	29
IMD-MME	32	29	53	42	-	-

Table 3.2.2(b). Average along-track forecast errors (ATE) in km for CS, Sagar

Lead time →	12H	24H	36H	48H	60 H	72 H
IMD-GFS	53	84	122	77	-	-
NCEP-GFS	75	133	189	175	-	-
UKMO	94	112	137	150	-	-
ECMWF	31	18	81	33	-	-
IMD-HWRF	2	32	72	87	57	15
IMD-MME	42	66	160	110	-	-

3.2.4. Intensity forecast errors by various NWP Models

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table **3.2.3.(a-b).** The intensity error was very high with HWRF model upto 36 hr forecasts. The probability of rapid intensification (RI) index of IMD is shown in **Table 3.2.4**. The model predicted no RI for CS, Sagar. However the probability of prediction was not in agreement with the actual change in intensity.

Table 3.2.3(a). Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model (Number of forecasts verified is given in the parentheses) in case of CS, Sagar

Lead time →	12H	24H	36H	48H
IMD-SCIP (AAE)	4.8(5)	8.3(4)	9.0(3)	5.0(1)
IMD-SCIP (RMSE)	5.5(5)	8.7(4)	10.9(3)	5.0(1)

Table 3.2.3(b). Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of HWRF model (Number of forecasts verified is given in the parentheses) in case of CS, Sagar

Lead time →	12H	24H	36H	48H	60H	72H
IMD-HWRF (AAE)	31.8(5)	29.0(5)	16.5(4)	6.6(3)	8.0(2)	6.0(1)
IMD-HWRF (RMSE)	33.8(5)	36.7(5)	17.1(4)	7.8(3)	10.3(2)	6.0(1)

Table 3.2.4. Probability of Rapid intensification of CS Sagar

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes(kt) occurred in 24h
12/16.05.2018	5.2 %	Very low	+15
00/17.05.2018	0 %	Nil	+15
12/17.05.2018	5.2 %	Very low	+5
00/18.05.2018	5.2 %	Very low	0

3.2.5. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.3.2.4**.

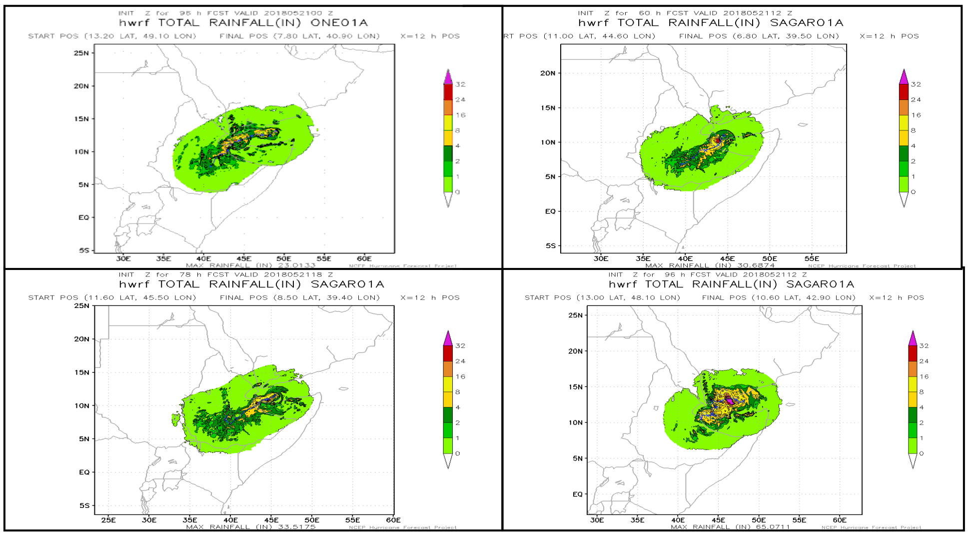


Fig.3.2.4: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 28th-30th May, 2017.

It indicates that HWRF model could capture the occurrence of rainfall over Somalia and adjoining regions, as it predicted the track well.

3.3. Extremely Severe Cyclonic Storm, ‘MEKUNU’ over the Arabian Sea (21 – 27 May 2018)

3.3.1. Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for MEKUNU

Fig. 3.3.1. shows the predicted zone of cyclogenesis for 1200 UTC of 21st May based on 1200 UTC of 15th-21st August upto 144 hrs lead period. The model could predict cyclogenesis zone correctly and consistently about 72 hours in advance. At the same time it was indicating a false potential zone for cyclogenesis over south BoB 48 & 72 hours in advance.

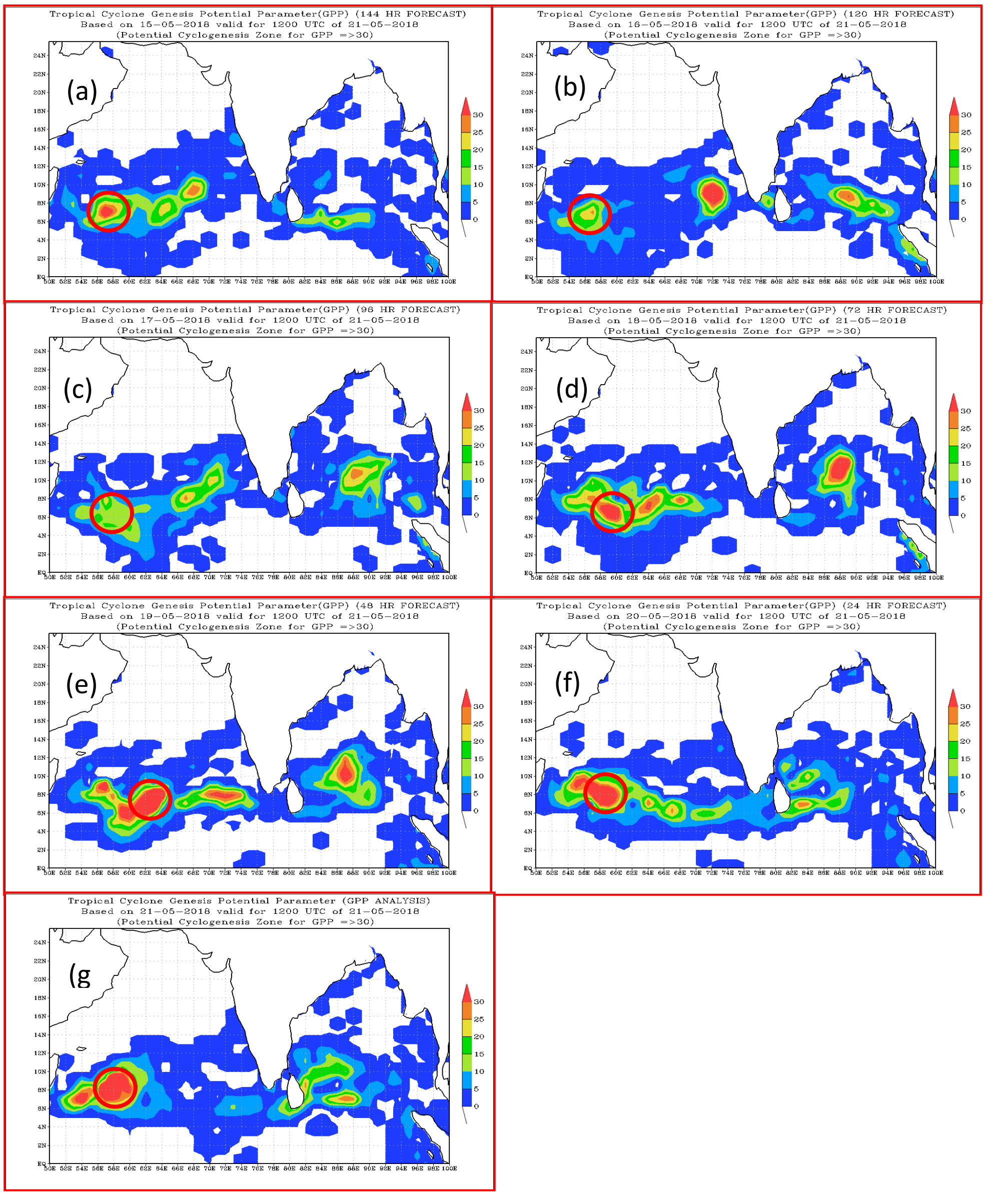


Fig. 3.3.1 (a-g): Predicted zone of cyclogenesis based on 1200 UTC of 15th to 21st May for 1200 UTC of 21st May (lead period 144 hrs).

The area average analysis kind forecasts of GPP (Fig. **3.3.2**) 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 21st, the model predicted weakening trend after 24 hours. It also indicated intensification after 72 hours. Similar trends were seen based on 0000 UTC analysis of 22nd. Actually the system didn't weaken at anytime till landfall.

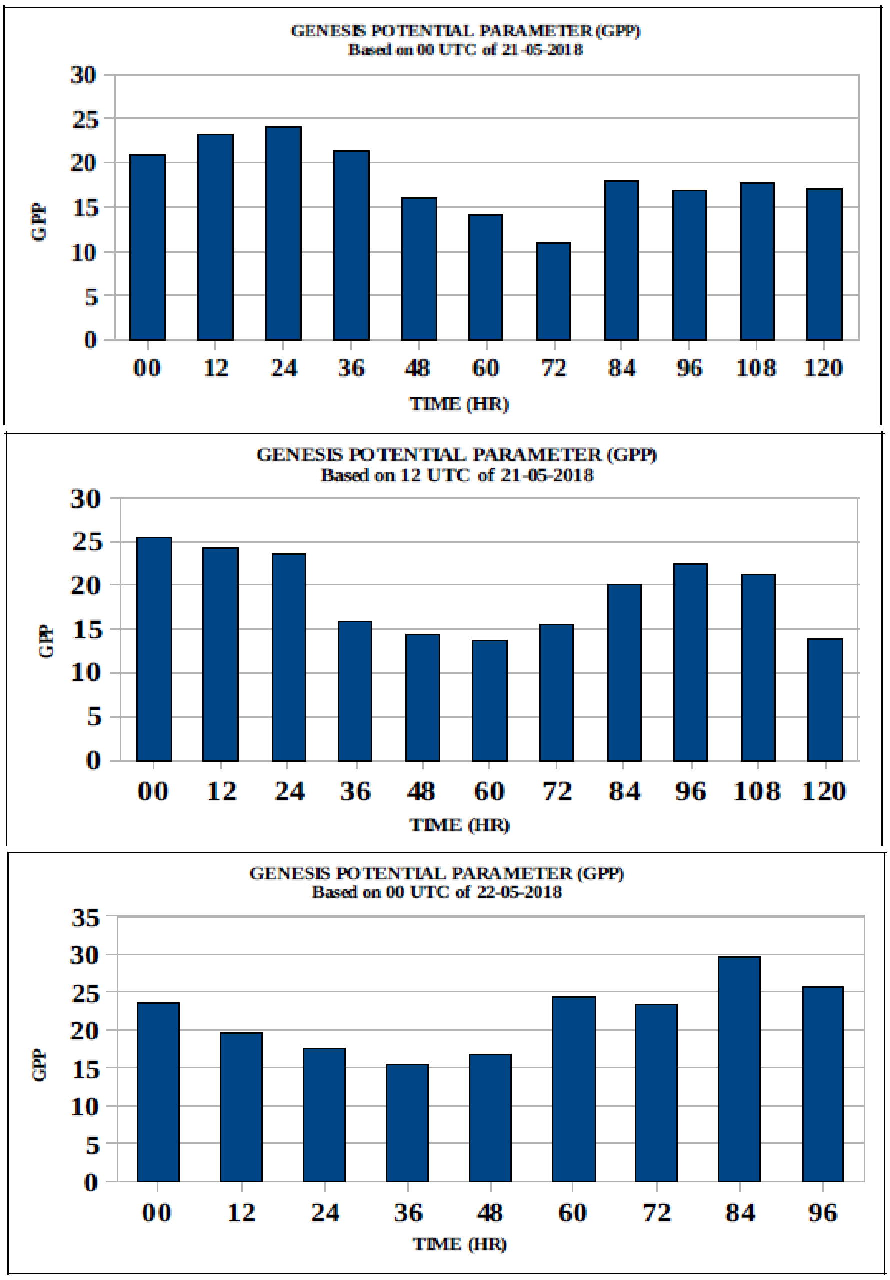


Fig. 3.3.2: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 21st and 0000 UTC of 22nd May, 2018

3.3.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.3.3.3. Based on initial conditions of 1200 UTC of 21st May, ECMWF & IMD GFS predicted landfall close to Salalah around 1200 UTC of 26th. UKMO, NCEP GFS and MME predicted landfall to the east of Salalah around 0000 UTC of 26th. JMA and WRF-VAR predicted weakening over sea and eastwards movement. The SCIP model predicted maximum intensification of system upto VSCS stage (81 kt) at the time of landfall. Probability of rapid intensification during next 24 hours was predicted as Low (21%). It also predicted rapid weakening of system after landfall (intensity falling to 53 kt (-28 kt) in next 12 hours). Many models on 21st could predict movement towards Oman coast close to Salalah but there was a delay in prediction of landfall time.

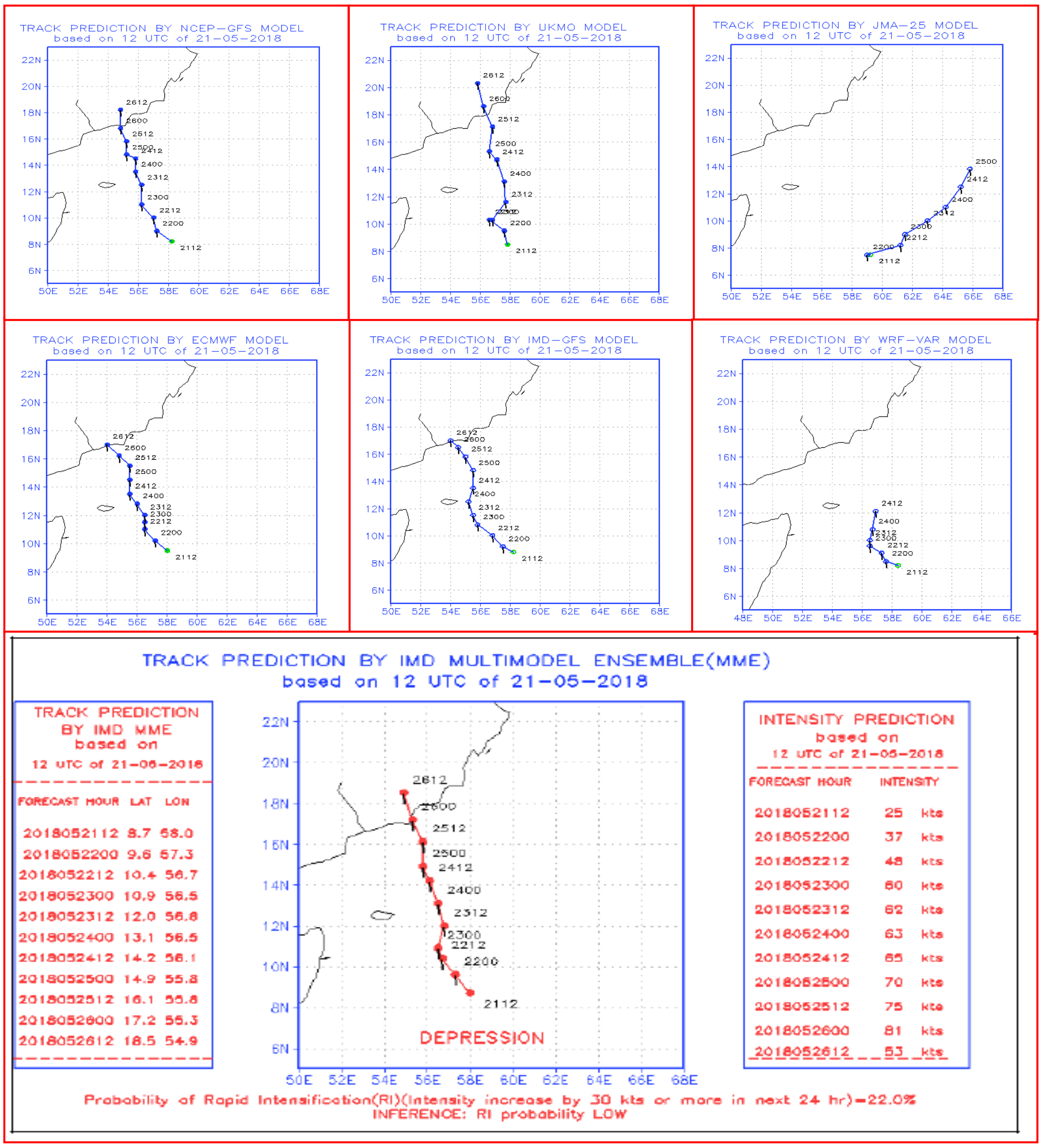


Fig. 3.3.3 (a): NWP model track forecast based on 1200 UTC of 21st May

Based on initial conditions of 0000 UTC of 22nd May, ECMWF & IMD GFS predicted landfall to the west of Salalah around 0000 UTC of 26th. NCEP GFS predicted landfall over Yemen around 0600 UTC of 26th. UKMO predicted landfall to the east of Salalah around 0000 UTC of 26th. MME predicted landfall close to Salalah around 0000 UTC of 26th. JMA and WRF-VAR predicted weakening over sea and movement off the actual track. The SCIP model predicted maximum intensification of system upto VSCS stage (87 kt) at the time of landfall. Probability of rapid intensification during next 24 hours was predicted as Low (9%). It also predicted rapid weakening of system after landfall (intensity falling to 51 kt (-36 kt) in next 12 hours). However, system didn't weaken rapidly after landfall. Most of the models on 22nd predicted movement towards Oman coast close to Salalah but there was a delay in predction of landfall time. But MME predicted landfall over Salalah around 0000 UTC of 26th.

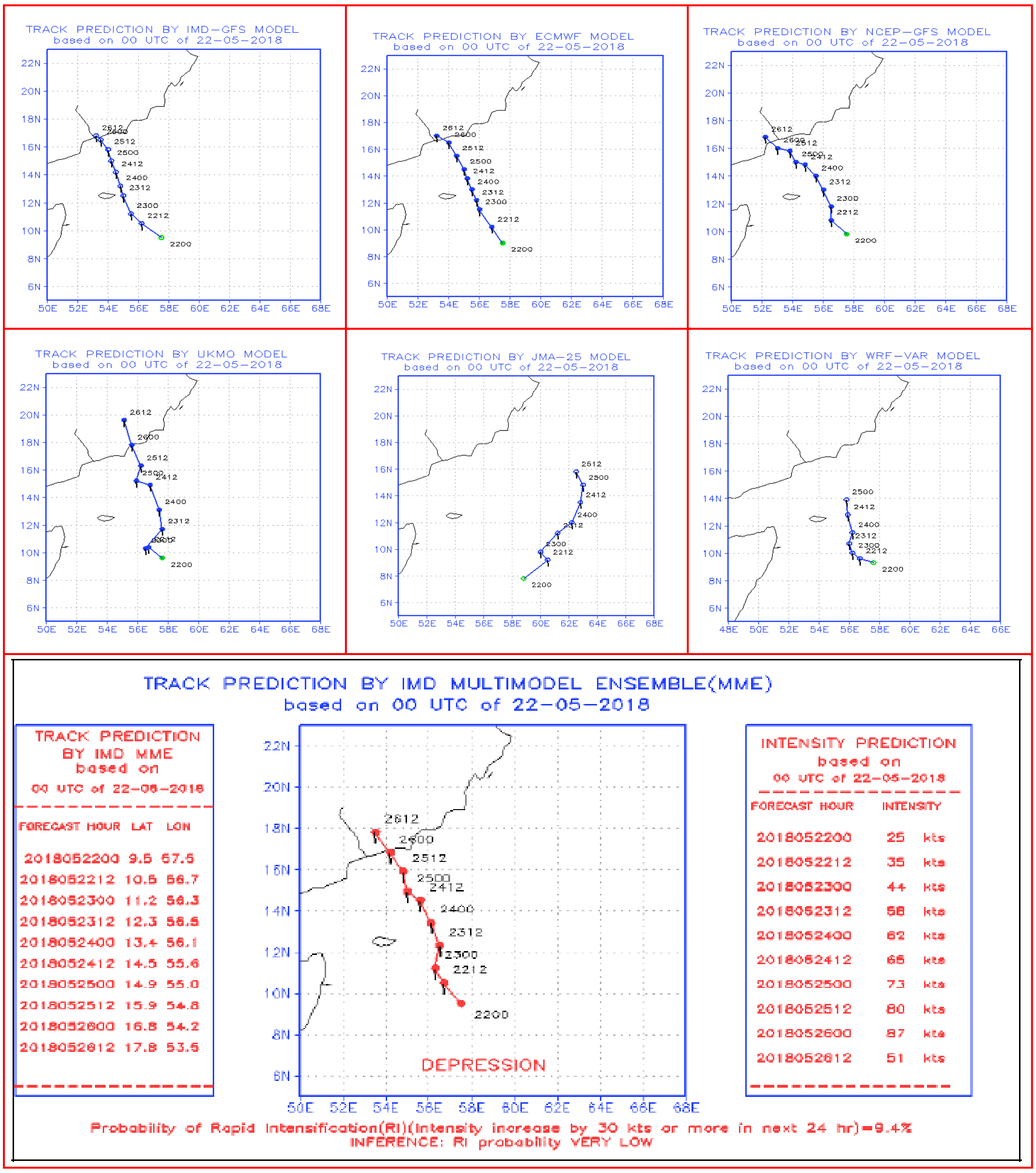


Fig. 3.3.3 (b): NWP model track forecast based on 0000 UTC of 22nd May 2018

Based on initial conditions of 0000 UTC of 23rd May, ECMWF & IMD GFS predicted landfall over Yemen around 0000 UTC of 26th. NCEP GFS predicted landfall over Yemen around 0600 UTC of 26th. UKMO predicted landfall to the east of Salalah around 0000 UTC of 26th. MME & NCEP GFS predicted landfall close to Salalah around 0000 & 1200 UTC of 26th respectively. HWRF predicted landfall close to Salalah around 1500 UTC of 26th. JMA and WRF-VAR predicted weakening over sea and movement off the actual track. The SCIP model also predicted maximum intensification of system upto VSCS stage (87 kt) after landfall. Probability of rapid intensification during next 24 hours was predicted as moderate (32%). HWRF predicted maximum intensification upto VSCS stage (73 kt) and gradual weakening of system.

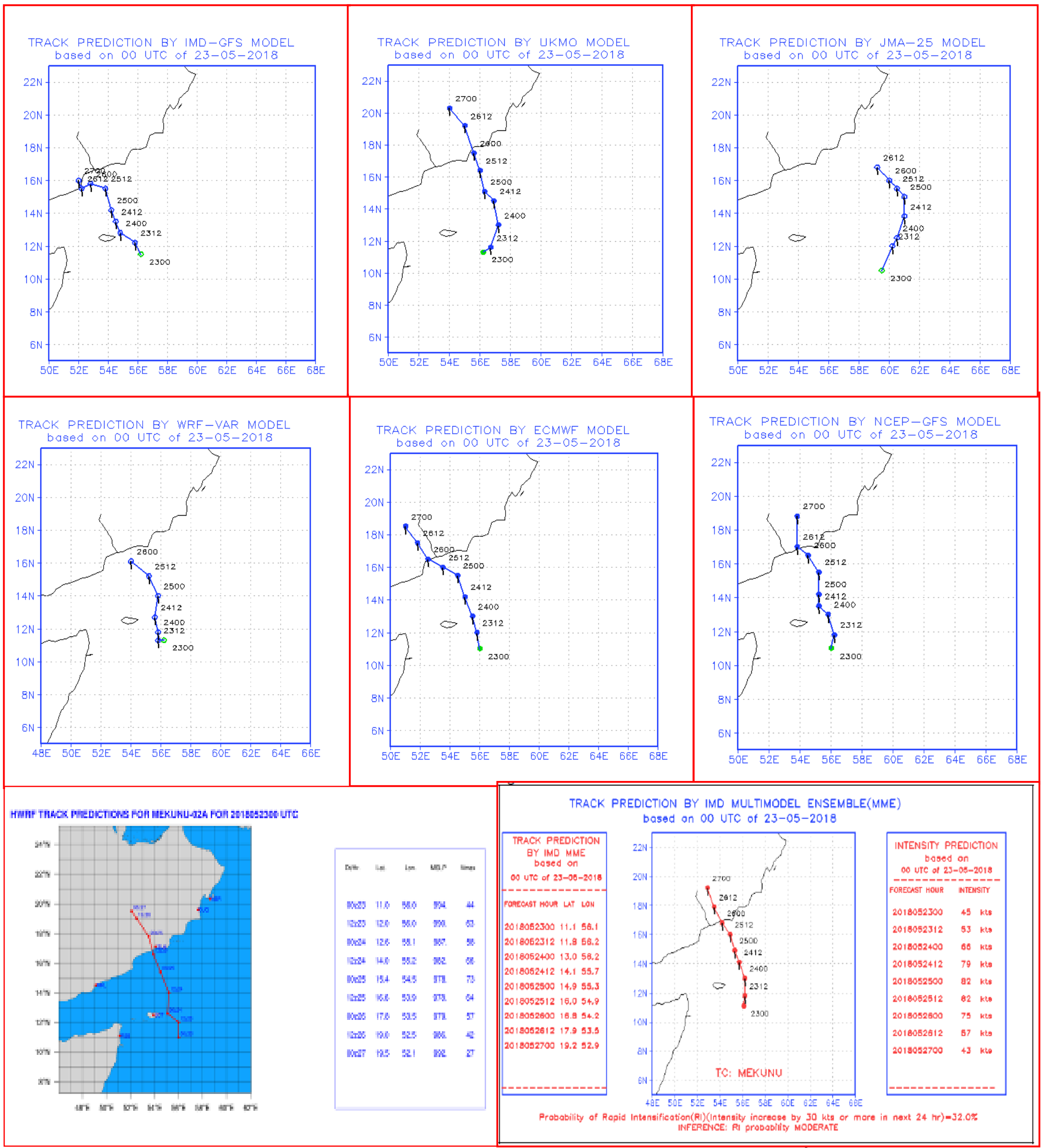


Fig. 3.3.3 (c): NWP model track forecast based on 0000 UTC of 23rd May

Based on initial conditions of 0000 UTC of 24th May, ECMWF, IMD GFS, UKMO, HWRF & MME predicted landfall close to Salalah between 1800 UTC of 25th to 0000 UTC of 26th. WRF-VAR & NCEP GFS predicted landfall over Oman-Yemen border between 0000 to 0600 UTC of 26th. JMA predicted landfall to the east of Salalah (about 200 km) around 1200 UTC of 26th. The SCIP model predicted maximum intensification of system upto VSCS stage (87 kt) prior to landfall around 1200 UTC of 25th with landfall at this intensity. Probability of rapid intensification during next 24 hours was predicted as moderate (32%). HWRF predicted maximum intensification upto VSCS stage (88 kt) around 0000 UTC of 25th and weakening of system prior to landfall (61 kt).

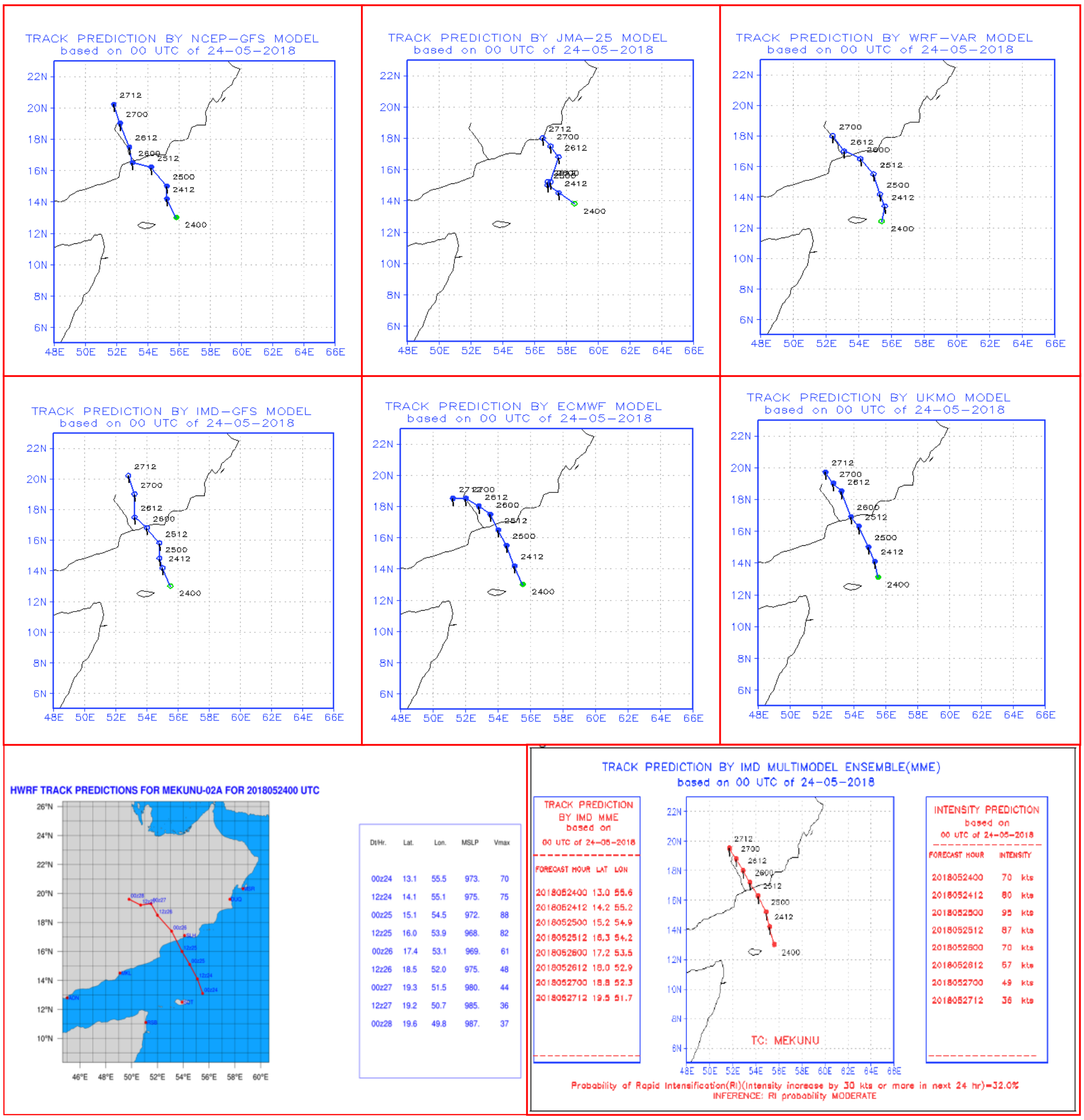


Fig. 3.3.3 (d): NWP model track forecast based on 0000 UTC of 24th May

Based on initial conditions of 0000 UTC of 25th May, ECMWF, UKMO, HWRF & MME predicted landfall close to Salalah between 1800 UTC & 2000 UTC of 25th. IMD GFS & NCEP GFS predicted landfall over Oman-Yemen border around 0000 to of 26th & 1800 UTC of 25th respectively. JMA predicted landfall to the east of Salalah (about 100 km) around 0000 UTC of 26th. WRF-VAR predicted landfall over Yemen around 0900 UTC of 26th. The SCIP model also predicted maximum intensification of system upto VSCS stage (88 kt) prior to landfall around 1200 UTC of 25th with landfall at this intensity. Probability of rapid intensification during next 24 hours was predicted as low (22%). HWRF predicted maximum intensification upto VSCS stage (83 kt) around 0000 UTC of 25th and landfall with this peak intensity.

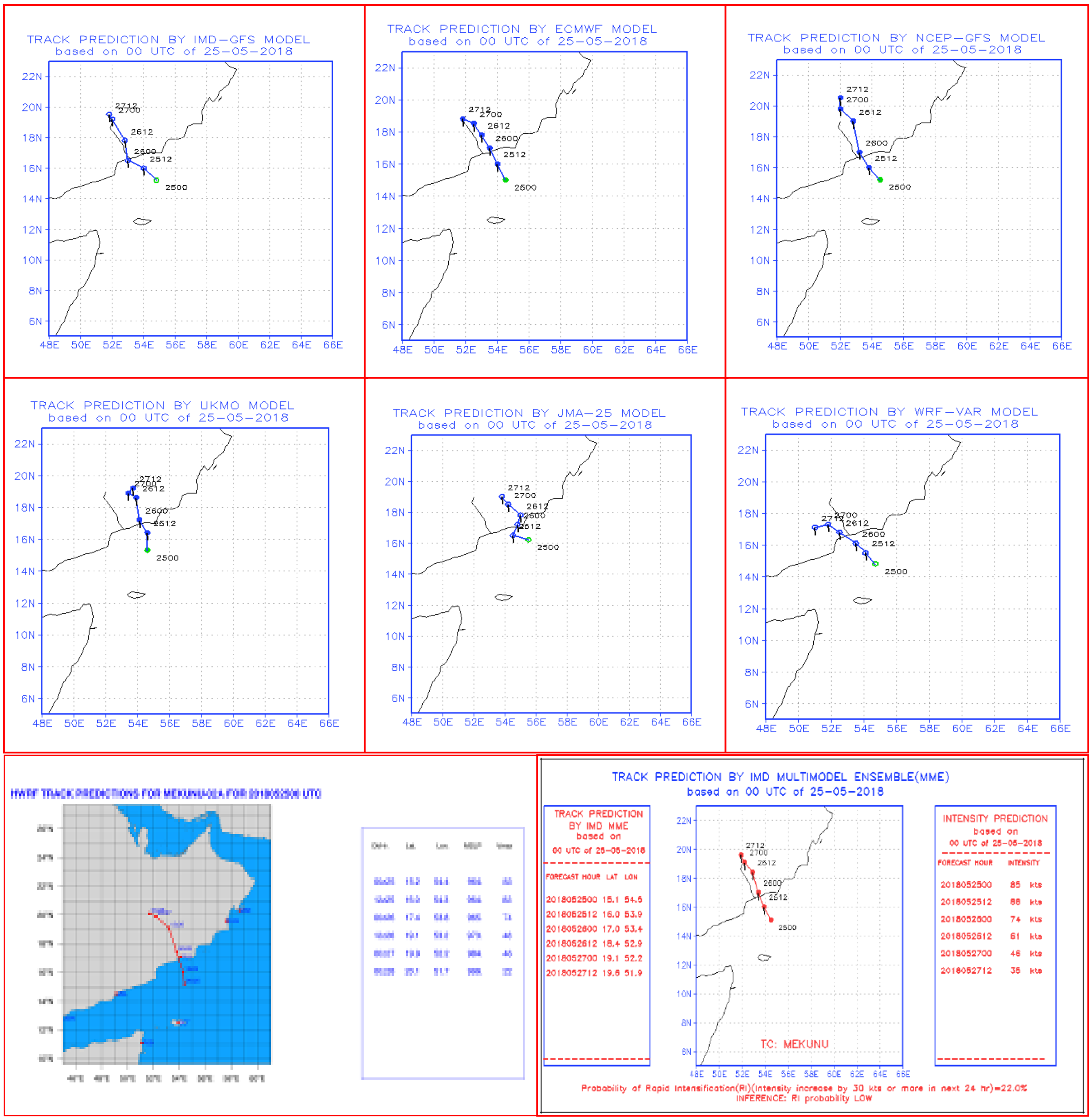


Fig. 3.3.3 (e): NWP model track forecast based on 0000 UTC of 25th May

Composite picture of forecast tracks based on initial conditions of 0000, 0600 & 1200 UTC during 21st -25th May by HWRF alongwith observed track is presented in Fig. 3.3.4. It indicates that till 1200 UTC of 22nd, HWRF predicted landfall to the east of Salalah. Thereafter, the model predicted landfall close to Salalah.

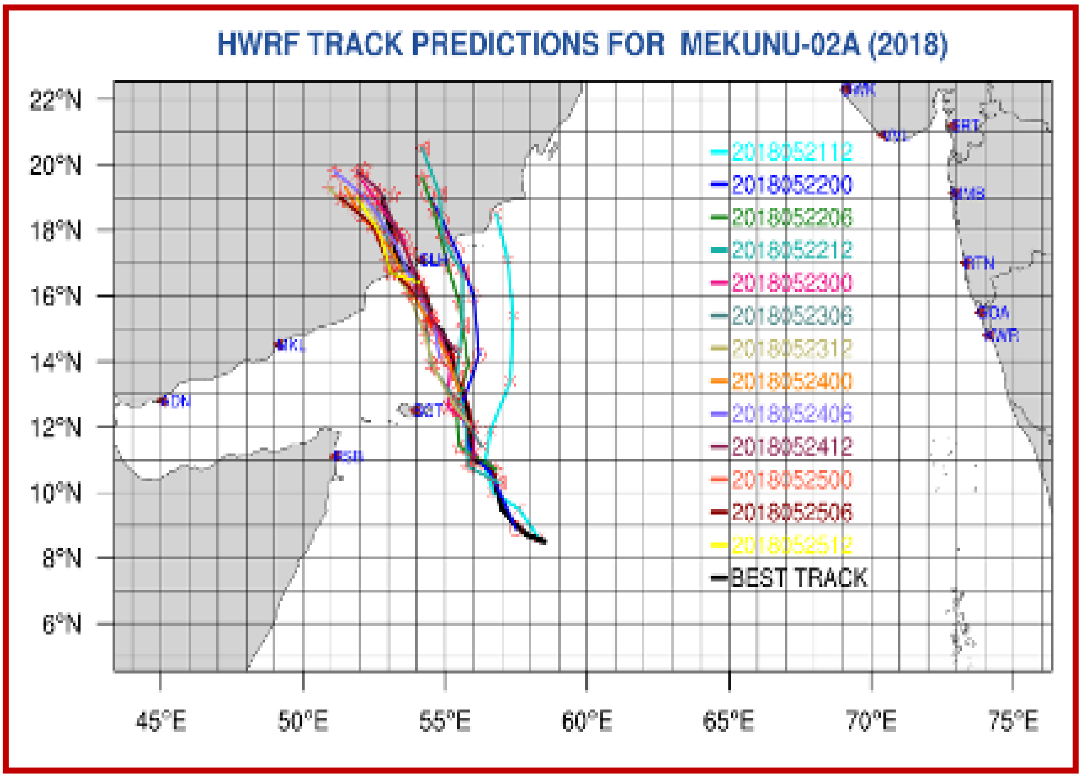


Fig. 3.3.4: Observed track and forecast tracks by HWRF based on initial conditions during 0000 UTC of 21st to 25th May

3.3.3 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 3.3.1. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of HWRF, MME & ECMWF were the least for 24 hours lead period. For 48 hours lead period, the errors were the least by ECMWF followed by MME and IMD HWRF. For 72 hours lead period, the errors were the least by MME followed by ECMWF. For 120 hours lead period errors were the least by ECMWF and IMD GFS followed by NCEP GFS and MME. Overall the errors were the least by MME followed by ECMWF for various lead periods. The average cross track errors (CTE) and along track errors (ATE) are presented in Table 3.3.2 (a-b). The CTE was relatively higher than ATE in respect of MME. In case of ECMWF model it was opposite for most of the lead periods.

Table 3.3.1: Average track forecast errors (Direct Position Error (DPE)) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	43(9)	69(9)	79(9)	74(8)	76(7)	103(6)	132(5)	198(4)	204(2)	179(1)
IMD-WRF	89(9)	143(9)	154(9)	194(8)	212(7)	174(6)	-	-	-	-
JMA	272(9)	349(9)	430(9)	543(8)	658(7)	756(6)	835(5)	-	-	-
NCEP-GFS	49(9)	61(9)	78(9)	94(8)	89(7)	86(6)	108(5)	144(4)	166(2)	190(1)
UKMO	60(9)	92(9)	130(9)	149(8)	159(7)	168(6)	218(5)	272(4)	294(2)	368(1)
ECMWF	53(9)	52(9)	43(9)	46(8)	57(7)	92(6)	116(5)	135(4)	162(2)	179(1)
IMD-HWRF	44(18)	51(18)	60(17)	86(15)	126(13)	163(11)	221(9)	239(8)	-	-
IMD-MME	46(9)	51(9)	56(9)	62(8)	68(7)	75(6)	82(5)	95(4)	134(2)	202(1)
NCUM	-	100(6)	-	155(7)	-	215(7)	-	277(5)	-	456(3)
NEPS	-	155(5)	-	236(6)	-	308(6)	-	481(6)	-	522(6)

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

Table 3.3.2 (a): Average cross-track forecast errors (CTE) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	23	45	53	55	56	79	111	175	190	178
IMD-WRF	81	137	139	174	194	161	-	-	-	-
JMA	128	203	247	317	379	430	472	-	-	-
NCEP-GFS	23	40	62	70	73	59	89	110	110	102
UKMO	29	42	63	61	48	52	62	58	20	52
ECMWF	21	25	20	28	30	56	74	87	152	178
IMD-HWRF	19	30	21	15	42	93	137	173	-	-
IMD-MME	23	17	27	30	36	54	67	67	84	78

Table 3.3.2(b). Average along-track forecast errors (ATE) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	32	44	50	45	41	53	63	91	74	22
IMD-WRF	30	36	59	70	69	54	-	-	-	-
JMA	213	263	332	423	526	615	683	-	-	-
NCEP-GFS	36	40	36	52	45	55	45	84	123	161
UKMO	48	73	101	129	149	160	206	264	293	364
ECMWF	45	38	32	32	45	59	70	78	54	22
IMD-HWRF	64	60	75	113	115	122	149	151	-	-
IMD-MME	36	46	44	53	55	49	46	59	95	186

Landfall point and time forecast errors are presented in Table 3.3.3 and 3.3.4. The landfall point error was the minimum for ECMWF model for 19, 31 and 43 hour forecast period as well as for 91 and 103 hours lead period. It was the minimum in case of MME for 55, 67 and 79 hours lead period. The landfall time error was the least in case of IMD-MME for most of the lead periods.

Table 3.3.3: Landfall point forecast errors (km) of NWP Models at different lead time

Forecast Lead Time (hour) →	7 hr	19 hr	31 hr	43 hr	55 hr	67 hr	79 hr	91 hr	103 hr
Based on	25 /12z	25 /00z	24 /12z	24 /00z	23 /12z	23 /00z	22 /12z	22 /00z	21 /12z
IMD-GFS	85	108	85	17	48	224	-	65	31
IMD-WRF	85	105	209	27	59	-	-	-	-
JMA	-	113	159	318	-	-	-	-	-
NCEP	27	48	55	108	51	17	41	162	112
UKMO	31	51	41	17	102	208	342	210	309
ECMWF	48	31	8	8	59	142	41	38	31
IMD-MME	27	41	8	31	41	48	38	48	169

Landfall Point Error: Landfall Forecast Point- Actual Landfall Point,

**: No forecast issued

The composite intensity track prediction by IMD SCIP model based on initial conditions of 0000 & 1200 UTC during 21st - 25th May is presented in Fig. 3.3.5. Overall, SCIP underestimated intensity of the system including the peak intensity.

Table-3.3.4. Landfall time forecast errors (hour) at different lead time (hr) ('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	7 hr	19 hr	31 hr	43 hr	55 hr	67 hr	79 hr	91 hr	103 hr
Based on	**25 May 12z**	**25 May 00z**	**24 May 12z**	**24 May 00z**	**23 May 12z**	**23 May 00z**	**22 May 12z**	**22 May 00z**	**21 May 12z**
IMD-GFS	+5	+5	+5	+6	+5	+18	-	+17	+17
IMD-WRF	+23	+15	+5	+11	+17	-	-	-	-
JMA	-	+3	+17	+41	-	-	-	-	-
NCEP	+1	+2	+2	+5	+5	+16	+15	+12	+6
UKMO	+5	+3	+3	+5	0	+7	+9	+5	+1
ECMWF	0	+3	-1	-3	+3	+5	+5	+11	+17
IMD-MME	+1	+2	0	0	+3	+5	+5	+5	+5

Landfall Time Error: Landfall Forecast Time- Actual Landfall Time

- : No forecast issued

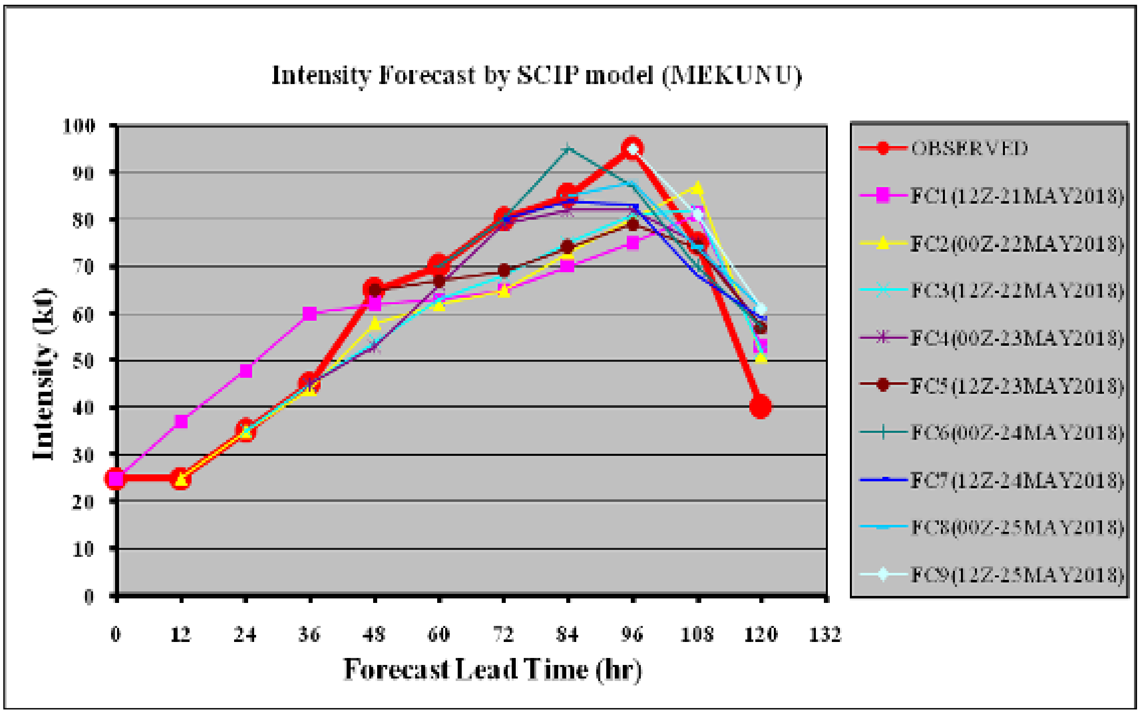


Fig. 3.3.5: Intensity prediction by SCIP Model

Table 3.3.5: 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 → (hrs)	12	24	36	48	60	72	84	96	108	120
IMD-SCIP (AAE)	4.6 (9)	9.3 (9)	9.6 (8)	9.4 (7)	10.5 (6)	11.6 (5)	13.5 (4)	14.7 (3)	8.5 (2)	13.0 (1)
IMD-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)	6.5	11.1	11.2	11.1	11.8	13.1	14.0	15.1	8.9	13.0
IMD-HWRF (RMSE)	9.3 (21)	10.7 (20)	10.2 (18)	19.8 (16)	17.6 (14)	14.4 (12)	15.8 (10)	11.6 (8)		

The intensity forecast errors by HWRF were significantly higher than IMD SCIP for 48 hours lead period. For other lead periods, the errors were comparable. For 72 and 96 hours lead period, the HWRF errors were less than the SCIP errors.

The probability of rapid intensification (RI) index by MME is shown in Table 3.3.6. Rapid intensification occurred at 1200 UTC of 23rd (65 kt at 23/1200 UTC & 35 kt at 22/1200 UTC). However, the RI index couldn't predict RI of the system.

Table 3.3.6: Probability of Rapid intensification (RI) by RI Model

Forecast based on	Probability of RI predicted	Chances of occurrence predicted	Intensity changes(kt) occurred in 24h
12/21.05.2018	22 %	LOW	+10
00/22.05.2018	9.4 %	VERY LOW	+20
12/22.05.2018	22 %	LOW	+30
00/23.05.2018	32 %	MODERATE	+25
12/23.05.2018	32 %	MODERATE	+15
00/24.05.2018	32 %	MODERATE	+15
12/24.05.2018	32 %	MODERATE	+15

3.3.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.3.3.6**. HWRF could successfully predict occurrence of rainfall along the predicted track even after the

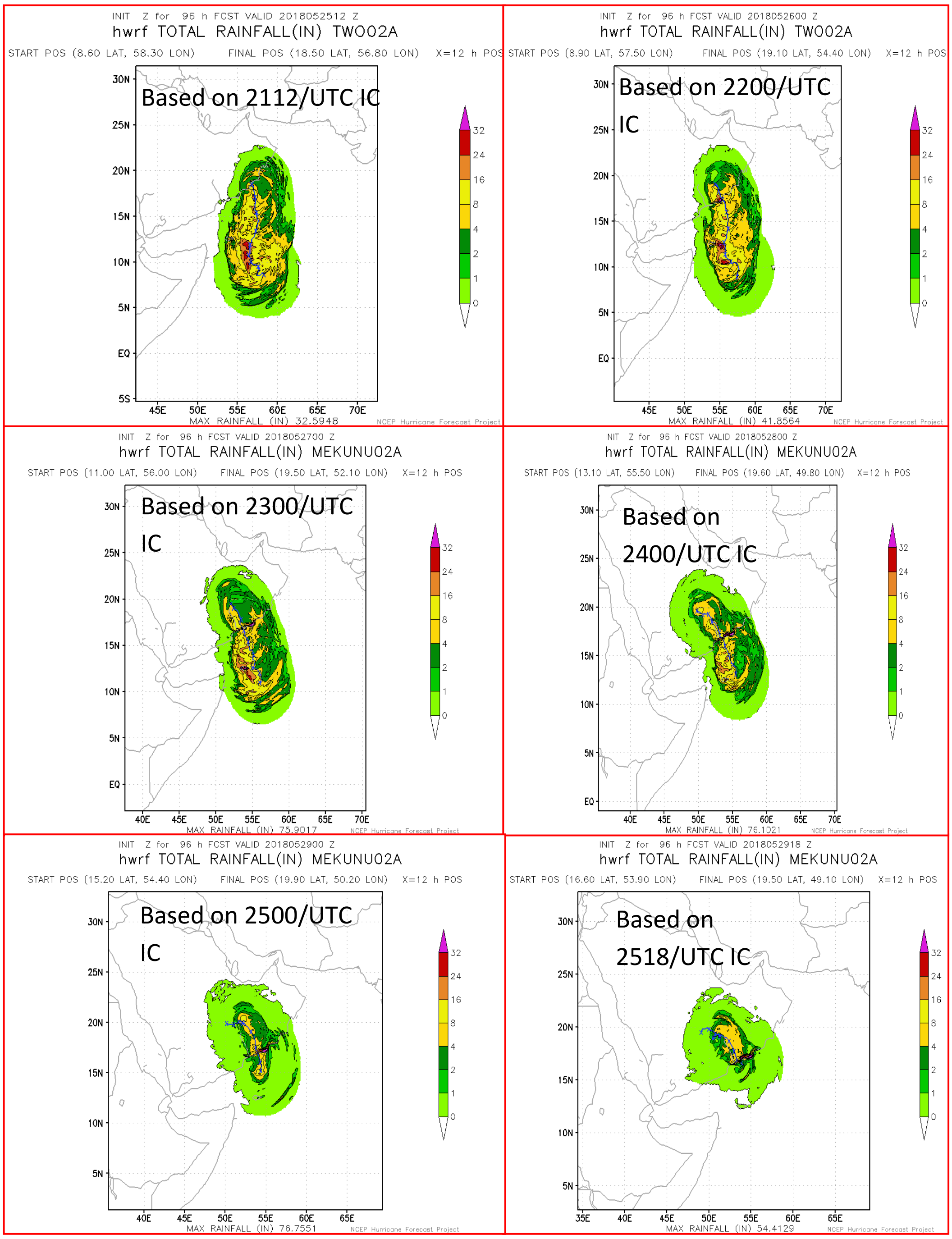


Fig.3.3.6: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 21th-25th May, 2018.

landfall of system. Based on 1200 UTC of 24th, the expected rainfall during 1200 UTC of 24th to 1200 UTC of 28th May is about 8-16 inches (20-40cm) over coastal areas of south Oman and southeast Yemen. It was predicted to be 20-25 inches (50-60 cm) at some places in south coastal Oman. Over interior areas of Oman, it was predicted to be around 8-10 inches (20-25 cm) during 1200 UTC of 24th to 1200 UTC of 28th May. As per the available rainfall reports from media at Oman, extremely heavy rainfall of the order of 30 cm was recorded on the day of landfall over Salalah.

3.3.5. Storm surge forecast

IMD predicts storm surge forecast based on guidance from Advance Circulation (ADCIRC) model and Indian Institute of Delhi Model. IMD predicted expected storm surge of 1.5 metre to 2 metre above astronomical tide during 1800 UTC of 25th to 0300 UTC of 26th. The maximum storm surge was expected over Salalah. Storm surge forecast by ADCIRC Model based on 0600 UTC observations of 23rd May is presented in **Fig. 3.3.7**.

Fig. 3.3.7: Storm Surge Forecast issued by INCOIS ADCIRC Model based on 0600 UTC of 23rd May, 2018

3.4. Cyclonic Storm “DAYE” over Bay of Bengal (19– 22 September 2018)

3.4.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for DAYE

The predicted zone of cyclogenesis for 0000 UTC of 20th September based on 0000 UTC of 15th-20th Sep. 2018 (upto 120 hrs lead period) is shown in Fig.3.4.1. The model could predict cyclogenesis zone correctly about 72 hrs in advance. The prediction of intensification of depression into cyclonic storm based on the above is presented in Fig.3.4.2.

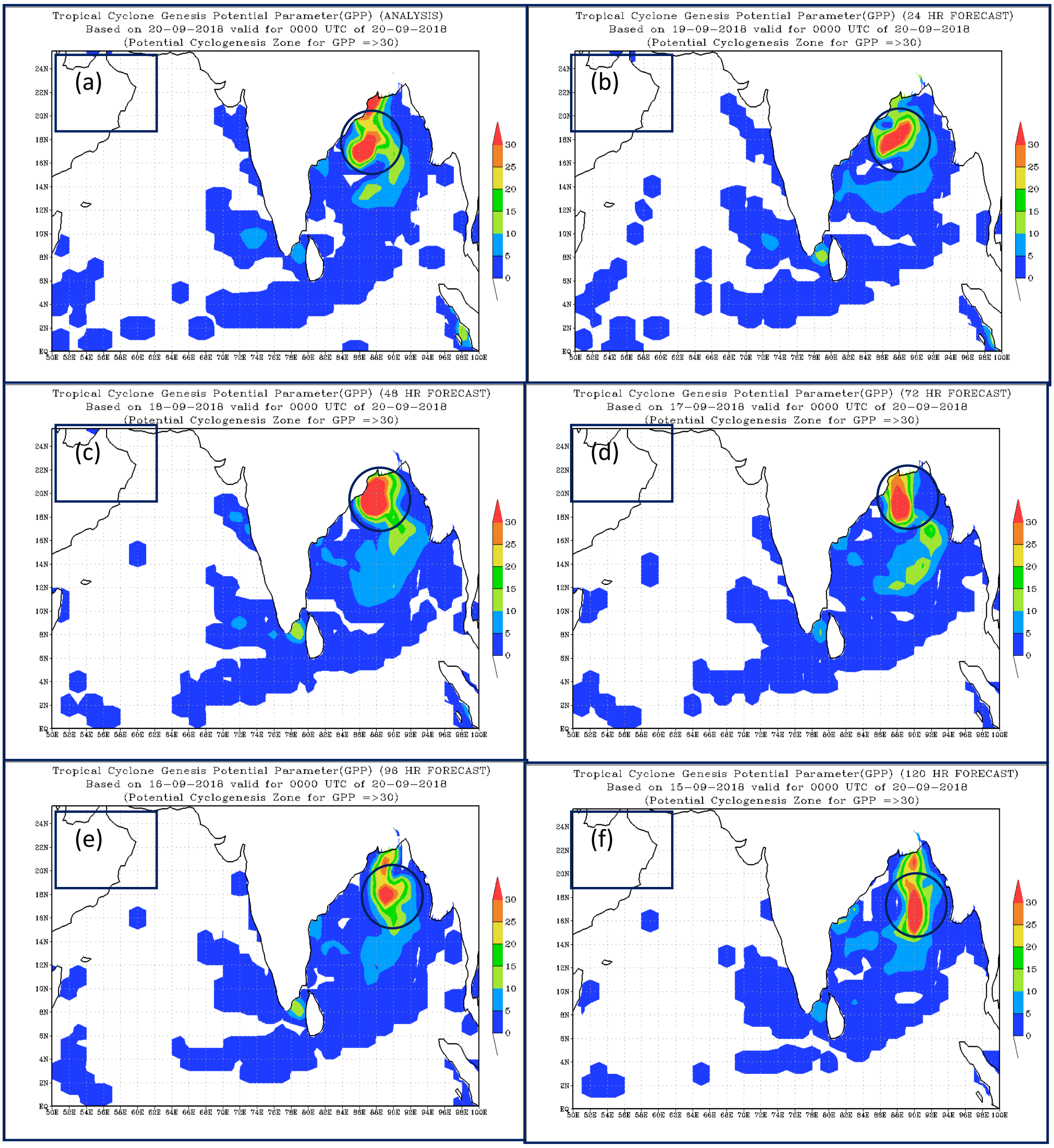


Fig.3.4.1 (a-f): Predicted zone of cyclogenesis based on 0000 UTC of 15-20th Sep. 2018 for 20th Sep. 2018

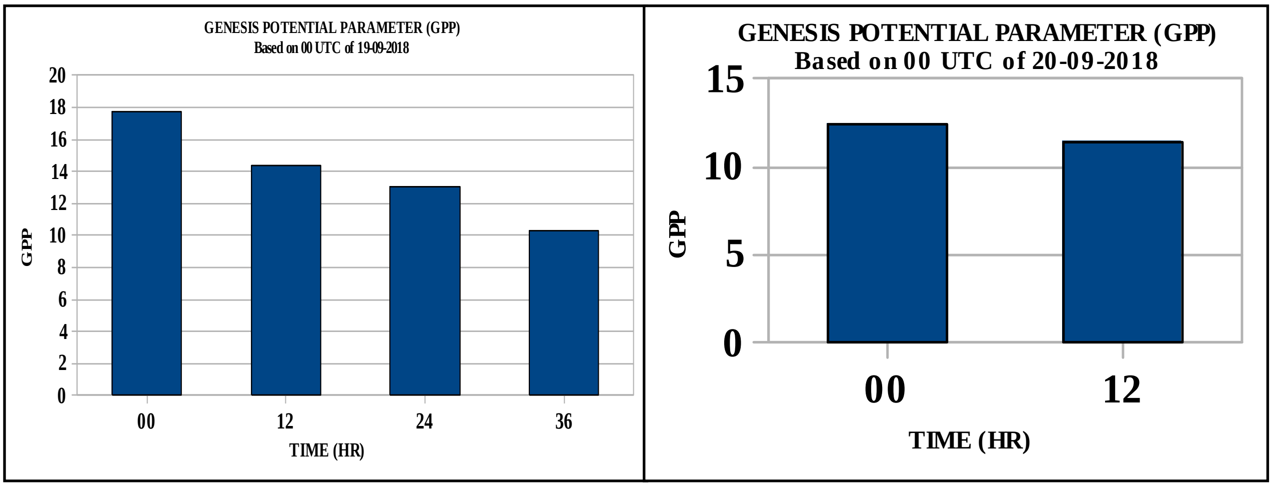


Fig. 3.4.2: Area average analysis and forecasts of GPP based on 0000 UTC of 19th and 20th September 2018

3.4.2 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.3.4.3**. Based on initial conditions of 0000 UTC of 20th September, most of the models indicated northwestward or west-northwestward movement and the landfall between Kalingapatnam and Gopalpur.

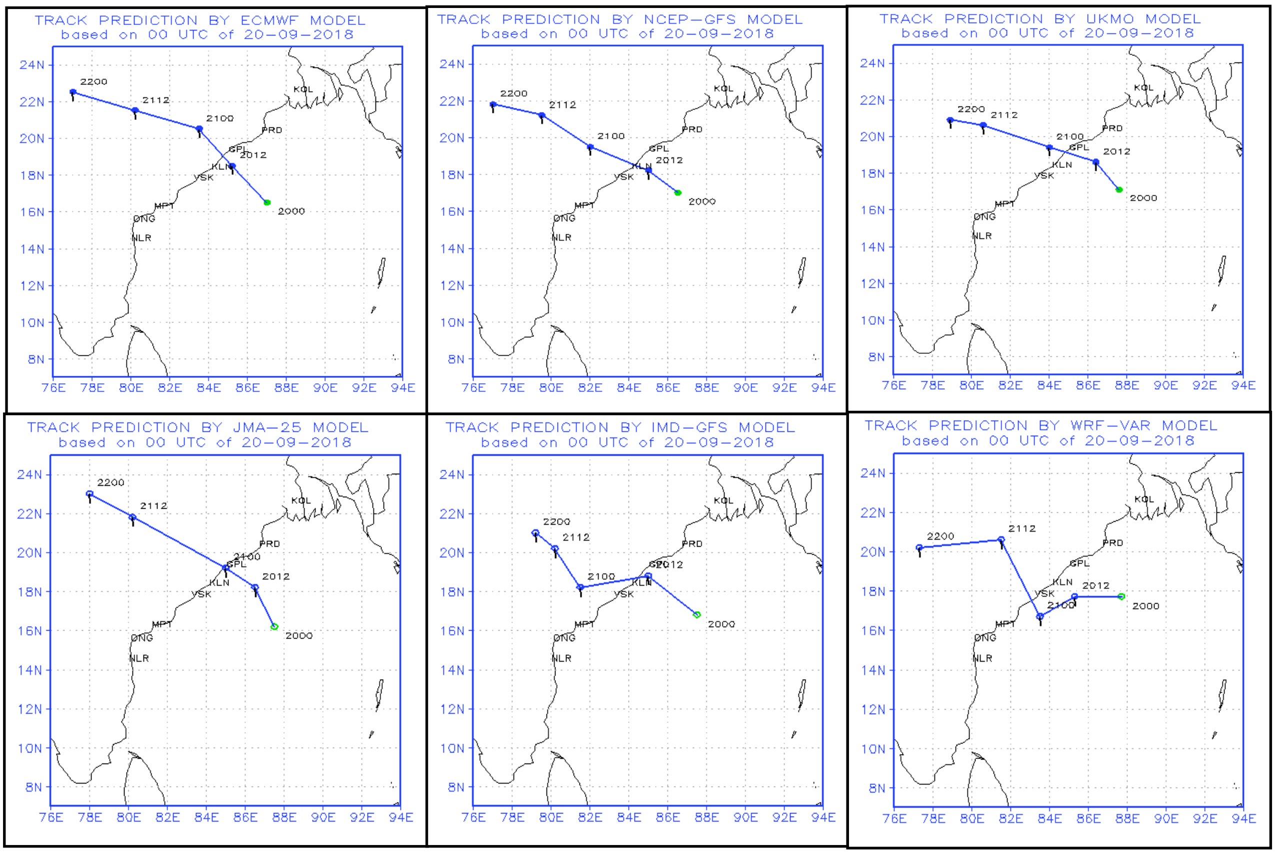


Fig. 3.4.3 (a): NWP model track forecast based on 0000 UTC of 20.09.2018

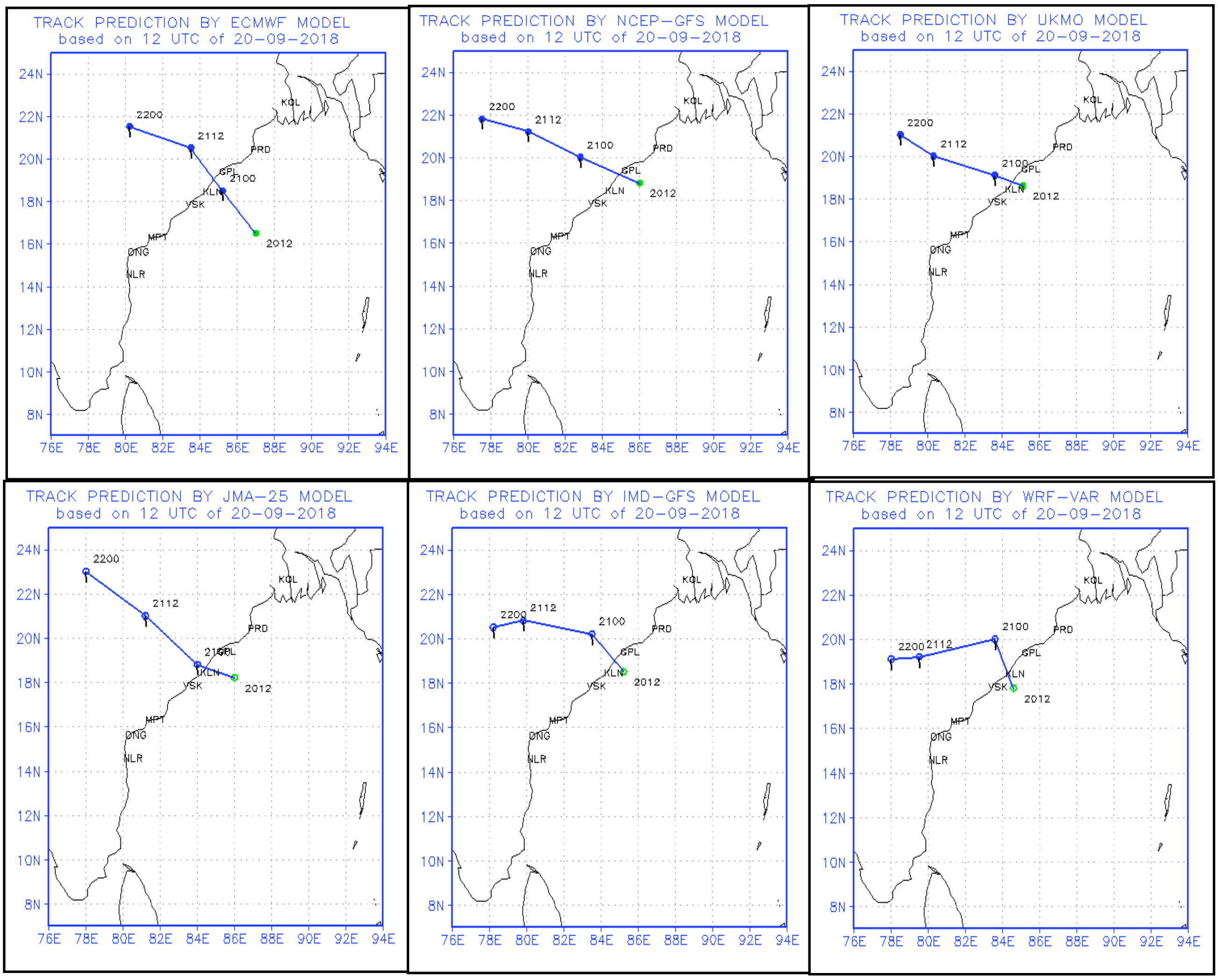


Fig. 3.4.3 (b): NWP model track forecast based on 1200 UTC of 20.09.2018

3.4.3. 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 3.4.1. From the verification of the forecast guidance available from various NWP models, It is found that the average track forecast errors for 24 hours lead period was minimum for MME followed by NCEP (GFS) model and for 48 hours lead period the errors were the least by ECMWF followed by NCEP (GFS). The landfall forecast errors are presented in Table 3.4.2. The landfall point errors for 7 hours lead period were the least for GFS group of models followed by ECMWF and for 20 hours lead period, errors were the least by JMA & UKMO followed by ECMWF. The landfall time errors for 7 hours lead period were the least for IMD MME followed by JMA and for 20 hours lead period, errors were the least by UKMO followed by IMD MME.

Table-3.4.1. Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H
IMD-GFS	63(2)	192(2)	187(2)	278(1)	-
IMD-WRF	52(2)	311(2)	267(2)	237(1)	-
JMA	107(2)	138(2)	91(2)	137(1)	-
NCEP-GFS	91(2)	108(2)	79(2)	57(1)	-
UKMO	84(2)	115(2)	159(2)	259(1)	-
ECMWF	147(2)	208(2)	181(2)	24(1)	-
IMD-HWRF	83(5)	159(5)	167(5)	136(3)	160(1)
IMD-MME	61(2)	101(2)	123(2)	98(1)	-
NCUM	-	166(4)	-	141(5)	-
NEPS	-	166(3)	-	190(3)	-

Table-3.4.2a. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	7:30 hr	19:30 hr
Based on	20 September 12z	20 September 00z
IMD-GFS	33	96
IMD-WRF	123	282
JMA	92	11
NCEP	11	123
UKMO	57	15
ECMWF	38	38
IMD-MME	72	62

Table-3.4.2b. Landfall time forecast errors (hour) at different lead time (hr)

Forecast Lead Time (hour) →	7:30 hr	19:30 hr
Based on	**20 September, 12z**	**20 September, 00z**
IMD-GFS	-4:30	-5:30
IMD-WRF	-4:30	+7:30
JMA	+1:30	+4:30
NCEP	-4:30	-4:30
UKMO	-2:30	+0:30
ECMWF	+8:30	-4:30
IMD-MME	+0:30	-2:30

('+' indicates delay landfall, '-' indicates early landfall)

3.4.4 Intensity forecast errors by various NWP Models

The intensity forecast errors of IMD-SCIP model and HWRF model are shown in Table **3.4.3(a-b).** The errors in intensity forecast were significantly less for IMD SCIP as compared to HWRF upto 24 hours lead period. However, for 36 hours lead period, the errors were less by HWRF as compared to IMD SCIP.

Table 3.4.3(a). 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
IMD-SCIP (AAE)	3.5(2)	3.0(2)	3.0(1)
IMD-SCIP (RMSE)	3.8	3.6	3.0

Table 3.4.3(b) Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of HWRF model (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H
IMD-HWRF (AAE)	6.6(5)	5.4(5)	2.2(5)	2.3(3)	5.0(1)
IMD-HWRF (RMSE)	8.0(5)	7.2(5)	2.7(5)	3.5(3)	5.0(1)

3.5.Very Severe Cyclonic Storm, 'LUBAN' over the Arabian Sea (06 – 15 October 2018)

3.5.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for VSCS Luban

Fig. 3.5.2 shows the predicted zone of cyclogenesis based on 0000 UTC of 2-7 Oct. for 0000 UTC of 7th Oct.

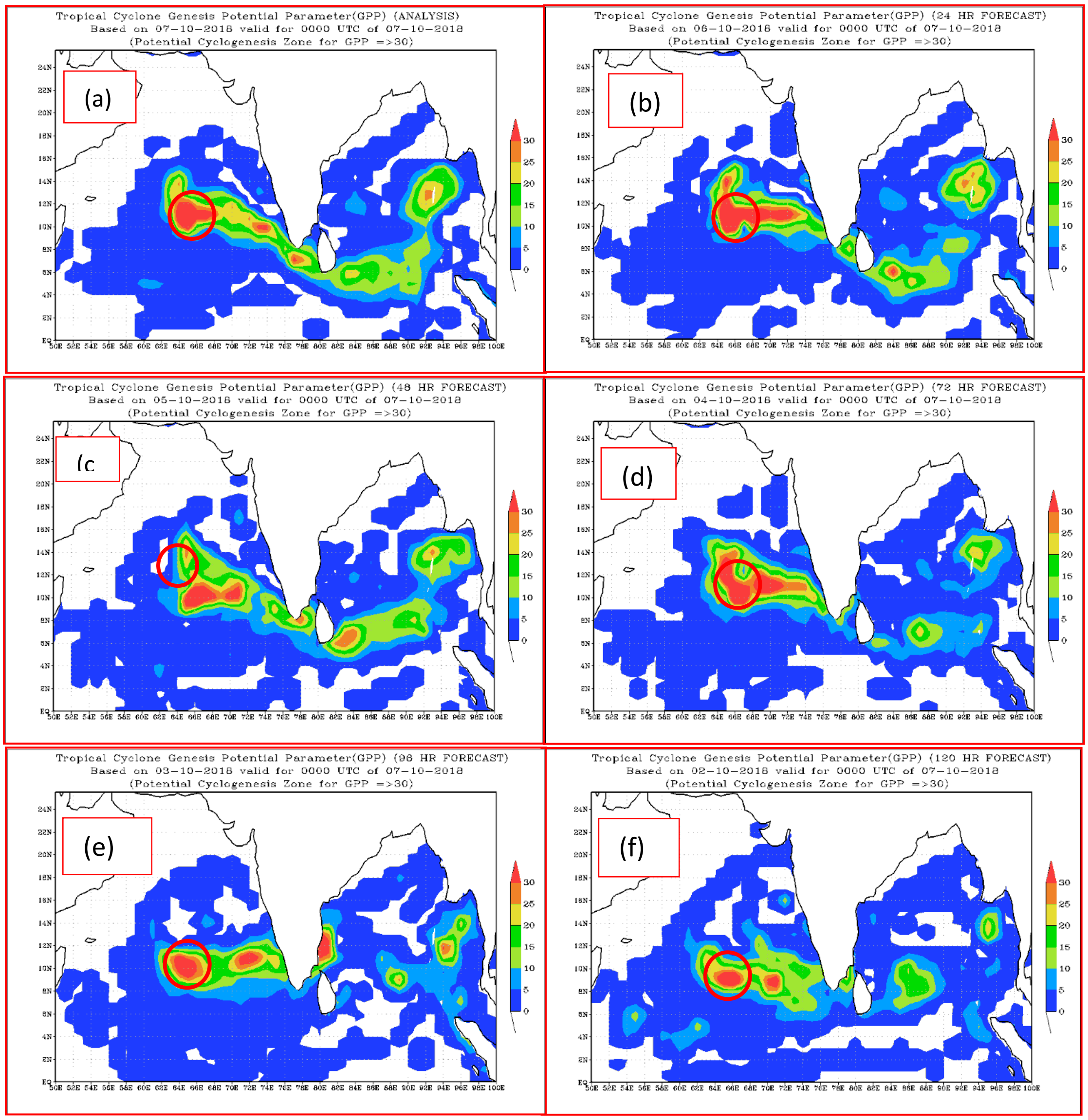


Fig.3.5.1(a-f): Predicted zone of cyclogenesis based on 0000 UTC of 2nd-7th October for 0000 UTC of 7th October.

The model could predict cyclogenesis zone correctly and consistently about 72 hours in advance. At the same time it was indicating a false potential zone for cyclogenesis over south BoB 48 & 72 hours in advance.

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 was also predicted by GPP developed by IMD. Conditions for developed system is average GPP ≥ 8.0 and the forecasts of GPP (Fig. 3.5.2) showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0). Based on 0000 & 1200 of the of 6th & 7th, the model predicted weakening of the system during initial stage. However, actually it did not happen. Weakening started from 12th morning only.

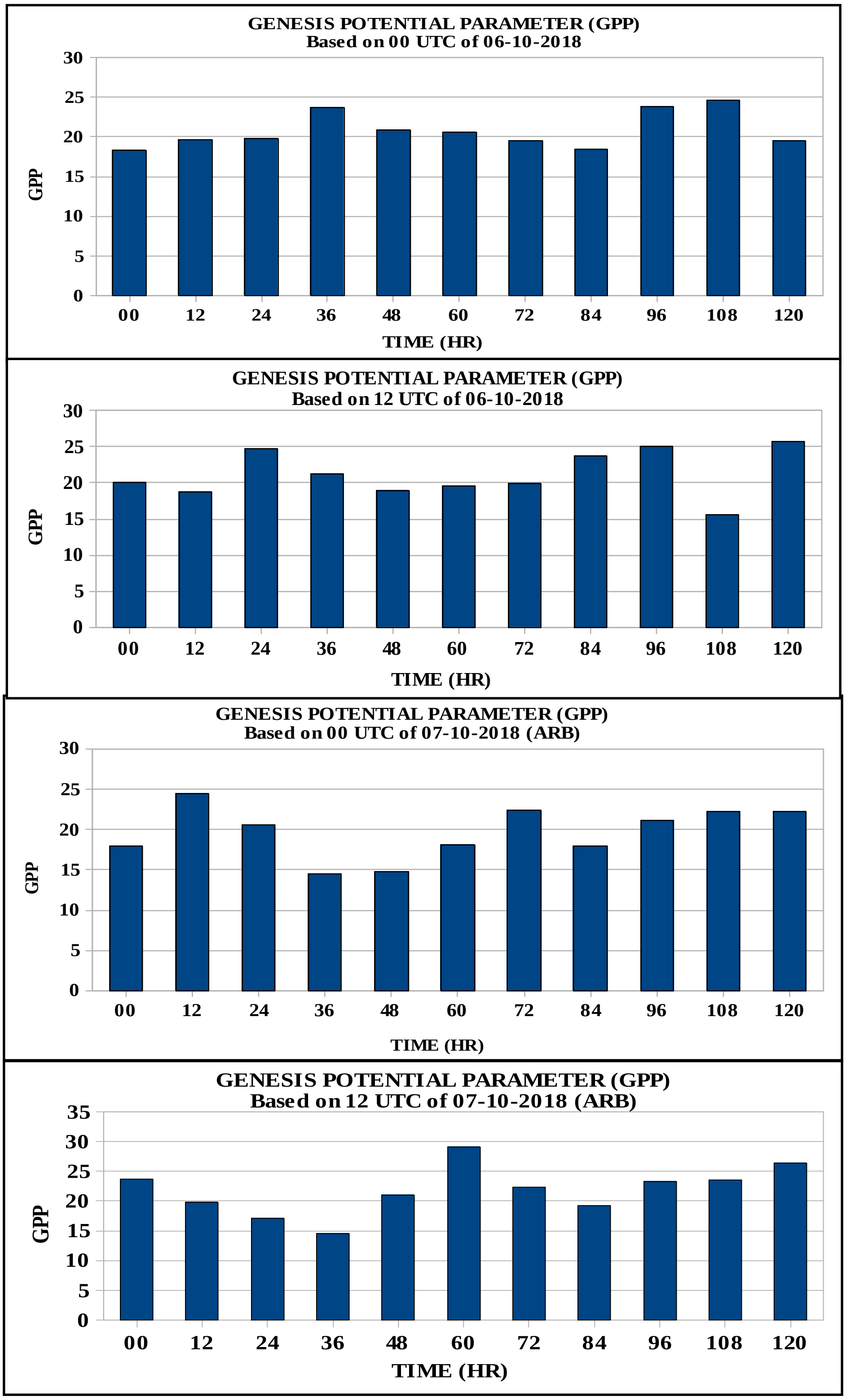


Fig. 3.5.2: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 6th & 7th October, 2018

3.5.2 Track prediction by NWP models

The track prediction by indivdual NWP models and multi-model ensemble technique are presented in Fig.3.5.3. Based on 0000 UTC of 7th Oct. most of the models were in agreement for northwestward movement towards Oman and adjoining Yemen coast.

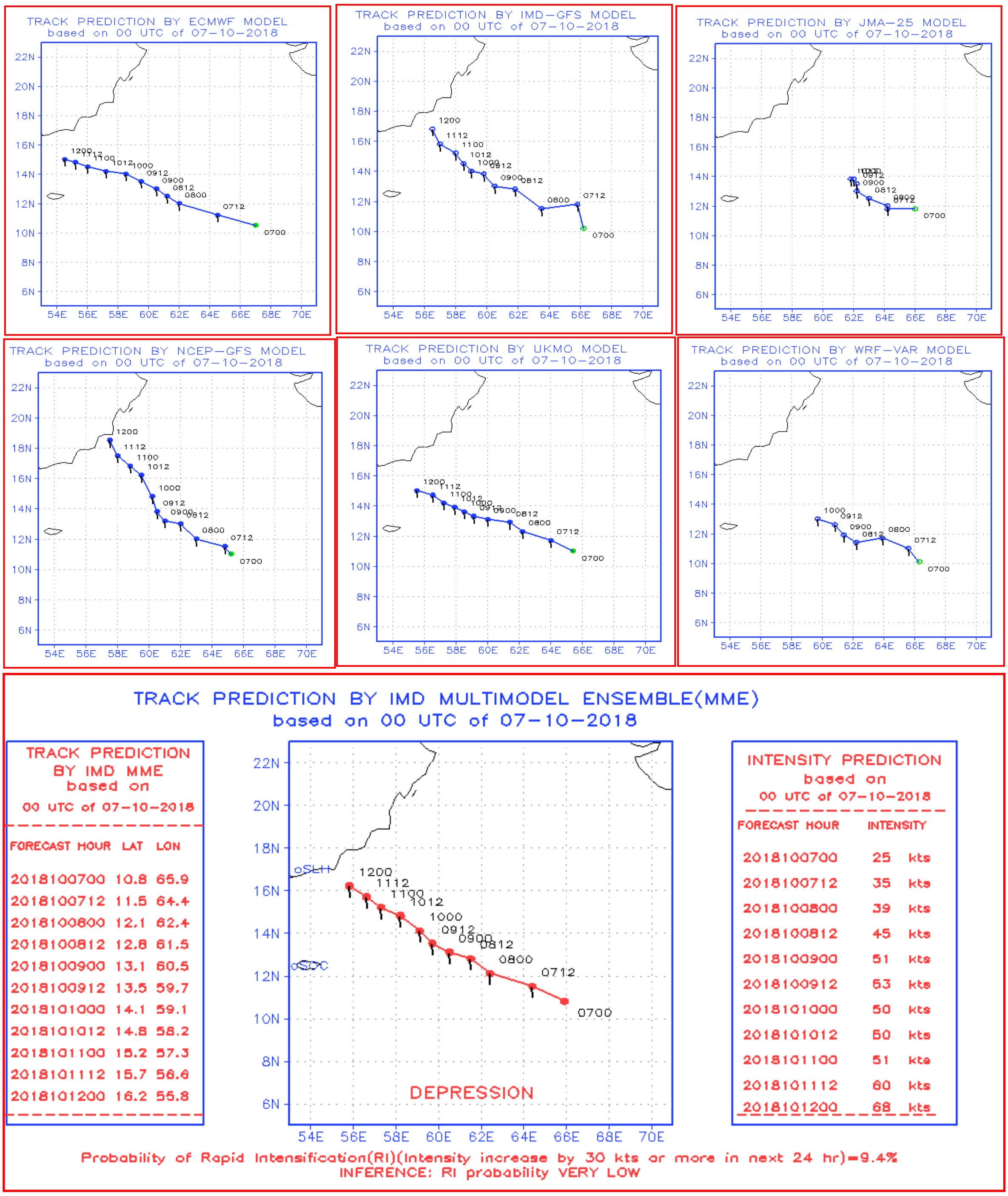


Fig.3.5.3(a). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 7th Oct. 2018

Based on 0000 UTC of 8th Oct. the models differed greatly in track forecast by the models. IMD GFS and NCEP GFS indicated landfall over south Oman during 1200-1800 UTC of 12th Oct. All other were indicating weakening over sea.

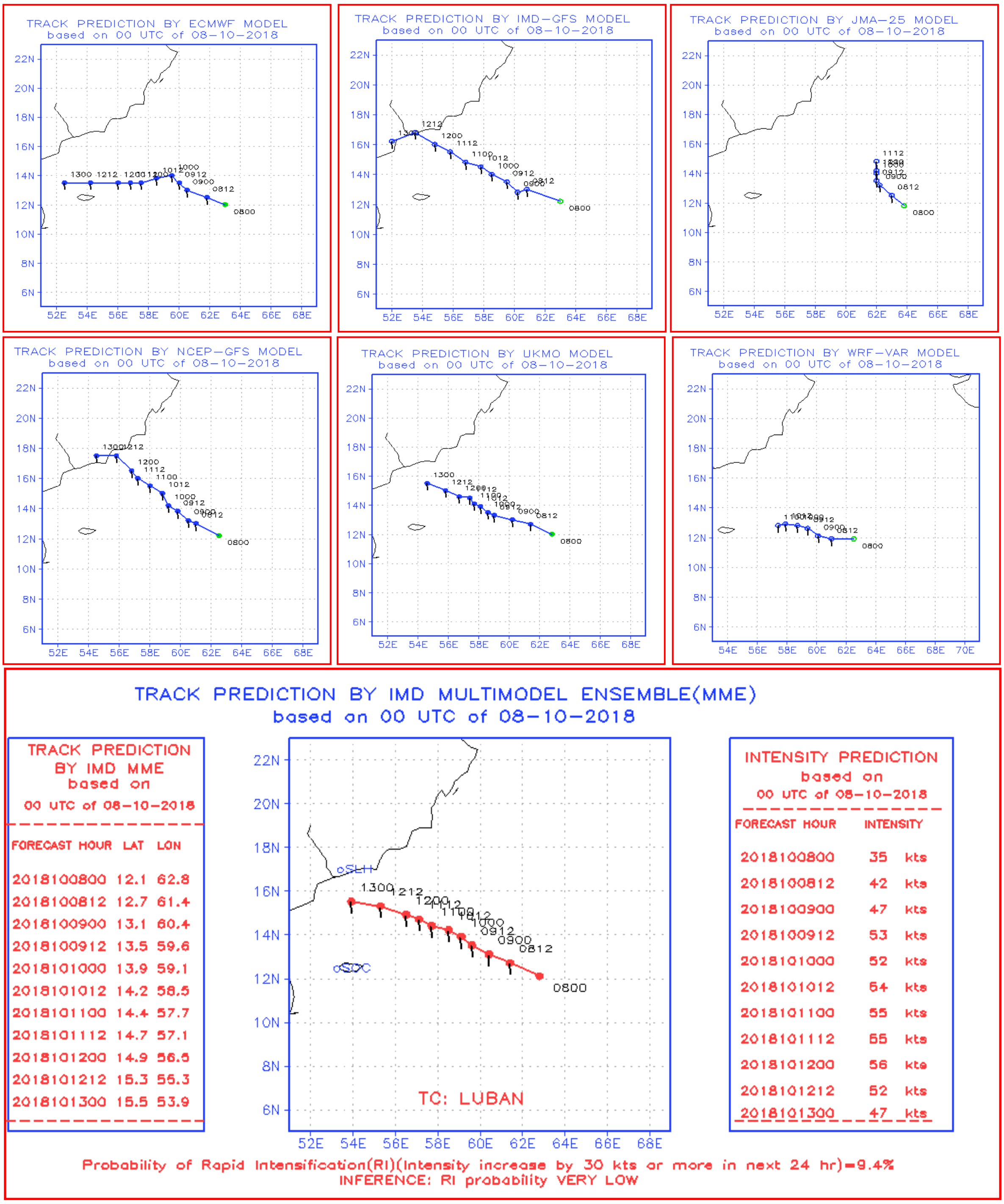


Fig.3.5.3(b). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 8th Oct. 2018

Based on 0000 UTC of 9th Oct. the models were in agreement again for northwestward movement towards Oman and adjoining Yemen coast. However, ECMWF indicated movement towards Gulf of Aden. IMD GFS, NCEP GFS, UKMO and MME indicated landfall near Yemen and adjoining Oman coast. JMA & WRF indicated weakening over westcentral Arabian Sea.

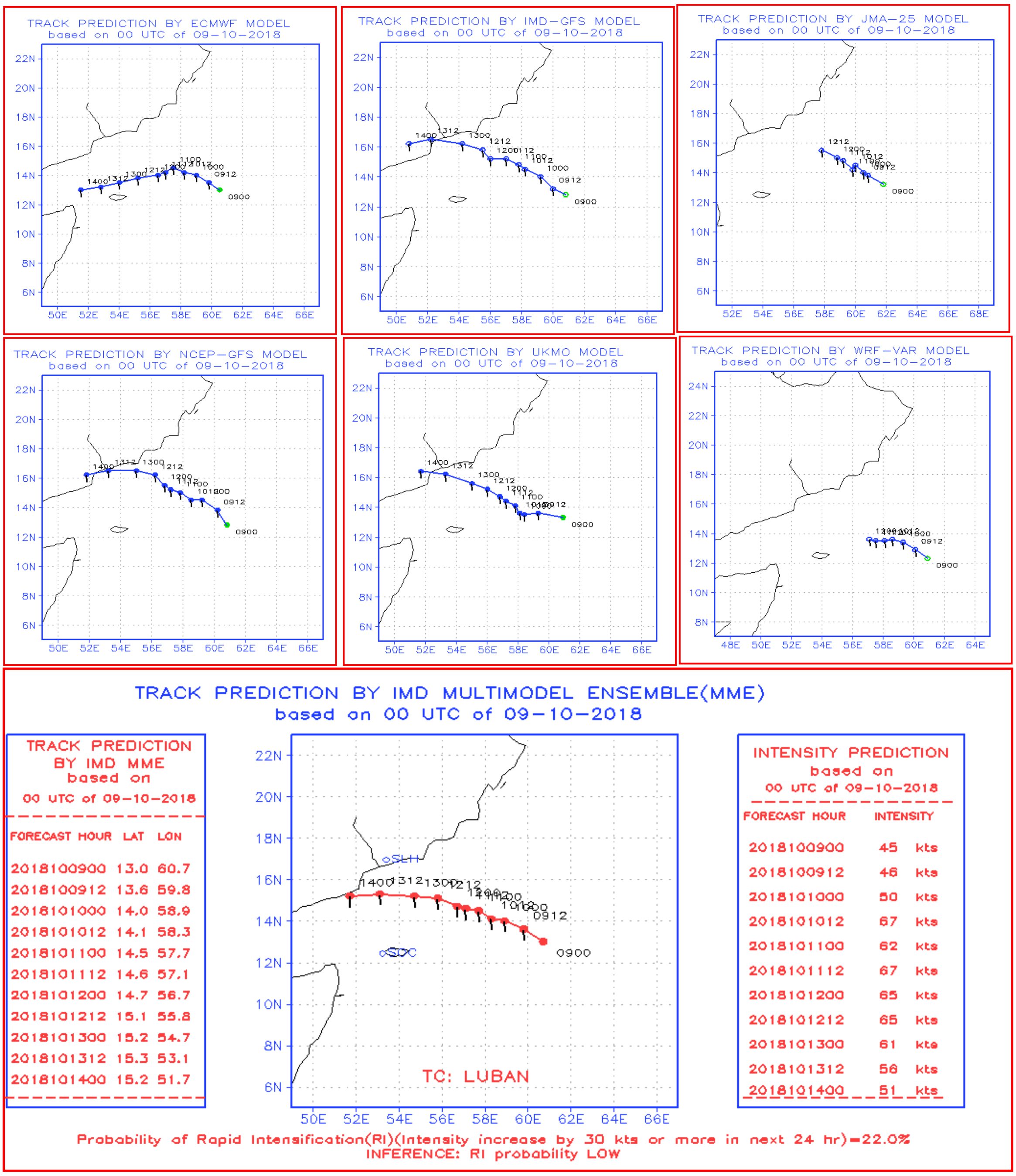


Fig.3.5.3(c). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 9th Oct. 2018

Based on 0000 UTC of 10th Oct. the models were in agreement again for northwestward movement towards Oman and adjoining Yemen coast. However, ECMWF indicated movement towards Gulf of Aden. IMD GFS, NCEP GFS, UKMO and MME indicated landfall near Yemen and adjoining Oman coast. WRF indicated weakening over westcentral Arabian Sea.

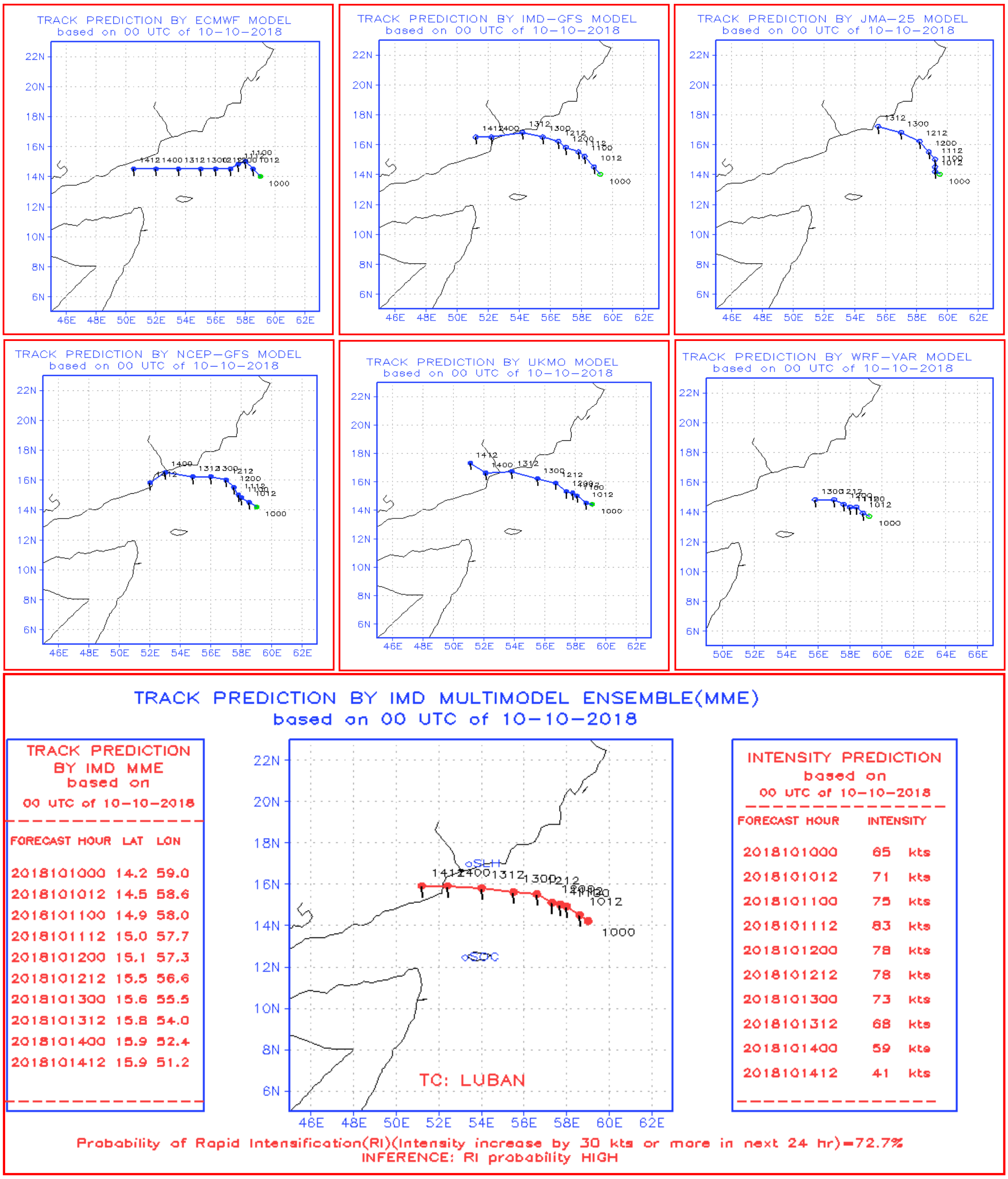


Fig.3.5.3(d). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 10th Oct. 2018

Based on 0000 UTC of 11th Oct. the models were in agreement again for northwestward movement towards Oman and adjoining Yemen coast. However, ECMWF indicated movement towards Gulf of Aden. IMD GFS, NCEP GFS, UKMO and MME indicated landfall near Yemen and adjoining Oman coast.The ECMWF, NCEP GFS indicated west-southwestward movement on 14th and MME from 1200 UTC of 14th.

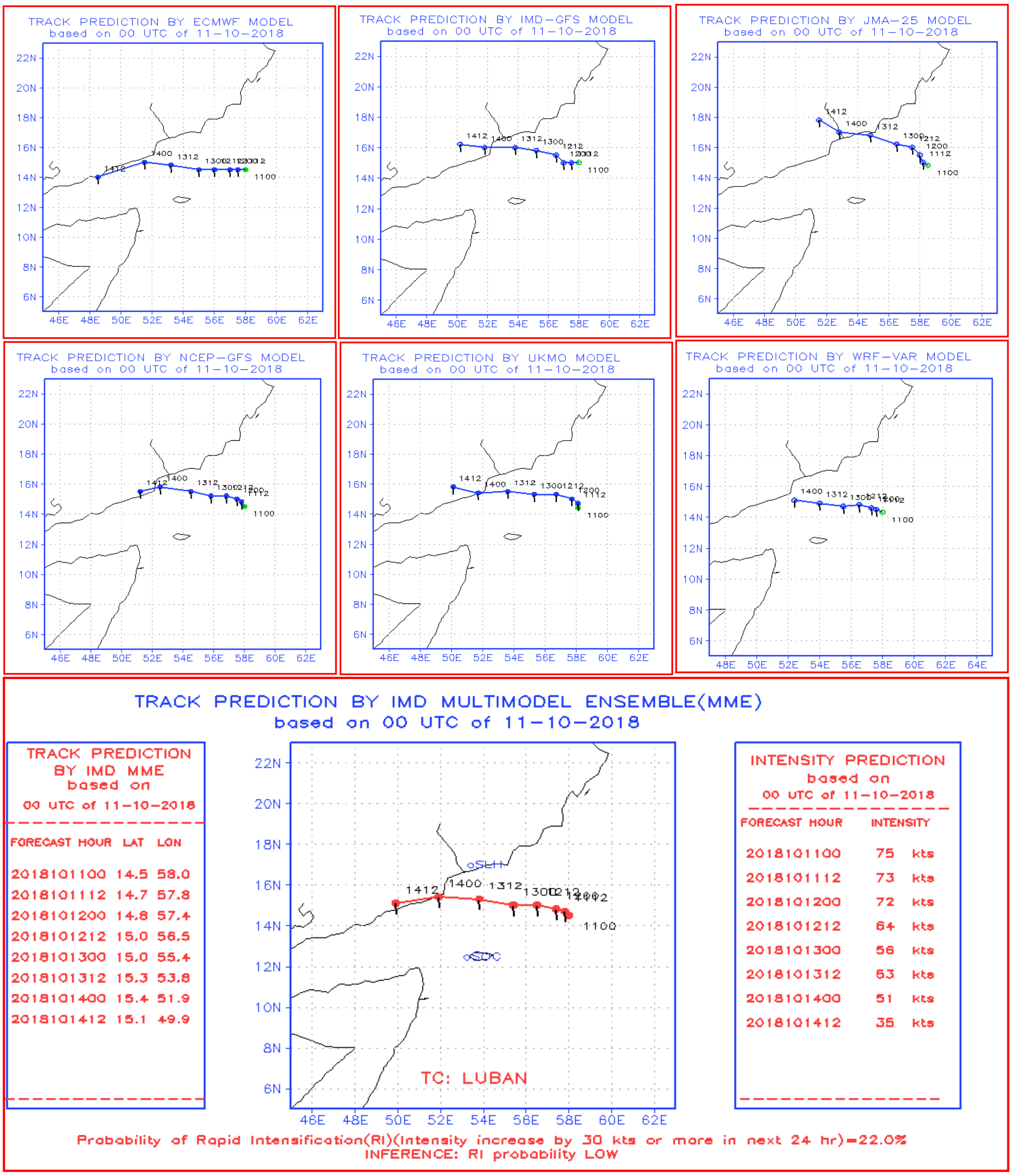


Fig.3.5.3(e). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 11th Oct. 2018

Based on 0000 UTC of 12th Oct. the models were in agreement again for northwestward movement towards Oman and adjoining Yemen coast. However, ECMWF, NCEP GFS and MME indicated movement towards Gulf of Aden skirting Yemen coast. IMD GFS, NCEP GFS, UKMO indicated landfall near Yemen coast.

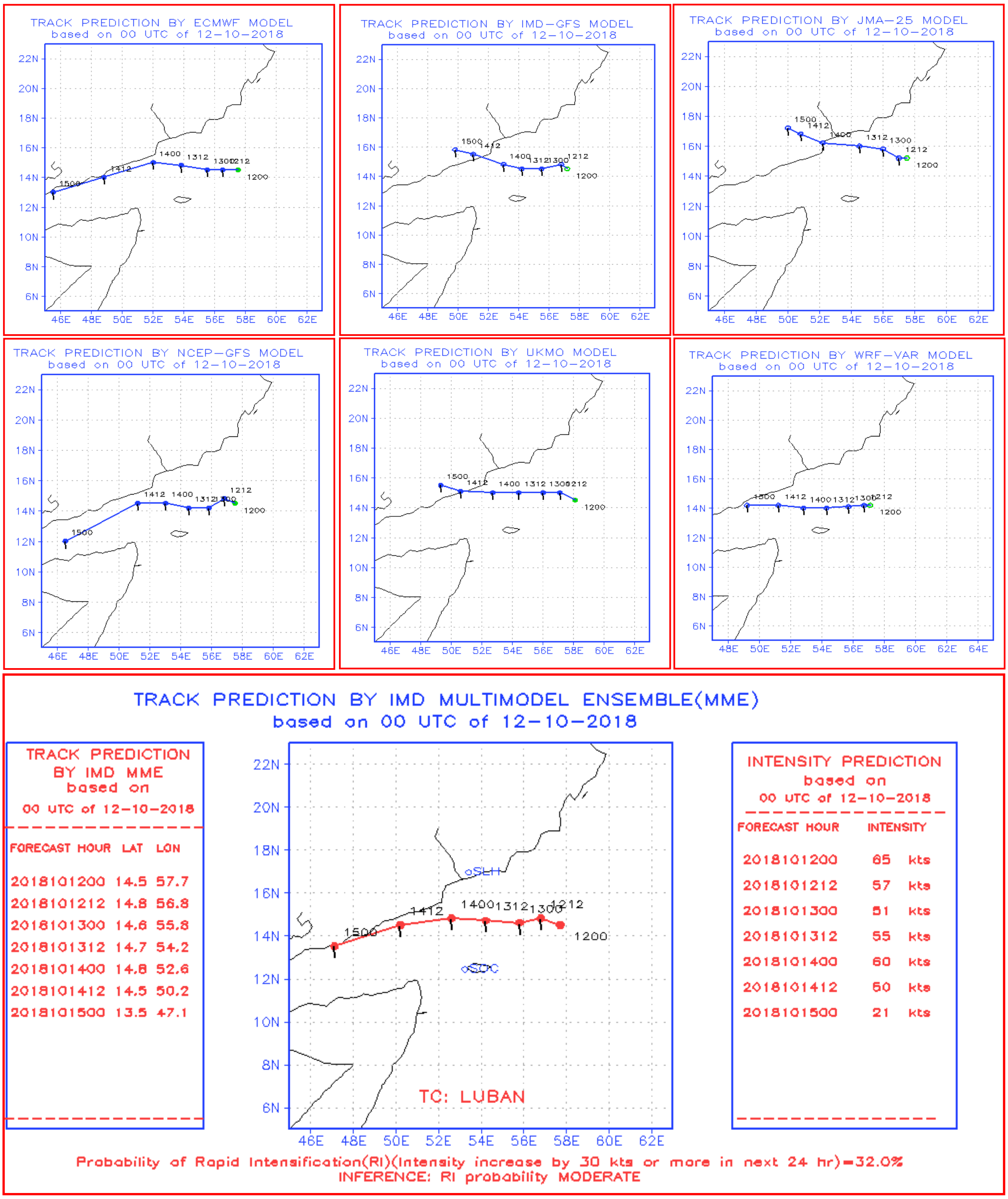


Fig.3.5.3(f). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 12th Oct. 2018

Based on 0000 UTC of 13th Oct. the models were in agreement for initial west-northwestward movement towards Yemen coast and then west-southwestward movement. However, ECMWF, NCEP GFS and MME indicated movement towards Gulf of Aden skirting Yemen coast. IMD GFS, JMA and UKMO indicated landfall near Yemen coast.

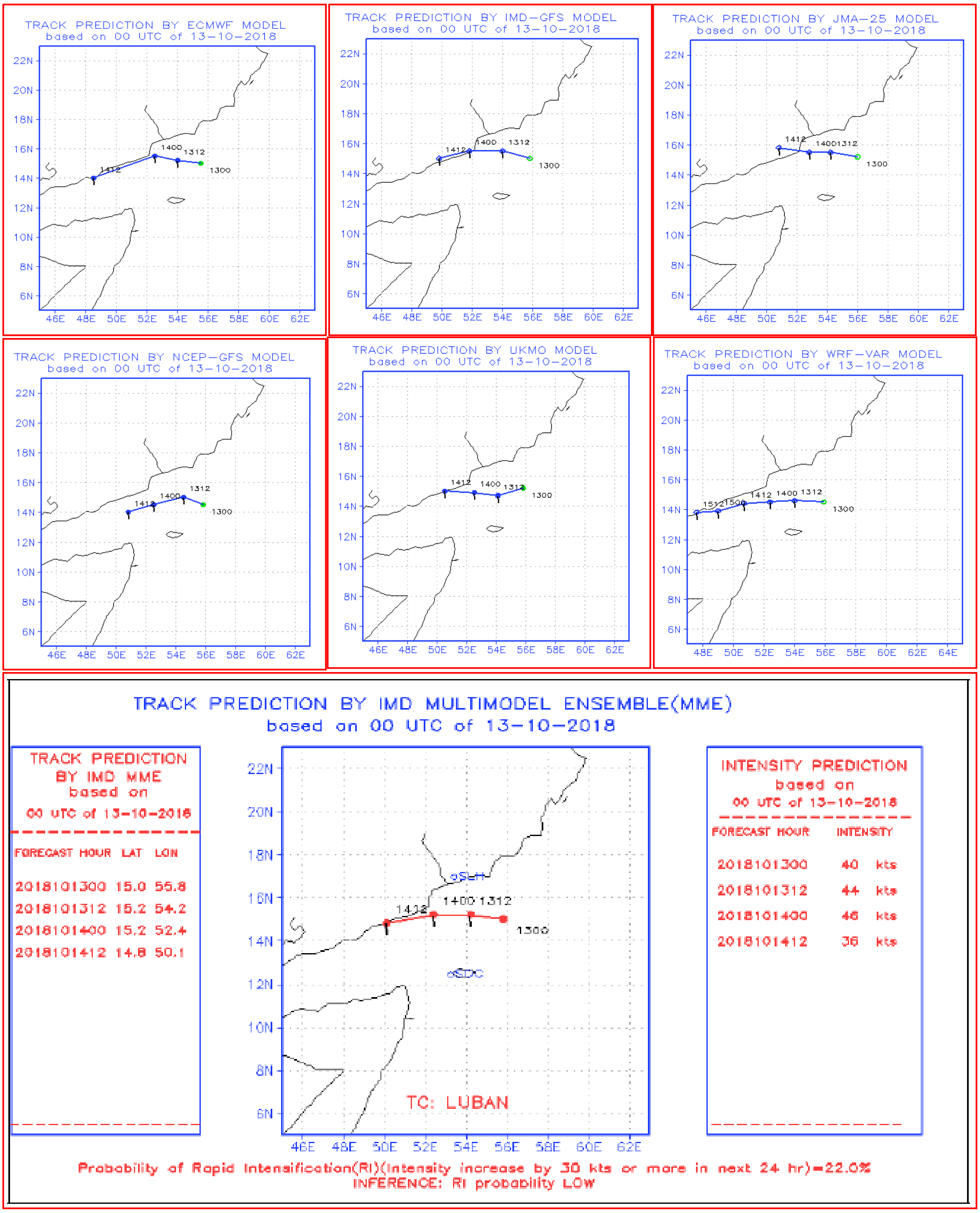


Fig.3.5.3(g). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 13th Oct. 2018

Based on 1200 UTC of 13th Oct. all the models except NCEP GFS indicated west-northwestward movement and landfall over Yemen. The NCEP GFS model showed west-southwestward movement towards Gulf of Aden.

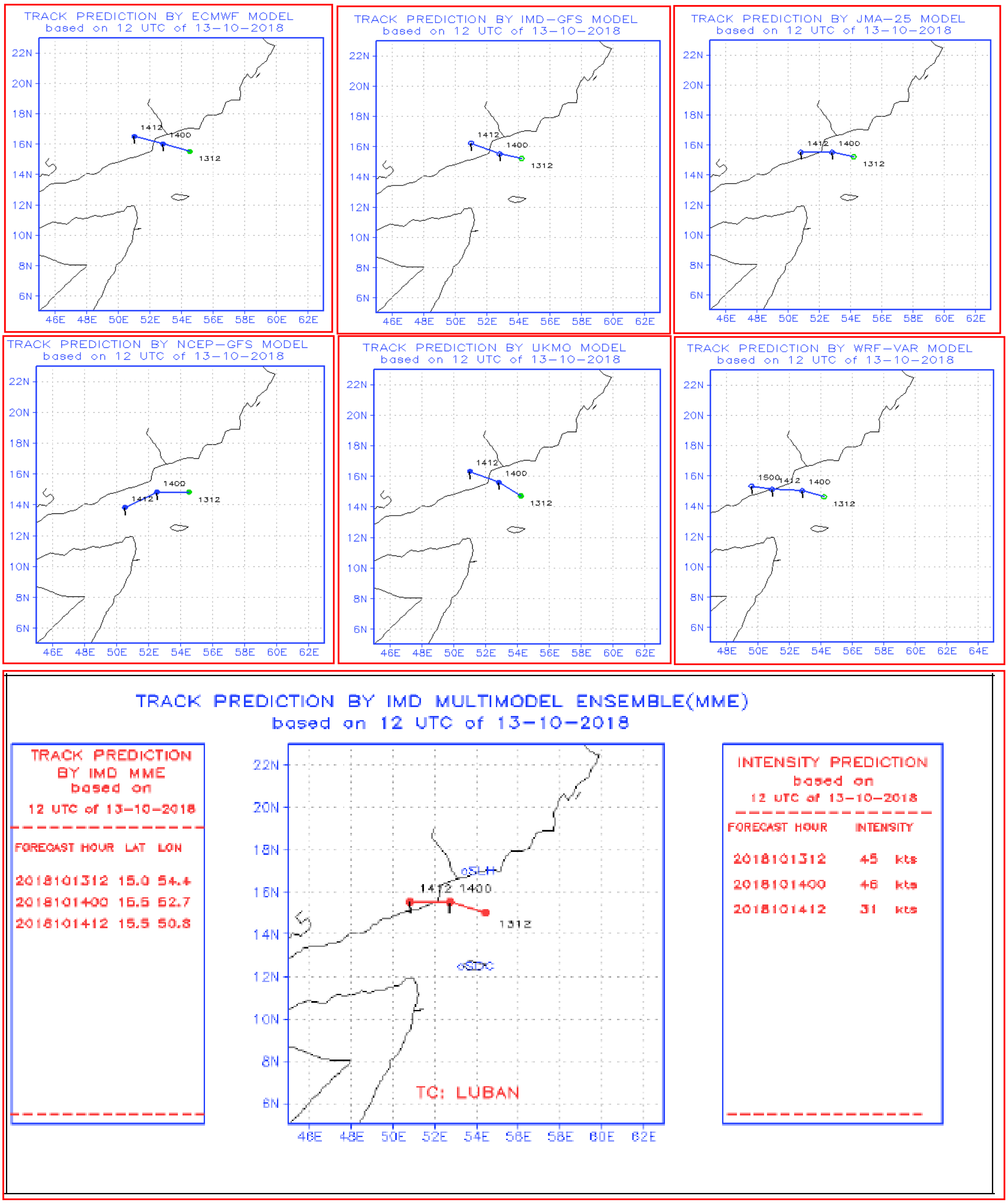
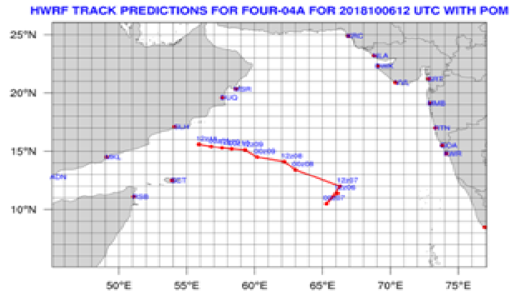
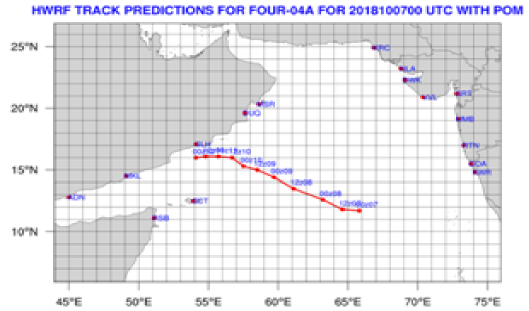


Fig.3.5.3 (h). Track prediction by indivdual NWP models and multi-model ensemble technique based on 0000 UTC of 7th Oct. 2018

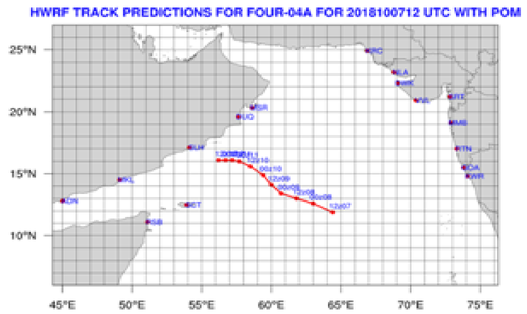
The track and intensity prediction by IMD-HWRF model for VSCS, Luban is presented in Fig.3.5.4. It indicates that the model could predict the track reasonably well indicating northwestward movement towards Yemen and adjoining south Oman coast based on 1200 UTC of 6th and 00 and 12 UTC of 7th. However, based on 00 UTC of 8th, it indicated west-southwestward movement towards Gulf of Aden after 72 hrs.



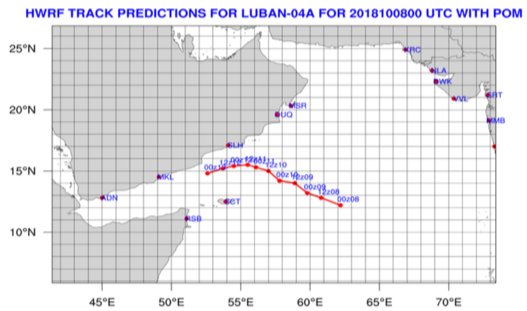
Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z06	11.4	66.1	1004	26.
00z07	10.5	65.3	999.	45.
12z07	12.0	66.3	996.	43.
00z08	13.4	63.0	995.	53.
12z08	14.1	62.2	989.	48.
00z09	14.5	60.2	986.	60.
12z09	15.1	59.3	980.	52.
00z10	15.2	58.3	967.	69.
12z10	15.3	57.6	958.	85.
00z11	15.4	56.8	960.	86.
12z11	15.6	55.9	964.	76.



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z07	11.7	65.8	1002	27
12z07	11.8	64.6	994.	36
00z08	12.6	63.2	992.	40
12z08	13.5	61.1	984.	57
00z09	14.4	59.7	985.	45
12z09	15.0	58.5	980.	49
00z10	15.3	57.5	977.	54
12z10	16.0	56.7	968.	64
00z11	16.1	55.7	972.	64
12z11	16.1	54.8	973.	63
00z12	16.0	54.1	975.	66



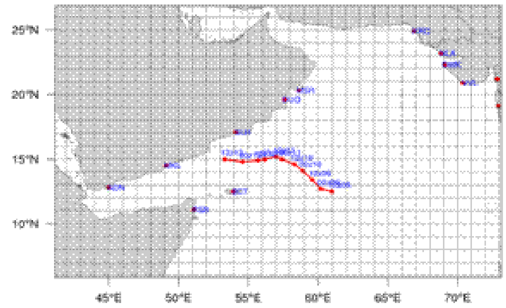
Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z07	11.9	64.4	1001	26.
00z08	12.6	63.0	992.	36.
12z08	13.0	61.8	984.	46.
00z09	13.4	60.7	982.	47.
12z09	14.1	60.0	972.	51.
00z10	14.9	59.4	964.	56.
12z10	15.6	58.5	955.	65.
00z11	16.0	57.7	958.	72.
12z11	16.1	57.2	963.	66.
00z12	16.1	56.7	966.	65.
12z12	16.1	56.2	972.	58.



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z08	12.2	62.2	999.	34
12z08	12.8	60.8	986.	51
00z09	13.2	59.8	986.	50
12z09	14.0	58.9	983.	54
00z10	14.2	57.8	978.	49
12z10	15.0	57.0	969.	66
00z11	15.3	56.1	965.	71
12z11	15.5	55.5	967.	70
00z12	15.4	54.5	975.	61
12z12	15.2	53.7	978.	62
00z13	14.8	52.6	982.	56

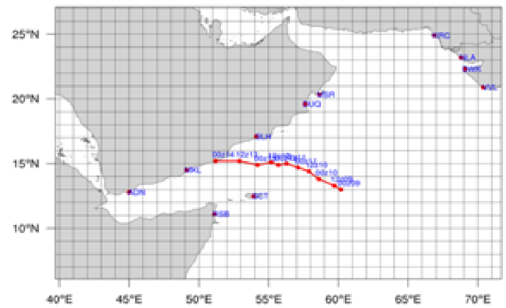
Fig.3.5.4. Track and intensity prediction by IMD-HWRF model for VSCS Luban

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018100812 UTC WITH POM



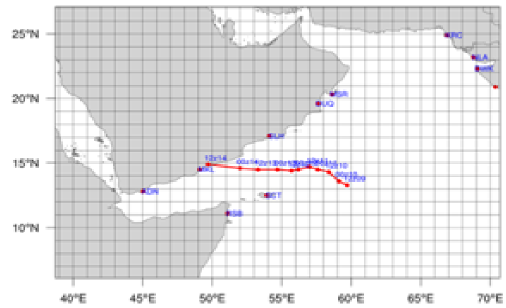
Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z08	12.5	61.0	994.	42.
00z09	12.7	60.2	990.	48.
12z09	13.4	59.6	985.	51.
00z10	14.1	58.9	980.	51.
12z10	14.6	58.3	972.	64.
00z11	15.0	57.4	966.	72.
12z11	15.2	57.0	961.	78.
00z12	15.0	56.2	969.	69.
12z12	14.9	55.7	971.	67.
00z13	14.8	54.6	972.	70.
12z13	15.0	53.3	971.	74.

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018100900 UTC WITH POM



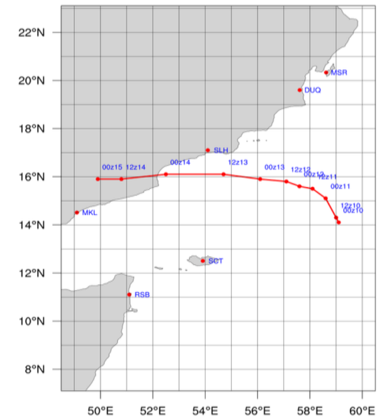
Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z09	13.0	60.2	992.	42
12z09	13.3	59.7	985.	56
00z10	13.8	58.6	986.	44
12z10	14.4	57.9	980.	53
00z11	14.7	57.1	973.	65
12z11	15.0	56.3	966.	73
00z12	14.9	55.7	973.	69
12z12	15.1	55.2	979.	58
00z13	14.9	54.2	985.	51
12z13	15.2	52.9	983.	61
00z14	15.2	51.2	989.	56

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018100912 UTC WITH POM



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z09	13.3	59.7	988.	55.
00z10	13.6	59.1	990.	44.
12z10	14.3	58.4	988.	45.
00z11	14.5	57.6	979.	59.
12z11	14.7	57.0	970.	69.
00z12	14.5	56.2	973.	68.
12z12	14.4	55.7	976.	63.
00z13	14.5	54.7	981.	58.
12z13	14.5	53.3	981.	63.
00z14	14.6	52.0	980.	65.
12z14	14.9	49.7	985.	62.

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101000 UTC WITH POM

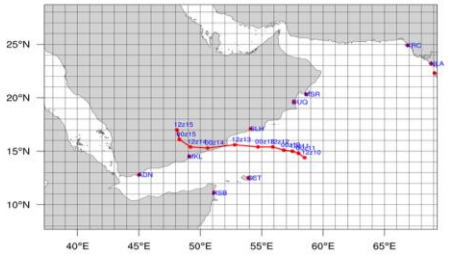


Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z10	14.1	59.1	983.	63
12z10	14.3	59.0	978.	49
00z11	15.1	58.6	979.	53
12z11	15.5	58.1	975.	60
00z12	15.6	57.6	976.	60
12z12	15.8	57.1	979.	56
00z13	15.9	56.1	983.	54
12z13	16.1	54.7	980.	62
00z14	16.1	52.5	984.	57
12z14	15.9	50.8	991.	51
00z15	15.9	49.9	996.	41

Fig.3.5.4 (contd). Track and intensity prediction by IMD-HWRF model for VSCS Luban

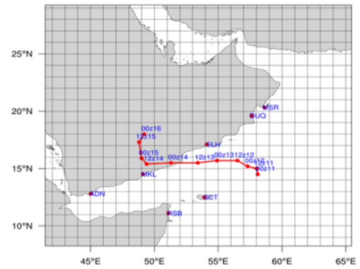
Based on 12 UTC of 8th, 00 and 12 UTC of 9th, it indicated initial northwestward movement and then nearly westward movement making landfall over Yemen coast near 15 deg. N. The predication based on 00UTC of 10th showed similar track but landfall near 16 deg. N. Similar track forecast continued based on initial condition of 12UTC of 10th and 00UTC of 11th but with landfall between 15 and 16 deg. N.

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101012 UTC WITH POM



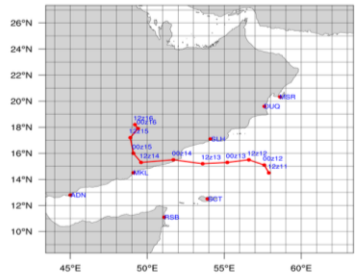
Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z10	14.4	58.5	975.	74.
00z11	14.8	58.0	972.	55.
12z11	15.0	57.5	976.	56.
00z12	15.1	56.8	980.	54.
12z12	15.4	55.9	981.	58.
00z13	15.4	54.7	983.	59.
12z13	15.6	52.8	982.	63.
00z14	15.3	50.6	991.	67.
12z14	15.4	49.2	997.	41.
00z15	16.1	48.3	1002	37.
12z15	17.0	48.1	1004	30.

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101100 UTC WITH POM



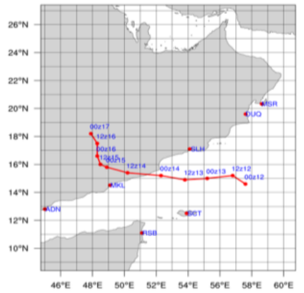
Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z11	14.5	58.1	975.	73
12z11	15.0	58.0	974.	50
00z12	15.2	57.3	983.	48
12z12	15.7	56.5	984.	50
00z13	15.7	54.9	986.	56
12z13	15.5	53.4	985.	56
00z14	15.5	51.3	989.	55
12z14	15.4	49.4	994.	50
00z15	15.9	49.0	999.	41
12z15	17.3	48.8	1003	32
00z16	18.0	49.2	1005	29

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101112 UTC WITH POM



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z11	14.5	57.9	981.	65.
00z12	15.1	57.6	983.	43.
12z12	15.5	56.6	988.	45.
00z13	15.3	55.2	989.	52.
12z13	15.2	53.6	984.	63.
00z14	15.5	51.7	986.	65.
12z14	15.3	49.6	997.	43.
00z15	16.0	49.1	1000	38.
12z15	17.2	48.9	1003	33.
00z16	17.9	49.4	1005	31.
12z16	18.2	49.2	1006	26.

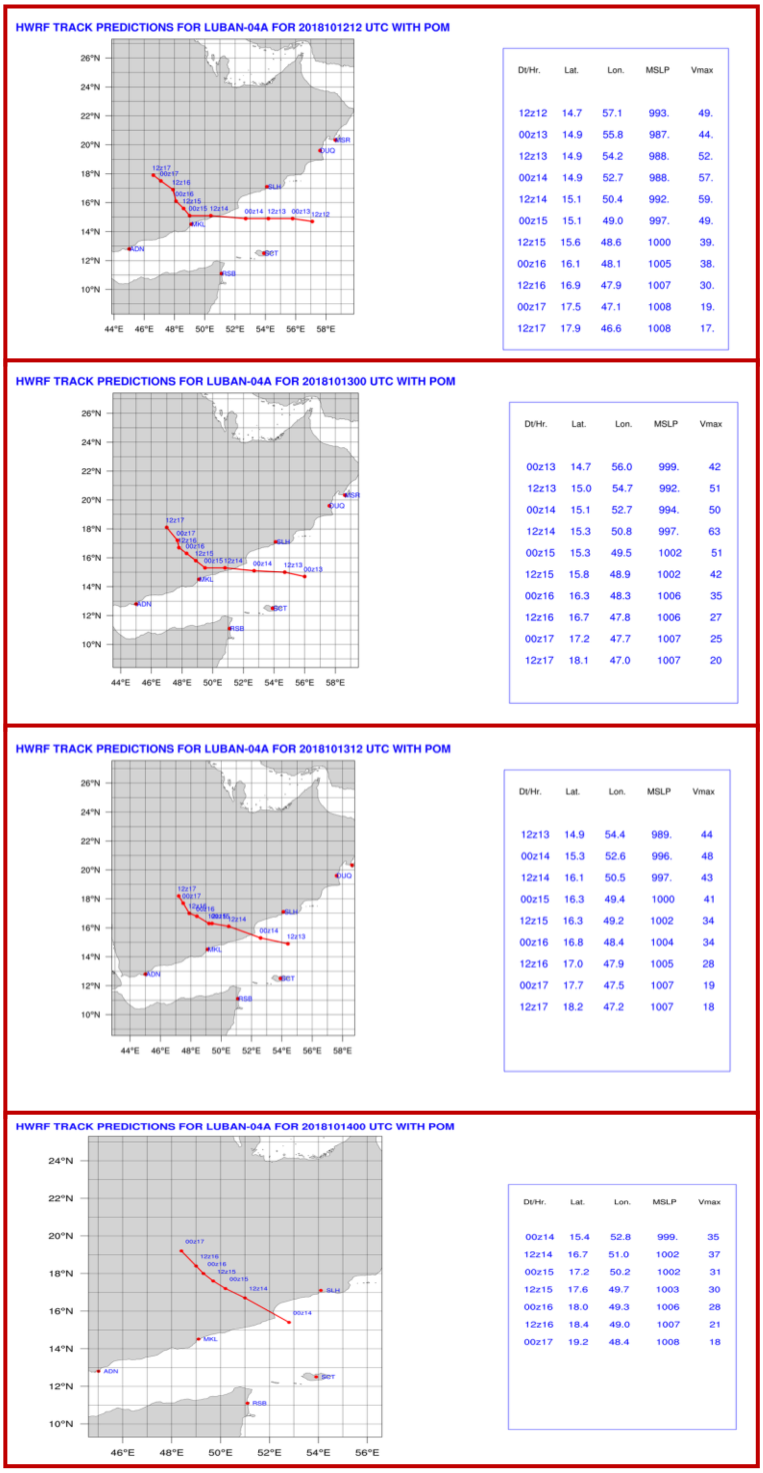
HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101200 UTC WITH POM



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z12	14.6	57.6	991.	52
12z12	15.2	56.8	987.	41
00z13	15.0	55.2	990.	45
12z13	14.9	53.8	990.	47
00z14	15.2	52.3	993.	49
12z14	15.4	50.2	999.	47
00z15	15.8	48.9	1002	49
12z15	16.0	48.5	1003	35
00z16	16.6	48.3	1007	33
12z16	17.5	48.3	1007	26
00z17	18.2	47.9	1009	19

Fig.3.5.4 (contd). Track and intensity prediction by IMD-HWRF model for VSCS Luban

The west-northwestward movement just before landfall between 15 and 16 deg. N was predicted based on initial condition of 12 UTC of 11th and 00 UTC of 12th. However again based on initial condition of 12 UTC of 12th and 00 UTC of 13th, the landfall was predicted near 15 deg. N. The northwestward movement of the system was predicted based on 12 UTC of 13th making landfall near 15.7 deg. N.



HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101212 UTC WITH POM

Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z12	14.7	57.1	993.	49.
00z13	14.9	55.8	987.	44.
12z13	14.9	54.2	988.	52.
00z14	14.9	52.7	988.	57.
12z14	15.1	50.4	992.	59.
00z15	15.1	49.0	997.	49.
12z15	15.6	48.6	1000	39.
00z16	16.1	48.1	1005	38.
12z16	16.9	47.9	1007	30.
00z17	17.5	47.1	1008	19.
12z17	17.9	46.6	1008	17.

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101300 UTC WITH POM

Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z13	14.7	56.0	999.	42
12z13	15.0	54.7	992.	51
00z14	15.1	52.7	994.	50
12z14	15.3	50.8	997.	63
00z15	15.3	49.5	1002	51
12z15	15.8	48.9	1002	42
00z16	16.3	48.3	1006	35
12z16	16.7	47.8	1006	27
00z17	17.2	47.7	1007	25
12z17	18.1	47.0	1007	20

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101312 UTC WITH POM

Dt/Hr.	Lat.	Lon.	MSLP	Vmax
12z13	14.9	54.4	989.	44
00z14	15.3	52.6	996.	48
12z14	16.1	50.5	997.	43
00z15	16.3	49.4	1000	41
12z15	16.3	49.2	1002	34
00z16	16.8	48.4	1004	34
12z16	17.0	47.9	1005	28
00z17	17.7	47.5	1007	19
12z17	18.2	47.2	1007	18

HWRF TRACK PREDICTIONS FOR LUBAN-04A FOR 2018101400 UTC WITH POM

Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z14	15.4	52.8	999.	35
12z14	16.7	51.0	1002	37
00z15	17.2	50.2	1002	31
12z15	17.6	49.7	1003	30
00z16	18.0	49.3	1006	28
12z16	18.4	49.0	1007	21
00z17	19.2	48.4	1008	18

Fig.3.5.4 (contd). Track and intensity prediction by IMD-HWRF model for VSCS Luban

Composite forecast tracks based on initial conditions of 0000, 0600 & 1200 UTC during 12 UTC of 7th to 00 UTC of 14th Oct. are presented in Fig. 3.5.5.

It indicates that most of the track forecasts indicated landfall to the south of the actual landfall point.

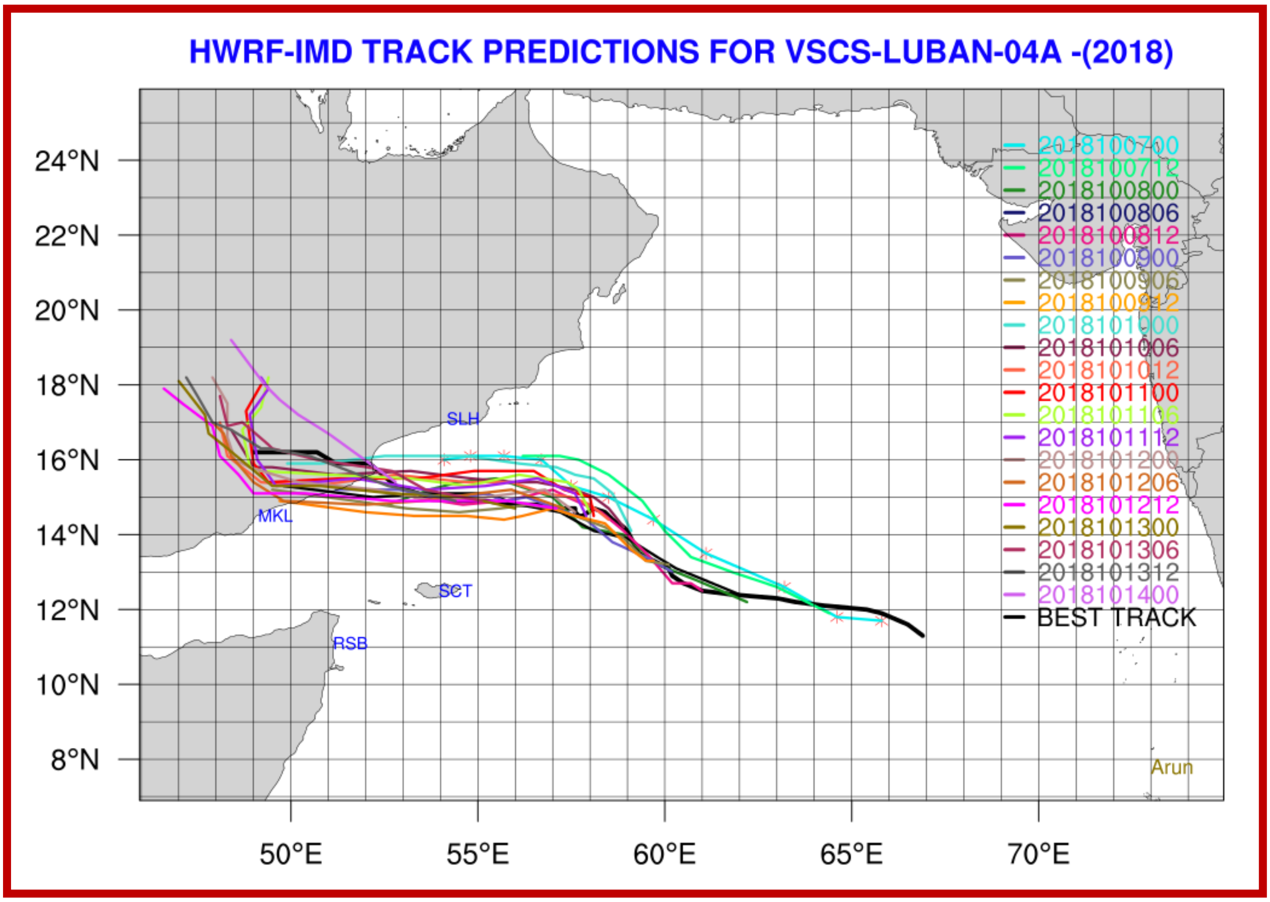


Fig. 3.5.5: Observed and forecast tracks by IMD HWRF model based on initial conditions during 1200 UTC of 7th to 0000 UTC of 14th October 2018.

3.5.3. 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 3.5.1. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast error was minimum for MME followed by ECMWF and UKMO models for 24 and 48 hr forecasts. For 72 hr forecasts, it minimum and similar for both MME and UKMO model. The error was minimum for UKMO model followed by MME for 96 and 120 hr forecasts.

Table-3.5.1. Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses)

Lead time	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	60(15)	70(15)	75(14)	105(13)	114(12)	141(12)	173(10)	213(9)	264(8)	306(7)
IMD-WRF	77(15)	92(15)	117(14)	138(13)	150(12)	147(12)	-	-	-	-
JMA	90(15)	119(15)	157(14)	189(13)	218(12)	240(12)	284(10)	-	-	-
NCEP-GFS	46(15)	70(15)	83(14)	100(13)	104(13)	160(12)	158(10)	247(9)	248(8)	371(70
UKMO	44(15)	50(15)	71(14)	71(13)	84(13)	98(12)	106(10)	122(9)	150(8)	204(7)
ECMWF	55(15)	50(15)	81(14)	70(13)	115(13)	166(12)	191(10)	218(9)	270(8)	338(7)
IMD-HWRF	51(30)	75(30)	86(28)	118(26)	148(24)	168(22)	188(20)	197(18)	205(16)	265(14)
IMD-MME	36(15)	42(15)	58(14)	54(13)	66(12)	99(12)	107(10)	145(9)	156(8)	232(7)
NCUM	-	60(14)	-	125(17)	-	148(17)	-	186(17)	-	285(14)
NEPS	-	56(14)	-	97(14)	-	138)13)	-	171(10)	-	245(9)

The landfall point and time forecast errors of the models are presented in Table 3.5.2 and 3.5.3 respectively. Either the landfall could not be predicted or the error was high in case of most of the models. Even the MME could not predict the landfall for most of the lead periods. Among the individual models, the 24 hr landfall point forecast error was minimum in case of HWRF model.

Table-3.5.2. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Lead time →	18H	30H	42H	54H	66H	78H	90H	102H	114H	126H
Based on	**13 / 12z**	**13 / 00z**	**12 / 12z**	**12 / 00z**	**11 / 12z**	**11 / 00z**	**10 / 12z**	**10 / 00z**	**09 / 12z**	**09 / 00z**
IMD-GFS	11	35	145	74	22	22	44	178	101	148
IMD-WRF	145	527	-	-	-	-	-	-	-	-
JMA	35	35	11	44	44	234	252	-	-	-
NCEP-GFS	-	-	-	-	25	0	15	24	11	67
UKMO	11	203	145	164	35	40	33	165	84	67
ECMWF	35	454	100	174	454	372	-	-	-	-
IMD-HWRF	31	0	187	241	55	35	22	16	99	176
IMD-MME	40	-	-	-	40	55	-	11	-	-

Table-3.5.3. Landfall time forecast errors (hour) at different lead time (hr)

Lead time →	18H	30H	42H	54H	66H	78H	90H	102H	114H	126H
Based on	13 / 12z	13 / 00z	12 / 12z	12 / 00z	11 / 12z	11 / 00z	10 / 12z	10 / 00z	09 / 12z	09 / 00z
IMD-GFS	-1	-8	+1	+3	-7	-8	-10	-15	-18	-20
IMD-WRF	+6	+18	-	-	-	-	-	-	-	-
JMA	-1	-1	-4	-6	-6	-13	-18	-	-	-
NCEP-GFS	-	-	-	-	+1	-3	-6	-6	-13	-10
UKMO	-2	+6	+1	+4	-6	-8	-6	-15	-15	-11
ECMWF	-2	+6	-3	-	0	+6	+6	-	-	-
IMD-HWRF	0	-3	+3	+6	-6	-12	-12	-12	0	0
IMD-MME	-1	-	-	-	-4	-6	-	-5	-	-

('+' indicates delay landfall, '-' indicates early landfall)

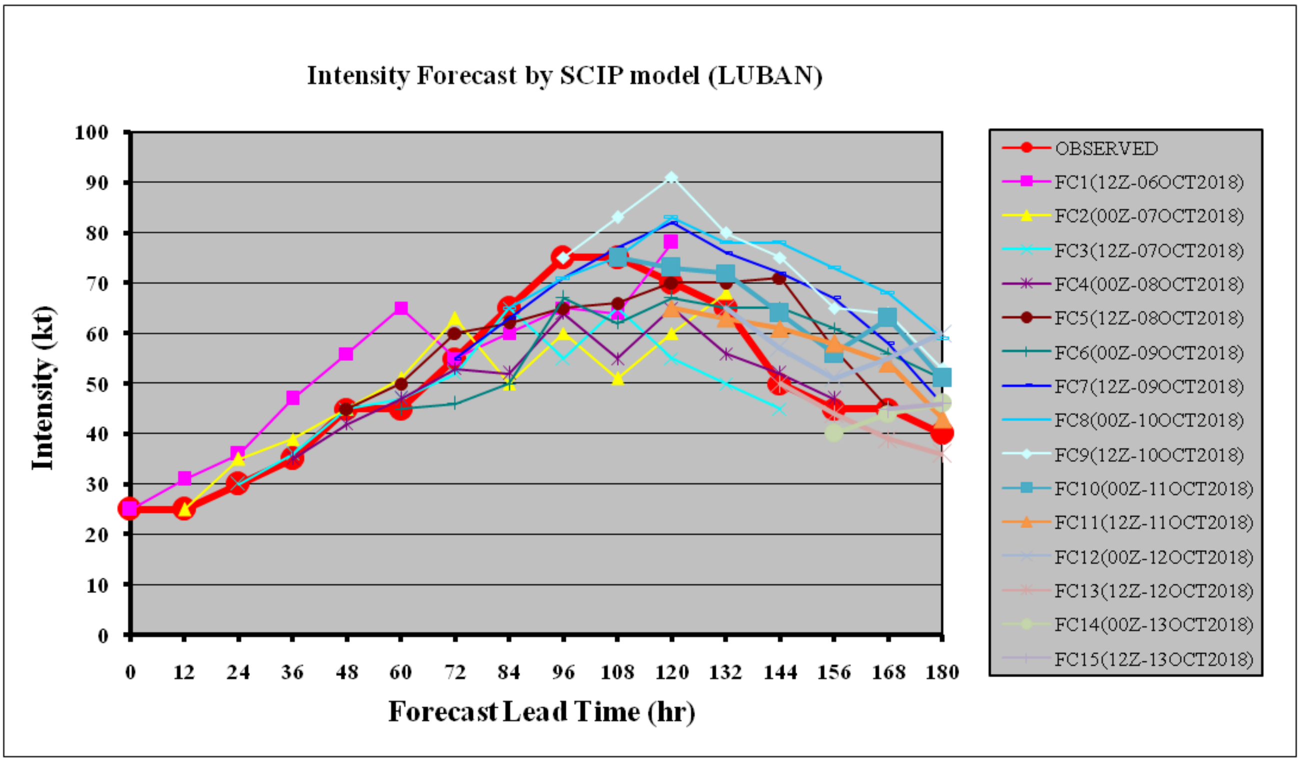


Fig.3.5.6. Intensity prediction by SCIP model of IMD

The intensity prediction by IMD SCIP model based on initial conditions of 0000 & 1200 UTC during 6th to 13 Oct. 2018 is presented in Fig. 3.5.6. Overall, SCIP underestimated intensity of the system during intensification stage and overestimated the intensity during weakening stage. The average absolute errors (AAE) and Root Mean Square errors (RMSE) are presented in Table 3.5.4 and that of HWRF model in Table 3.5.5. On comparison, the error is higher in case of HWRF model for all time scales. The error in SCIP model was also higher (more than 15 knots) for 72 and 96 hr forecasts.

Table-3.5.4 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)	4.2 (15)	6.6 (14)	7.5 (13)	12.2 (12)	11.9 (11)	13.5 (10)	12.6 (9)	15.9 (8)	9.6 (7)	4.8 (6)
IMD-SCIP (RMSE)	4.9	8.6	9.2	13.4	14.5	16.7	14.2	16.6	10.4	6.1

Table-3.5.5 Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of HWRF model (Number of forecasts verified is given in the parentheses)

Lead time →	**12H**	**24H**	**36H**	**48H**	**60H**	**72H**	**84H**	**96H**	**108H**	**120H**
HWRF (AAE)	11.1 (30)	10.8 (30)	11.4 (28)	10.4 (26)	11.5 (24)	11.0 (22)	10.9 (20)	12.2 (18)	13.6 (16)	15.6 (14)
HWRF (RMSE)	13.8	13.6	13.7	13.3	13.5	12.9	12.9	13.4	15.9	17.9

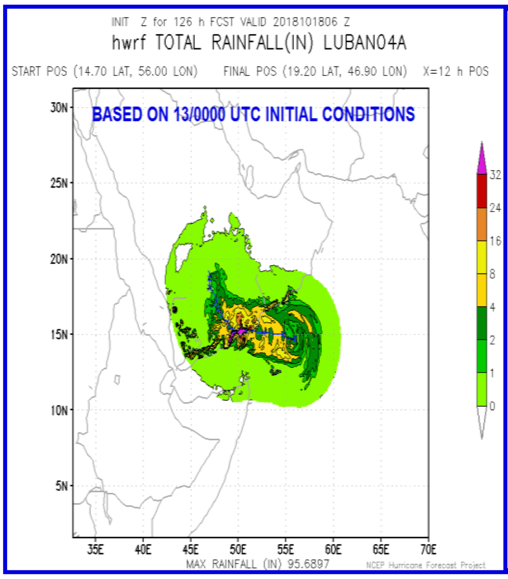
Table 3.5.6: Probability of Rapid intensification (RI) by RI Model

Forecast based on	**Probability of RI predicted**	**Probability of RI**	**Intensity changes(kt) in 24hrs**
0000UTC/07.10.2018	09.4 %	Very low	+10
0000UTC/08.10.2018	09.4 %	Very low	+10
0000UTC/09.10.2018	22.0 %	Low	+20
0000UTC/10.10.2018	72.7 %	High	+10
0000UTC/11.10.2018	22.0 %	Low	-10
0000UTC/12.10.2018	32.0 %	Moderate	-20
0000UTC/13.10.2018	22.0 %	Low	-05

The probability of rapid intensification (RI) index by MME is shown in Table 3.5.6. Rapid intensification occurred during 0600 UTC of 9th to 0600 UTC of 10th Oct. with increase in wind speed from 45 knots to 75 knots. However, the RI index couldn't predict RI of the system based on 0000 UTC of 09th, as it indicated low probability (22% probability). Though it predicted rapid intensification based on 0000 UTC of 10th with probability of 72%, there was change in intensity by 10 knots only during 0000UTC of 10th to 0000 UTC of 11th Oct.

3.5.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.3.5.7**. HWRF could successfully predict occurrence of rainfall along the predicted track even after the landfall of system. Based on 1200 UTC of 24th, the expected rainfall during 1200 UTC of 24th to 1200 UTC of 28th May is about 8-16 inches (20-40cm) over coastal areas of south Oman and southeast Yemen. It may be 20-25 inches (50-60 cm) at some places in south coastal Oman. Over interior areas of Oman, it may be around 8-10 inches (20-25 cm) during 1200 UTC of 24th to 1200 UTC of 28th May. As per the available rainfall reports from media at Oman, extremely heavy rainfall of the order of 30 cm was recorded on the day of landfall over Salalah.



Heavy Rainfall Guidance:

(i) Yemen: Based on initial conditions of 13/00 UTC, HWRF model predicts, the cumulative rainfall during the period of next 5 days (0000 UTC of 13th - 0000 UTC of 18th October) is likely to be more than 30 inches along coastal areas of Yemen around the point of landfall between longitude 48^0E & 51^0E. The intensity of rainfall gradually decreases towards interior Yemen becoming 16 -30 inches in the right forward sector.

(ii) Oman: Rainfall is expected to be 8-16 inches in some pockets in the area around Salalah in south Oman.

Fig.3.5.7: Typical Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 13th October, 2018

3.5.5. Storm surge forecast

IMD predicts storm surge forecast based on guidance from INCOIS, Advance Circulation (ADCIRC) model and Indian Institute of Delhi Model. IMD predicted expected storm surge of 1 metre above astronomical tide at the time of landfall based on initial condition of 11th. It was further revised as 0.5 metre above the astronomical tide based on 0000 UTC of 13th Oct. Storm surge forecast by ADCIRC Model based on 0000 UTC observations of 13th Oct. 2018 is presented in **Fig.3.5.8**.

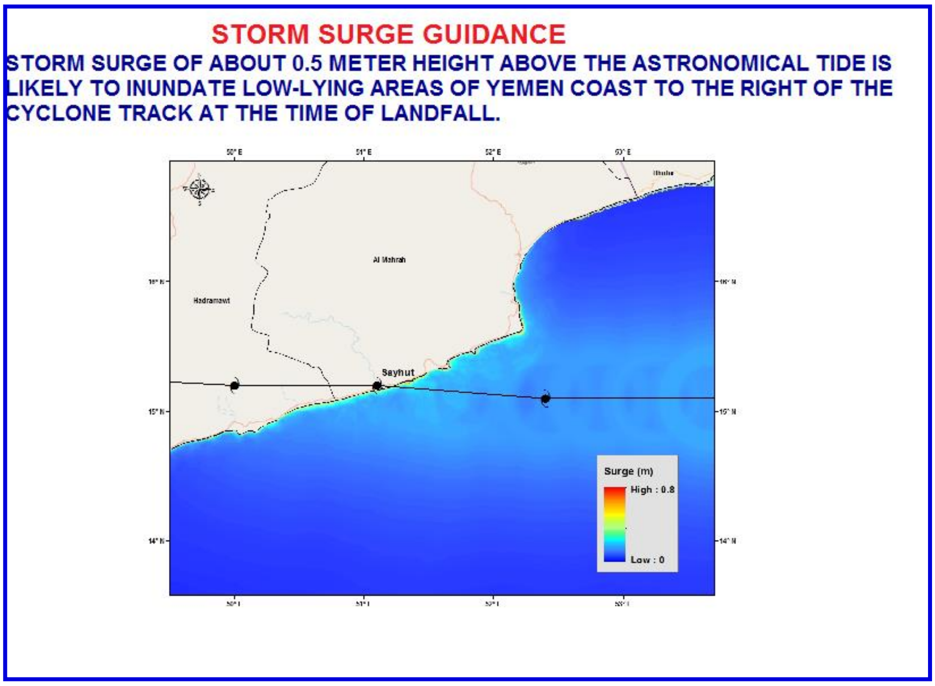


Fig.3.5.8: Typical Storm Surge guidance from INCOIS based on 0000 UTC of 13th October 2018.

3.6 Very Severe Cyclonic Storm "Titli" over Eastcentral Bay of Bengal (08-13 October 2018)

3.6.1. Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for VSCS Titli

Fig. 3.6.1 shows the predicted zone of cyclogenesis based on 0000 UTC of 3rd to 8th October for 0000 UTC of 8th October.

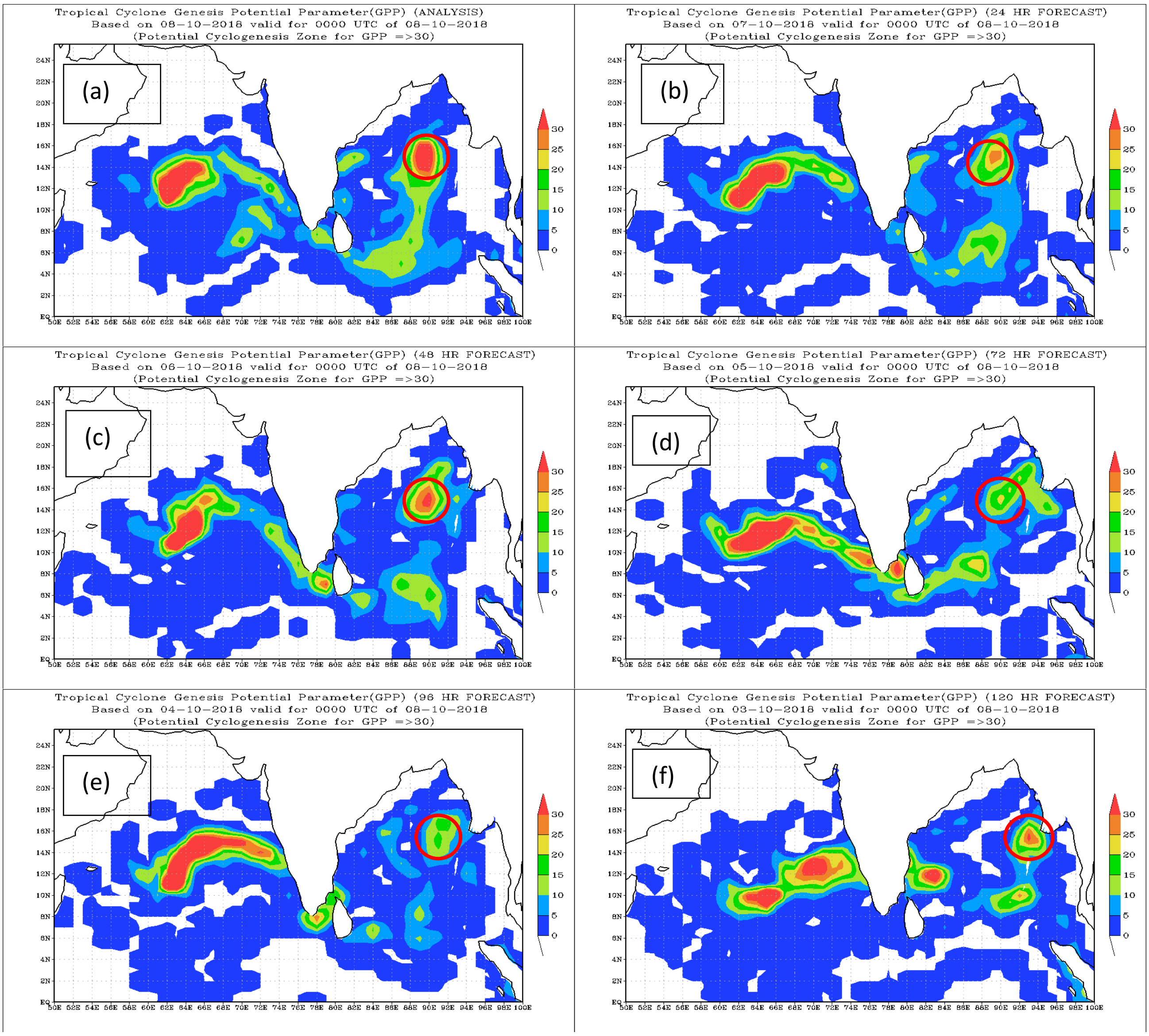


Fig. 3.6.1(a-f): Predicted zone of cyclogenesis based on 0000 UTC of 3rd October (120 hours in advance) to 8th October (0 hours in advance) 2018.

The model could predict cyclogenesis zone correctly and consistently at 0000 UTC of 6th (48 hours in advance) and 0000 UTC of 3rd (120 hours in advance). At the same time it was indicating a false potential zone for cyclogenesis over southwest BoB (120 hours in advance).

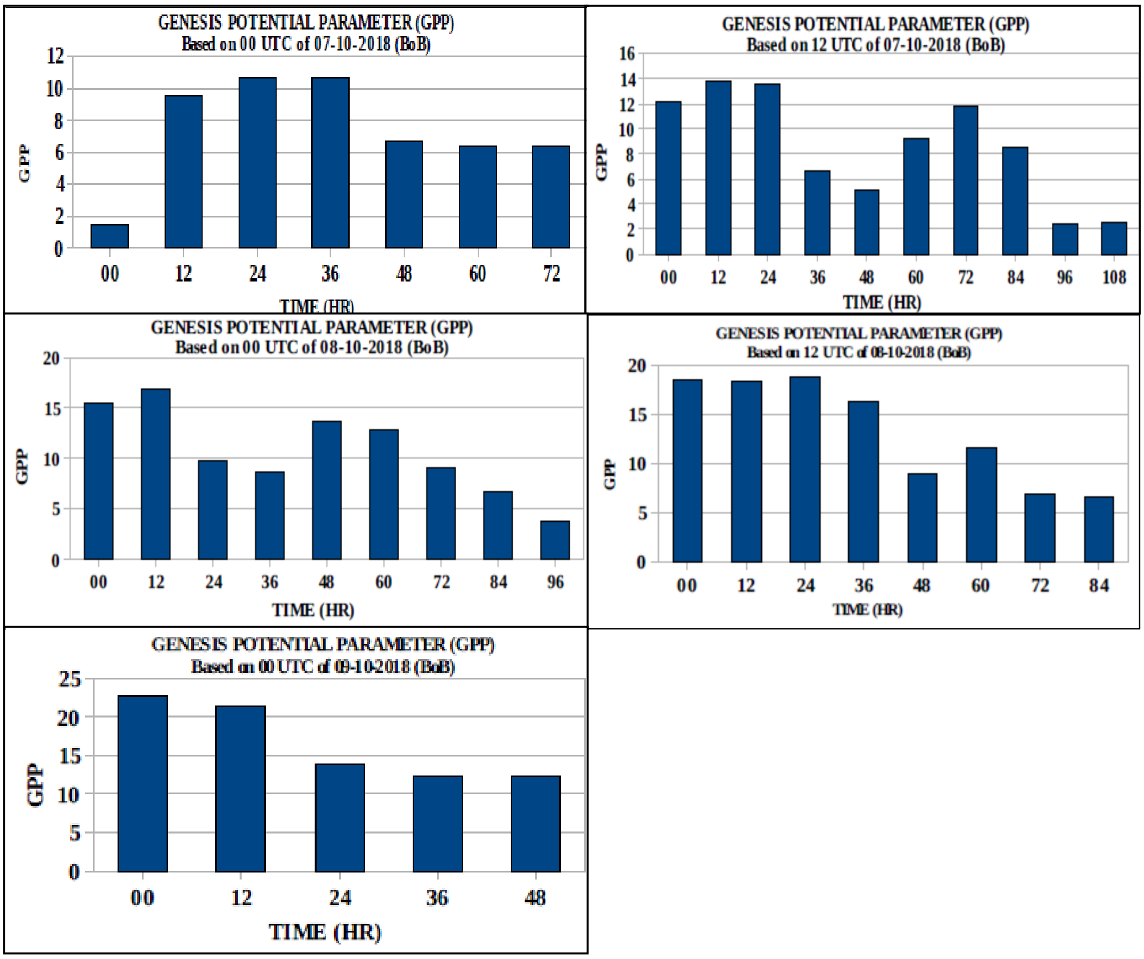


Fig. 3.6.2: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 07st and 0000 UTC of 09nd October, 2018

The area average analysis based on 0000 UTC of 7th indicated cyclogenesis during 1200 UTC of 7th to 1200 UTC of 8th with weakening trend thereafter. The analysis based on 1200 UTC of 7th indicated cyclogenesis till 1200 UTC of 8th with weakening till 1200 UTC of 9th and again cyclogenesis during 0000 UTC of 10th to 0000 UTC of 11th and no cyclogenesis thereafter. Based on 0000 UTC of 8th, it indicated cyclogenesis with intensification for next 12 hours, weakening for next 24 hours followed by intensification during subsequent 24 hours and weakening thereafter. Based on 1200 UTC of 8th, it indicated cyclogenesis during 1200 of 8th to 0000 UTC of 10th with weakening on 1200 UTC of 10th followed by intensification till 0000 UTC of 11th and weakening thereafter. Based on 0000 UTC of 9th, it indicated cyclogenesis upto 0000 UTC of 11th but with weakening trend from 0000 UTC of 10th. Thus, during initial stages it picked up cyclogeneis and intensification correctly. But weakening of system around 10th and during landfall was not correctly predicted. The system never weakened in between and during landfall.

3.6.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.3.6.3. Based on initial conditions of 0000 UTC of 9th October, all the models predicted northwestwards movement towards north Andhra Pradesh and adjoining south Odisha coasts. Most of the models were predicting landfall around noon of 11th. All models except WRF-VAR were predicting northeastwards recurvature after landfall.

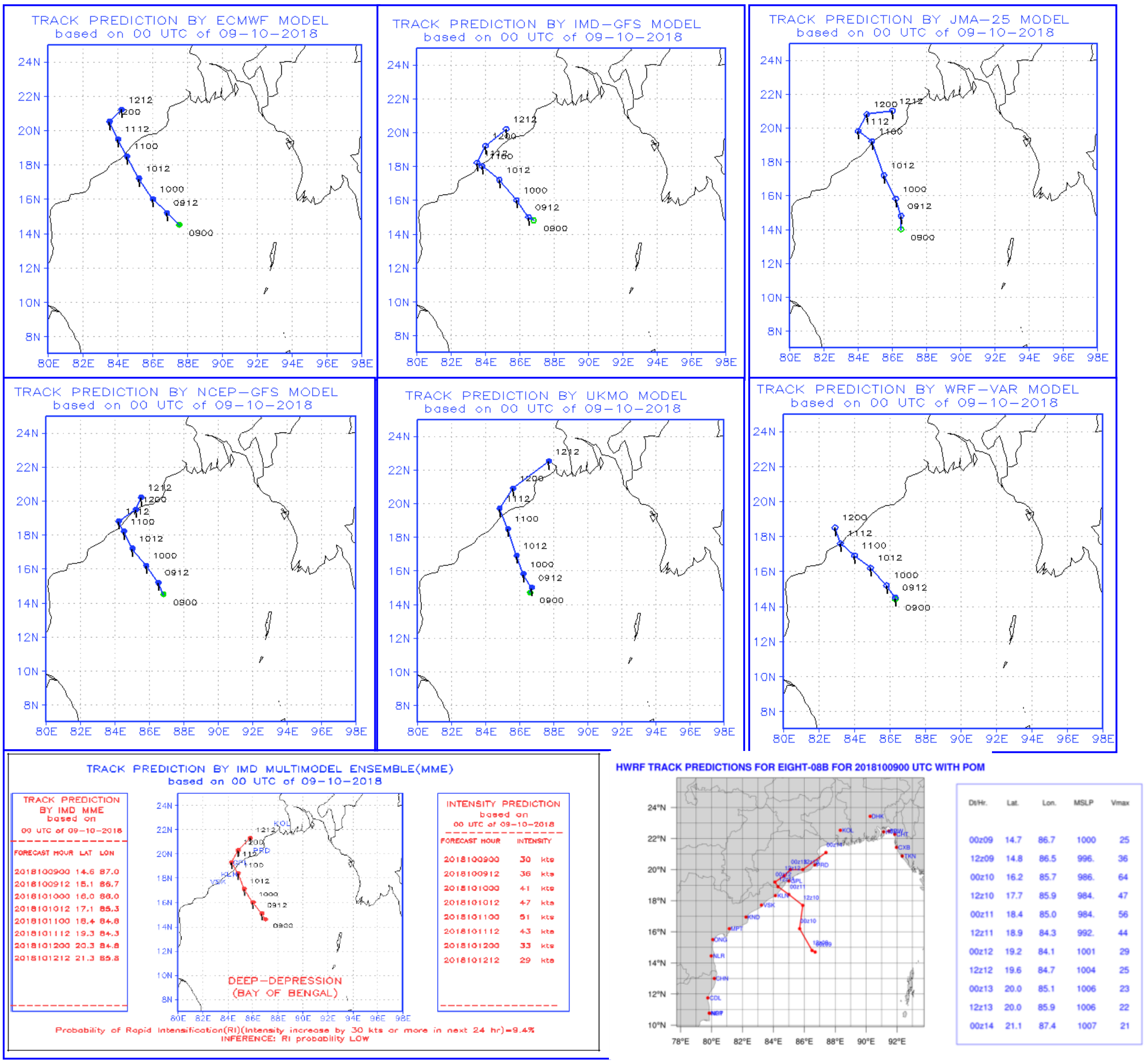


Fig. 3.6.3 (a): NWP model track forecast based on 0000 UTC of 9th October

Based on initial conditions of 0000 UTC of 10th October, all the models predicted northwestwards movement towards north Andhra Pradesh and adjoining south Odisha coasts. Most of the models were predicting landfall around 0000 UTC of 11th except WRF-VAR and NCEP GFS which were indicating landfall around 1200 UTC of 11th. All models were predicting northeastwards recurvature after landfall. IMD-MME and HWRF were correctly predicting intensity at the time of landfall around 80 kts. Both the models were also predicting rapid intensification during 0000 UTC of 10th to 11th and also rapid weakening after landfall.

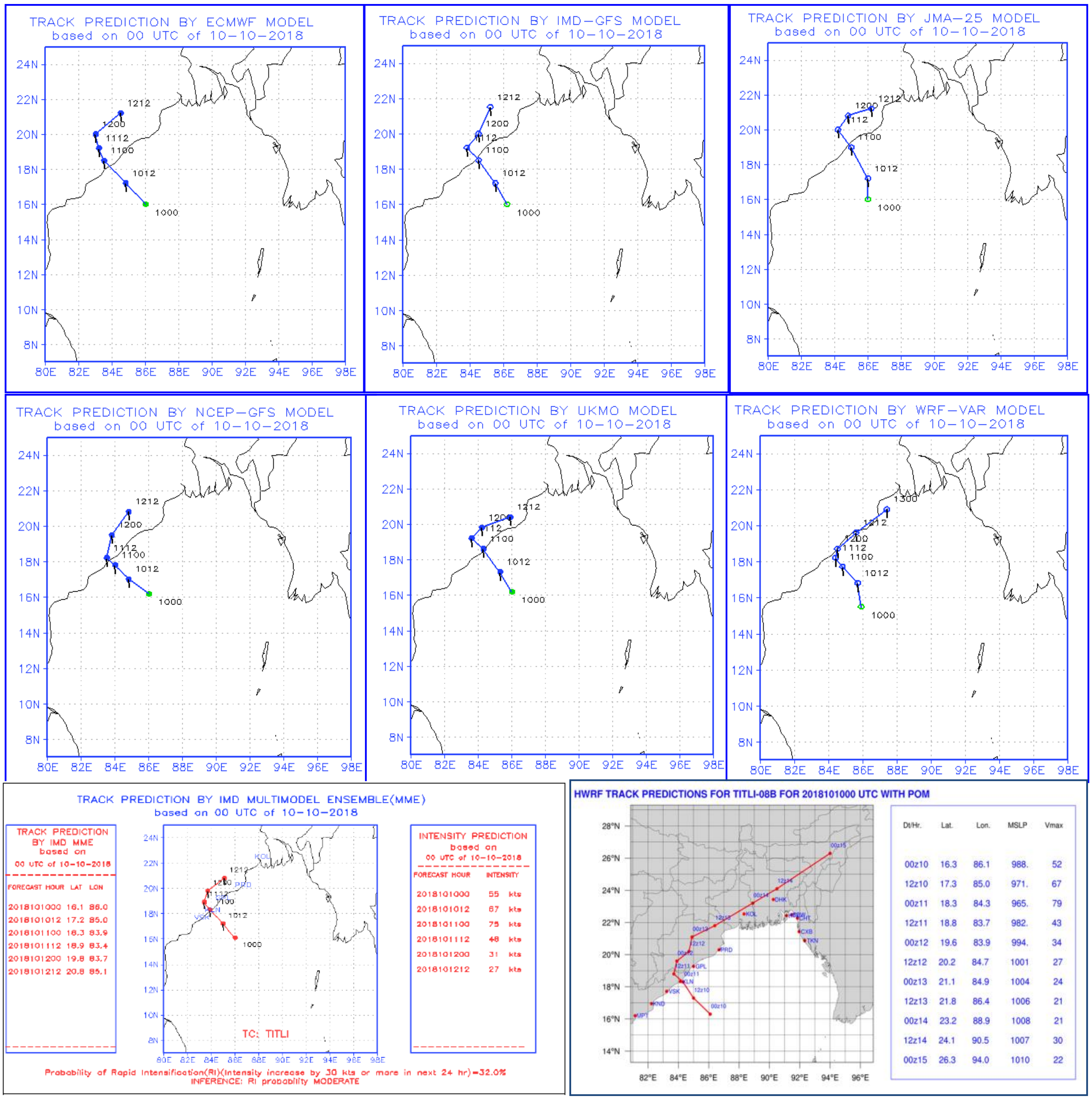


Fig. 3.6.3 (b): NWP model track forecast based on 0000 UTC of 10th October

3.6.3. 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 3.6.1. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors for 24 hours lead period were the least by UKMO followed by IMD-GFS, IMD-MME, ECMWF and HWRF. For 48 hours lead period, the errors were the least by IMD-MME followed by ECMWF and IMD GFS. For 72 hours lead period, the errors were the least by JMA followed by IMD-MME. Overall the errors were the least by MME followed by JMA for various lead periods.

Table 3.6.1: Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H
IMD-GFS	31(5)	45(5)	63(5)	77(5)	97(4)	129(3)	130(2)	76(1)
IMD-WRF	103(5)	119(5)	161(5)	197(5)	208(4)	227(3)	-	-
JMA	71(5)	80(5)	55(5)	86(5)	43(4)	37(3)	50(2)	-
NCEP-GFS	44(5)	80(5)	90(5)	93(5)	108(4)	128(3)	133(2)	-
UKMO	34(5)	36(5)	63(5)	90(5)	85(4)	134(3)	178(2)	122(1)
ECMWF	48(5)	56(5)	56(5)	83(5)	99(4)	131(3)	124(2)	119(1)
IMD-HWRF	42(9)	58(9)	84(9)	119(8)	168(6)	230(4)	210(2)	-
IMD-MME	35(5)	48(5)	60(5)	74(5)	74(4)	57(3)	46(2)	122(1)
NCUM		99(8)		153(9)		142(8)		148(6)
NEPS		99(9)		135(9)		172(8)		165(6)

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

Landfall point and time forecast errors are presented in Table 3.6.2 and 3.6.3. For 24 hours lead period, the landfall point error was within 50 km for IMD-GFS, IMD-WRF, JMA, UKMO followed by HWRF and MME. For 48 hours lead period errors were the least by MME followed by HWRF, ECMWF and NCEP GFS. Overall it can be seen that model errors were significantly less for all lead periods except IMD WRF.

Table 3.6.2: Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	12 hr	24 hr	36 hr	48 hr	60 hr
Based on	**10 /12z**	**10 /00z**	**09 /12z**	**09 /00z**	**08 /12z**
IMD-GFS	0	35	79	115	35
IMD-WRF	191	25	22	199	238
JMA	46	46	46	61	-
NCEP	35	131	99	49	92
UKMO	0	39	61	61	39
ECMWF	0	92	55	35	49
HWRF	33	69	45	22	-
IMD-MME	15	77	39	10	22

Landfall time error for all lead periods by IMD-MME, IMD-HWRF, IMD GFS, JMA and ECMWF were significantly less. Models could very well predict the landfall time of the system.

Table-3.6.3. Landfall time forecast errors (hour) at different lead time (hr)

Forecast Lead Time (hour) →	12 hr	24 hr	36 hr	48 hr	60 hr
Based on	**10 /12z**	**10 /00z**	**09 /12z**	**09 /00z**	**08 /12z**
IMD-GFS	0	0	0	0	-1
IMD-WRF	+24	+24	+1	+12	+12
JMA	0	+1	+1	0	-
NCEP	+1	+10	+12	+6	+12
UKMO	-2	0	+12	+9	0
ECMWF	+4	-2	+5	+1	+3
HWRF	0	0	+3	+6	-
IMD-MME	0	0	+6	+6	0

('+' indicates delay landfall, '-' indicates early landfall)

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

3.6.3.1. Intensity prediction by SCIP Model

The composite intensity track prediction by IMD SCIP model based on initial conditions of 0000 & 1200 UTC during 8th - 10th October is presented in Fig. 3.6.4. Overall, SCIP underestimated the intensity of the system including the peak intensity.

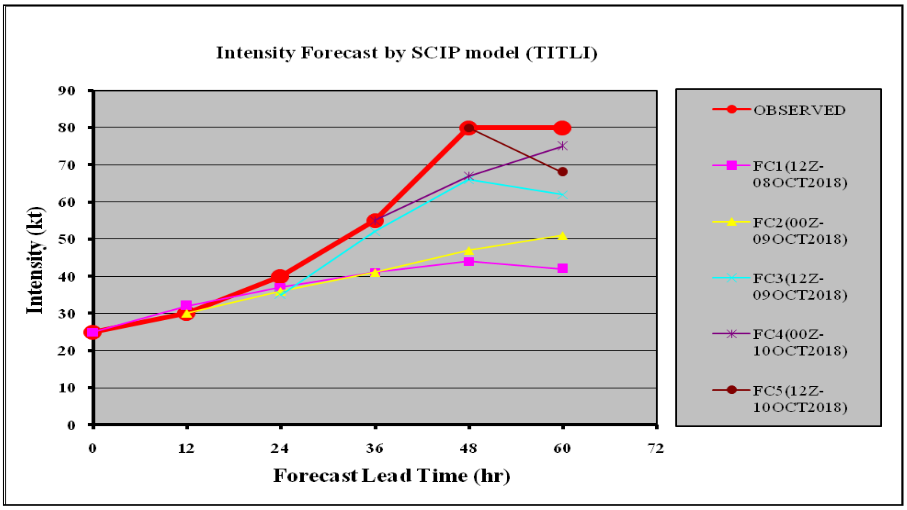


Fig.3.6.4: Intensity prediction by SCIP Model

The absolute and root mean square errors in intensity forecast by IMD SCIP and IMD HWRF are presented in Table 3.6.4. The intensity forecast errors by HWRF were significantly less as compared to IMD-SCIP for all lead periods. The comparative analysis of intensity predicted by IMD-SCIP and observed intensity is presented in Fig.3.6.5. It can be seen that IMD-SCIP overall underestimated the intensity of the model.

Table-3.6.4 Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model and HWRF model

Lead Time→	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr
IMD-SCIP (AAE)	6.8(5)	9.0(4)	21.7(3)	32.5(2)	38.0(1)		
HWRF (AAE)	7.5 (9)	7.4 (9)	9.3 (9)	8.6 (8)	2.1 (6)	2.2 (4)	2.1 (2)
IMD-SCIP(RMSE)	8.3	10.3	23.2	32.7	38.0		
HWRF(RMSE)	8.7	10.2	10.3	10.3	2.4	2.6	2.8

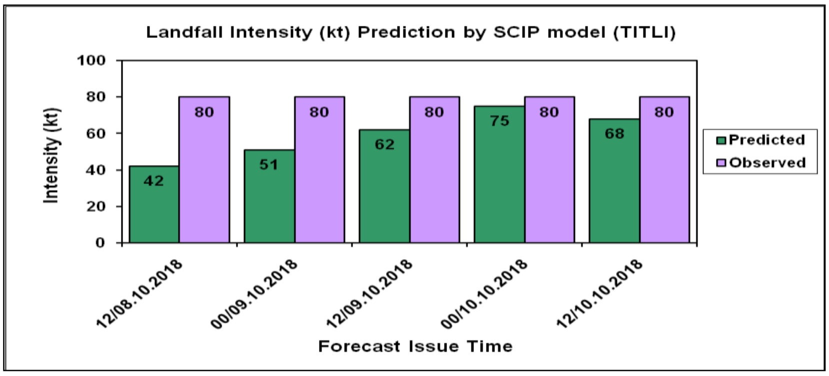


Fig. 3.6.5: **Comparative analysis of intensity predicted by IMD-SCIP and observed intensity**

3.6.3.2. Decay after landfall

Based on 0000 UTC of 11th, the decay model predicted more rapid decay as compared to actual decay in intensity of the system. However, the update based on 0600 UTC of 11th could correctly predict the decrease in intensity after landfall. Comparative analysis of intensity forecast by Decay Model based on 00 & 06 UTC of 11th October and actual intensity is presented in Fig. 3.6.6.

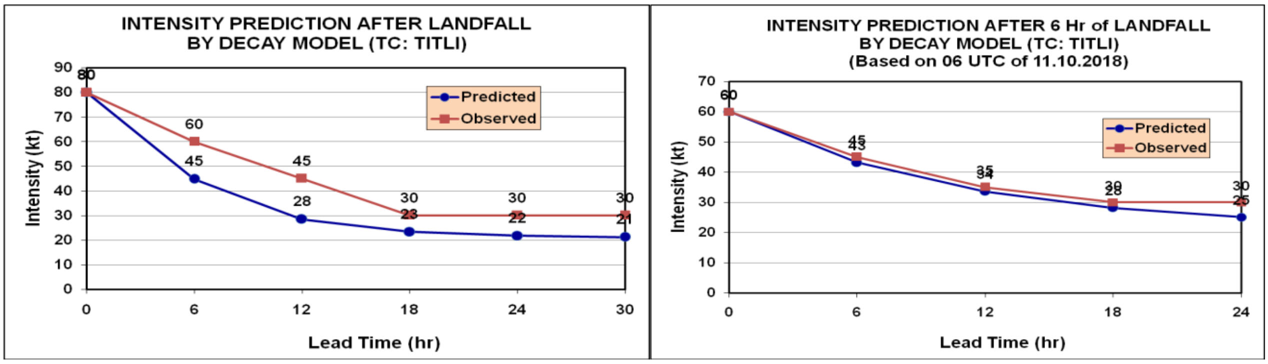


Fig. 3.6.6: Intensity prediction after landfall based on 00 & 06 UTC of 11th compared to actual intensity.

3.6.3.3. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model are presented in **Fig.3.6.7**. HWRF could successfully predict occurrence of rainfall along the predicted track even after the landfall of system. It also predicted the rainfall upto north eastern parts of the country.

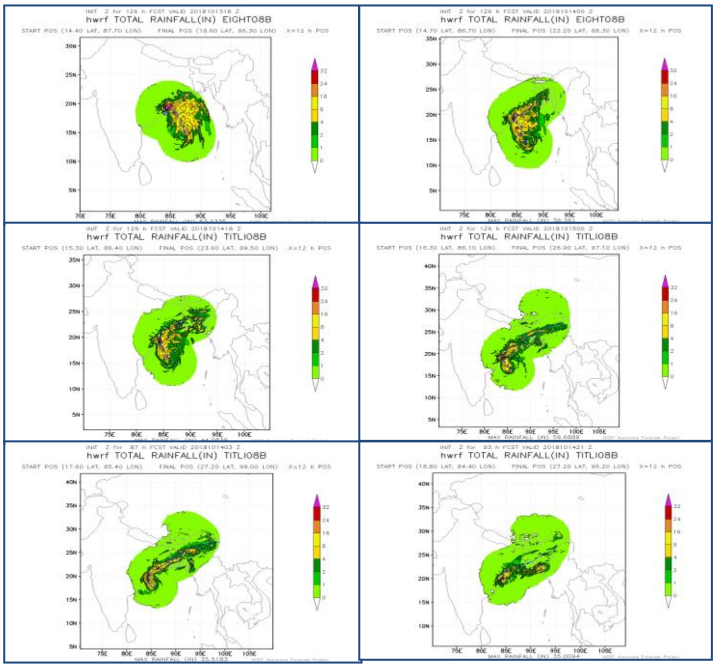


Fig.3.6.7: Heavy rainfall forecast by HWRF based on initial conditions of 00 & 12 UTC of 8th-11th October, 2018.

3.6.3.4. Storm surge forecast

IMD predicts storm surge forecast based on guidance from Advance Circulation (ADCIRC) model and Indian Institute of Delhi Model.

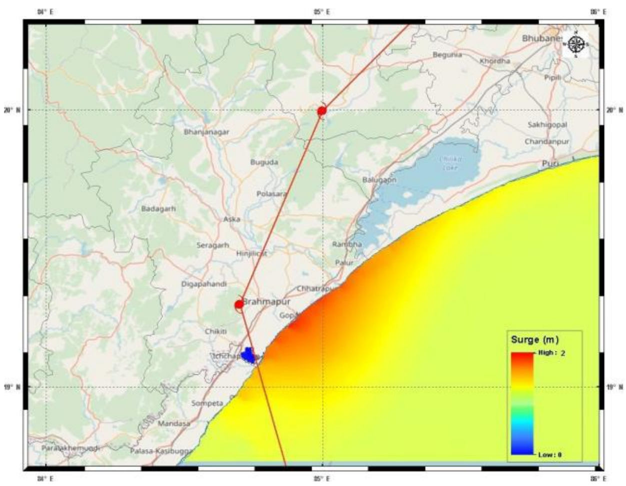


Fig. 3.6.8: Storm Surge Forecast issued by ADCIRC Model based on 1800 UTC of 10th October, 2018

IMD predicted storm surge of height of about 1.0 meter above astronomical tide to inundate low lying areas of Srikakulam district of Andhra Pradesh; Ganjam, Khurda & Puri districts of Odisha at the time of landfall. Gopalpur Port (Odisha) reported tide height of 0.85m and Palasa (Andhra Pradesh) reported tide height of about 1meter on 11th at the time of landfall. Storm surge forecast by ADCIRC Model based on 1800 UTC observations of 10th October is presented in **Fig.3.6.8**.

3.7. Very Severe Cyclonic Storm "Gaja" over southeast Bay of Bengal (10-19 November 2018)

3.7.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for GAJA

Fig. 3.7.1 (a-f) shows the predicted zone of cyclogenesis based on 0000 UTC of 5th to 10th November for 0000 UTC of 10th November. The model could predict cyclogenesis zone correctly and consistently at 0000 UTC of 10th based on 0000 UTC of 5th – 10th November over southeast and adjoining north Andaman Sea (120 hrs in advance of actual genesis). The analysis and 6 days forecast based on initial conditions of 0000 UTC of 9th November is presented in Fig. 3.7.1 (g-m). It can be seen that movement of potential zone of cyclogenesis was correctly captured by the model.

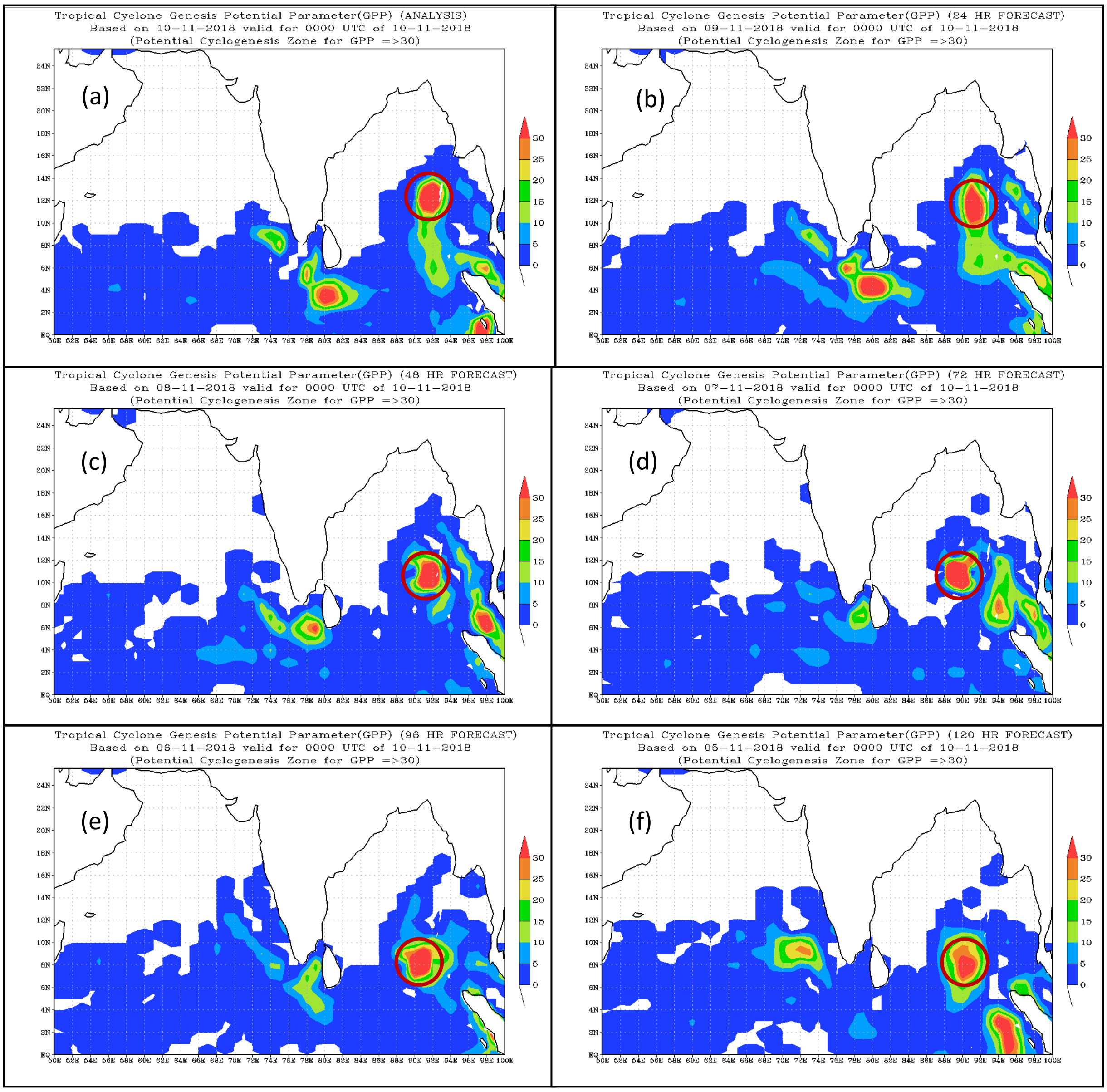


Fig. 3.7.1 (a-f): Predicted zone of cyclogenesis for 10th November based on 0000 UTC of 5th -10th November initial conditions

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 was also predicted. 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. 3.7.2) showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0). However, based on 0000 UTC analysis of 10th, the model predicted intensification upto 36 hrs and weakening trend thereafter. Similarly, the area average analysis based on 1200 UTC of 10th predicted weakening trends around 11th and 13th morning. However, the system didn't show any weakening signal till landfall. However, till 15th, the model predicted the system to maintain cyclonic storm intensity.

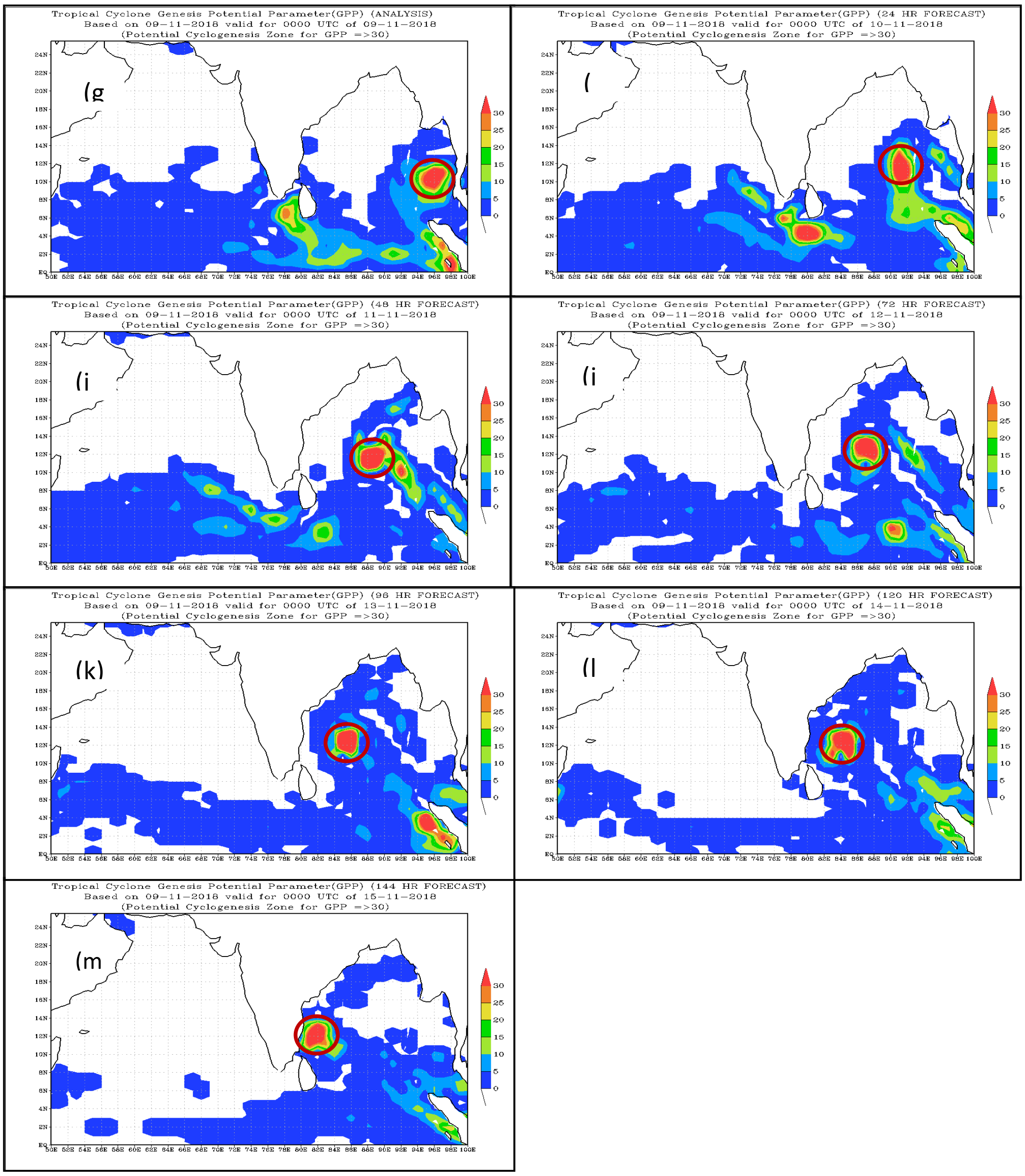


Fig. 3.7.1 (g-m): 24-hrly Predicted zone of cyclogenesis based on 0000 UTC of 9th upto144 hours

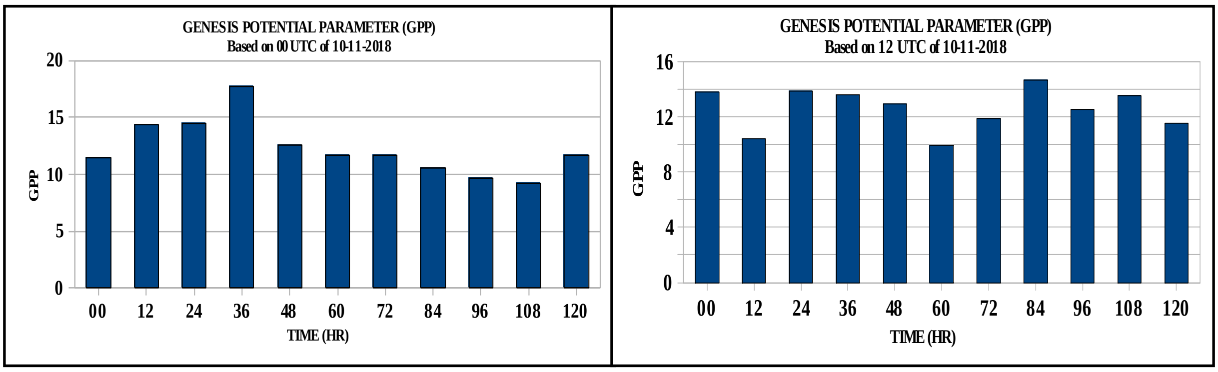


Fig. 3.7.2: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 10th November, 2018

3.7.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.3.7.3. Based on initial conditions of 0000 UTC of 10th November, all models except IMD-GFS and UKMO were predicting weakening of the system over sea. Both the models were predicting landfall around 0600 UTC of 15th over north Tamil Nadu.

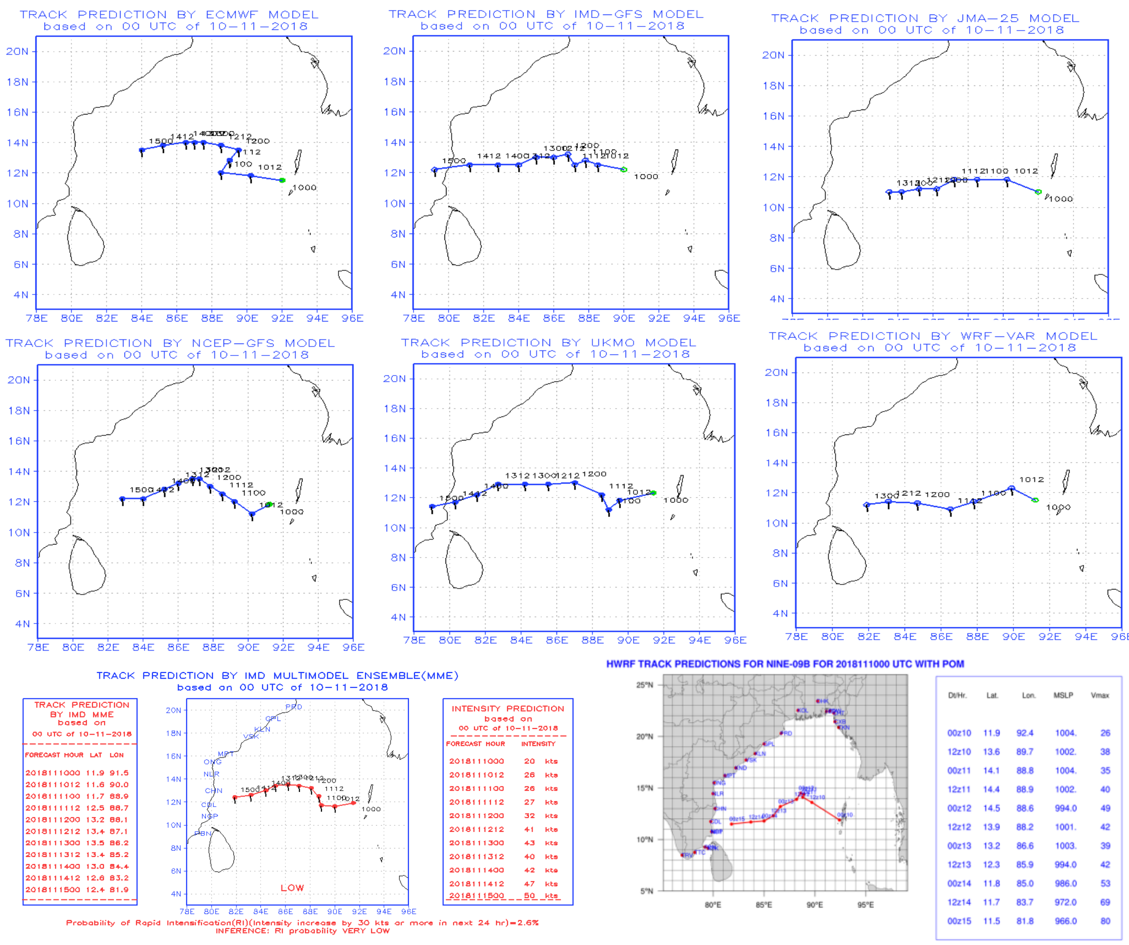


Fig. 3.7.3 (a): NWP model track forecast based on 0000 UTC of 10th November

Based on initial conditions of 0000 UTC of 11th November, WRF-VAR, NCEP GFS, HWRF and JMA were predicting weakening over sea prior to landfall. All other models including ECMWF, IMD-GFS, MME, UKMO were predicting landfall over north Tamil Nadu to the north of Nagapattinam between 0600 to 1200 UTC of 15th.

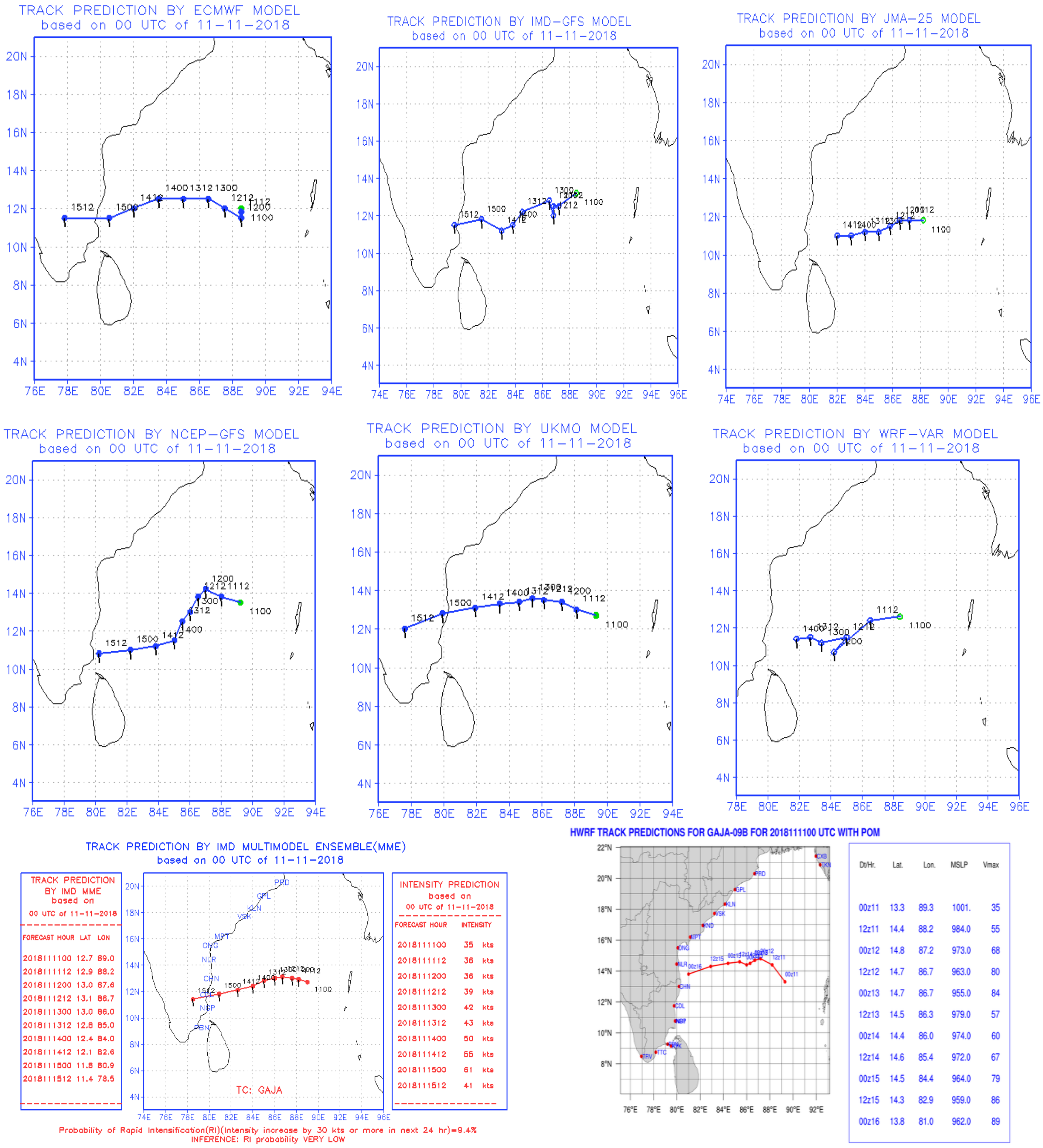


Fig. 3.7.3 (b): NWP model track forecast based on 0000 UTC of 11th November

Based on initial conditions of 0000 UTC of 12th November, none of the models could capture looping during 12th-13th. Models like IMD-GFS, JMA indicated landfall to the north of Nagapattinam. HWRF predicted landfall over Chennai. MME and ECMW predicted landfall to the south of Nagapattinam. NCEP GFS and UKMO predicted the southwestwards movement with the system entering Palk Strait and hitting coast near Kanyakumari and Tuticorin respectively. There was also large variation w.r.t. landfall time.

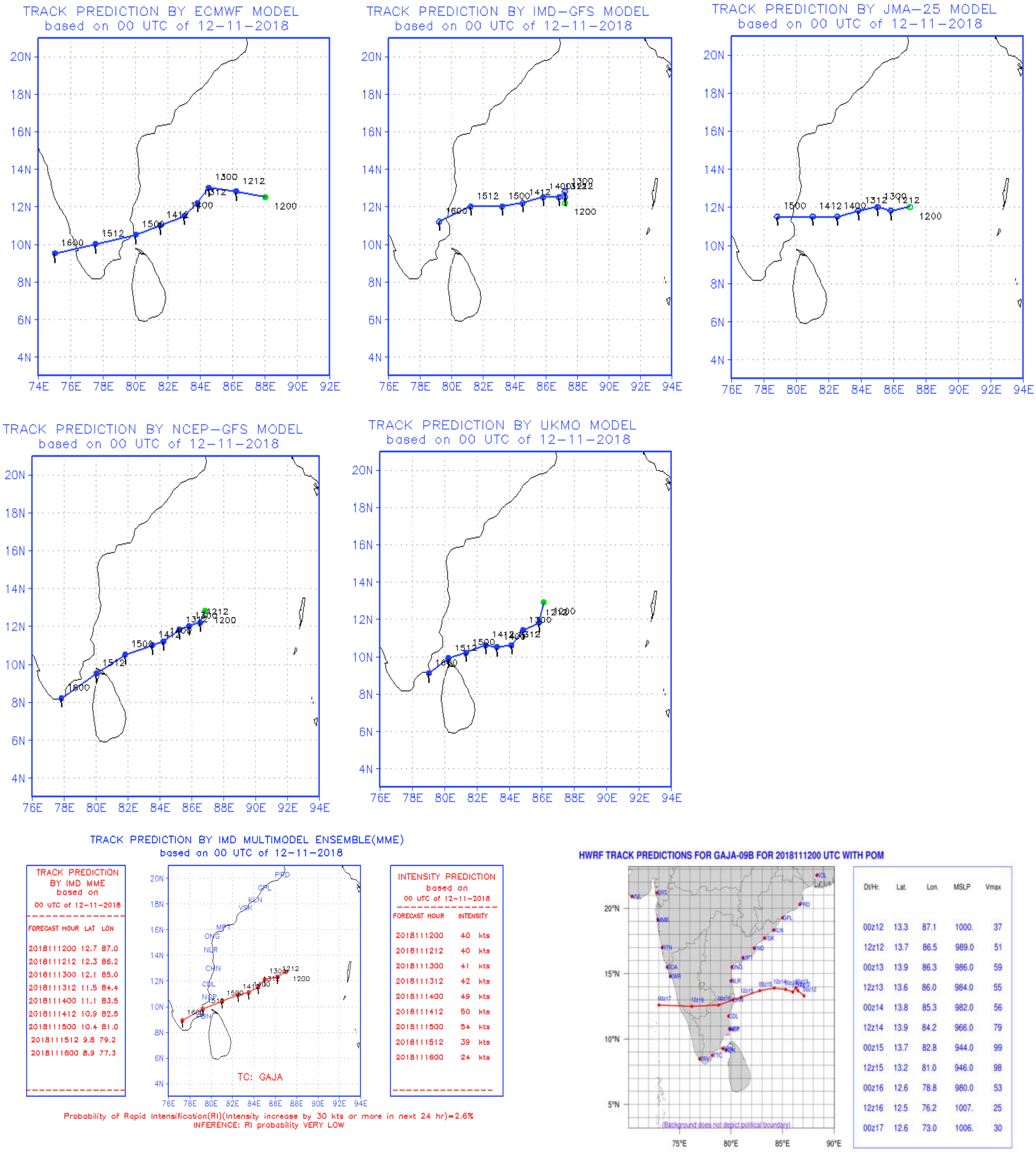


Fig. 3.7.3 (c): NWP model track forecast based on 0000 UTC of 12th November

Based on initial conditions of 0000 UTC of 13th November, IMD-GFS and NCEP-GFS predicted landfall over north Sri Lanka. All other models were predicting landfall to the north of Nagapattinam. HWRF and UKMO even predicted emergence of the system into Arabian Sea.

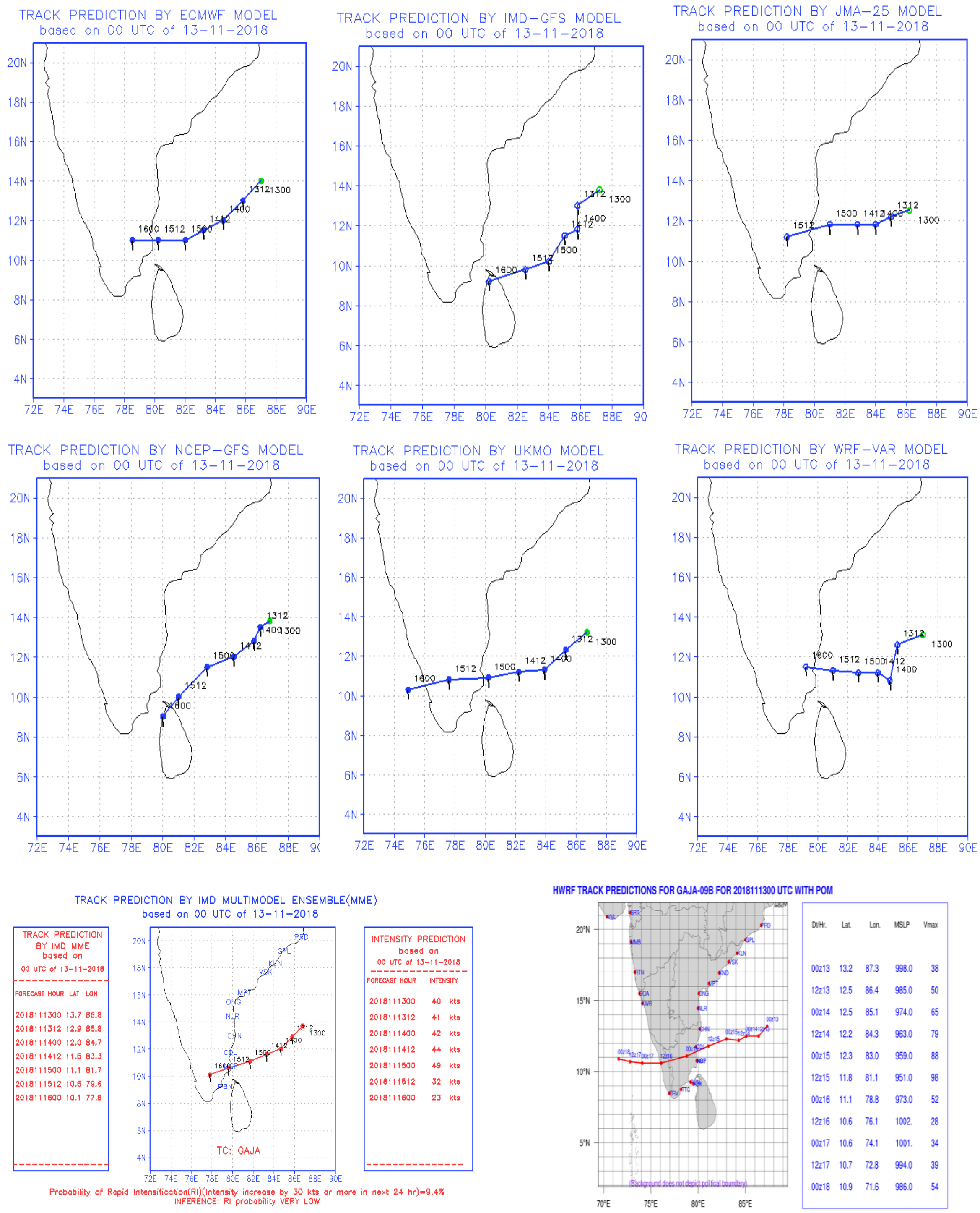


Fig. 3.7.3 (d): NWP model track forecast based on 0000 UTC of 13th November

Based on initial conditions of 0000 UTC of 14th November, NCEP-GFS and IMD GFS predicted weakening of the system over southwest BoB. Only HWRF was predicting emergence of the system into Arabian Sea. All other models like ECMWF, UKMO, WRF-VAR, JMA, HWRF & MME predicted landfall close to Nagapattinam between 1800 UTC of 15th to 0600 UTC of 16th. The intensity predicted at the time of landfall by HWRF was around 80 kts and that by MME was around 34 kts.

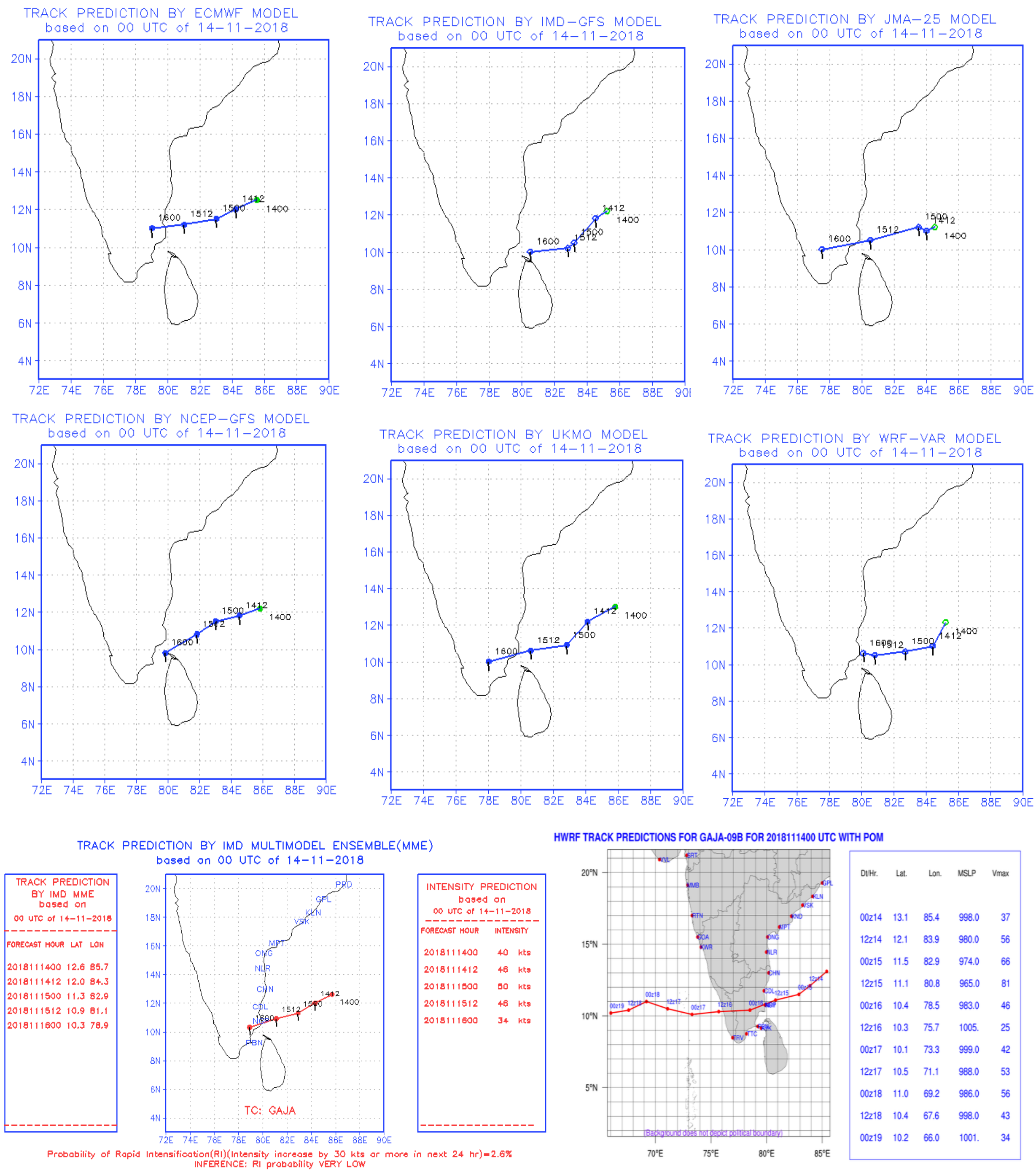


Fig. 3.7.3 (e): NWP model track forecast based on 0000 UTC of 14th November

Based on initial conditions of 0000 UTC of 15th November, models like ECMWF, JMA, HWRF & MME predicted landfall close to Nagapattinam around 0000 UTC of 16th. NCEP-GFS, IMD GFS, WRF-VAR and UKMO predicted landfall to the south of Nagapattinam between 0000 & 0600 UTC of 16th. The intensity predicted at the time of landfall by HWRF was around 80 kts and that by MME was around 54 kts. Only HWRF and NCEP GFS were predicting emergence of the system into Arabian Sea.

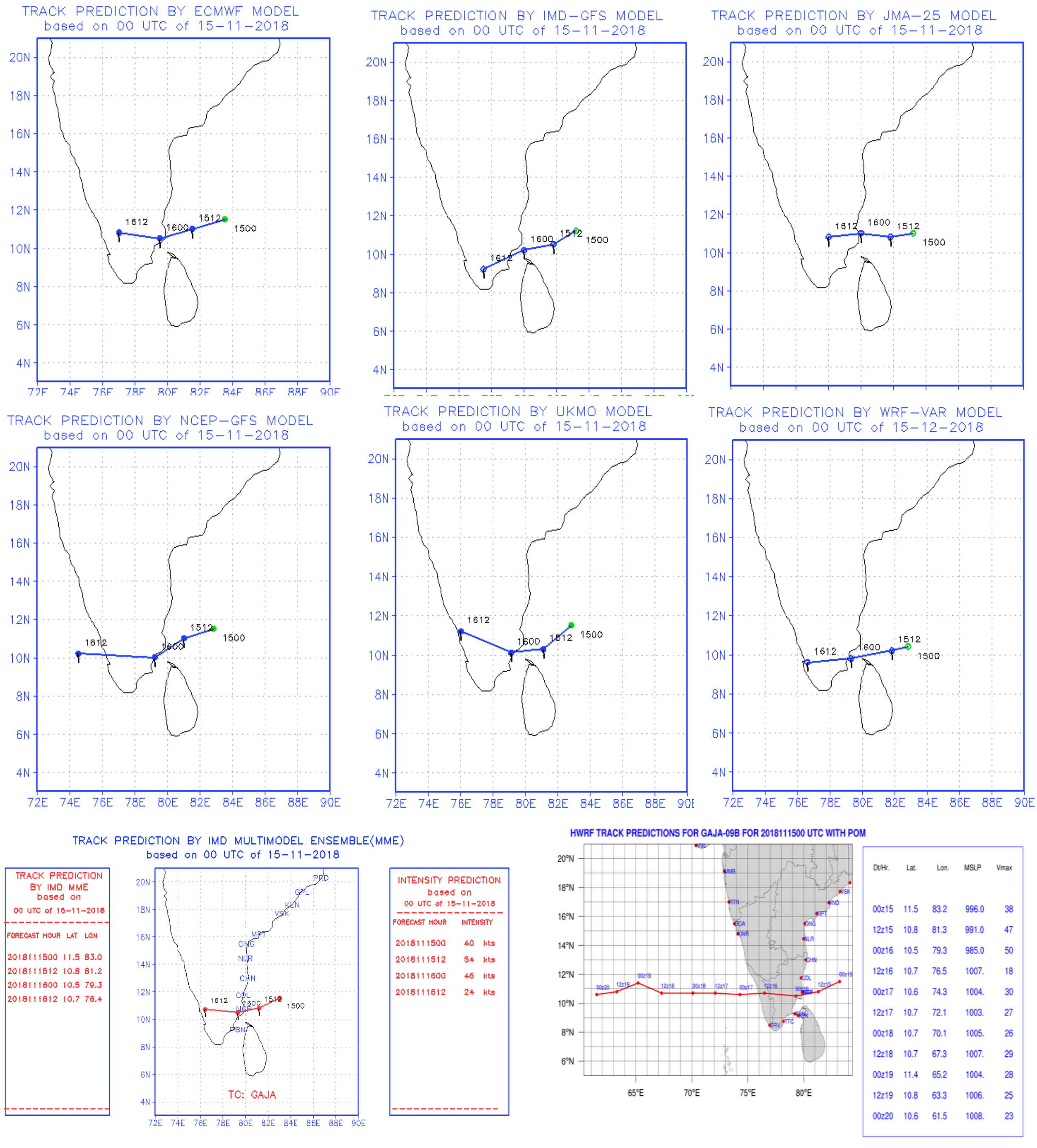


Fig. 3.7.3 (f): NWP model track forecast based on 0000 UTC of 15th November

Based on initial conditions of 0000 UTC of 17th November, all the models were indicating near westwards movement of the system upto southwest AS and weakening over sea. Both MME and HWRF were capturing initial intensity as 30 kts and predicting the system to intensify upto cyclonic storm intensity by 0000 UTC of 18th. The system was predicted to weaken gradually thereafter.

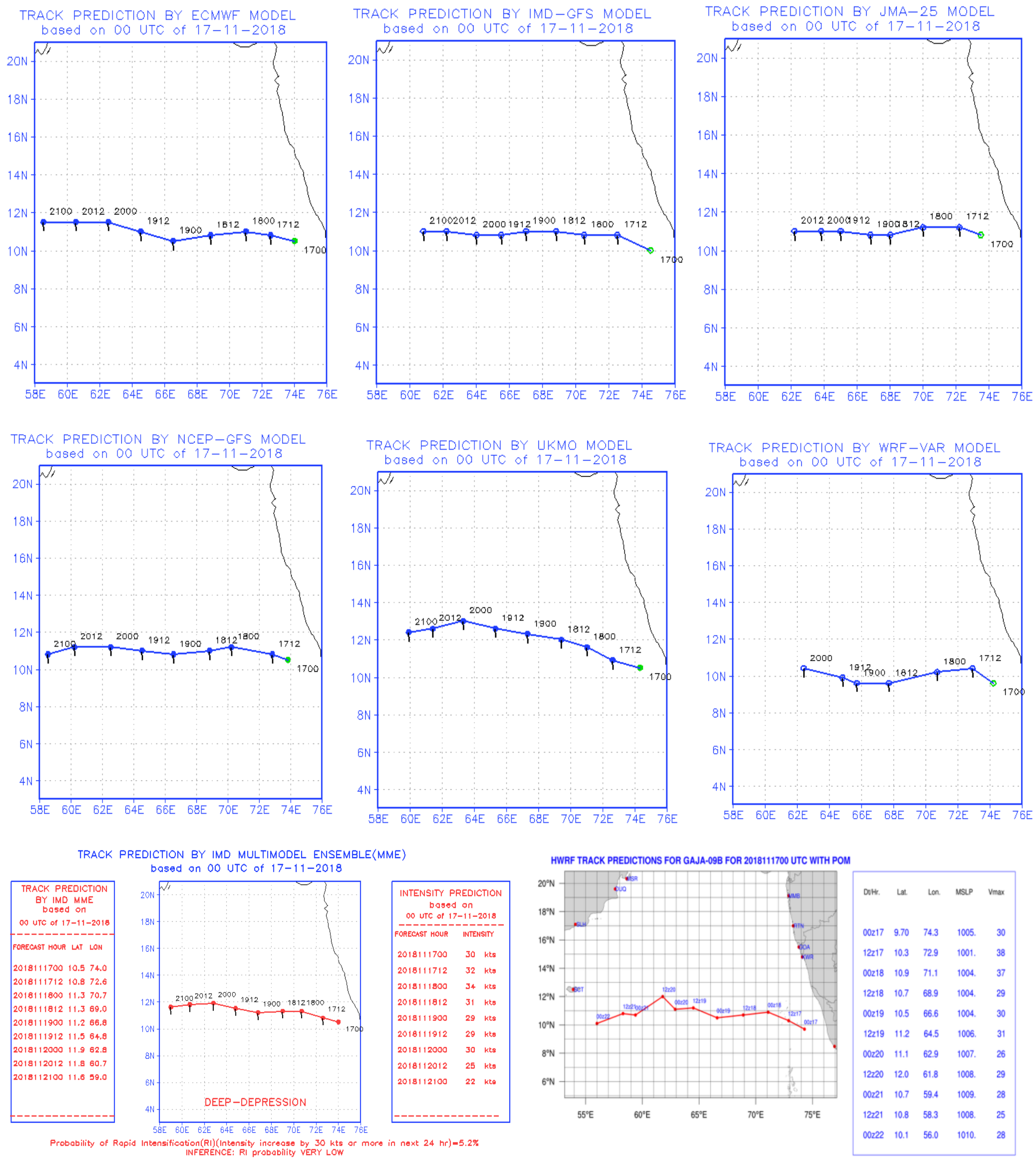


Fig. 3.7.3 (g): NWP model track forecast based on 0000 UTC of 17th November

Based on initial conditions of 0000 UTC of 18th November, models like ECMWF, JMA, NCEP-GFS, WRF-VAR and MME were indicating near westwards movement of the system upto southwest AS and weakening over sea. However, IMD GFS was predicting initial westwards movement followed by northwestwards movement. While HWRF was predicting initial westwards movement followed by southwestwards movement. MME was predicting the system to retain depression stage till 1200 UTC of 21st and HWRF predicted the same till 0000 UTC of 24th.

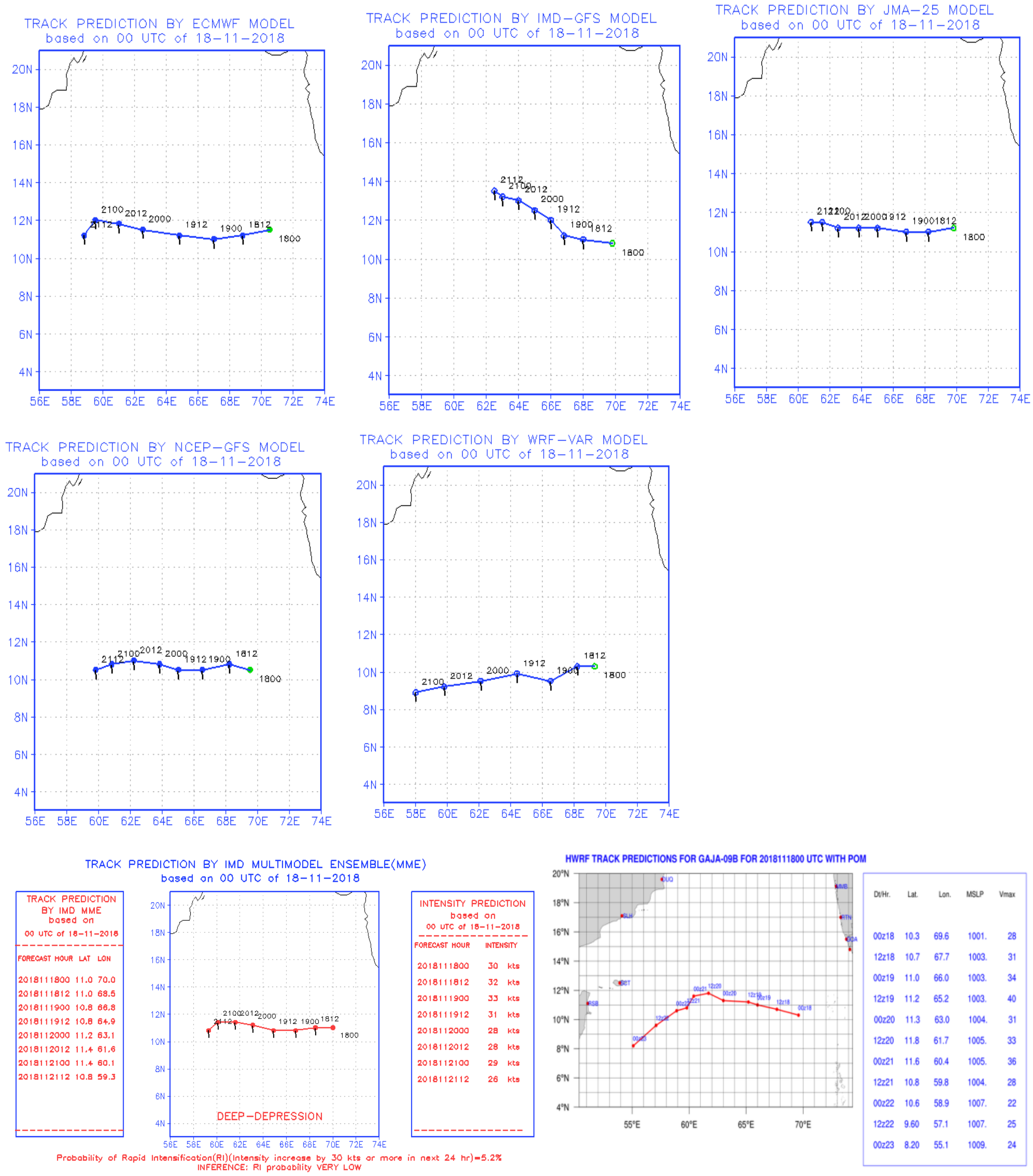


Fig. 3.7.3 (h): NWP model track forecast based on 0000 UTC of 18th November

Based on initial conditions of 0000 UTC of 19th November, all the models except HWRF were indicating near westwards movement of the system upto southwest AS and weakening over sea. However, HWRF was predicting initial westwards movement followed by southwestwards movement and landfall over Somalia on 24th.

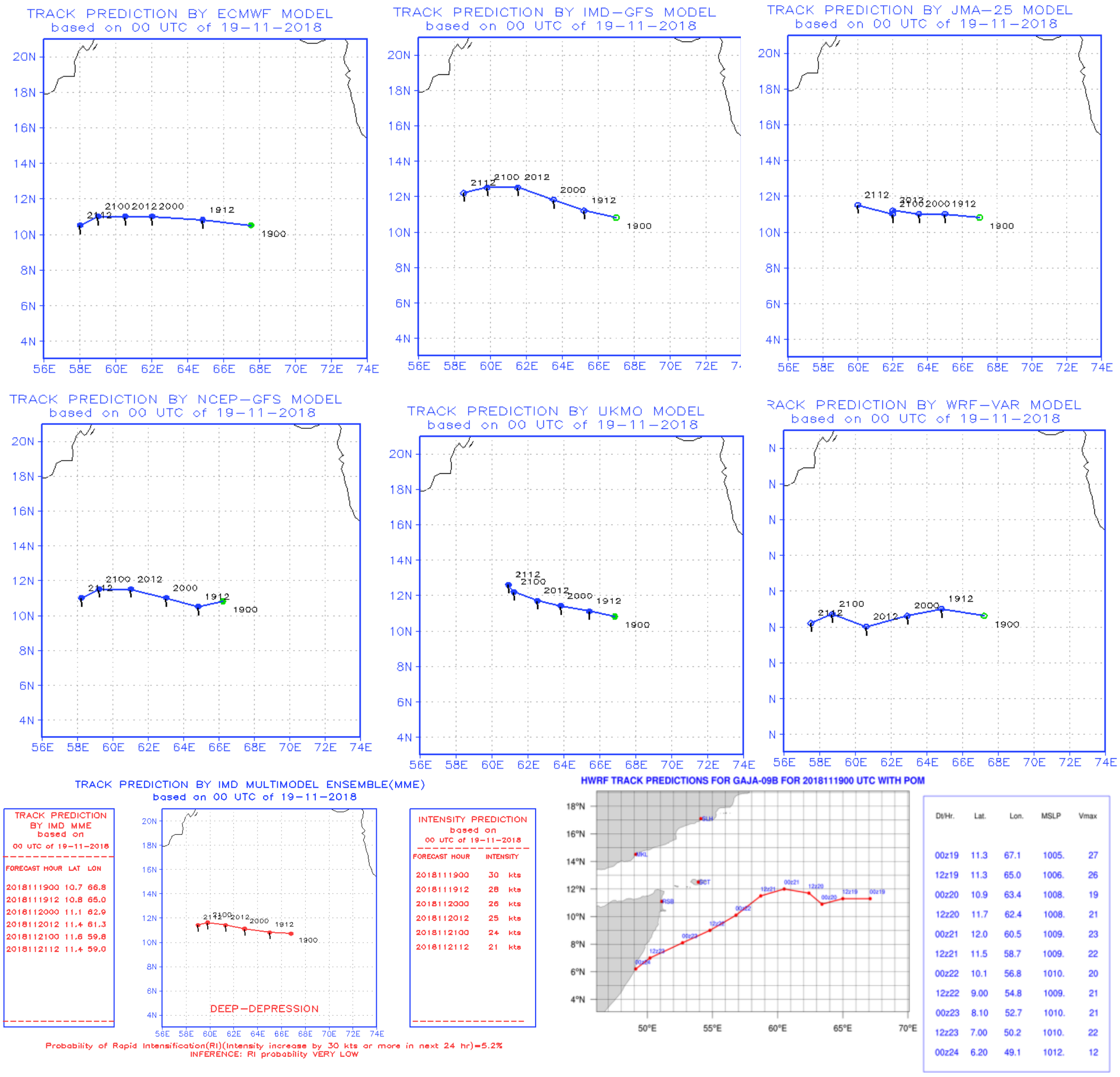


Fig. 3.7.3 (i): NWP model track forecast based on 0000 UTC of 19th November

Hence to conclude, to a good extent models could capture the movement, landfall characteristics and emergence of the system into AS. But intensity at the time of landfall and dissipation of the system was not consistently correctly captured. MME underestimated the intensity of the system throughout its life cycle. HWRF could predict the intensity during landfall correctly, but dissipation of system on 24th and landfall over Somalia was not correctly captured.

3.7.3. 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 3.7.1. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of NCEP-GFS and IMD HWRF were the least followed by IMD-GFS, MME & ECMWF for 24 hours lead period. For 48 hours lead period, the errors were the least by IMD-GFS followed by MME, NCEP GFS, HWRF and ECMWF. For 72 hours lead period, the errors were the least by NCEP GFS followed by HWRF, IMD GFS, MME and ECMWF. Overall the errors were the least by NCEP-GFS, IMD-GFS and HWRF followed by MME & ECMWF for various lead periods.

Table 3.7.1: Average track forecast errors (Direct Position Error (DPE)) in km

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	89(16)	92(15)	112(14)	99(12)	131(9)	142(7)	151(6)	169(5)	227(3)	442(2)
IMD-WRF	115(16)	182(15)	183(14)	240(12)	326(9)	442(7)	-	-	-	-
JMA	133(16)	134(15)	155(14)	215(12)	303(9)	384(7)	337(6)	-	-	-
NCEP-GFS	70(16)	83(15)	107(14)	113(12)	121(9)	130(7)	126(6)	143(5)	92(3)	123(2)
UKMO	106(16)	144(15)	163(14)	198(12)	262(9)	342(7)	346(6)	316(5)	411(3)	458(2)
ECMWF	83(16)	118(15)	99(14)	126(12)	160(9)	159(7)	233(6)	271(5)	271(3)	245(2)
IMD-HWRF	82(33)	84(31)	89(29)	127(27)	134(25)	141(24)	162(24)	187(23)	207(21)	227(19)
IMD-MME	71(16)	96(15)	98(14)	113(12)	153(9)	182(7)	206(6)	207(5)	218(3)	172(2)
NCUM	-	125(13)	-	116(18)	-	162(16)	-	250(13)	-	349(11)
NEPS	-	110(16)	-	110(18)	-	149(19)	-	320(18)	-	481(14)

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

Landfall point forecast errors (LPE) are presented in Table 3.7.2. The landfall point error was the minimum for IMD-HWRF model 20 and 68 hrs lead period followed by MME, ECMWF and UKMO. For 44 hrs lead period, LPE was the least for JMA followed by UKMO, IMD HWRF and MME. Overall upto 72 hrs lead period, the errors by IMD HWRF were the least and beyond that the errors by MME and ECMWF were the least.

Table 3.7.2: Landfall point forecast errors (km) of NWP Models at different lead time

Lead time →	20H	32H	44H	56H	68H	80H	92H	104H	116H	128H
Based on	**15/00z**	**14/ 12z**	**14/00z**	**13/12z**	**13/ 00z**	**12/12z**	**12/00z**	**11/12z**	**11/00z**	**10/12z**
IMD-GFS	91	37	-	168	-	62	106	117	117	-
IMD-WRF	174	101	-	40	106	-	-	62	-	-
JMA	62	62	6	40	139	173	117	174	-	-
NCEP-GFS	83	30	-	-	-	-	333	84	-	-
UKMO	61	30	17	84	62	30	174	62	265	210
ECMWF	30	40	84	40	62	62	12	84	128	139
IMD-MME	40	40	40	40	40	83	79	84	128	150
IMD-HWRF	5	40	28	27	23	230	285	171	192	--

Landfall Point Error = Landfall Forecast Point- Actual Landfall Point, “-“ : No forecast

Landfall time forecast errors (LTE) are presented in Table 3.7.3. For 20 hr lead period LTE was the least by IMD-HWRF followed by MME, ECMWF and UKMO. For 44 hr lead period, LTE was the least for ECMWF & MME followed by IMD-HWRF. For 68 hr lead period, LTE was the least by IMD-WRF followed by IMD-HWRF and ECMWF. Overall the errors by IMD-HWRF were the least followed by IMD GFS.

Table-3.7.3: Landfall time forecast errors (hr) at different lead time (hr)

Lead time →	**20H**	**32H**	**44H**	**56H**	**68H**	**80H**	**92H**	**104H**	**116H**	**128H**
Based on	**15/00z**	**14/12z**	**14/00z**	**13/12z**	**13/00z**	**12/12z**	**12/00z**	**11/12z**	**11/00z**	**10/12z**
IMD-GFS	+8	+1	-	+2	-	+3	-2	+4	-9	-
IMD-WRF	+5	+2	-	-4	0	-	-	-32	-	-
JMA	+5	0	-5	-8	-15	-20	-1	-20	-	-
NCEP-GFS	+4	+5	-	-	-	-	+4	-12	-	-
UKMO	+3	-3	-5	+1	-18	+20	+4	-32	-22	-21
ECMWF	+1	-2	-1	-3	-6	-2	-19	-15	-16	-13
IMD-MME	+1	0	-1	-2	-9	-6	-8	-20	-14	-7
IMD-HWRF	0	0	-3	0	-3	-9	-3	-3	-3	--

('+' indicates delay in landfall, '-' indicates early landfall)

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

The composite intensity prediction by IMD SCIP model based on initial conditions of 0000 & 1200 UTC during 10th-17th November is presented in Fig. 3.7.4. Overall, SCIP underestimated intensity of the system including the peak intensity.

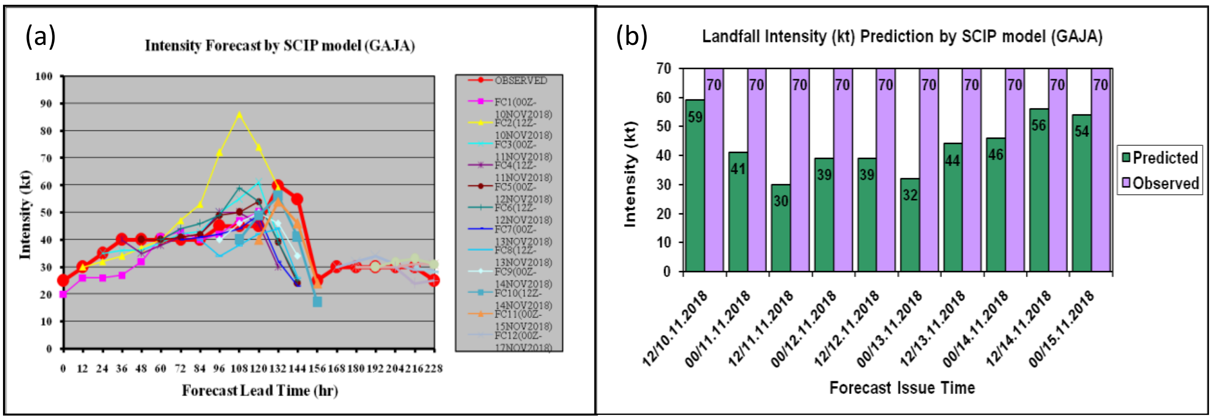


Fig. 3.7.4 (a): Composite intensity prediction by SCIP Model based on 0000 and 1200 UTC during 10th—14th and 17th November and (b) landfall intensity predicted and observed

The average intensity forecast errors by IMD-SCIP and IMD-HWRF are presented in Table 3.7.4. It is seen that the intensity forecast errors by HWRF were significantly higher than IMD SCIP for all lead periods except 84 & 96 hrs.

Table 3.7.4: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots by SCIP and HWRF models (Number of forecasts verified is given in the parentheses)

Lead time → (hrs)	12	24	36	48	60	72	84	96	108	120
IMD-SCIP (AAE)	3.5 (16)	4.2 (15)	4.6 (14)	7.2 (12)	10.1 (9)	12.6 (7)	14.8 (6)	24.2 (5)	16.7 (3)	3.0 (2)
IMD-HWRF (AAE)	10.6 (33)	13.3 (31)	16.4 (29)	16.1 (27)	13.9 (25)	13.8 (24)	13.4 (24)	13.7 (23)	16.8 (21)	18.4 (19)
IMD-SCIP (RMSE)	4.4	5.0	6.8	9.6	14.3	15.9	19.0	27.6	20.0	3.6
IMD-HWRF (RMSE)	13.6	18.3	21.5	22.2	18.9	20.5	17.6	16.9	22.0	22.5

Comparative analysis of predicted decay after landfall based on initial conditions of 2100 UTC of 15th and 0300 UTC of 16th vis-à-vis actual decay is presented in Fig. 3.7.5. It can be seen that based on 2100 UTC of 15th initial conditions, the decay predicted was much steeper than actually realized. However, the decay model could better predict the fall in intensity of the system after landfall based on 0300 UTC initial conditions of 16th.

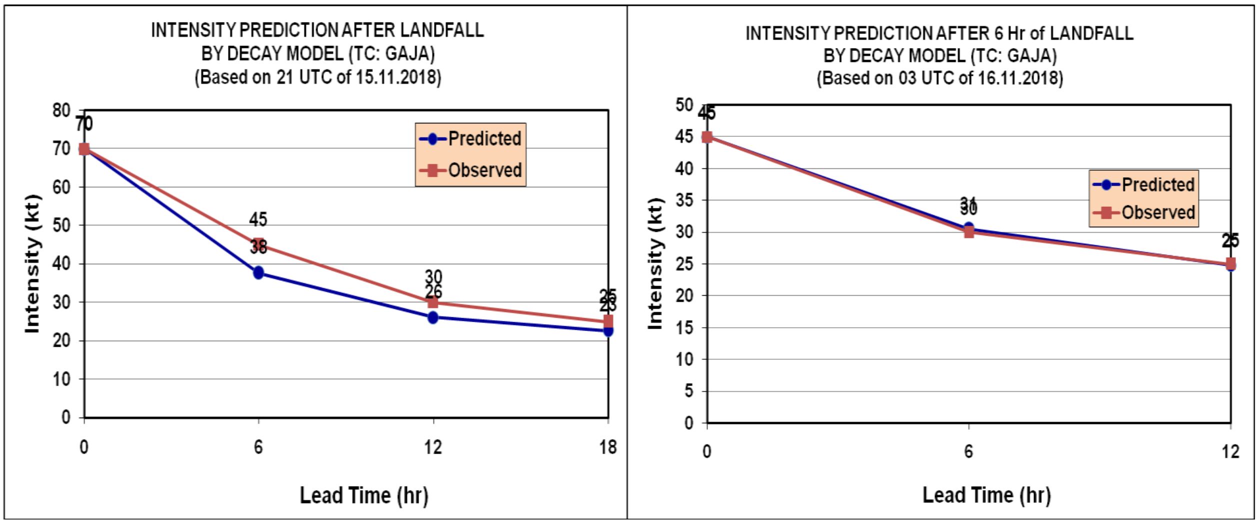


Fig. 3.7.5. Decay after landfall (i) based on 2100 UTC of 15.11.2018 and (ii) updated forecast based on 0300 UTC of 16.11.2018

3.7.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model based on 0600 UTC during 10th-15th and 17th-18th are presented in **Fig. 3.7.6**. HWRF could successfully predict occurrence of rainfall along the predicted track even after the landfall of system and during re-emergence into AS over north Kerala coast. Based on 06 UTC of 11th, the expected cumulative rainfall in

126 hrs was about 8-16 inches (20-40cm) over coastal areas of north Tamil Nadu and at isolated places over south Andhra Pradesh. Based on 06 UTC of 12th- 14th, the expected cumulative rainfall in 126 hrs was about 8-16 inches (20-40cm) at few places over north Tamil Nadu and north Kerala. On 15th, cumulative rainfall of about 20-40 cm for next 126 hrs over few places of north Tamil Nadu and isolated places of north Kerala was predicted.

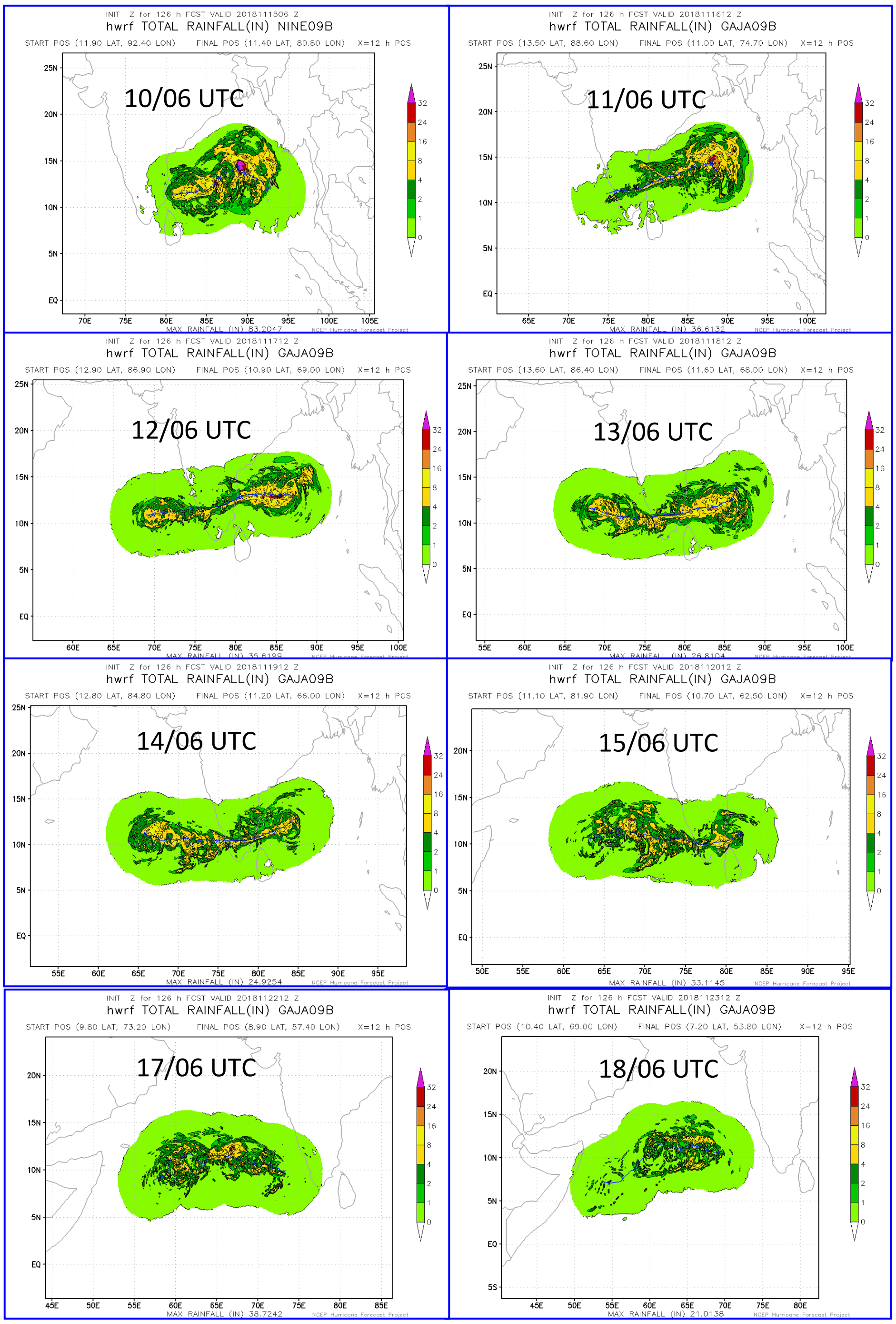


Fig. 3.7.6: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 10th-18th November, 2018.

3.7.5. Storm surge forecast

IMD predicted storm surge forecast based on guidance from Advance Circulation (ADCIRC) model and Indian Institute of Delhi Model. IMD predicted Storm surge of about 1 metre above astronomical tide inundated low lying areas upto about 1 km from the coast near the landfall point. Typical storm surge forecast by ADCIRC Model based on 0300 UTC observations of 12th November is presented in **Fig. 3.7.7**.

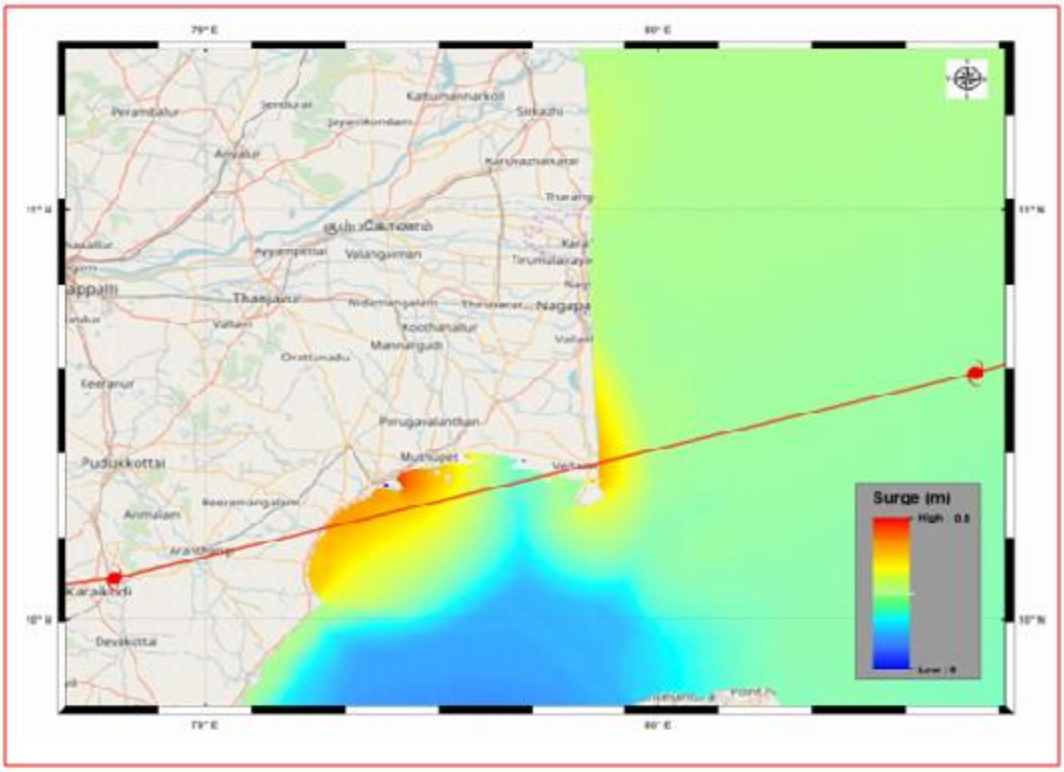


Fig. 3.7.7: Storm Surge Forecast issued by ADCIRC Model based on 0300 UTC of 12th November, 2018

3.8. Severe Cyclonic Storm "PHETHAI" over southeast Bay of Bengal (13-18 December 2018)

3.8.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for PHETHAI

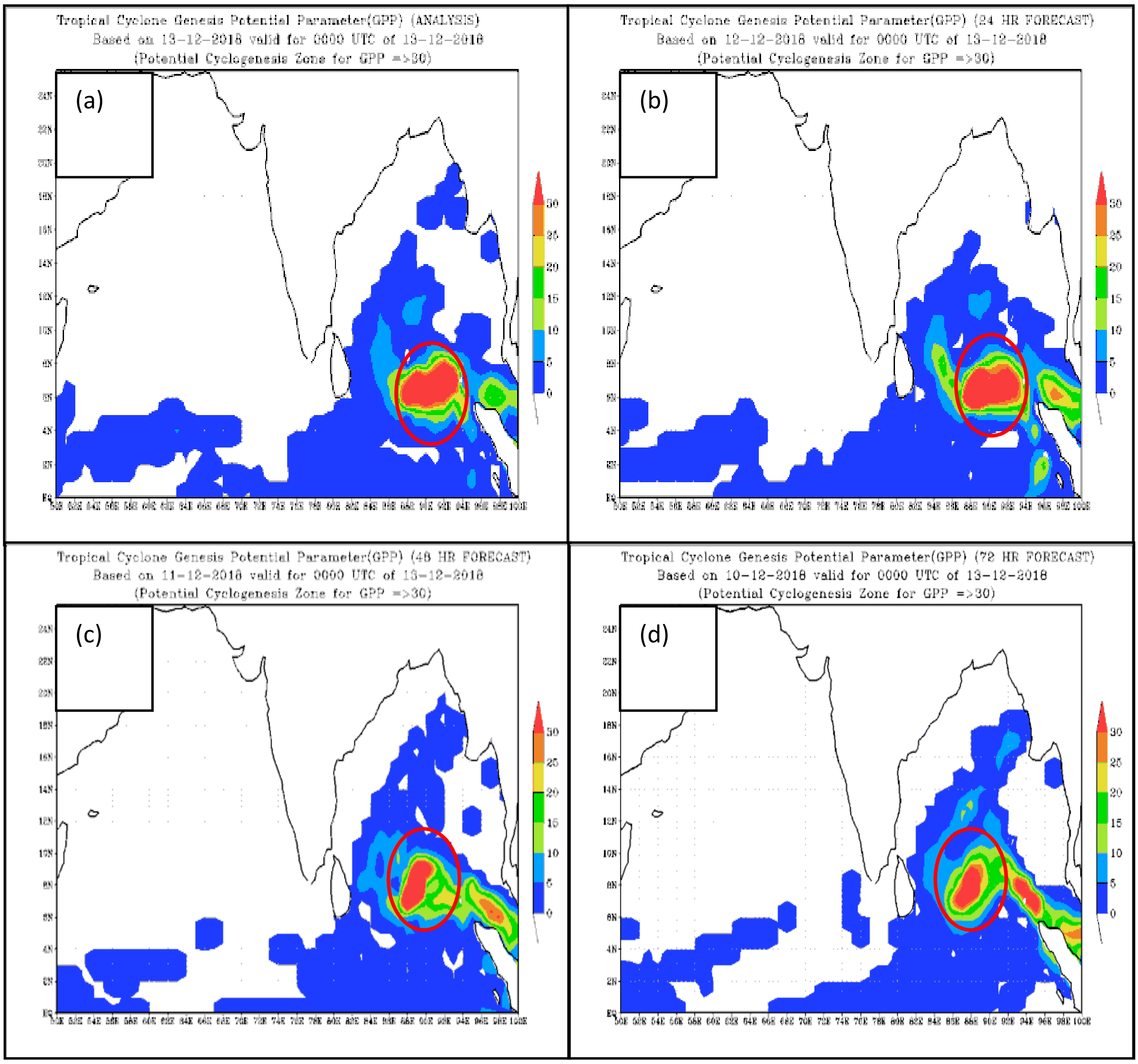


Fig.3.8.1(i) (a-d): Predicted zone of cyclogenesis for 0000 UTC of 13th based on 0000 UTC of 10–13th December 2018

Fig. 3.8.1(i) (a-d) indicates that the GPP could predict the potential zone for cyclogenesis on 13th over central parts of south BoB and adjoining EIO correctly about 96 hours in advance.

The model could predict cyclogenesis zone correctly about 72 hrs in advance. It indicated potential for intensification of the system into a Cyclonic storm based on initial condition of 00 UTC of 11th Dec onwards. Fig. 3.8.2 shows area average analysis of GPP.

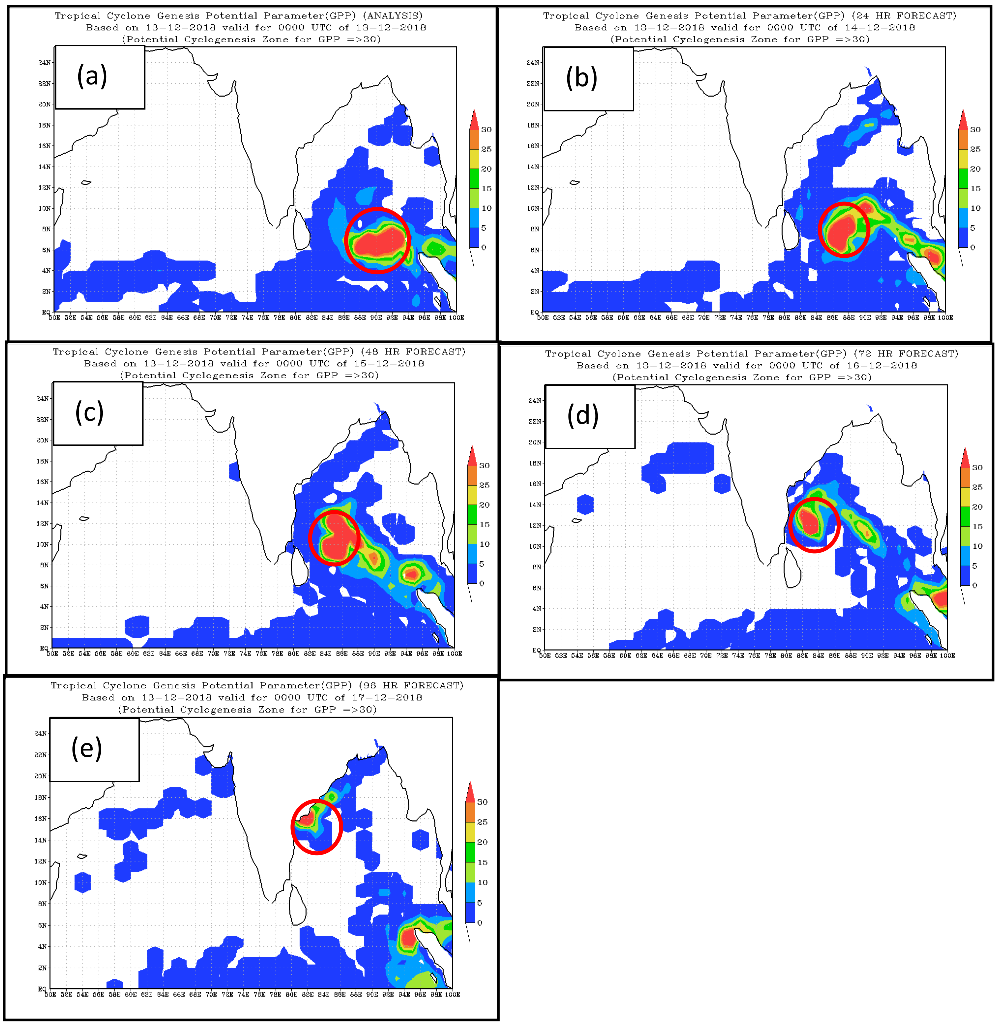


Fig.3.8.1(ii) (a-e): Predicted zone of cyclogenesis based on 0000 UTC of 13 December 2018 (at stage Depression) for 0000 UTC of 13th-17th December

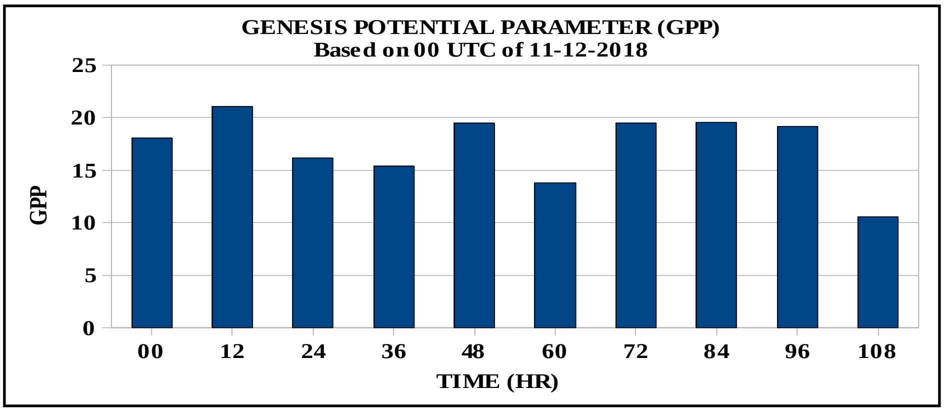


Fig.3.8.2(i) Area average analysis and forecasts of GPP based on 0000 UTC of 11.12.2018

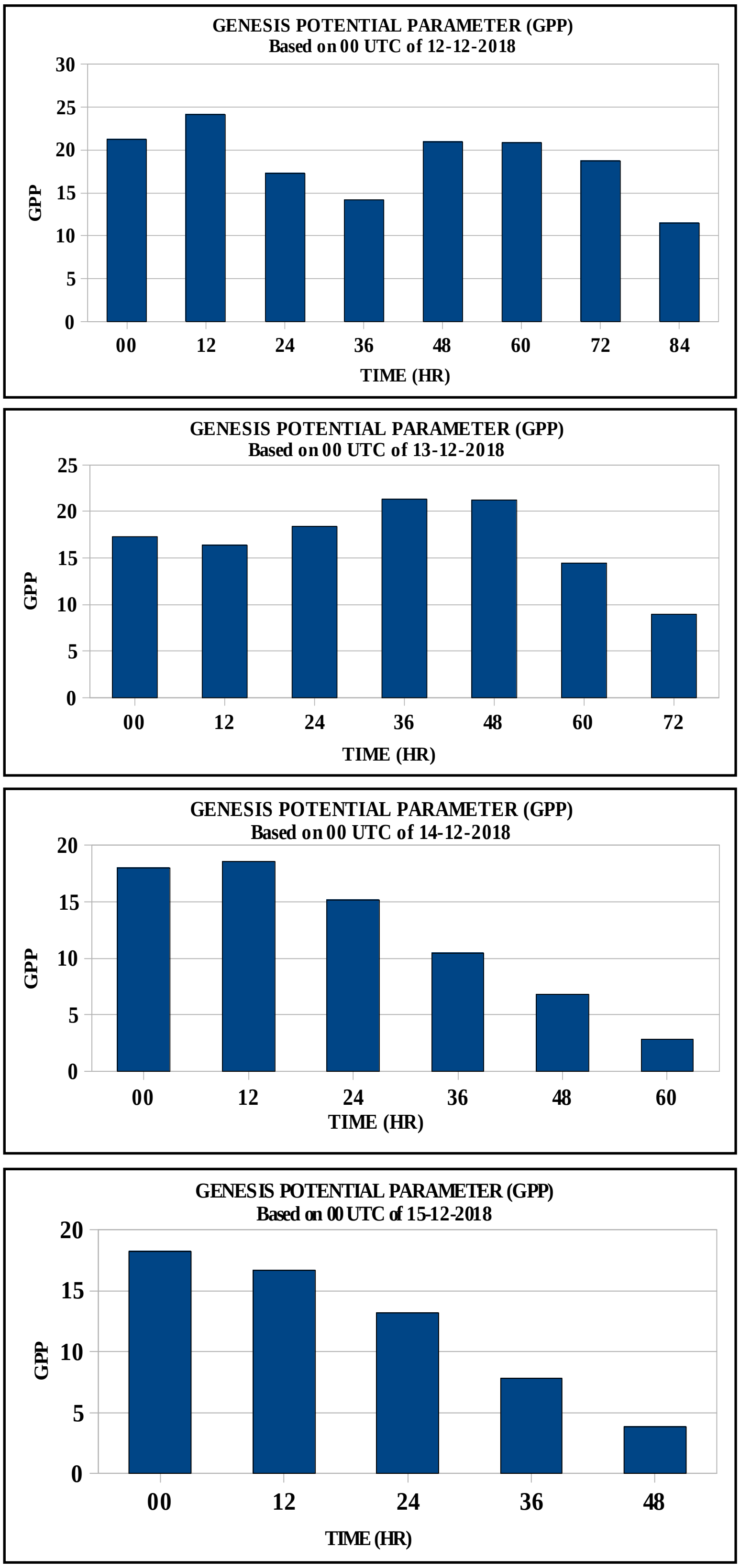


Fig. 3.8.2(ii) Area average analysis and forecasts of GPP based on 0000 UTC of 12 Dec to 15 Dec. 2018.

3.8.2 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig. 3.8.3**. Based on initial conditions of 0000 UTC of 13th December, most of the models indicated initial northwestward movement towards north Andhra Pradesh coast however only NCEP GFS and IMD GFS models indicated landfall over north Andhra Pradesh coast around Kakinada around 00UTC of 17th Dec.

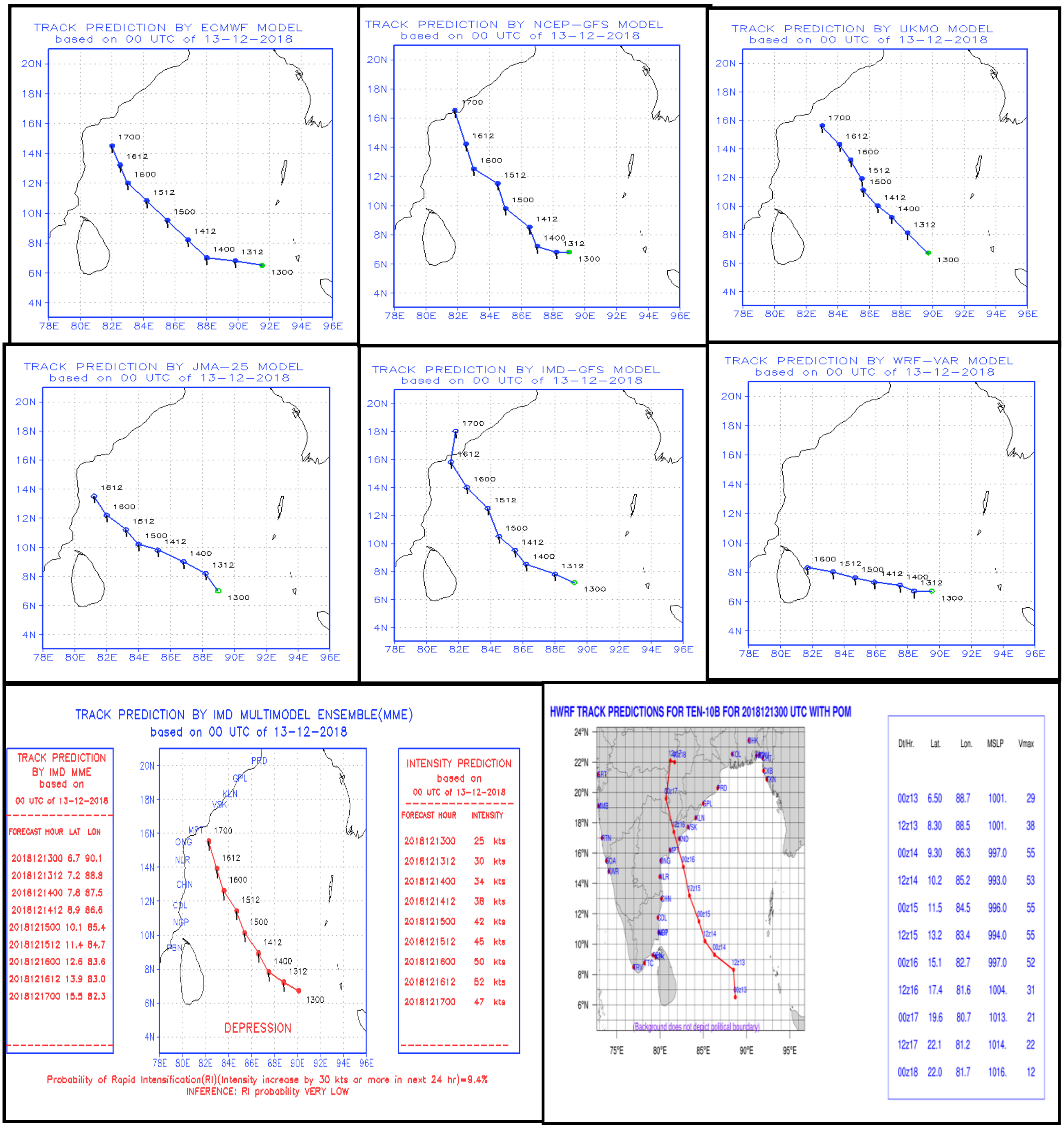


Fig. 3.8.3 (a): NWP model track forecast based on 0000 UTC of 13.12.2018

Based on initial conditions of 0000 UTC of 14th December, models including ECMWF, NCEP GFS and IMD MME indicated initial northwestward movement towards north Andhra Pradesh coast with increase in northward component of movement thereafter without landfall. Models like UKMO, JMA and IMD GFS predicted landfall over Andhra Pradesh. However, they varied w.r.t. landfall point and time. The forecast landfall point by IMD GFS and UKMO was closer to actual landfall point.

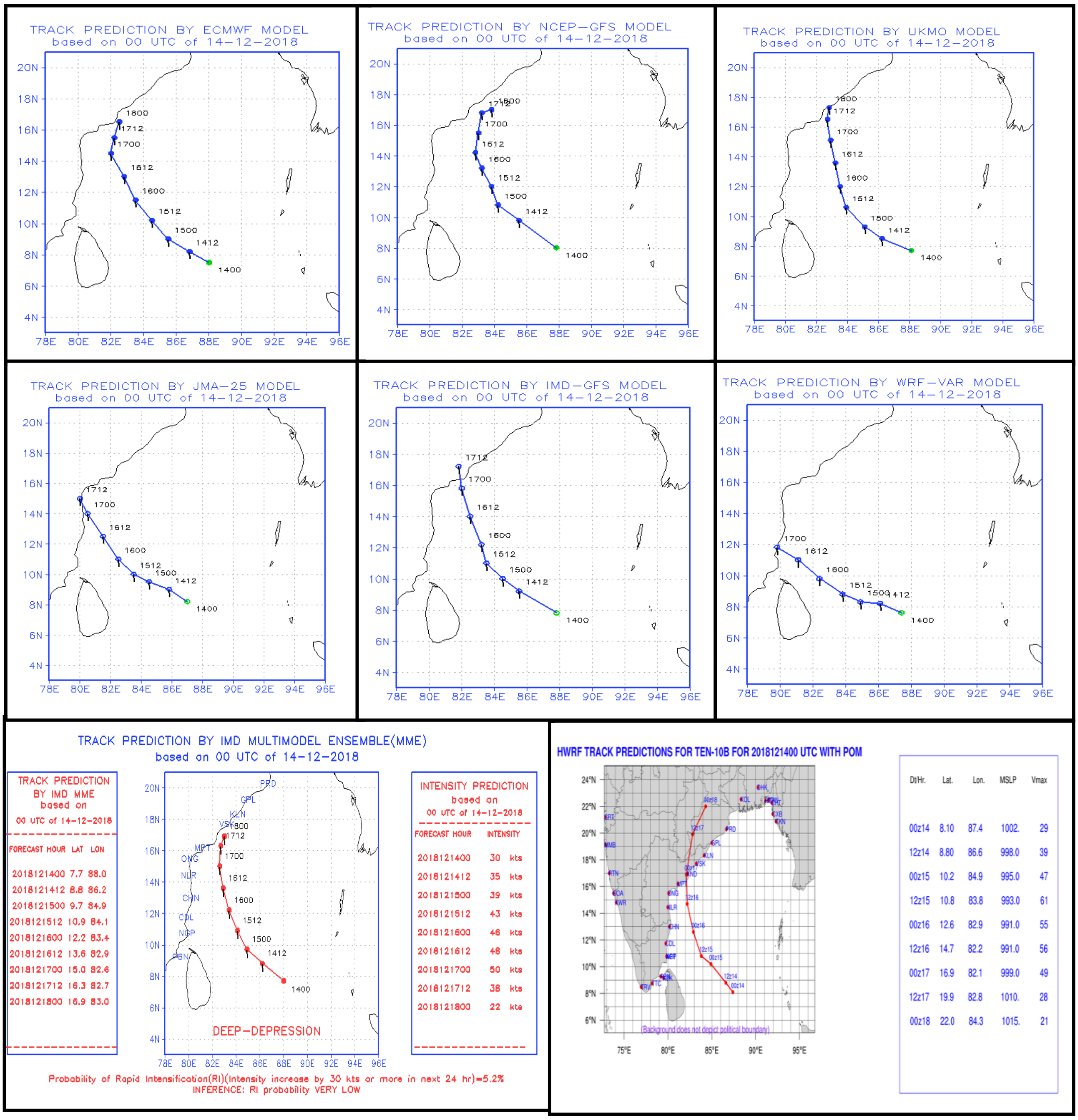


Fig. 3.8.3 (b): NWP model track forecast based on 0000 UTC of 14.12.2018

Based on initial conditions of 0000 UTC of 15th December, models including ECMWF, NCEP GFS, UKMO, IMD GFS and IMD MME indicated initial northeastwards recurvature from 0000 UTC of 17th onwards. Models like IMD GFS, NCEP GFS and WRF predicted landfall over north Andhra Pradesh. However, they varied w.r.t. landfall point and time.

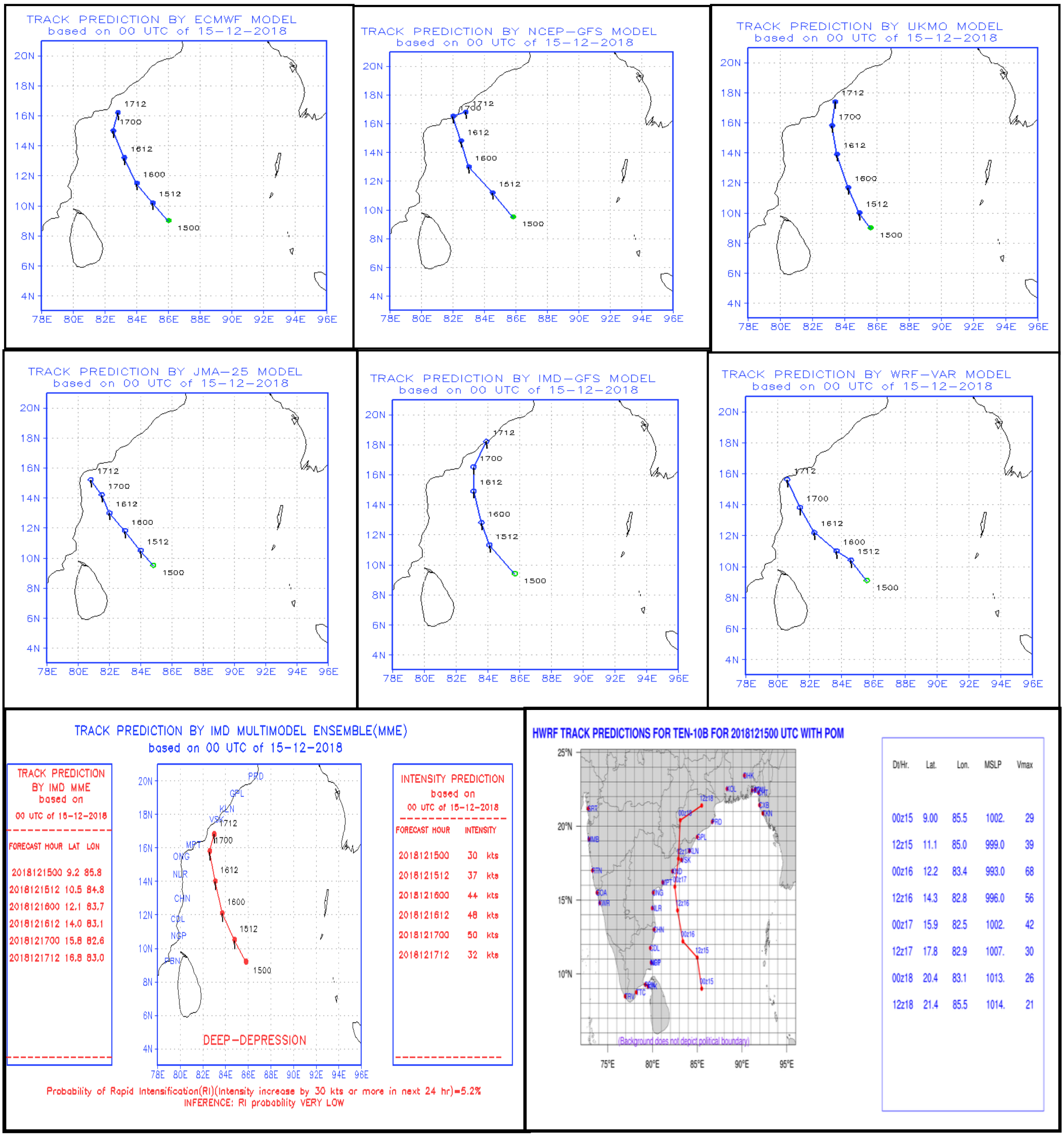


Fig. 3.8.3 (c): NWP model track forecast based on 0000 UTC of 15.12.2018

Based on initial conditions of 0000 UTC of 16th December, models including ECMWF, JMA, IMD GFS and WRF VAR indicated landfall over north Andhra Pradesh. IMD GFS and WRF VAR predicted landfall time closer to actual landfall time. NCEP GFS, UKMO and MME predicted weakening of system over sea.

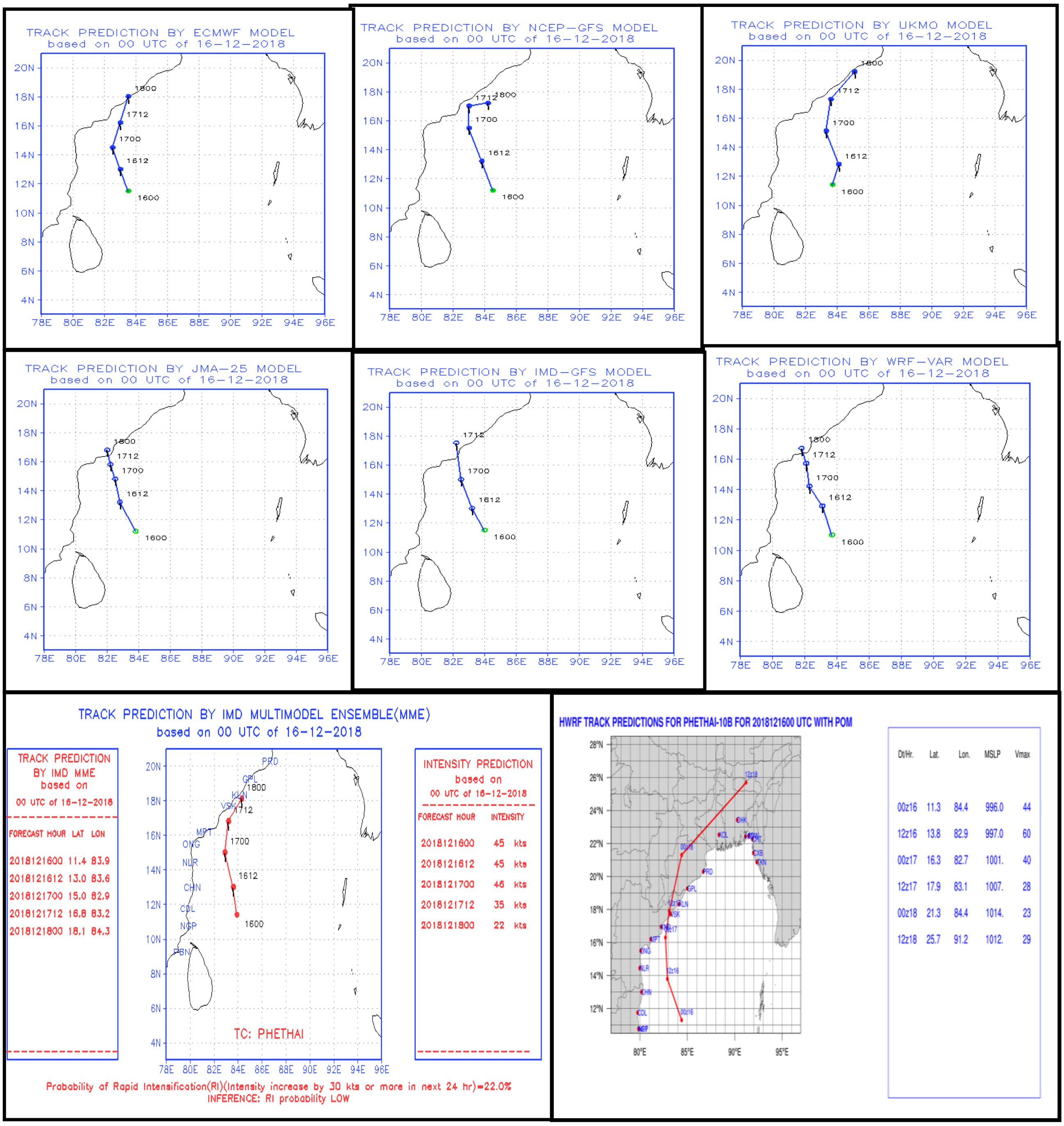


Fig. 3.8.3 (d): NWP model track forecast based on 0000 UTC of 16.12.2018

Based on initial conditions of 0000 UTC of 17th December, models including NCEP GFS, UKMO, IMD GFS and IMD MME indicated landfall over north Andhra Pradesh around 1200 UTC of 17th. ECMWF, JMA and WRF VAR predicted weakening of system over sea.

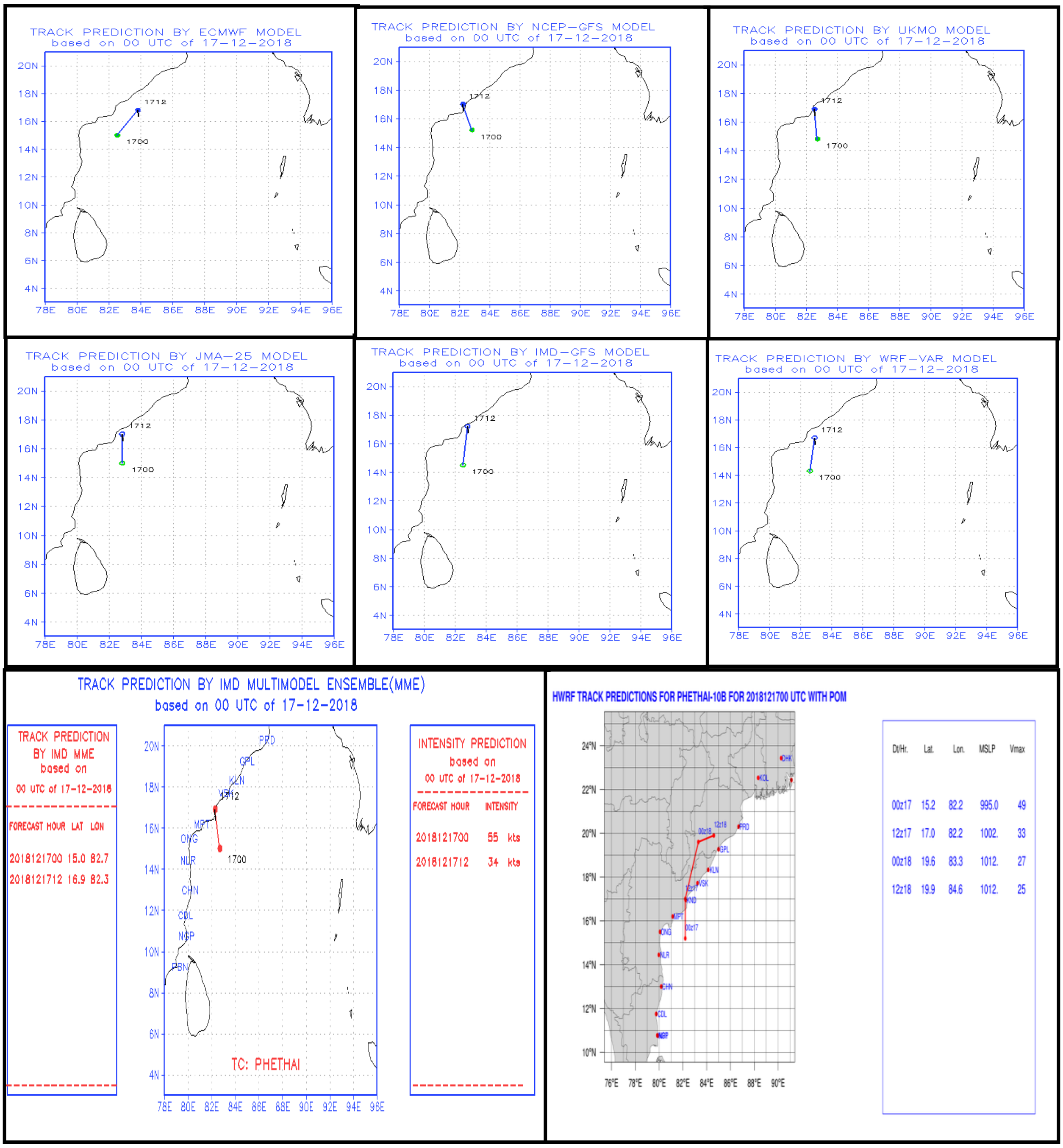


Fig. 3.8.3 (e): NWP model track forecast based on 0000 UTC of 17.12.2018

Comparing different models IMD GFS was consistent in predicting landfall near Kakinada while other models were mostly indicating recurvature over the sea before landfall and weakening based on initial condition of 14th to 17th Dec.

3.8.2. Track forecast errors

Average track forecast errors by various NWP models is presented in Table 3.8.1 (a). For 24, 48 and 72 hours lead period, the error in track forecast was the least by ECMWF followed by IMD MME. For 96 hours lead period, the error in track forecast was the least by IMD MME followed by UKMO.

Table-3.8.1 (a). Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108 H
IMD-GFS	83(9)	120(8)	137(7)	147(6)	180(5)	164(4)	177(3)	314(2)	-
IMD-WRF	63(9)	114(8)	175(7)	242(6)	326(5)	425(4)	-	-	-
JMA	80(9)	115(8)	155(7)	187(6)	215(5)	243(4)	252(3)	-	-
NCEP-GFS	97(9)	145(8)	144(7)	158(6)	140(5)	113(4)	115(3)	111(2)	-
UKMO	74(9)	90(8)	135(7)	162(6)	151(5)	166(4)	117(3)	88(2)	-
ECMWF	85(9)	70(8)	66(7)	61(6)	84(5)	93(4)	110(3)	132(2)	-
IMD-HWRF	95(18)	142(16)	175(14)	208(12)	212(10)	287(8)	342(6)	387(4)	412(2)
IMD-MME	62(9)	74(8)	91(7)	114(6)	108(5)	108(4)	55(3)	73(2)	-

Along track errors (ATE)and cross track errors (CTE) by HWRF model are presented in Tables 3.8.1 (b) and 2 (c). These tables show that DPE was largely contributed by CTE i.e. the forecast tracks were not close to observed track. ATE that is the errors in speed of movement of the storm.

Table-3.8.1 (b). Along the Track (AT) Forecast Error in km of IMD-HWRF Model

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr
HWRF	61(18)	65(16)	82(14)	99(12)	67(10)	93(8)	58(6)	123(4)	280(2)

(Number of forecasts verified is given in the parentheses) ::

Table-3.8.1 (c): Cross the Track (CT) Forecast Error in km of IMD-HWRF Model

Lead Time	12 Hr	24 Hr	36 Hr	48 Hr	60 Hr	72 Hr	84 Hr	96 Hr	108 Hr
HWRF	132 (18)	205 (16)	237 (14)	264 (12)	292 (10)	296 (8)	325 (6)	389 (4)	403 (2)

(Number of forecasts verified is given in the parentheses) :

3.8.3. Landfall forecast errors:

Average errors in landfall point and time are presented in Table 3.8.2 and 3.8.3. The tables indicate that most of the models didn't predict landfall at different lead times . The landfall point errors of IMD GFS and NCEP GFS were significantly less as compared to other models. The landfall time errors were the least by IMD HWRF upto 72 hours lead period.

Table-3.8.2. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H
Based on	17 /00z	16 / 12z	16 / 00z	15 / 12z	15 /00z	14 / 12z	14 / 00z	13 / 12z	13 /00z
IMD-GFS	93	77	8	27	246	-	47	85	85
IMD-WRF	-	-	47	-	-	-	673	-	-
JMA	-	87	27	-	-	-	316	324	-
NCEP-GFS	8	-	-	52	27	8	-	18	51
UKMO	57	230	-	-	-	-	87	-	-
ECMWF	-	-	190	27	-	52	-	-	-
IMD-MME	39	-	-	-	-	-	-	82	-
IMD-HWRF	15	23	124	273	110	88	25	74	39

Table 3.8.3: Landfall time forecast errors (hour) at different lead time (hr)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H
Based on	17/ 00z	16/ 12z	16/ 00z	15/ 12z	15/ 00z	14/ 12z	14 / 00z	13/ 12z	13/ 00z
IMD-GFS	+4	+3	0	-4	+4	-	-3	-8	-6
IMD-WRF	-	-	+1	-	-	-	-8	-	-
JMA	-	+6	+12	-	-	-	+4	-8	-
NCEP-GFS	+2	-	-	+4	-8	-8	-	-8	-8
UKMO	+4	+4	-	-	-	-	+16	-	-
ECMWF	-	-	+16	+4	-	+4	-	-	-
IMD-MME	+4	-	-	-	-	-	-	+4	-
IMD-HWRF	0	0	3	0	3	0	-9	-12	-18

('+' indicates delay landfall, '-' indicates early landfall)

3.8.4. Intensity forecast errors by various NWP Models

The intensity forecast by IMD SCIP for different lead periods based on 00 & 12 UTC during 13th – 16th December is presented in Fig. 3.8.4. The intensity forecasts of

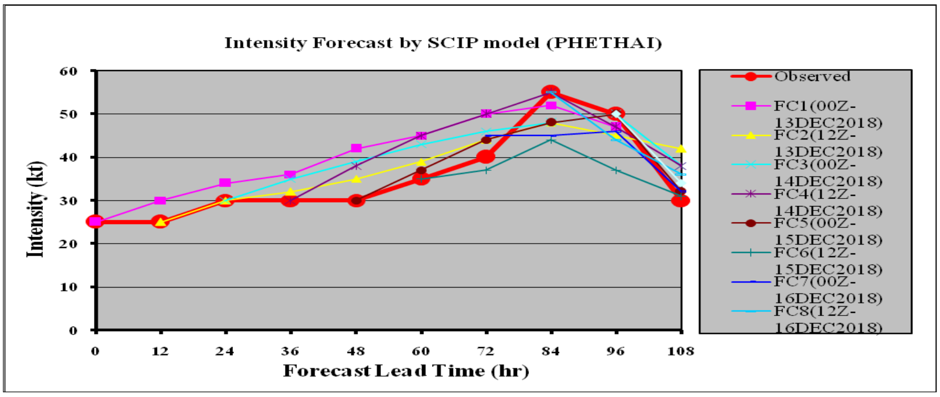


Fig. 3.8.4: Intensity forecast by IMD SCIP for different lead periods based on 00 & 12 UTC during 13th – 16th December

IMD-SCIP model and HWRF model are shown in Table 3.8.4. The intensity error was very high with HWRF model. It indicates that intensity prediction based on 12 UTC of 13th and 00 UTC of 15th December was closer to actual intensity.

The average absolute cross & Root Mean Square errors by IMD(SCIP) & HWRF model is presented in Table 3.8.4. It is seen that errors in intensity forecast by IMD (SCIP) model were comparatively lesser than HWRF model for all lead periods.

Table 3.8.4: 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 →	12H	24H	36H	48H	60H	72H	84H	96H	108H
IMD-SCIP (AAE)	4.8(9)	6.3(8)	7.3(7)	3.8(6)	5.2(5)	6.3(4)	5.3(3)	7.5(2)	
HWRF (AAE)	9.7(18)	13.6(16)	14.6(14)	13.2(12)	10.4(10)	7.9(8)	12.7(6)	14.5(4)	8.5(2)
IMD-SCIP (RMSE)	5.6	7.0	8.0	5.7	6.0	7.3	5.7	8.7	
HWRF (RMSE)	11.6	16.2	17.7	15.4	13.4	10.3	15.1	17.9	8.5

3.8.4.2 Landfall intensity predicted by SCIP Model

The landfall intensity predicted by IMD SCIP model for first and second landfall is presented in Fig.3.8.5 (a-b).

(i) First landfall: The forecast intensity was closer to observed intensity at the time of landfall most of the times except based on initial conditions of 00 UTC of 14th and & 00 & 12 UTC of 15th December**.**

(ii) Second landfall: IMD SCIP model overestimated the intensity during second landfall for all initial conditions during 12th to 17th.

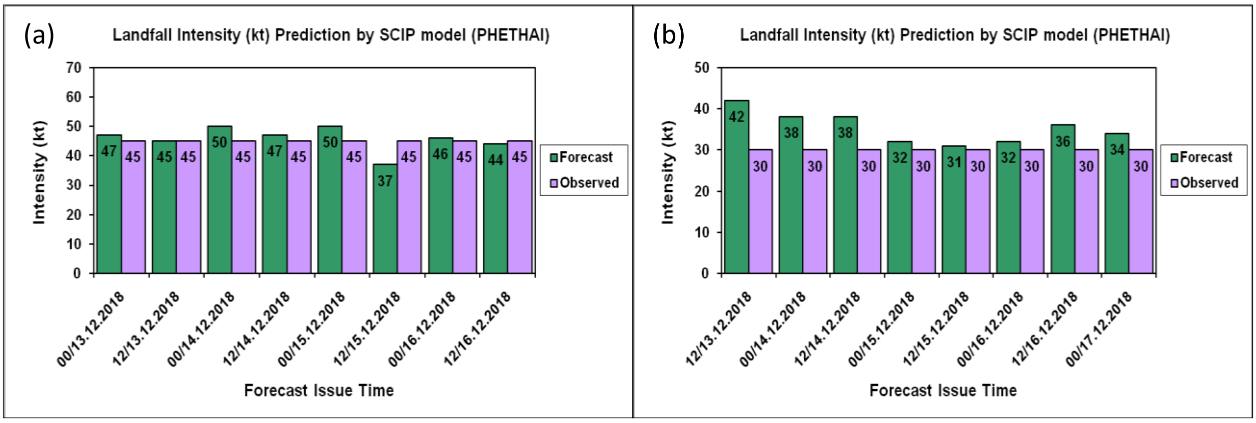


Fig. 3.8.5 (a-b): The landfall intensity predicted by IMD SCIP model for first and second landfall

3.9. Annual average forecast error and skill of NWP models for cyclones over the north Indian Ocean during 2018

3.9.1. Forecast Skill of Genesis Potential Parameter (GPP) during 2018

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) is 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 2018.

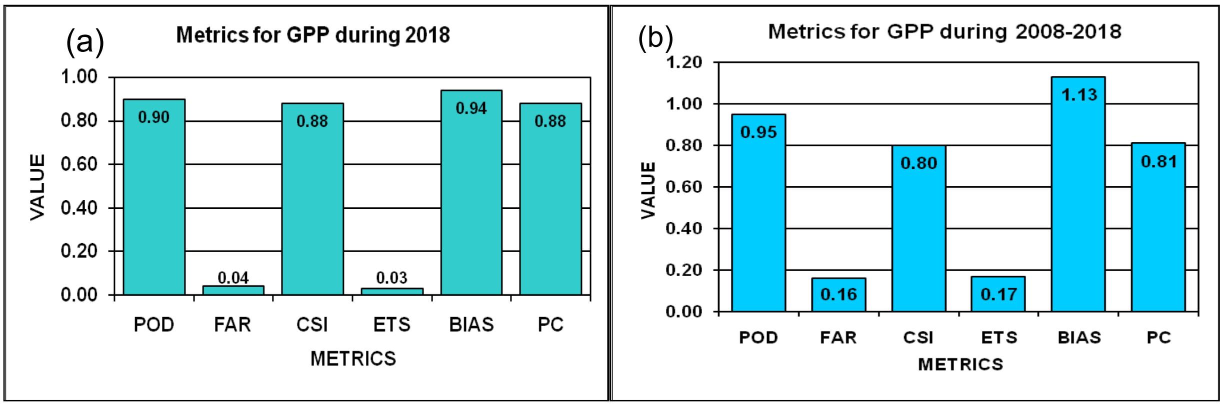


Fig. 3.9.1. POD, FAR, CSI, ETS, BIAS and PC for all genesis forecasts of GPP during (a) 2018 and (b) 2008-2018.

3.9.2. Mean track forecast error (km) – 2018

The annual average track forecast errors (Direct position error (DPE)) of various models during the year 2018 are shown in Table 3.9.1(Fig. 3.9.2). The 24 hr track forecast errors is less than 100 km for all models except JME and WRF, 48 hr track forecast errors is less than 100 km for ECMWF and MME and more than 150 for WRF and JMA, 72hr track forecast errors is less than 150 km for NCEP, IMD GFS and MME, 96hr track forecast errors is less than 150 km for MME, and 120hr track forecast errors is less than 220 km for MME. Track forecast error of HWRF model ranged from 66 km at 12h to 243 km at 120h. Consensus track forecast error of MME ranged from 53 km at 12h to 217 km at 120h. Mean model track forecast error (km) during 2009-2018 (84h to 120h for the period 2013-2018) is presented in the Fig 3.9.3 (MME, NCEP, ECMWF, JMA from 2009; IMD GFS, UKMO, IMD WRF from 2010 and HWRF from 2013). Fig. 3.9.3 and Fig. 3.9.4 shows MME forecast was most robust than other model guidance. Mean MME track forecast error (km) during 2009-2018 (84h to 120h for the period 2013-2018) is presented in the Fig 3.9.3. Year wise mean MME track forecast error (km) during 2009-2018 is shown in Fig 3.9.4 below.

Table-3.9.1: Annual average track forecast errors (DPE) of various models for the year 2018

Lead time →	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84hr	96hr	108hr	120hr
IMD-GFS	67 (62)	87 (59)	102 (55)	105 (48)	118 (37)	136 (32)	157 (26)	197 (21)	242 (13)	307 (10)
IMD-WRF	88 (54)	138 (52)	158 (50)	193 (43)	227 (36)	247 (30)	-	-	-	-
JMA	129 (56)	158 (54)	192 (51)	246 (45)	303 (37)	348 (31)	384 (24)	-	-	-
NCEP	66 (62)	91 (59)	106 (55)	111 (47)	111 (37)	131 (32)	134 (26)	187 (20)	199 (13)	303 (10)
UKMO	73 (60)	93 (58)	120 (54)	139 (48)	150 (37)	176 (32)	190 (26)	187 (20)	232 (13)	251 (9)
ECMWF	68 (62)	77 (59)	82 (55)	79 (48)	109 (37)	138 (32)	172 (26)	202 (21)	253 (13)	304 (10)
IMD-HWRF	66 (118)	87 (114)	100 (106)	128 (94)	149 (81)	173 (70)	199 (61)	213 (53)	217 (39)	243 (33)
IMD-MME	53 (62)	67 (59)	83 (55)	85 (48)	94 (37)	110 (32)	115 (26)	142 (21)	167 (13)	217 (10)
NCUM	-	122 (8)	-	144 (7)	-	170 (5)	-	323 (4)	-	208 (1)
NEPS	-	219 (10)	-	232 (8)	-	245 (6)	-	208 (4)	-	214 (2)

(Number of forecast verified given in the parentheses)

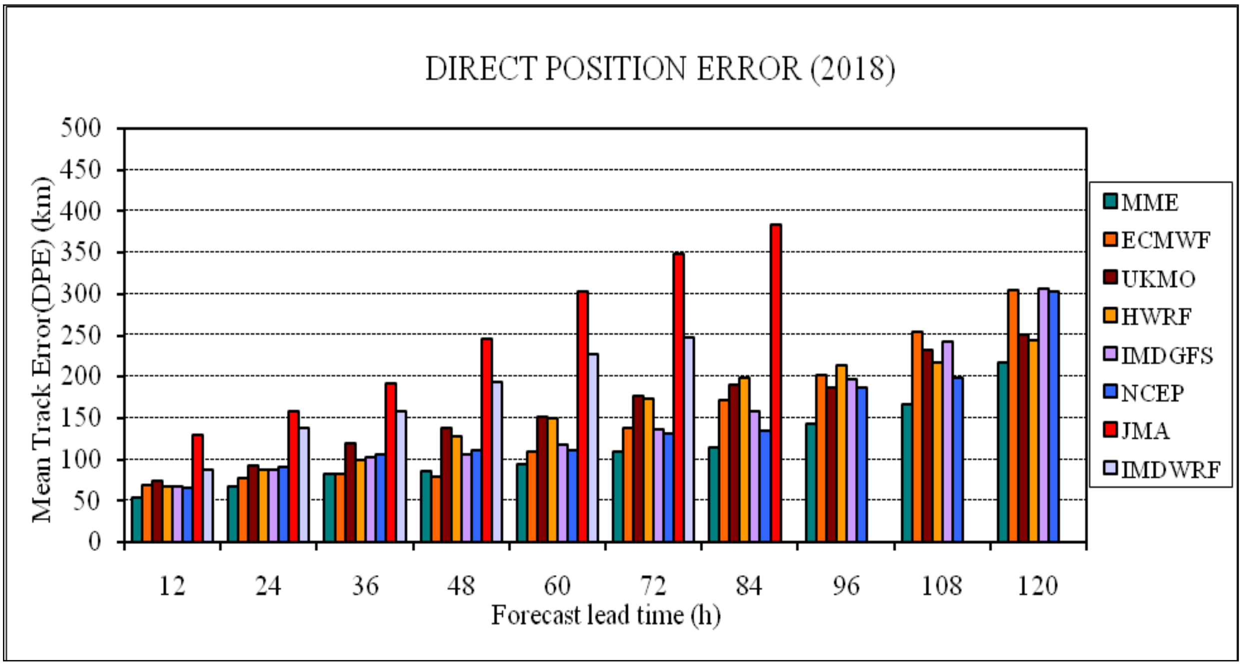


Fig. 3.9.2. Mean track forecast error (km) during 2018

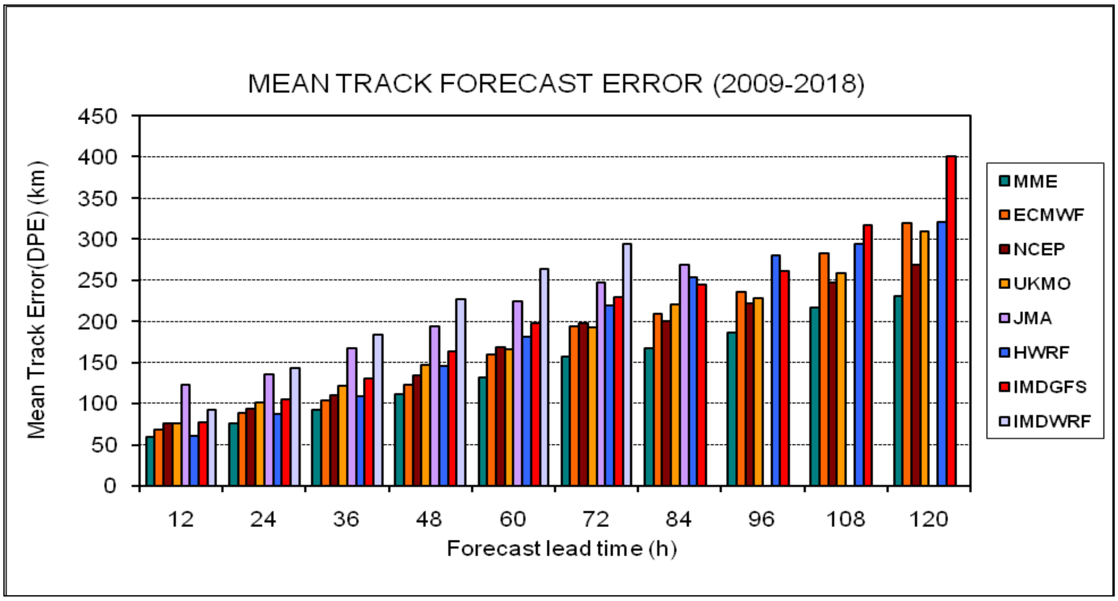


Fig. 3.9.3. Mean model track forecast error (km) during 2009-2018 (84h to 120h for the period 2013-2018) (MME, NCEP, ECMWF, JMA from 2009; IMD GFS, UKMO, IMD WRF from 2010 and HWRF from 2013)

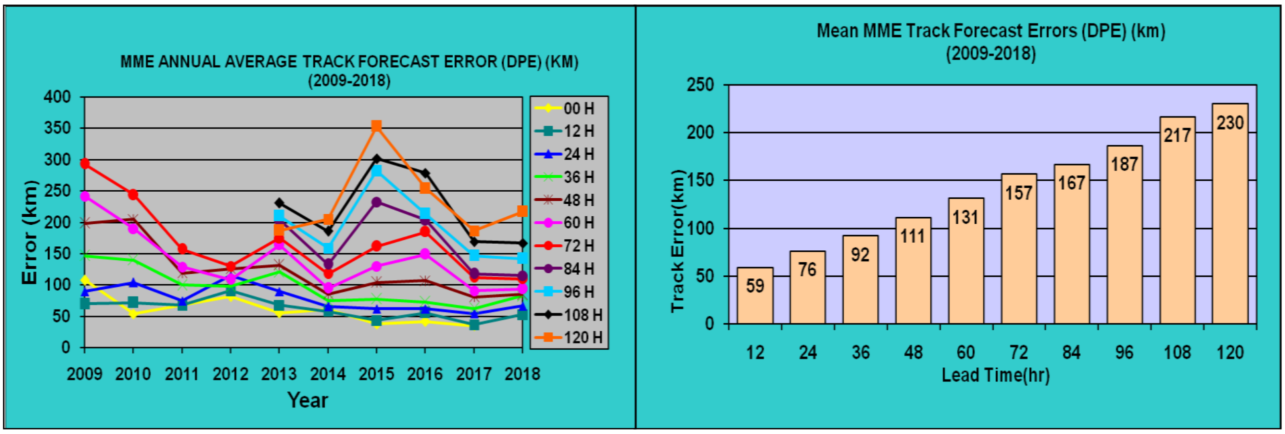


Fig. 3.9.4. (a) Year wise MME track forecast error (km) during 2009-2018 (b) Mean MME track forecast error (km) during 2009-2018 (84h to 120h for the period 2013-2018)

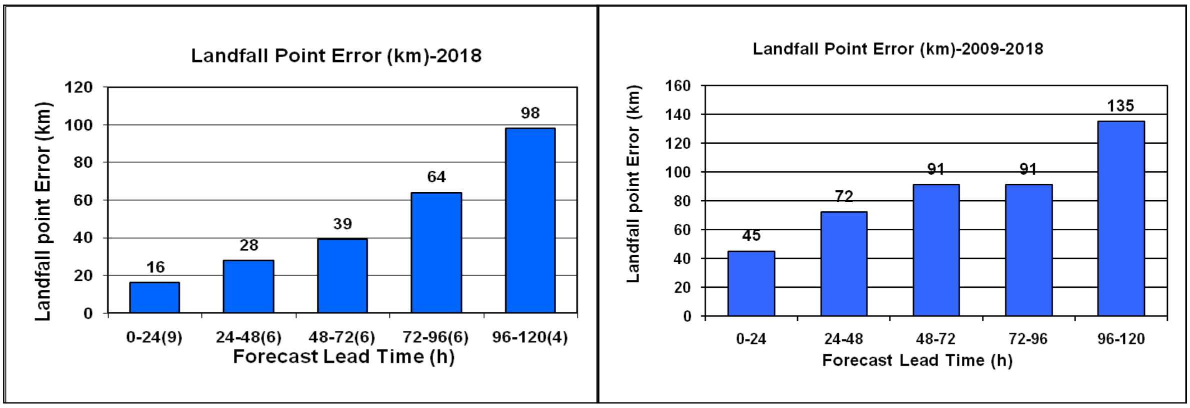


Fig. 3.9.5. Mean landfall point forecast error (km) of MME (a) during 2018 (b) during 2009-2018

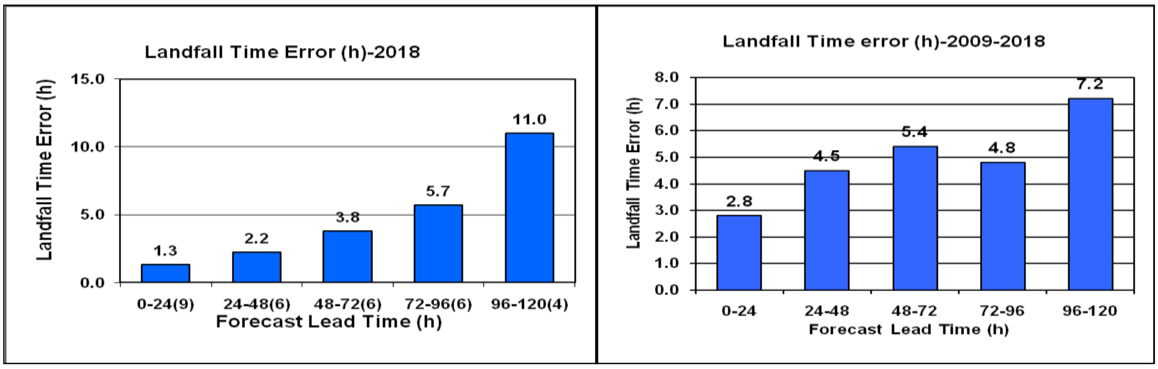


Fig. 3.9.6. Mean landfall time error (h) of MME (a) during 2018 (b) during 2009-2018

3.9.3 Mean Intensity forecast error (kt) -2018

3.9.3.1. SCIP model -2018

The annual average intensity forecast errors of SCIP model are shown in Table 3.9.2. The absolute average error(AAE) is 6.4 kts at 24hr, 9.8 kts at 48hr, 11.8 kts at 72hr, 16.8 kts at 96hr and 5.3 at 120 kts for all the cyclonic storms over the North Indian Seas during the year 2018.

Table-3.9.2: The annual average intensity forecast errors (kt) AAE and RMSE (root mean square error) of SCIP for all the systems during 2018

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-SCIP (AAE)	4.9 (63)	6.4 (57)	7.6 (51)	9.8 (40)	13.1 (32)	11.8 (26)	12.4 (22)	16.8 (17)	11.2 (13)	5.3 (9)
IMD-SCIP (RMSE)	7.4	8	10.1	12.7	18.9	14.7	14.9	19.4	13.2	6.8

(Number of forecast verified given in the parentheses)

Year wise and mean intensity forecast error (kt) by SCIP model during 2008-2018 for 12h to 120h forecasts are presented in Fig 3.9.7 and mean intensity forecast error (kt) of SCIP model during 2008-2018 is shown in Fig. 3.9.8.

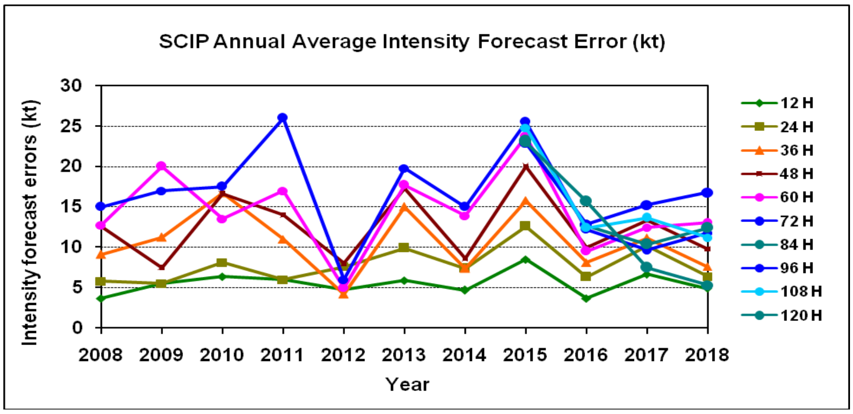


Fig. 3.9.7: Year wise intensity forecast error (kt) by SCIP model during 2008-2018 for 12h to 120 h forecasts

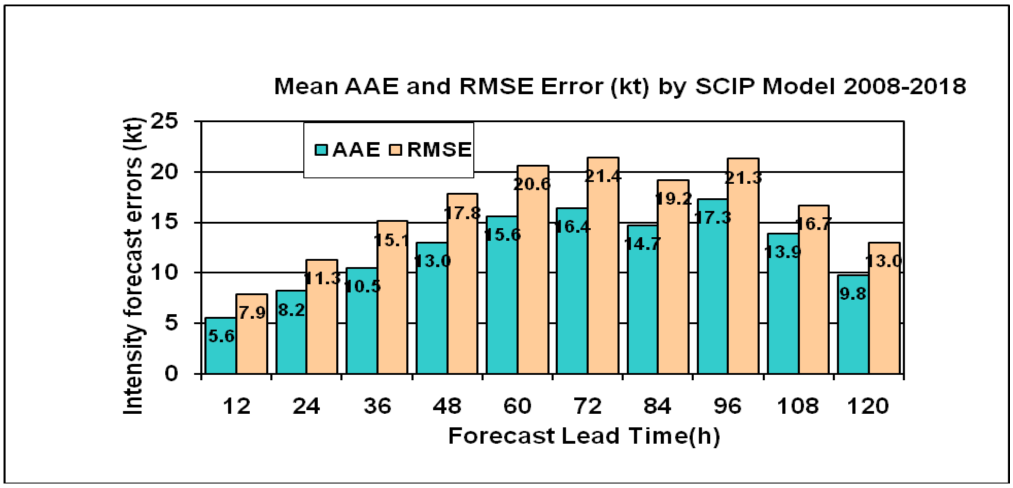


Fig. 3.9.8. Mean Intensity forecast error (kt) of SCIP model during 2008-2018

3.9.3.2. HWRF model -2018

The annual average intensity forecast errors (kt) of HWRF model for the systems during 2018 are shown in Table 3.9.3.

Table-3.9.3 Average Absolute Error (kt) and RMSE of INTENSITY of IMD-HWRF Model-2018

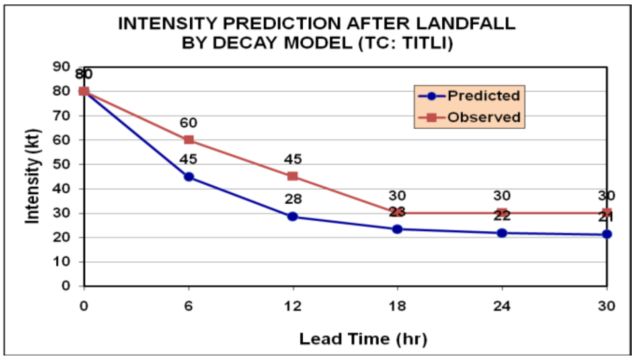
Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
AAE	10.6 (118)	11.9 (114)	12.2 (106)	8.6 (94)	11.5 (81)	11.1 (70)	12.1 (61)	12.4 (53)	15.1 (39)	17.2 (33)
RMSE	14.9	15.3	15.1	16.4	14.8	14.8	15.1	15.0	18.8	20.5

(Number of forecasts verified is given in the parentheses)

3.9.4 Decay after landfall -2018

The verification of cyclone intensity forecast after the landfall (Decay model forecast) is presented below for the landfalling cyclone Titli and Gaja.

3.9.4.1. Cyclone TITLI



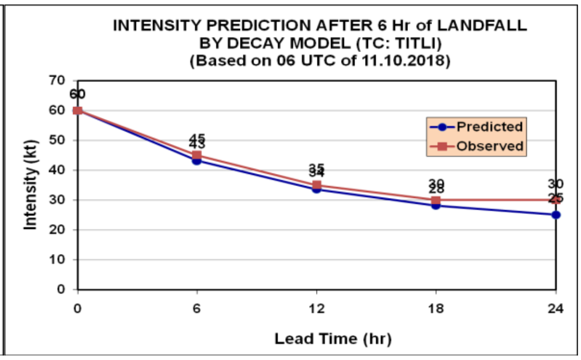


Fig. 3.9.9(a) Based on 0000 UTC of 11.10.2018 (b) Updated forecast based on 0600 UTC of 11.10.2018

The above figure indicated that the model could predict well the rate of decay after 6 hours of landfall, However, it overestimated the decay in the forecast issued in the time of landfall.

3.9.4.2. Cyclone GAJA

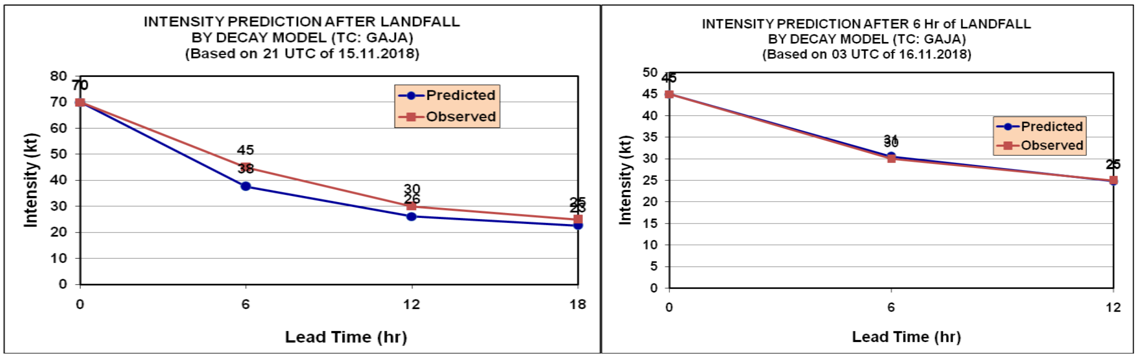


Fig. 3.9.10(a) Based on 2100 UTC of 15.11.2018 (b) Updated forecast based on 0300 UTC of 16.11.2018

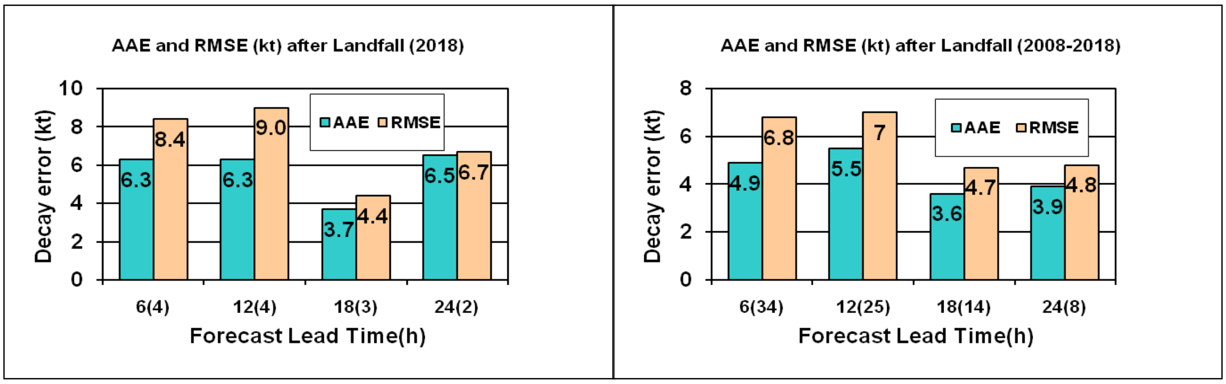


Fig. 3.9.11. Mean decay (after landfall) forecast error (kt) of DECAY model(a) in 2018 (b) during 2008-2018 (Number of forecast verified given in the parentheses)

The performance of the model was similar in case of Gaja like that of Titli. However, the error was relatively less

CHAPTER-IV

PERFORMANCE OF RSMC, NEW DELHI
IN TRACK AND INTENSITY PREDICTION OF CYCLONES DURING 2018

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 2018. 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, Iran, Maldives, Myanmar, Thailand, Pakistan, Qatar, Oman, Saudi Arabia, Sri Lanka, UAE 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 bulletins were 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, From 2018 onwards, The quantitative track & intensity forecast for +12, +24, +36, +48, +60, +72 hrs. lead period was issued from depression stage. 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 2018 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 storm during 2018

Bulletins issued during ‘Sagar'

Bulletins for national disaster management agencies	:	27
Bulletin for WMO/ESCAP Panel counties		

(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 27
Tropical cyclone advisory for international civil aviation : 13

Bulletins issued during 'Mekunu'

Bulletins for national disaster management agencies : 43
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 43
Tropical cyclone advisory for international civil aviation : 20

Bulletins issued during 'Daye'

Bulletins for national disaster management agencies : 18
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 07
Tropical cyclone advisory for international civil aviation : 05

Bulletins issued during 'Luban'

Bulletins for national disaster management agencies : 54
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 65
Tropical cyclone advisory for international civil aviation : 29

Bulletins issued during 'Titli'

Bulletins for national disaster management agencies : 37
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 43
Tropical cyclone advisory for international civil aviation : 12

Bulletins issued during 'Gaja'

Bulletins for national disaster management agencies : 65
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 61
Tropical cyclone advisory for international civil aviation : 34

Bulletins issued during ' Phethai '

Bulletins for national disaster management agencies : 33
Bulletin for WMO/ESCAP Panel counties
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 32
Tropical cyclone advisory for international civil aviation : 16

Bulletins issued for all cyclonic storm during 2018

Bulletins for national disaster management agencies : 277
RSMC bulletin for WMO/ESCAP Panel member countries
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 278
TCAC bulletin for international civil aviation : 129

***Bulletins issued for all cyclonic disturbances (depression and above) during 2018**

Bulletins for national disaster management agencies : 330
RSMC bulletin for WMO/ESCAP Panel member countries
(Special Tropical Weather Outlook and Tropical Cyclone Advisory) : 303
TCAC bulletin for international civil aviation : 129

The number of bulletins issued during 2009-2018 for all cyclones over the NIO is shown in Fig.4.1.1 for comparison.

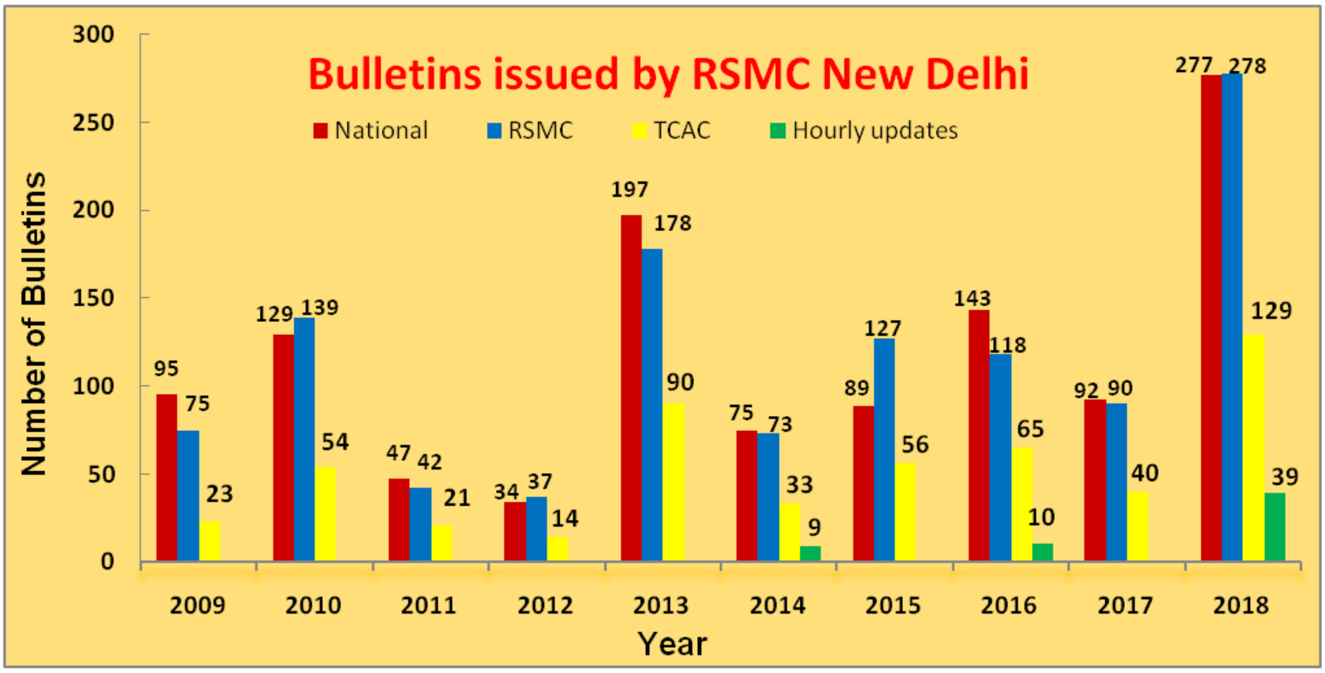


Fig 4.1.1: Total Number of bulletins issued by RSMC, New Delhi for all cyclones during 2009-2018

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 seven cyclonic storms during 2018 is described in following sections:

4.3.1 Cyclonic Storm "Sagar" over Arabian Sea (16 – 21 May 2018)

4.3.1.1. Genesis Forecast

- First information regarding formation of a low pressure area over the central parts of south AS and adjoining central AS around 15th May and it's movement towards Yemen coast with further intensification into D in subsequent 48 hrs was predicted in Tropical Weather Outlook issued at (1130 IST) 0600 UTC of 11th May (72 & 108 hours in advance of formation of low pressure area & D respectively). Low pressure area formed over southwest AS on 14th and D formed over Gulf of Aden at 1200 UTC of 16th.

4.3.1.2. Landfall Forecast

- First information regarding landfall of system near northwest Somalia (near 11.3°N/43.1°E) around 0900 UTC of 19th was issued at 1400 UTC of 17th May (42 hours in advance of actual landfall). The system crossed Somalia coast near 10.65°N/44.0°E between 0800-0900 UTC of 19th May.
- The landfall point forecast errors for 12, 24, and 36 hrs lead period were 6.6, 40.4, and 100.5 km respectively and the landfall time forecast errors for 12, 24, and 36 hrs lead period were 1.0, 1.0, and 5.5 hrs respectively **(Fig. 4.3.1.1).**

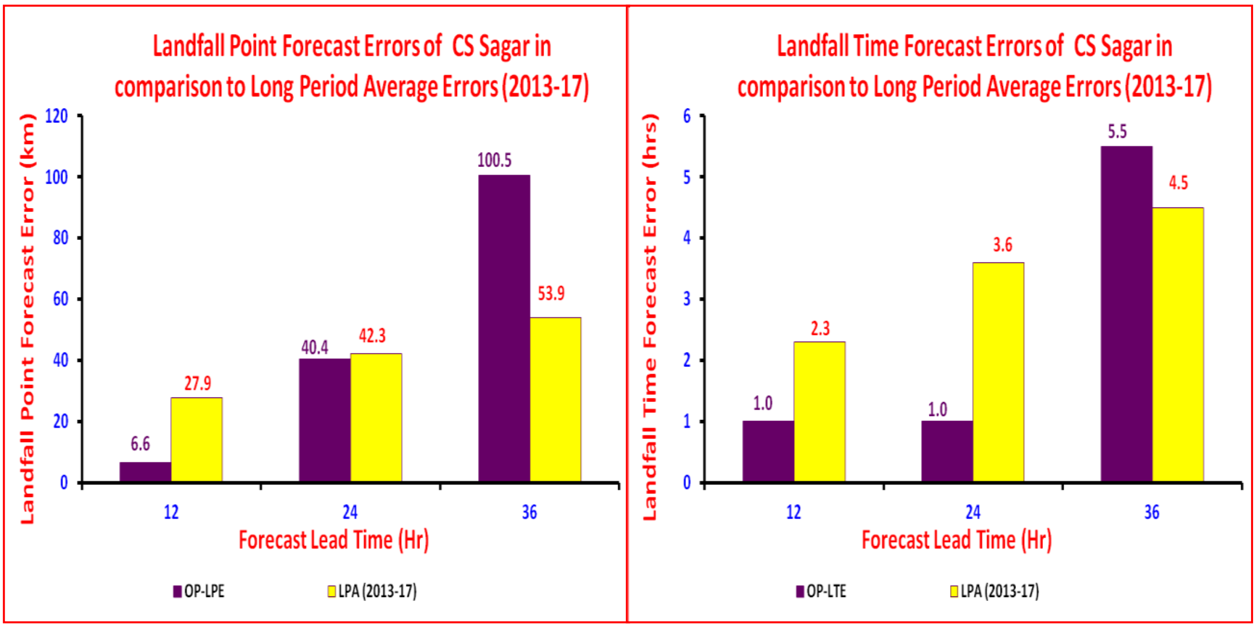


Fig. 4.3.1.1: Landfall Point Errors (LPE) and Landfall Time Errors (LTE) for CS Sagar

- First bulletin issued at 1500 UTC observations of 16th May indicated that the system would move west-northwestwards towards Yemen coast during next 24 hours and then west-southwestwards during subsequent 48 hours. The track shows that the system moved west-northwestwards upto 0300 UTC of 17th (for 15 hours) and then west-southwestwards till its weakening into a WML at 0300 UTC of 20th May (for subsequent

72 hours). Thus the track of the system including its west-southwestward recurvature was well predicted.

- The typical example of observed and forecast track with cone of uncertainty is presented in **Fig.4.3.1.2.** The graphics showing observed and forecast tracks for different lead periods is presented in **Fig.4.3.1.3.**

Table 4.3.1.1: Landfall Point and Time Error in association with ESCS Mekunu

Lead Period (hrs)	Base Time (UTC)	Landfall Point (^{0}N/^{0}E)		Landfall Time (UTC)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	18/18	10.7/44.1	10.7/44.0	19/0830	19/0730	6.6	1.0	53.9	4.5
24	18/06	10.9/43.7	10.7/44.0	19/0630	19/0730	40.4	1.0	94.8	5.4
36	17/18	11.4/43.5	10.7/44.0	19/0200	19/0730	100.5	5.5	115.4	4.6

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point,
LTE= Forecast Landfall Time-Actual Landfall Time

4.3.1.3. Track Forecast

- The track forecast error for 12, 24, and 48 hrs lead period were 42.7, 49.6, and 117.2 km respectively, which is significantly less than the average track forecast errors of 57, 93, and 144 km during last five years (2013-17). The track forecast skill was about 18%, 53%, and 64% against the long period average (LPA) of 45%, 55%, and 68% during 2013-17 for 12, 24 and 48 hrs lead period respectively. (**Fig.4.3.1.4**).

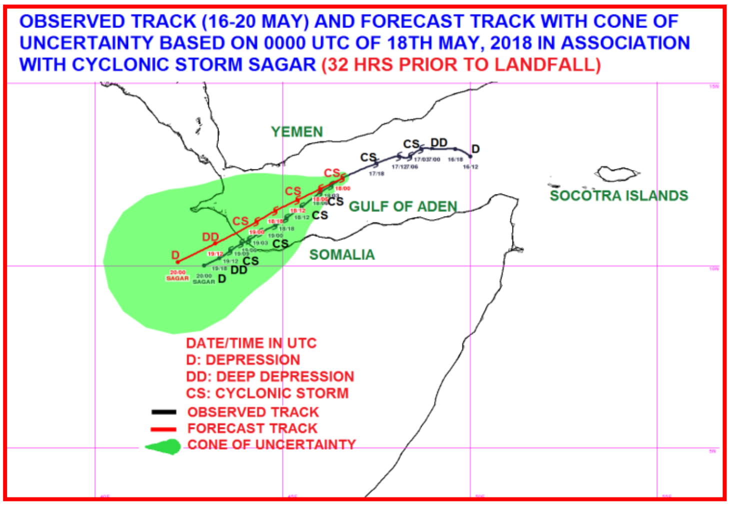


Fig.4.3.1.2: Observed and forecast track with cone of uncertainty based on 0000 UTC of 18th May, 2018 in association with CS Sagar

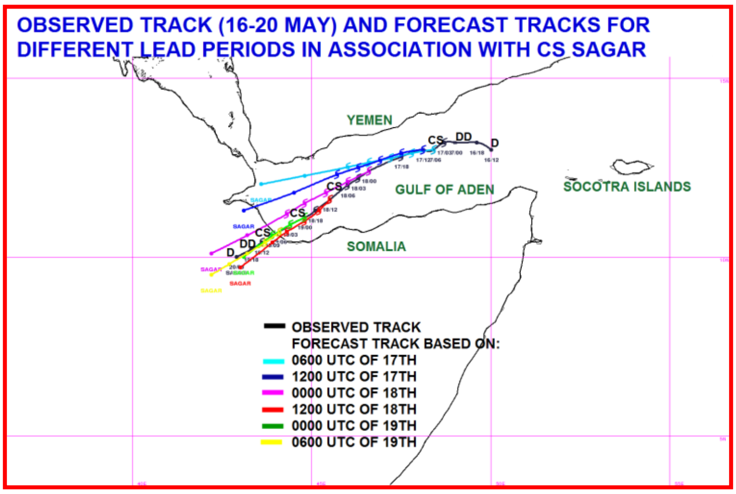


Fig.4.3.1.3: Observed track and forecast tracks for different lead periods

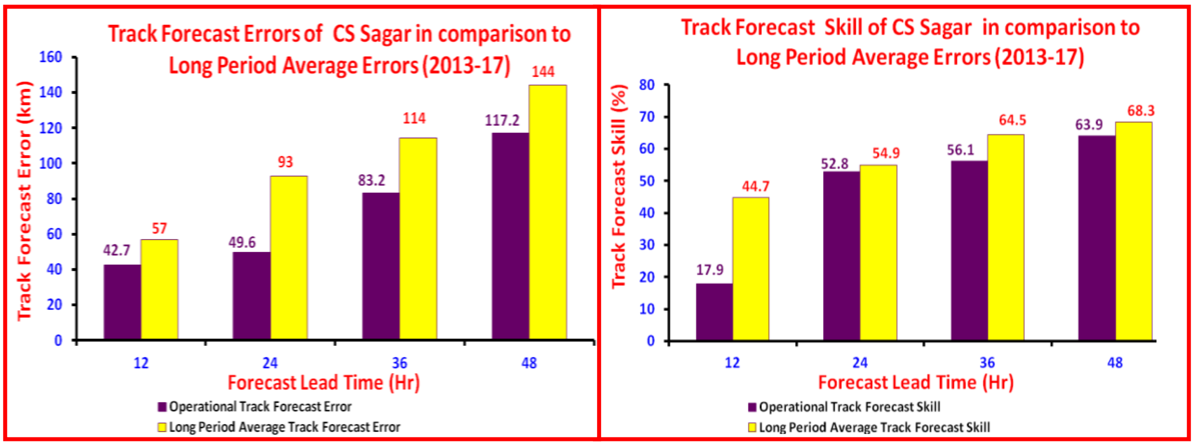


Fig.4.3.1.4: Track Forecast Errors and Skill for CS Sagar

Table 4.3.1.2: Average Track forecast error in association with ESCS Mekunu

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2013-17)	
				Track forecast error (km)	Skill (%)
12	12	42.7	17.9	57	44.7
24	10	49.6	52.8	93	54.9
36	8	83.2	56.1	114	64.5
48	4	117.2	63.9	144	68.3

N: No. of observations verified, LPA: Long Period Average (2013-17)

4.3.1.4. Intensity Forecast

- First wind warning issued at 2000 UTC of 16th indicated that the system would intensify upto a cyclonic storm.
- The warning issued at 0200 UTC of 18th indicated that the system would cross Somalia coast as a CS with MSW of 65-75 kmph (37 knots) (32 hours in advance). The system crossed Somalia coast as a CS with MSW of 40 kts. Typical graphical product giving wind distribution is presented in **Fig. 4.3.1.5.**
- The absolute error (AE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 2.2, 7.0 and 10.8 knots against the LPA of 6.3, 10.4, and 15.5 knots respectively. The skill in intensity (wind) forecast based on AE for 12, 24 and 48 hrs lead period was 34.3, 17.6 and 46.3% against the LPA of 22.3, 37.1 and 56.8% respectively. (**Fig.4.3.1.6**)
- The root mean square error (RMSE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 2.7, 8.1 and 12.7 knots against the LPA of 8.7, 14.0, and 20.6 knots respectively. The skill based on RMSE of intensity (wind) forecast for 12, 24 and 48 hrs lead period was 53.8, 22.1 and 47.5% against the LPA of 28.0, 40.1 and 60.0% respectively. (**Fig.4.3.1.7**)

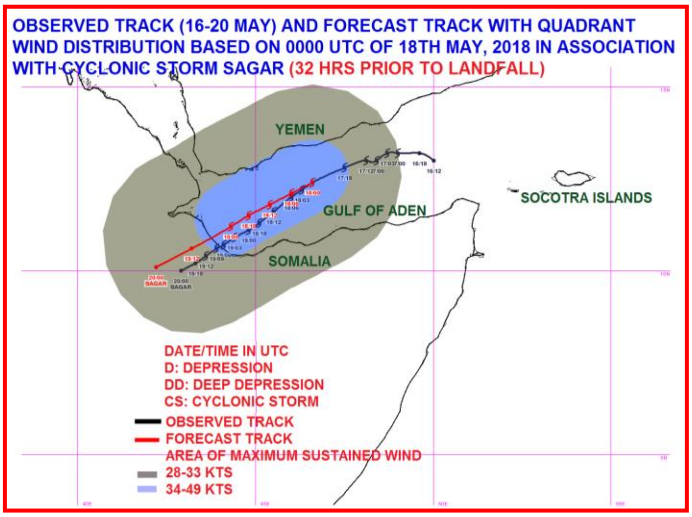


Fig.4.3.1.5: Observed and forecast track with quadrant wind distribution based on 0000 UTC of 18th May, 2018 in association with CS Sagar

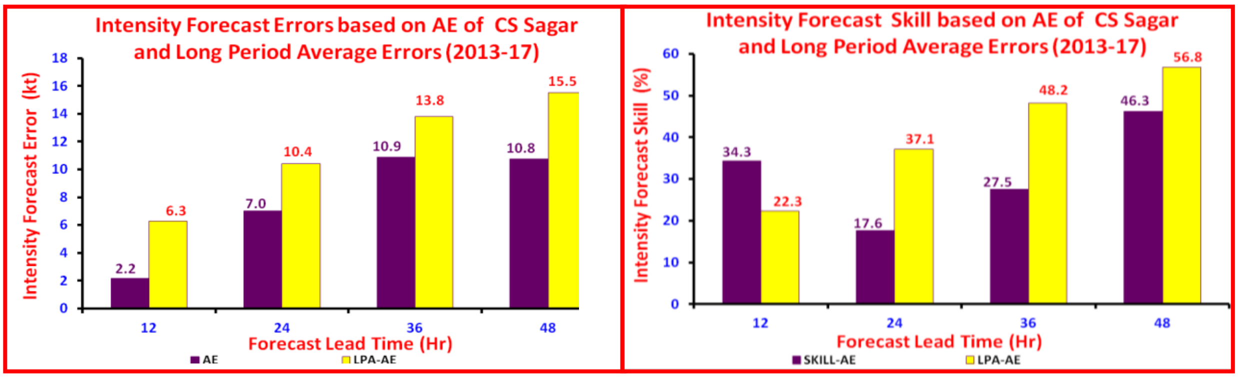


Fig. 4.3.1.6: Absolute errors (AE) of intensity forecast and skill for CS Sagar

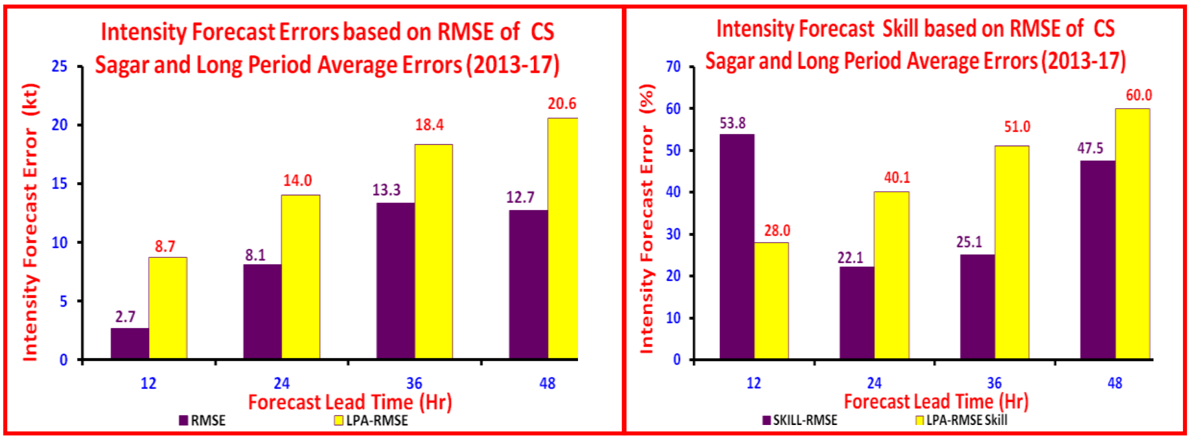


Fig. 4.3.1.7: Root mean square errors (RMSE) of intensity forecast and skill for CS Sagar

Table 4.3.1.3: Average Intensity forecast error in association with ESCS Mekunu

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2013-17)		LPA Skill (%) in Intensity forecast (2013-17)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	12	2.2	2.7	34.3	53.8	6.3	8.7	22.3	28.0
24	10	7.0	8.1	17.6	22.1	10.4	14.0	37.1	40.1
36	8	10.9	13.3	27.5	25.1	13.8	18.4	48.2	51.0
48	4	10.8	12.7	46.3	47.5	15.5	20.6	56.8	60.0

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17).

4.3.2. Extremely Severe Cyclonic Storm, 'MEKUNU' over the Arabian Sea (21 – 27 May 2018)

4.3.2.1 Genesis Forecast

- First information regarding formation of a low pressure area over southeast AS was given in Tropical Weather Outlook issued in the morning (0600 UTC) of 20th May with moderate probability (51-75%) of it's intensification into a D during next 24-48 hours (36 hours in advance of formation of D). D formed over southwest AS at 1200 UTC of 21st.

4.3.2.2. Landfall Forecast

- First bulletin issued around noon (0600 UTC) of 20th May indicated that the system would move towards south Oman-southeast Yemen coasts (about 138 hours in advance of actual landfall).
- First information regarding landfall of cyclone near south Oman-southeast Yemen coast close to Salalah around morning of 26th May was issued at 0300 UTC of 22nd May (88 hours in advance of actual landfall). The system crossed south Oman coast near 16.85°N/53.75°E around midnight (between 1830 & 1930 UTC) of 25th May.
- The landfall point forecast errors for 24, 48 and 72 hrs lead period were 17.2, 12.5 and 29.0 km respectively and the landfall time forecast errors for 24, 48 and 72 hrs lead period were 7.0, 8.0, and 7.0 hrs respectively (Fig. 4.3.2.1 and Table 4.3.2.1).

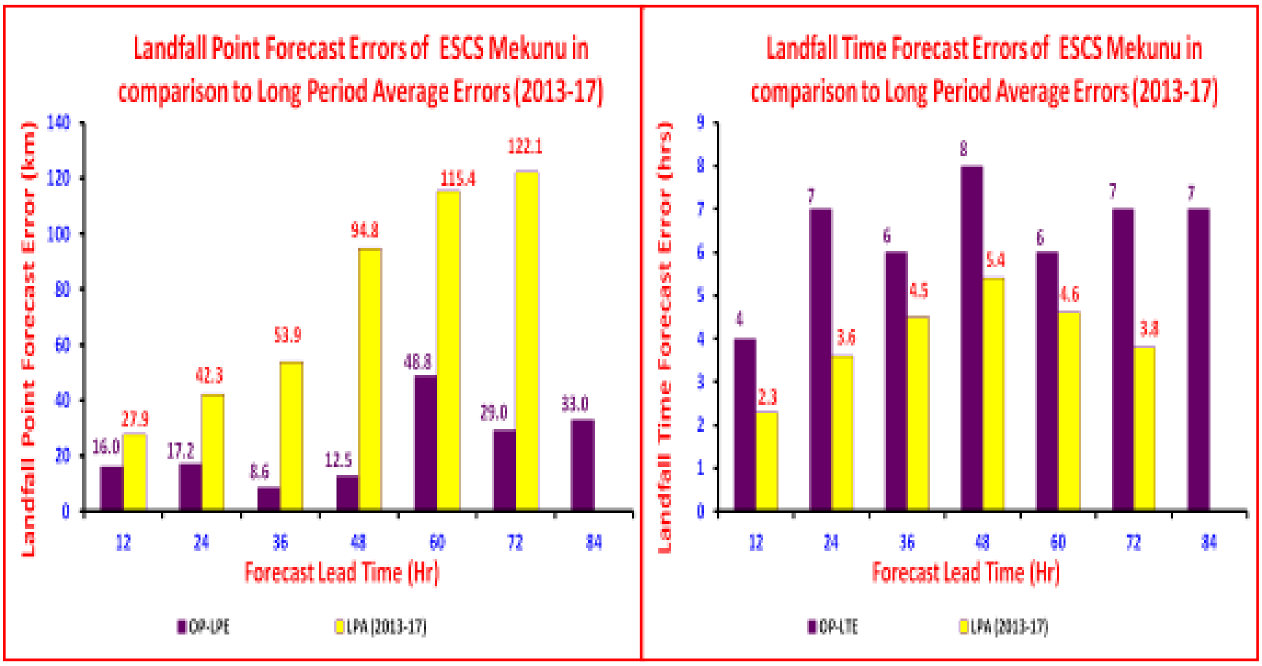


Fig.4.3.2.1: Landfall Point Forecast Error (LPE) and Landfall Time Forecast Errors (LTE) of ESCS Mekunu

Table 4.3.2.1: Landfall Point and Time Error in association with ESCS Mekunu

Lead Period (hrs)	Base Time (UTC)	Landfall Point ($^0N/^0E$)		Landfall Time (UTC)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	25/06	16.8/53.6	16.9/53.8	25/2300	25/1900	16.0	4	27.9	2.3
24	24/18	16.9/53.9	16.9/53.8	26/0200	25/1900	17.2	7	42.3	3.6
36	24/06	16.9/53.8	16.9/53.8	26/0100	25/1900	8.6	6	53.9	4.5
48	23/18	16.9/53.8	16.9/53.8	26/0300	25/1900	12.5	8	94.8	5.4
60	23/06	16.7/53.3	16.9/53.8	26/0100	25/1900	48.8	6	115.4	4.6
72	22/18	17.0/54.0	16.9/53.8	26/0200	25/1900	29.0	7	122.1	3.8
84	22/00	17.0/54.0	16.9/53.8	26/0200	25/1901	33.0	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

4.3.2.3 Track Forecast

- The track based on 0000 UTC of 22nd **(Fig.** 4.3.2.1**)** shows that the system moved north-northwestwards towards south Oman-southeast Yemen coast.
- Typical graphics showing observed and forecast tracks for different lead periods is presented in **Fig.** 4.3.2.2**.** It indicates that for all lead periods track was well predicted. The observed and a typical forecast track with cone of uncertainty based 0000 UTC of 23rd is presented in **Fig.** 4.3.2.3**.**
  The track forecast error for 24, 48, and 72 hrs lead period were 48.8, 63.3, and 79.4 km respectively, which is significantly less than the average track forecast errors of 93, 144 and 201 km during last five years (2013-17). The track forecast skill was about 54.9%, 68.3%, and 71.6% against the long period average (LPA) of 45%, 55%, and 68% during 2013-17 for 24, 48 and 72 hrs lead period respectively. (**Fig.** 4.3.2.4 **and Table** 4.3.2.2).

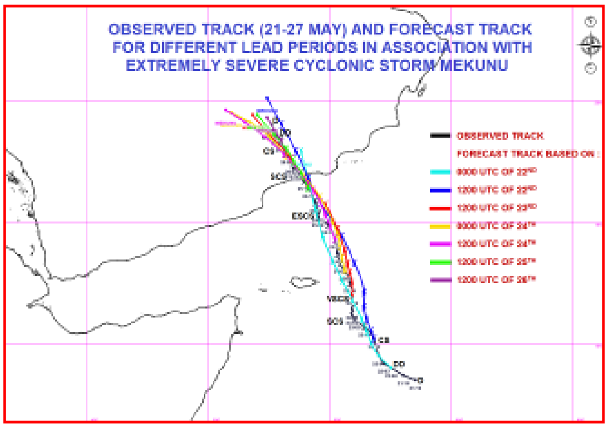


Fig. 4.3.2.2: Observed track and forecast tracks for different lead periods

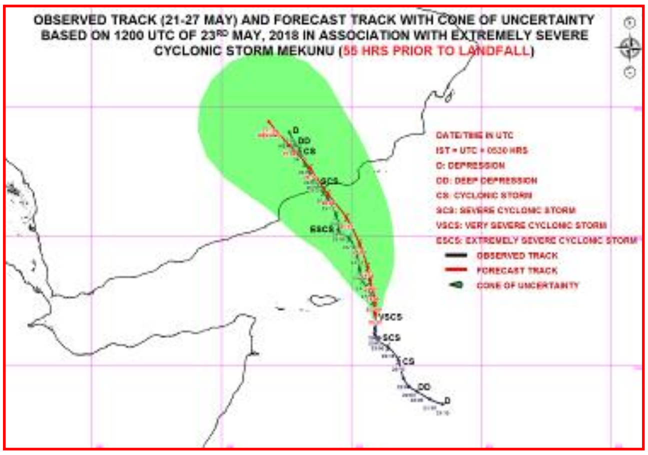


Fig. 4.3.2.3: Observed and forecast track with cone of uncertainty based on 1200 UTC of 23rd May, 2018 in association with ESCS Mekunu

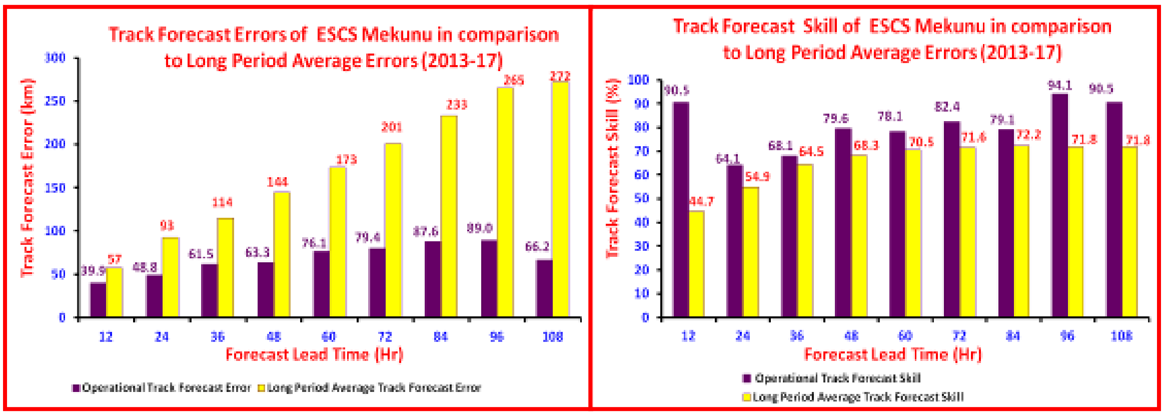


Fig. 4.3.2.4**: Track Forecast Errors and Skill for ESCS Mekunu**

Table 4.3.2.2: Average Track forecast error in association with ESCS Mekunu

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2013-17)	
				Track forecast error (km)	Skill (%)
12	20	39.9	90.5	57	44.7
24	17	48.8	64.1	93	54.9
36	16	61.5	68.1	114	64.5
48	14	63.3	79.6	144	68.3
60	12	76.1	78.1	173	70.5
72	10	79.4	82.4	201	71.6
84	7	87.6	79.1	233	72.2
96	5	89.0	94.1	265	71.8
108	3	66.2	90.5	272	71.8

N: No. of observations verified, LPA: Long Period Average (2013-17)

4.3.2.4 Intensity Forecast

- First information regarding intensification of system into a cyclonic storm was issued in Tropical Weather Outlook issued around noon (0600 UTC) of 20th May.
- First information that the system would cross south Oman-southeast Yemen coasts near Salalah as a VSCS with MSW of 150-160 kmph was issued in the morning(0300 UTC) of 22nd May (about 88 hours in advance of landfall).
- The wind warning was further updated in the morning (0300 UTC) of 24th May to 160-170 kmph (about 39 hours in advance of landfall) and in the evening (1200 UTC) of 25th May to 170-180 kmph (about 7 hours in advance of landfall). The system crossed south Oman-southeast Yemen coasts as an ESCS with MSW of 170-180 kmph.
- Typical graphical product giving wind distribution around the cyclone based on 1200 UTC of 23rd May 2018 is presented in **Fig.** 4.3.2.5**.**
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 5.5, 14.1 and 14.7 knots against the LPA of 10.4, 15.5 and 15.4 knots respectively. The skill based on AE of intensity (wind) forecast for 24, 48 and 72 hrs lead period was 74.9, 56.7 and 71.7% against the LPA of 37.1, 56.8 and 69.3% respectively. (**Fig.** 4.3.2.6 **and Table** 4.3.2.3)
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 6.9, 16.1 and 16.2 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill based on RMSE of intensity (wind) forecast for 24, 48 and 72 hrs lead period was 77.9%, 60.9% and 76.7% against the LPA of 40.1, 60.0 and 73% respectively. (**Fig.** 4.3.2.7 and Table 4.3.2.3)

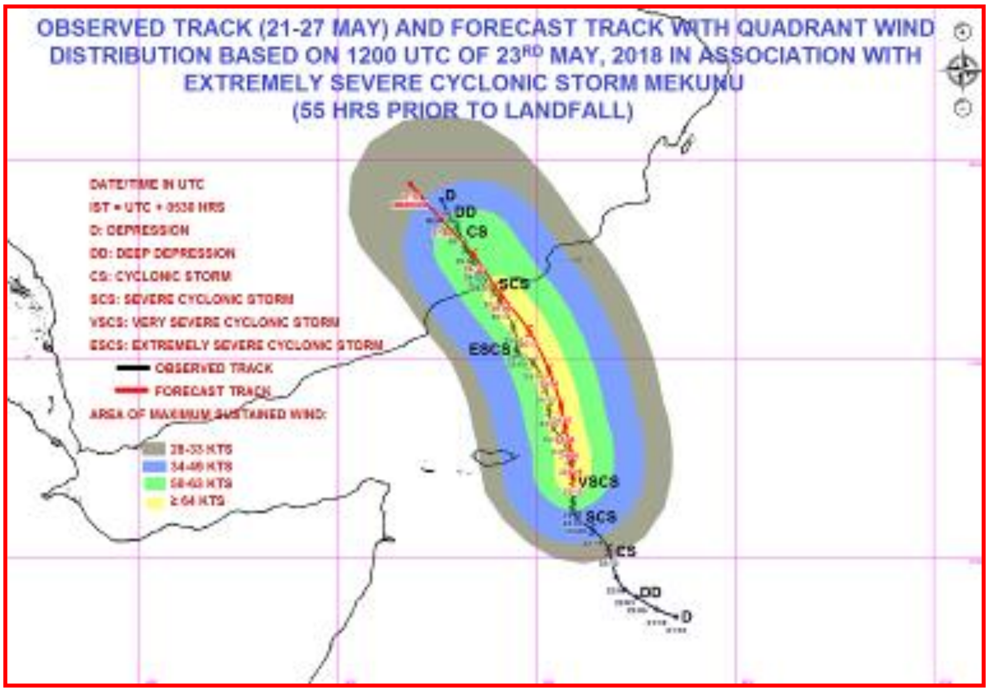


Fig. 4.3.2.5: Observed and forecast track with quadrant wind distribution based on 1200 UTC of 23rd May, 2018 in association with ESCS Mekunu

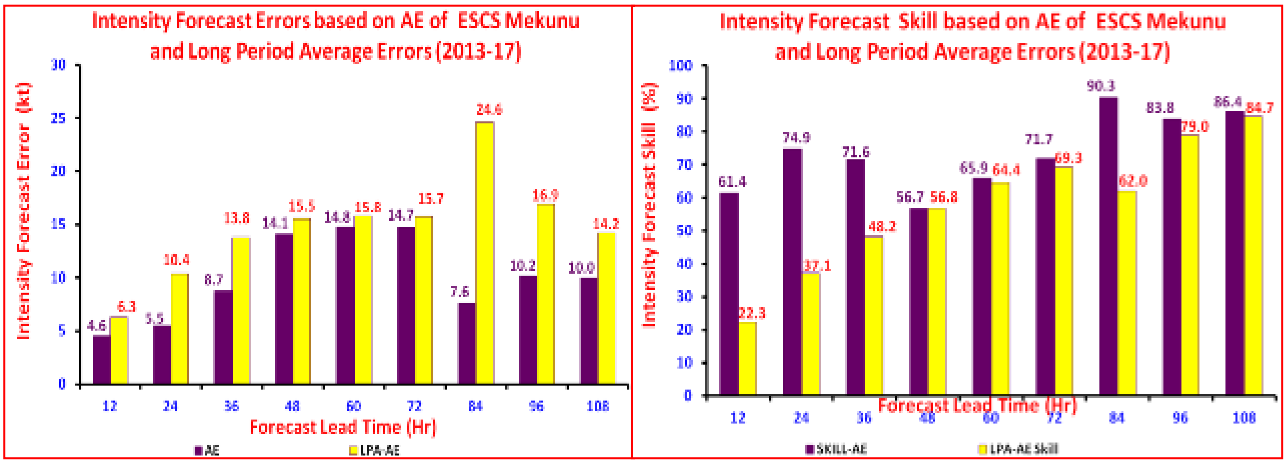


Fig.4.3.2.6: Absolute errors (AE) of intensity forecast and skill for ESCS Mekunu

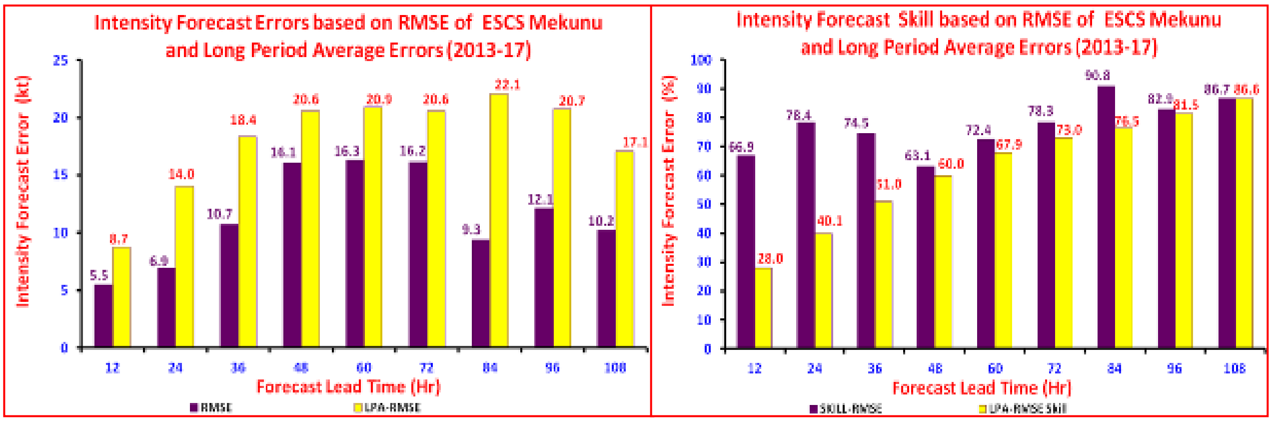


Fig. 4.3.2.7: Root mean square errors (RMSE) of intensity forecast and skill for ESCS Mekunu

Table 4.3.2.3:Average Intensity forecast error in association with ESCS Mekunu

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA (2013-17)Intensity forecast			
						Error (kts)		Skill (%)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	20	4.6	5.5	61.4	66.9	6.3	8.7	22.3	28.0
24	17	5.5	6.9	74.9	78.4	10.4	14.0	37.1	40.1
36	16	8.7	10.7	71.6	74.5	13.8	18.4	48.2	51.0
48	14	14.1	16.1	56.7	63.1	15.5	20.6	56.8	60.0
60	12	14.8	16.3	65.9	72.4	15.8	20.9	64.4	67.9
72	10	14.7	16.2	71.7	78.3	15.7	20.6	69.3	73.0
84	7	7.6	9.3	90.3	90.8	24.6	22.1	62.0	76.5
96	5	10.2	12.1	83.8	82.9	16.9	20.7	79.0	81.5
108	3	10.0	10.2	86.4	86.7	14.2	17.1	84.7	86.6

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17).

4.3.3. Cyclonic Storm "DAYE" over Bay of Bengal (19-22 September 2018)

4.3.3.1. Genesis Forecast

- First information regarding formation of an LPA over the central & adjoining north BoB around 18th and low (1-25%) probability of it's intensification into depression around 19th was issued in the Tropical Weather Outlook at 0600 UTC of 16th September (about 54 hours in advance of formation of LPA & 84 hours in advance of formation of depression). Thereafrer, the probability of formation of depression was upgrated to moderate and high in the tropical weather outlook issued on 17th and 18th September. The LPA formed over eastcentral BoB and adjoining Myanmar at 0900 UTC of 18th and depression formed over eastcentral BoB in the night (1500 UTC) of 19th.

4.3.3.2. Landfall Forecast

- First information regarding west-northwestwards movement of system towards south Odisha-north Andhra Pradesh coasts was issued in Tropical Weather Outlook issued at 0600 UTC of 17th Sep. (about 30 hours prior to landfall).
- The information regarding landfall of system near south Odisha-north Andhra Pradesh coasts between Kalingapatnam and Paradip close to Puri during late night of 20th & early morning of 21st was given in the first bulletin issued at 1700 UTC of 19th (about 24 hours in advance). The system crossed south Odisha and adjoining north Andhra Pradesh coasts close to Gopalpur near 19.27^{0}N/84.92^{0}E during 1900-2000 UTC of 20th September 2018.
- The landfall point was further updated in the bulletin issued on 20th at 0330 UTC that the system would cross south Odisha-north Andhra Pradesh coasts between Kalingapatnam and Puri close to Gopalpur around midnight of 20th (about 16 hours prior to landfall) with maximum sustained wind speed of 55-65 kmph gusting to 75 kmph. Pre-Cyclone Watch was issued for Odisha and north Andhra Pradesh coasts.
- The warning was further updated in the bulletin issued at 0700 UTC of 20th that the system would cross south Odisha-north Andhra Pradesh coasts between Kalingapatnam and Puri close to Gopalpur around midnight of 20th (about 12 hours prior to landfall) with maximum sustained wind speed of 60-70 kmph gusting to 80 kmph. Cyclone Alert for south Odisha and north Andhra Pradesh coasts was issued. It was upgraded to Cyclone Warning for south Odisha and north Andhra Pradesh coasts at 1630 UTC of 20th.
- The error in landfall point for 12 hours lead period was 39.7 km against long period average (LPA) (2013-17) of 29.7 km and the error in landfall time for 12 hours lead period was 3.5 hours against LPA of 2.3 hours.

4.3.3.3. Track Forecast

- The track forecast error for 24, and 48 hrs lead period were 63.1, and 58.5 km respectively, which is significantly less than the average track forecast errors of 93 and 144 km during last five years (2013-17). The track forecast skill was significantly higher being about 85%, and 93% against the long period average (LPA) of 55% and 68% during 2013-17 for 24 and 48 hrs lead period respectively. (**Fig. 4.3.3.1, Table 4.3.3.1**).

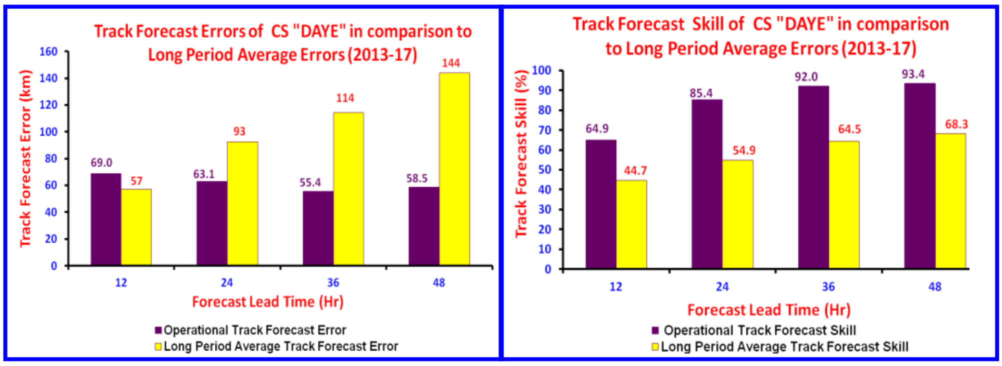


Fig. 4.3.3.1: Track Forecast Errors and Skill for CS Daye

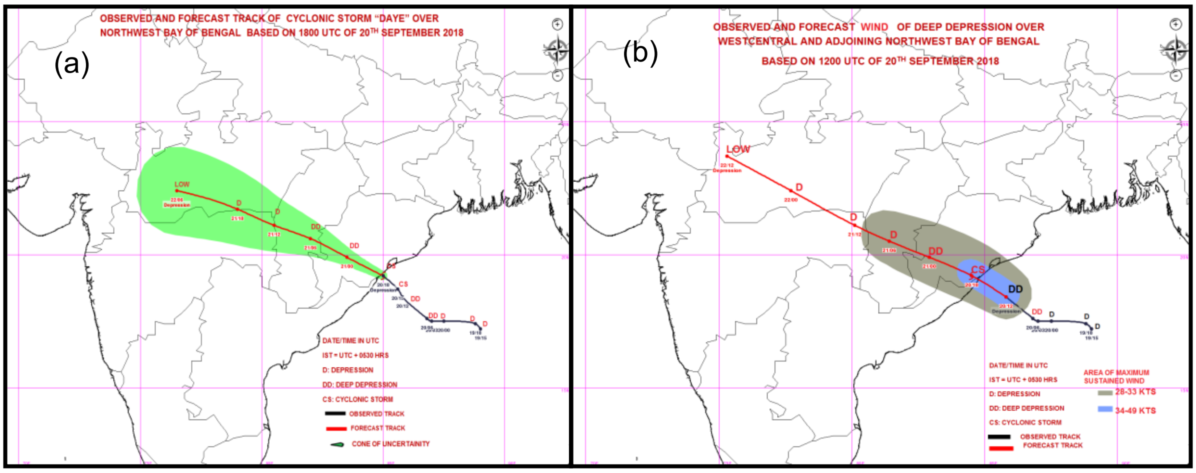


Fig. 4.3.3.2: Observed and forecast track with (a) cone of uncertainty based on 1800 UTC of 20th Sep. 2018 in association with CS Daye (b) wind distribution

Table 4.3.3.1: Average Track forecast error in association with CS Daye

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2013-17)	
				Track forecast error (km)	Skill (%)
12	5	67.5	65.6	57	44.7
24	4	70.9	83.5	93	54.9
36	4	54.2	92.2	114	64.5
48	3	58.5	93.4	144	68.3

4.3.3.4. Intensity Forecast

- The absolute error (AE) of intensity (wind) forecast for 24 and 48 hrs lead period were 1.1 and 6.1 knots against the LPA of 10.4 and 15.5 knots respectively. The skill in intensity (wind) forecast based on AE for 24 and 48 hrs lead period was 92.3 and 81.3% against the LPA of 37.1 and 56.8% respectively (**Fig. 4.3.3.3, Table 4.3.3.2**).

- The root mean square error (RMSE) of intensity (wind) forecast for 24 and 48 hrs lead period were 1.6 and 6.1 knots against the LPA of 14.0, and 20.6 knots respectively. The skill based on RMSE of intensity (wind) forecast for 24 and 48 hrs lead period was 89.8 and 81.8% against the LPA of 40.1 and 60.0% respectively (**Fig. 4.3.3.4**).

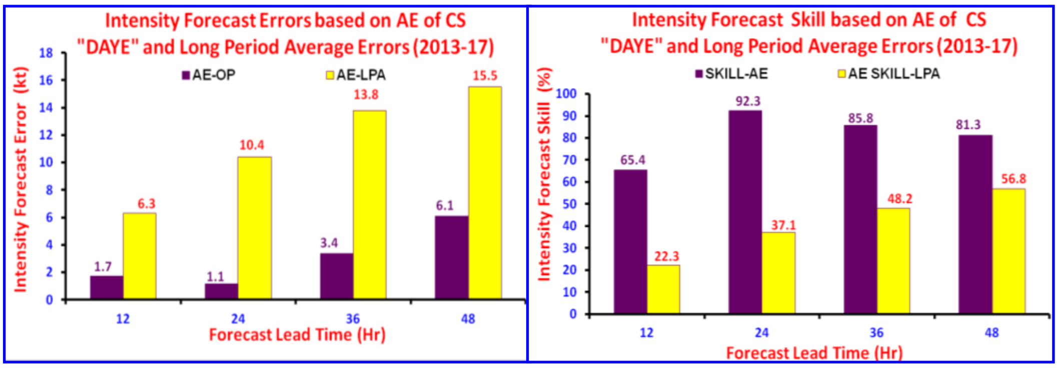


Fig. 4.3.3.3: Absolute errors (AE) of intensity forecast and skill for CS Daye

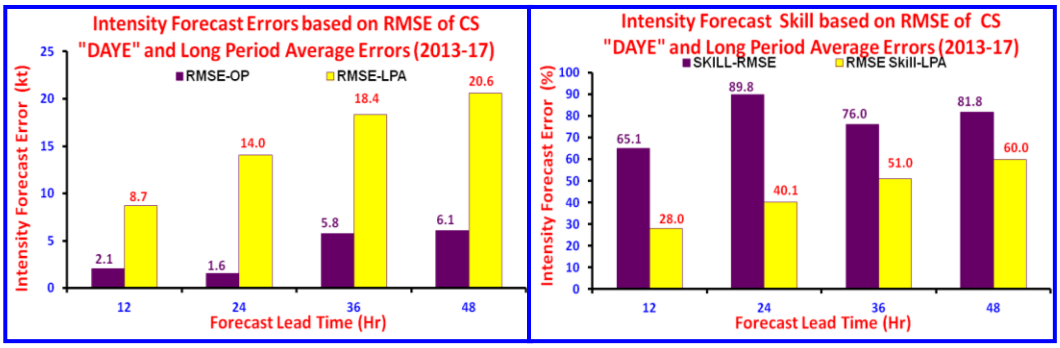


Fig. 4.3.3.4: RMSE of intensity forecast and skill for CS Daye

Table 4.3.3.2: Average Intensity forecast error in association with CS Daye

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2013-17)		LPA Skill (%) in Intensity forecast (2013-17)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	5	1.7	2.1	65.4	65.1	6.3	8.7	22.3	28.0
24	4	1.1	1.6	92.3	89.8	10.4	14.0	37.1	40.1
36	4	3.4	5.8	85.8	76.0	13.8	18.4	48.2	51.0
48	2	6.1	6.1	81.3	81.8	15.5	20.6	56.8	60.0

4.3.4. Very Severe Cyclonic Storm, 'LUBAN' over the Arabian Sea (06 – 15 October 2018)

4.3.4.1. Genesis Forecast

- First information about formation of low pressure area (LPA) over southeast AS around 5th was issued in Tropical weather outlook dated the 3rd October at 0600 UTC (about 45 hours in advance of formation of LPA). The LPA formed over southeast AS & neighbourhood at 0300 UTC of 5th October. In the same bulletin, it was also forecast that the LPA would concentrate into a depression by 7th October (about 69 hours in advance of formation of D). Depression formed over southeast & adjoining eastcentral AS in the afternoon (0900 UTC) of 6th October.

4.3.4.2. Landfall Forecast

- First information that the system crossing Yemen and adjoining Oman coasts around 1200 UTC of 13th was near 15.2^{0}N/51.4^{0}E was issued in the Tropical Cyclone Advisory issued at 1600 UTC of 8th October (about 5 days and 15 hours prior to landfall). The system crossed coast near 15.8^{0}N/52.2^{0}E between 0530-0600 UTC of 14th.
- The advisory was further updated in the Tropical Cyclone Advisory issued at 0600 UTC of 12th October that the system would cross Yemen coast between Riyan (Mukalla) and Al-Ghaidah (Yemen) close to 15^{0}N around noon (0600-0900 UTC) of 14th.
- The landfall forecast errors are presented in Table 4.3.4.1.
- The landfall point forecast errors were about 172.2, 103.8 and 103.8 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 42.3, 94.8 and 122.1 km respectively. The landfall time forecast errors were about 1.0, 1.0 and 1.0 hours for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 3.6, 5.4 and 3.8 hours respectively. The landfall point error was significantly less than long period average (LPA) of past five years for all lead periods (Fig. 4.3.4.1)

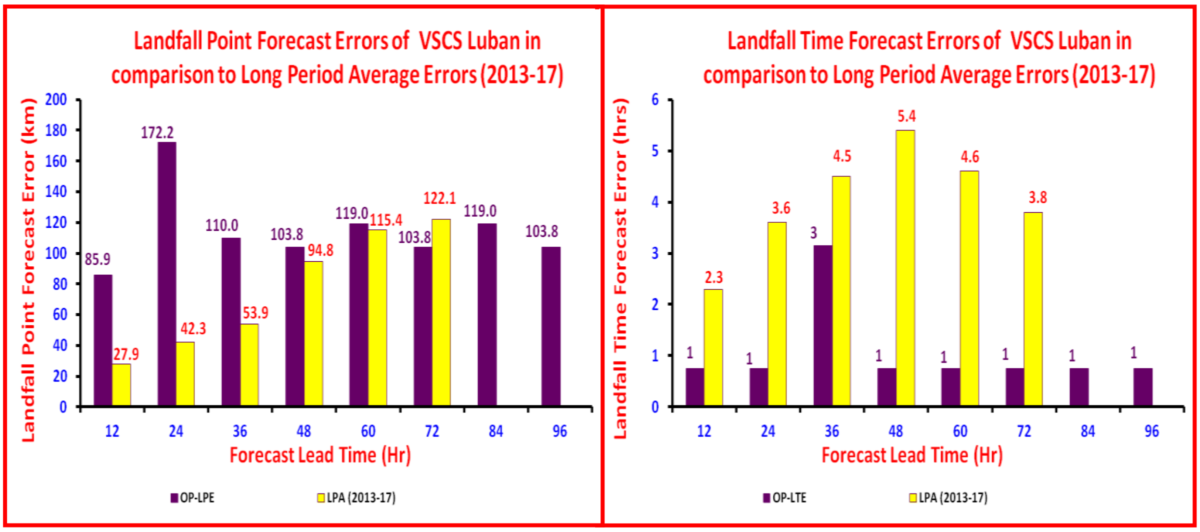


Fig. 4.3.4.1. Landfall Point (km) and Time (hrs) Errors for VSCS Luban

Table 4.3.4.1: Landfall Point & Time Forecast Errors of VSCS, Luban

Lead Period (hrs)	Base Time (UTC)	Landfall Point				Landfall Time (UTC)		Operational Error		LPA error (2013-17)	
		Forecast		Actual		Fore-cast	Actual	LPE (km)	LTE (hrs)	LPE (km)	LTE (hrs)
		Lat(^{0}N)	Long(^{0}N)	Lat(^{0}N)	Long(^{0}N)						
12	13/18	15.3	51.6	15.8	52.2	14/0500	14/0545	85.9	1	27.9	2.3
24	13/06	15.1	50.8	15.8	52.2	14/0630	14/0545	172.2	1	42.3	3.6
36	12/18	15.2	51.4	15.8	52.2	14/0900	14/0545	110.0	3	53.9	4.5
48	12/06	15.3	51.4	15.8	52.2	14/0630	14/0545	103.8	1	94.8	5.4
60	11/18	15.2	51.3	15.8	52.2	14/0500	14/0545	119.0	1	115.4	4.6
72	11/06	15.3	51.4	15.8	52.2	14/0630	14/0545	103.8	1	122.1	3.8
84	10/18	15.2	51.3	15.8	52.2	14/0630	14/0545	119.0	1	-	-
96	10/06	15.3	51.4	15.8	52.2	14/0500	14/0545	103.8	1	-	-

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point, LTE= Forecast Landfall Time-Actual Landfall Time

4.3.4.3. Track Forecast

- First information that the system will move northwestwards was issued at 0600 UTC 3rd October in the daily Tropical Weather Outlook even before the formation of the LPA over southeast AS (about 11days prior to landfall).
- The warning was further updated in the daily Tropical Weather Outlook issued at 0600 UTC of 4th, that the system would move northwestwards towards Oman coast (about 10days prior to landfall).
- In the first bulletin issued at 1200 UTC of 6th October, it was specifically mentioned that the system would move towards south Oman & adjoining Yemen coasts (about 7.5 days prior to landfall).

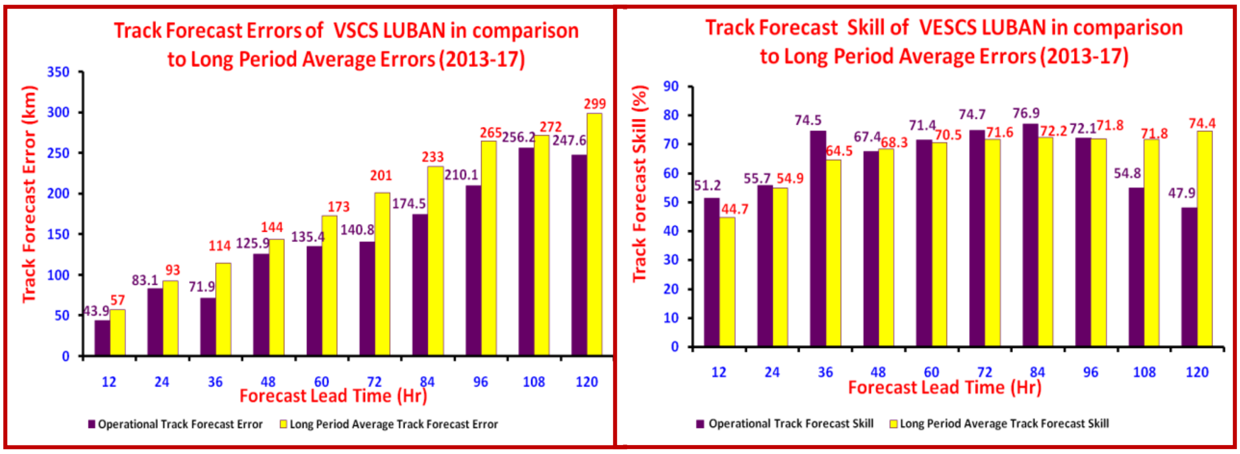


Fig. 4.3.4.2: Track Forecast Errors and Skill for VSCS Luban

- The track forecast errors were about 83.1, 125.9 and 140.8 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 93, 144 and 201 km respectively. The track forecast skill was about 55.7, 67.4 and 74.7 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 54.9, 68.3 and

71.6% respectively. The track forecast errors were significantly less than the past five years average for all lead period and the skill was comparable or even more than past five years average. The skill was less for lead periods beyond 108 hours. (Fig. 4.3.4.2, Table 4.3.4.1).

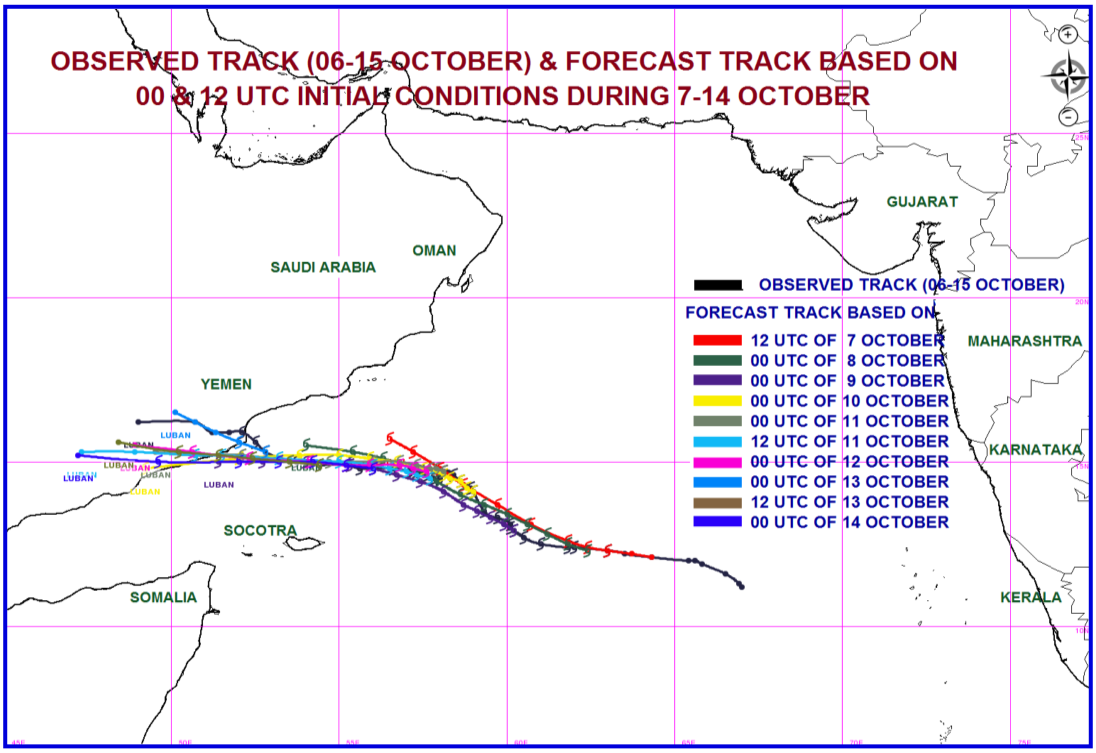


Fig. 4.3.4.3: Observed track and forecast tracks for different lead periods

- The track forecast based on 0000 & 1200 UTC during 7th-14th October and observed track during 6th -15th October is presented in Fig. 4.3.4.3. It indicates that for all lead periods track was well predicted. The observed and a typical forecast track with cone of uncertainty based 0000 UTC of 09th Oct. is presented in Fig. 4.3.4.4.

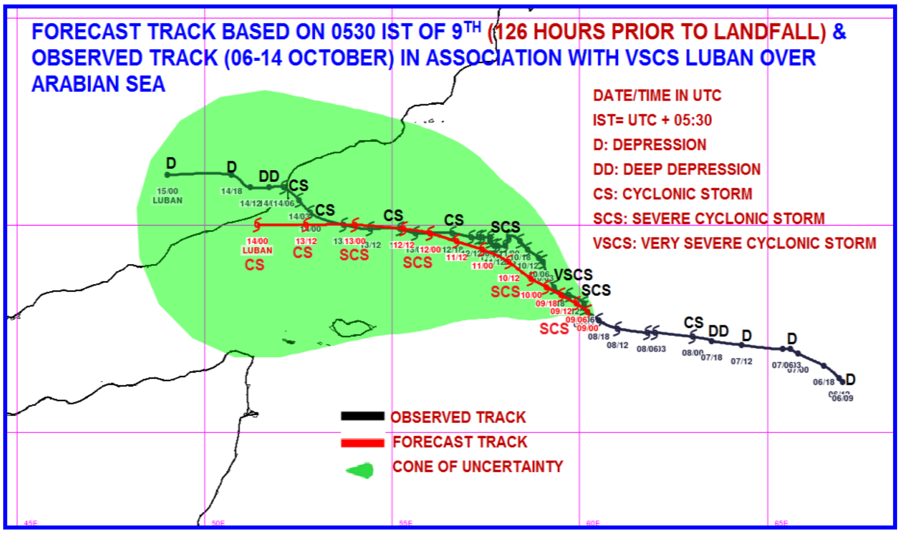


Fig. 4.3.4.4: Observed track of VSCS Luban and forecast track based on 0000 UTC of 9th October

Table 4.3.4.2: Average Track forecast error in case of VSCS, Luban

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2013-17)	
				Track forecast error (km)	Skill (%)
12	27	43.9	51.2	57	44.7
24	26	83.1	55.7	93	54.9
36	24	71.9	74.5	114	64.5
48	22	125.9	67.4	144	68.3
60	20	135.4	71.4	173	70.5
72	18	140.8	74.7	201	71.6
84	16	174.5	76.9	233	72.2
96	13	210.1	72.1	265	71.8
108	11	256.2	54.8	272	71.8
120	7	247.6	47.9	299	74.4

N: No. of observations verified, LPA: Long Period Average (2013-17)

4.3.4.4. Intensity Forecast

- First information that the system would intensify into a cyclonic storm was given in the Tropical Weather issued at 0600 UTC of 3rd October (about 120 hrs in advance of intensification of system into a cyclonic storm on 0600 UTC of 9th).
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 9.9, 13.5 and 16.2 knots against the LPA of 10.4, 15.5 and 15.7 knots respectively. The skill in intensity (wind) forecast based on AE for 24, 48 and 72 hrs lead period was 24.4, 46.5 and 59.0% against the LPA of 37.1, 56.8 and 69.3% respectively (**Fig. 4.3.4.5, Table 4.3.4.3**).
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 12.1, 15.2 and 17.7 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill in intensity (wind) forecast based on RMSE for 24, 48 and 72 hrs lead period was 28.4, 55.3 and 67.5% against the LPA of 40.1, 60.0 and 73.0% respectively **(Fig. 4.3.4.6, Table 4.3.4.3**). For all lead periods, the RMSE in intensity forecast were significantly less as compared to past five years average.
- Typical wind distribution forecast product is presented in **Fig. 4.3.4.7**.

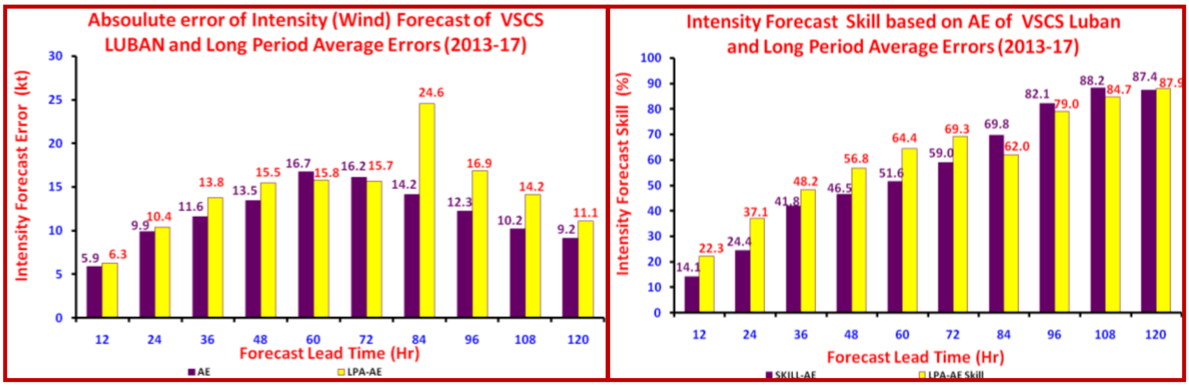


Fig. 4.3.4.5: Absolute errors (AE) of intensity forecast and skill for VSCS Luban

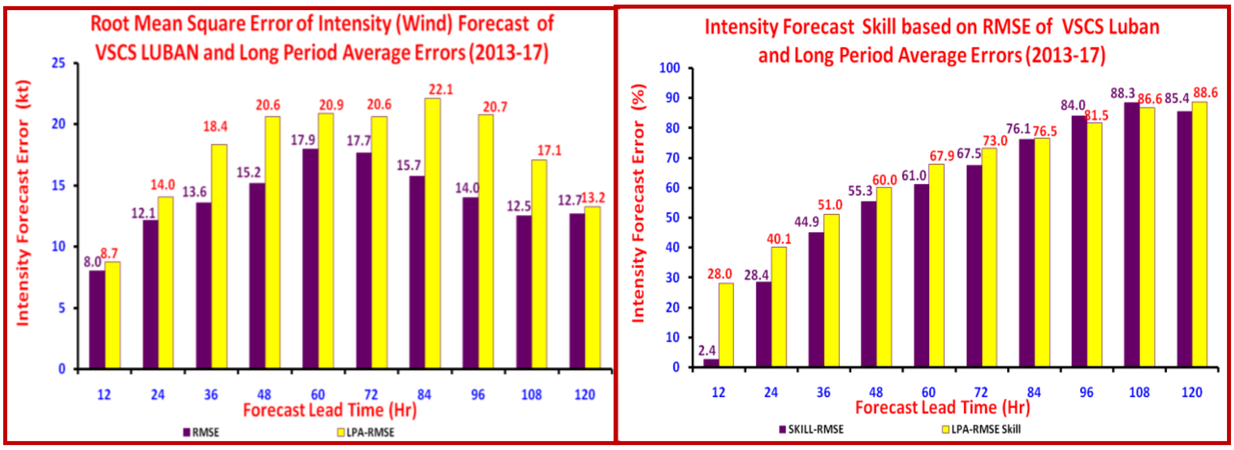


Fig. 4.3.4.6: Root Mean Square Errors (RMSE) of intensity forecast and skill for VSCS Luban

Table 4.3.4.3: Average Intensity forecast error in association with VSCS Luban

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2013-17)		LPA Intensity forecast Skill (%) (2013-17)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	27	5.9	8.0	61.4	66.9	6.3	8.7	22.3	28.0
24	26	9.9	12.1	74.9	78.4	10.4	14.0	37.1	40.1
36	24	11.6	13.6	71.6	74.5	13.8	18.4	48.2	51.0
48	22	13.5	15.2	56.7	63.1	15.5	20.6	56.8	60.0
60	20	16.7	17.9	65.9	72.4	15.8	20.9	64.4	67.9
72	18	16.2	17.7	71.7	78.3	15.7	20.6	69.3	73.0
84	16	14.2	15.7	90.3	90.8	24.6	22.1	62.0	76.5
96	13	12.3	14.0	83.8	82.9	16.9	20.7	79.0	81.5
108	11	10.2	12.5	86.4	86.7	14.2	17.1	84.7	86.6
120	7	9.2	12.7	87.4	85.4	11.1	13.2	87.9	88.6

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17).

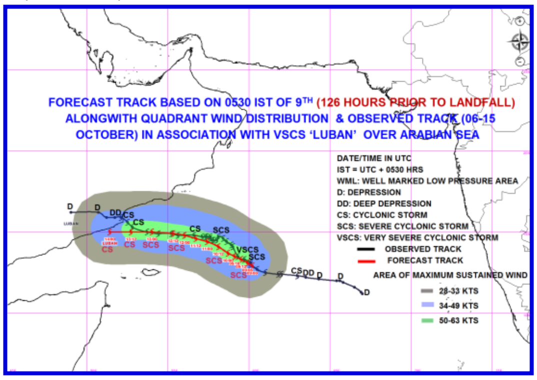


Fig. 4.3.4.7: Wind distribution graphics based on 0000 UTC of 9th October

4.3.5. Very Severe Cyclonic Storm “Titli” over Eastcentral Bay of Bengal (08-13 October 2018)

4.3.5.1 Genesis Forecast

- First information about formation of low pressure area (LPA) over south Bay of Bengal and neighbourhood around 8th was issued in Press Release dated the 5th October at 1310 IST (about 45 hours in advance of formation of LPA). LPA formed at 0300 UTC of 7th.
- In the Press Release issued on 7th (based on 0300 UTC, issued at 1330 IST), it was mentioned that, the LPA would become well marked low pressure area (WML) during next 12 hours and concentrate into a Depression during subsequent 24 hours (about 9 hours in advance of formation of WML and 24 hours in advance of formation of depression). WML formed at 1200 UTC of 7th over southeast BoB and adjoining north Andaman Sea and depression formed over eastcentral BoB at 0300 UTC of 8th.

4.3.5.2 Landfall Forecast

- First information about that the system would cross Odisha and adjoining north Andhra Pradesh coasts between Gopalpur and Kalingapatnam around 11th morning was given in the bulletin issued at 0900 hrs IST of 9th October (about 43 hours prior to landfall). The system crossed north Andhra Pradesh and south Odisha coasts near Palasa (18.8^0N/84.5^0E) to the southwest of Gopalpur during 0430-0530 IST of 11th.
- The landfall point was further specified in the bulletin issued at 2030 hrs IST of 10th October that the system would cross Odisha and adjoining north Andhra Pradesh coasts close to Gopalpur around 11th morning (about 9 hours in advance). Typical observed and forecast track is presented in Fig. 4.3.5.1.

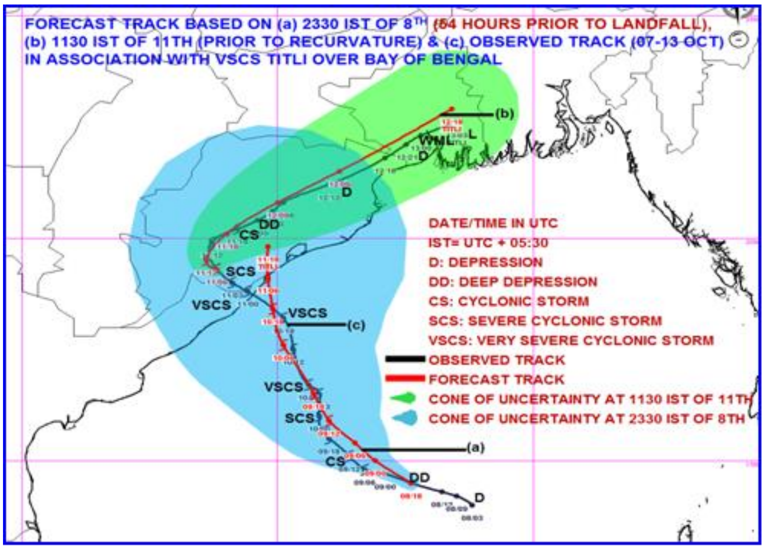


Fig. 4.3.5.1: Observed track of VSCS Titli and forecast based on 1800 UTC of 8th and 0600 UTC of 11th (prior to recurvature)

- The landfall point forecast errors were about 15.6, 15.6 and 46.7 km for 24, 48 and 60 hrs lead period against past five year (2013-17) average errors of 42.3, 94.8 and 115.4 km respectively. The landfall time forecast errors were about 5.0, 3.0 and 3.5 hours for

24, 48 and 60 hrs lead period against past five year (2013-17) average errors of 3.6, 5.4 and 4.6 hours respectively. The landfall point error was significantly less than long period average (LPA) of past five years for all lead periods (Fig. 4.3.5.2) and Table 4.3.5.1.

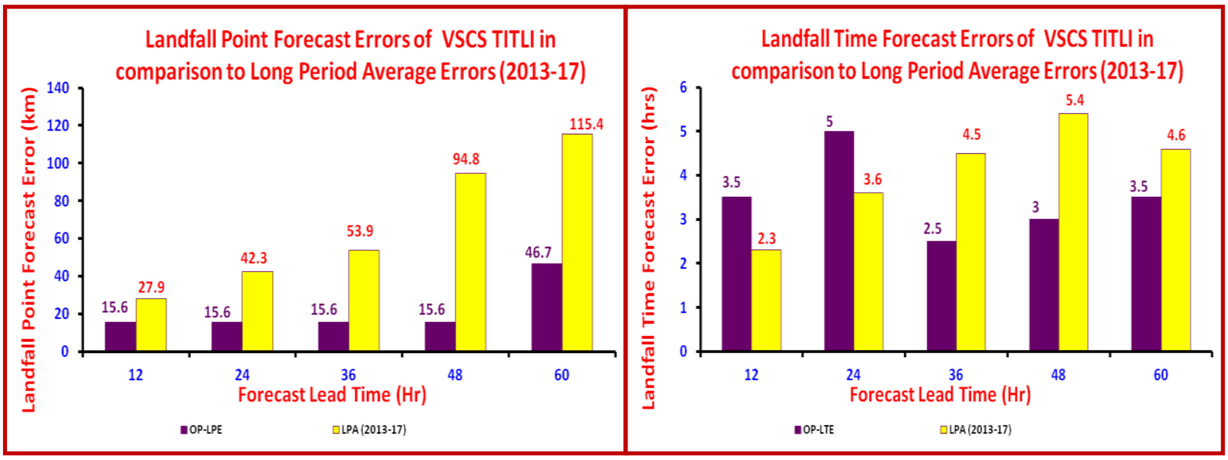


Fig. 4.3.5.2: Landfall Point (km) and Time (hrs) Errors for VSCS Titli

Table 4.3.5.1: Landfall Point (km) and Time Error (hrs) in association with VSCS Titli

Lead Period (hrs)	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	10/12	18.9/84.6	18.8/84.5	11/0300	10/2330	15.6	3.5	27.9	2.3
24	10/00	18.9/84.6	18.8/84.5	11/0430	10/2330	15.6	5.0	42.3	3.6
36	09/12	18.9/84.6	18.8/84.5	11/0230	10/2330	15.6	2.5	53.9	4.5
48	09/00	18.9/84.6	18.8/84.5	11/0250	10/2330	15.6	3.0	94.8	5.4
60	08/12	19.1/84.7	18.8/84.5	11/0300	10/2330	46.7	3.5	115.4	4.6

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point,
LTE= Forecast Landfall Time-Actual Landfall Time

4.3.5.3 Track Forecast

- First information that the system will move towards Odisha & adjoining north Andhra Pradesh Coasts from 8th onwards for next 72 hours was issued in Press Release dated the 5th October at 1310 IST (about 45 hours in advance of formation of LPA and 140 hours prior to landfall).
- In the first Bulletin issued on 8th, it was mentioned that the system would move northwestwards towards Odisha and adjoining north Andhra Pradesh coasts during next 72 hours.
- First information about the northeastwards recurvature of system towards Gangetic West Bengal across coastal Odisha from 12th morning was given in the bulletin issued at 1130 IST 9th October (about 60 hours in advance, recurvature started at 1500 UTC of 11th).

➢ The track forecast errors were about 98, 114 and 113 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 93, 144 and 201 km respectively. For all the lead periods beyond 36 hours, the track forecast errors were less than the past five years average. For 12 & 24 hours lead period, it was comparable to past five years average (Fig. 4.3.5.3) (Table 4.3.5.2).

Table 4.3.5.2: Average Track forecast error in association with VSCS Titli

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2013-17)	
				Track forecast error (km)	Skill (%)
12	15	58.9	42.4	57	44.7
24	13	98.4	48.9	93	54.9
36	11	103.9	57.0	114	64.5
48	9	114.4	47.3	144	68.3
60	7	109.7	42.9	173	70.5
72	5	113.0	29.9	201	71.6
84	1	140.9	42.7	233	72.2

N: No. of observations verified, LPA: Long Period Average (2013-17)

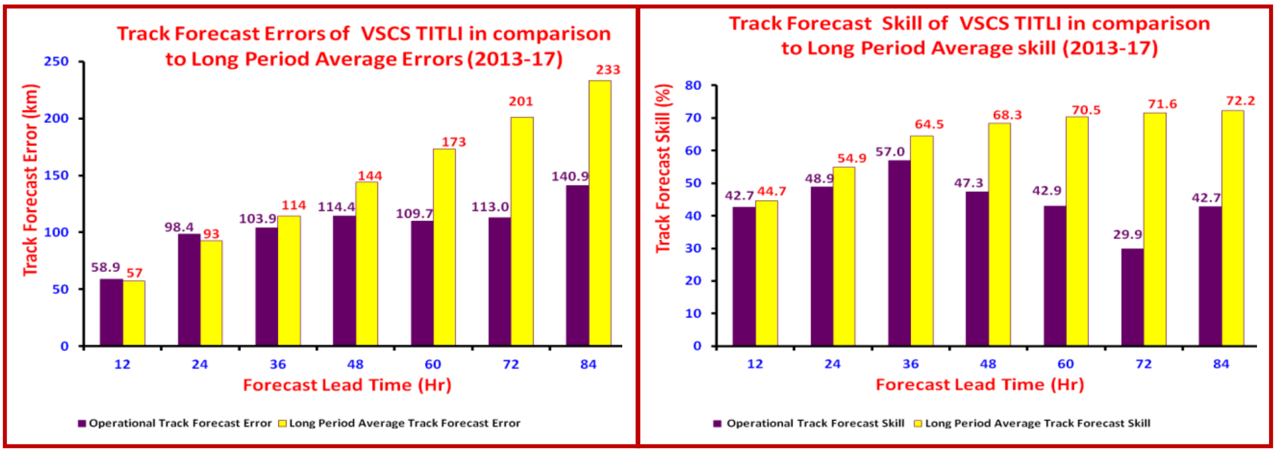


Fig. 4.3.5.3: Track Forecast Errors and Skill for VSCS Titli

4.3.5.4 Intensity Forecast

➢ First information that the system would cross coast as a VSCS with maximum sustained wind speed of 140-150 kmph gusting to 165 kmph was issued at 0400 hours IST of 11th (about 5 hours prior to landfall).

➢ The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 10.8, 10.3 and 2.0 knots against the LPA of 10.4, 15.5 and 15.7 knots respectively. The skill in intensity (wind) forecast based on AE for 24, 48 and 72 hrs lead period was 69.7, 85.3 and 96.0% against the LPA of 37.1, 56.8 and 69.3%

respectively (**Fig. 4.3.5.4 and Table 4.3.5.3)**. For all lead periods, the errors in intensity forecast were significantly less and skill was significantly high.

- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 12.6, 17.0 and 2.8 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill in intensity (wind) forecast based on RMSE for 24, 48 and 72 hrs lead period was 71.2, 79.8 and 94.9% against the LPA of 40.1, 60.0 and 73.0% respectively (**Fig. 4.3.5.5 and Table 4.3.5.3)**. For all lead periods, the errors in intensity forecast were significantly less and skill was significantly high.

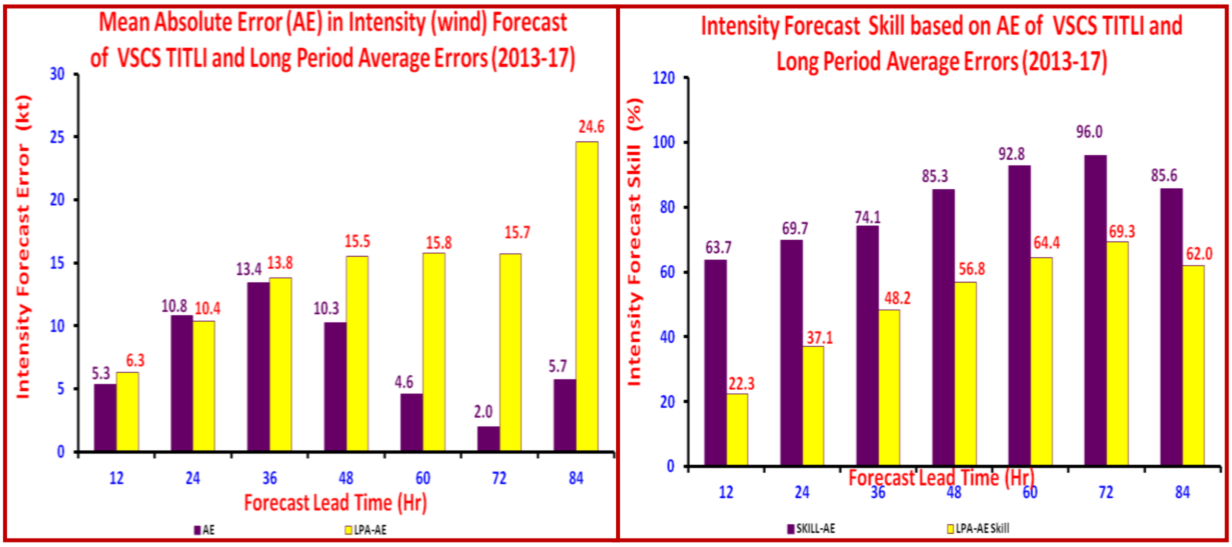


Fig. 4.3.5.4: Absolute errors (AE) of intensity forecast and skill for VSCS Titli

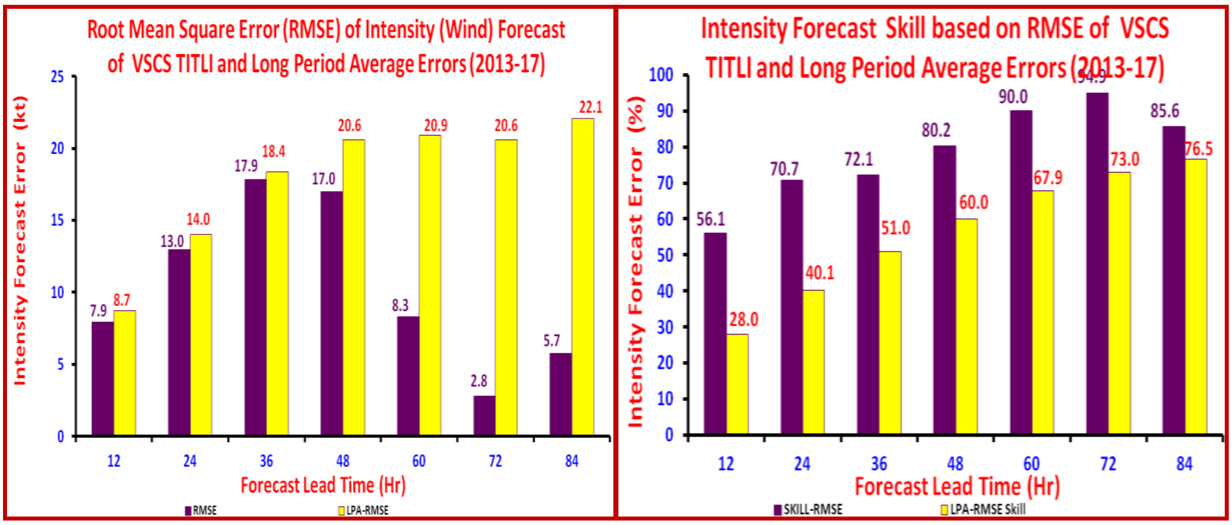


Fig. 4.3.5.5: Root Mean Square Errors (RMSE) of intensity forecast and skill for VSCS Titli

Table 4.3.5.3: Average Intensity forecast error in association with VSCS Titli

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2013-17)		LPA Skill (%) in Intensity forecast (2013-17)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	15	5.3	7.9	63.7	56.1	6.3	8.7	22.3	28.0
24	13	10.8	13.0	69.7	70.7	10.4	14.0	37.1	40.1
36	11	13.4	17.9	74.1	72.1	13.8	18.4	48.2	51.0
48	9	10.3	17.0	85.3	80.2	15.5	20.6	56.8	60.0
60	7	4.6	8.3	92.8	90.0	15.8	20.9	64.4	67.9
72	5	2.0	2.8	96.0	94.9	15.7	20.6	69.3	73.0
84	1	5.7	5.7	85.6	85.6	24.6	22.1	62.0	76.5

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17).

4.3.5.5 Verification of Adverse Weather associated with the system:

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table **4.3.5.4-4.3.5.6**. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table 4.3.5.4 Verification of Heavy Rainfall Forecast

Date/Base Time of observation (UTC)	24 hr Heavy rainfall warning ending at 0830 hrs IST of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
08/10/2018 0300 UTC	**For 9th October**: Heavy rainfall (H) at isolated places over south coastal Odisha. **For 10th October** Heavy to very heavy rainfall (H-VH) at a few places and extremely heavy falls (Ex. H) at isolated places over coastal Odisha, heavy falls at isolated places over north coastal Andhra Pradesh (CAP) and H-VH falls at isolated places over Gangetic West Bengal (GWB). **For 11th October** H-VH at a few places and Ex.H falls at isolated places over coastal & adjoining interior Odisha, H at isolated places over north CAP and H-VH at isolated places over GWB. **For 12th October:** H at isolated places over north coastal Odisha	**10th October** Moderate rainfall occurred at a few places over coastal Odisha **11th October** **Odisha:-** Heavy to very heavy rainfall at a few places over coastal Odisha and extremely heavy rainfall at isolated places over south coastal Odisha **Gangetic West Bengal:-** Isolated

09/10/2018 0300 UTC	**For 9th October:** H at isolated places over south coastal Odisha and north CAP from evening/night and H at isolated places over Mizoram & Tripura. **For 10th October** H-VH at a few places and Ex.H falls at isolated places over coastal Odisha, H at isolated places over north coastal Andhra Pradesh (CAP), H-VH at isolated places over Gangetic West Bengal (GWB) and H at isolated places over Mizoram & Tripura.. **For 11th October** H-VH at a few places and Ex.H falls at isolated places over coastal & adjoining interior Odisha, H at isolated places over north CAP and H-VH at isolated places over GWB, H at isolated places over Assam & Meghalaya and H-VH falls at isolated places over Mizoram & Tripura. **For 12th October:** H at isolated places over north coastal Odisha, H-VH at isolated places over GWB, Assam & Meghalaya and Mizoram & Tripura.	heavy to very heavy rainfall over coastal districts **Coastal Andhra Pradesh:** Heavy to extremely heavy rainfall at a few places over Srikakulam district. **12th October** **Coastal Andhra Pradesh:** Heavy to extremely heavy rainfall at a few places over Srikakulam district. **Odisha:** Heavy to very heavy rainfall at a few places and extremely heavy rainfall at isolated places over south and north coastal Odisha **Gangetic West Bengal:** Heavy rainfall at isolated places over coastal districts **Assam, Meghalaya, Mizoram and Tripura**: **Moderate rainfall upto 5 cm at many places** **13th October** **Assam & Meghalaya:** Heavy rainfall at isolated places **Nagaland, Manipur, Mizoram & Tripura:** Heavy rainfall at isolated places **Gangetic West**
10/10/2018 0300 UTC	**For 10th October** H-VH at a few places and Ex.H at isolated places over coastal Odisha and isolated H over interior Odisha, H-VH falls at isolated places over north CAP & GWB. **For 11th October** H-VH at a few places and extremely heavy falls at isolated places over coastal Odisha and isolated H over interior Odisha, H-VH at isolated places over north CAP & GWB, H-VH at isolated places over Mizoram & Tripura. **For 12th October:** H falls at isolated places over north coastal Odisha, H-VH falls at isolated places over GWB, Assam & Meghalaya and Mizoram & Tripura. **For 13th October:** H at isolated places over Assam & Meghalaya and Mizoram & Tripura.	
11/10/2018 0300 UTC	**For 11th October** H-VH at a few places and Ex.H at isolated places over south Odisha, H-VH at isolated places over north CAP & GWB, Assam & Meghalaya and Mizoram & Tripura. **For 12th October:** H-VH at isolated places over Odisha, heavy to very heavy falls at a few places over GWB, H-VH and Ex.H falls at isolated places over Assam & Meghalaya and	

	H-VH falls at isolated places over Mizoram & Tripura. **For 13th October:** H falls at isolated places over GWB, H-VH and Ex.H at isolated places over Assam & Meghalaya and H-VH at isolated places Mizoram & Tripura.	**Bengal:** Heavy to very heavy rainfall at isolated places over coastal West Bengal **Odisha:-** Heavy to very heavy rainfall at isolated places over north Odisha. **14th October** **Assam & Meghalaya:** Heavy rainfall at isolated places over Meghalaya
12/10/2018 0300 UTC	**For 12th October:** H-VH and Ex.H at isolated places over north Odisha, H-VH at isolated places over GWB, Assam & Meghalaya and Mizoram, Tripura & Manipur **For 13th October:** H-VH at isolated places over GWB, Assam & Meghalaya and Mizoram, Tripura & Manipur	
13/10/2018 0300 UTC	H at isolated places very likely over south Assam, east Meghalaya, Mizoram, Tripura and Manipur during next 24 hours	

Table 4.3.5.5 Verification of Gale/Squally Wind Forecast issued by IMD

Date/ Time of observation (UTC)	Gale/ Squally wind Forecast for north Andhra Pradesh, Odisha and West Bengal	Realised wind speed
08/10/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph is very likely to commence along & off along north Andhra Pradesh, Odisha and West Bengal coast from 9th afternoon. • It is very likely to increase gradually becoming 70-80 kmph gusting to 90 kmph from 10th October 2018 evening onwards along & off south Odisha & adjoining districts of north Andhra Pradesh coasts and 55-65 kmph gusting to 75 kmph along & off north Odisha, west Bengal and remaining districts of north Andhra Pradesh coasts.	• Gopalpur: Maximum wind speed of 126 kmph at 0430 hrs IST of 11th. • Gopalpur recorded 55 kmph wind speed at 1730 IST of 11th and 45 kmph at 0830 IST of 12th October. • Bhawanipatna(Kalahandi district) reported 52 kmph at 1730 IST of 11th. • Puri reported
09/10/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph is very likely to commence along & off along north Andhra Pradesh, Odisha and West Bengal coast from today, the 9th October night. • It is very likely to increase gradually becoming 80-90 kmph gusting to 100 kmph from 10th October 2018 evening onwards along & off south Odisha & adjoining districts of north Andhra Pradesh coasts and 55-65 kmph gusting to 75 kmph along & off north Odisha, west Bengal and remaining districts of north Andhra Pradesh coasts.	
10/10/2018 0300 UTC	• Gale wind speed reaching 60-70 kmph gusting to 80 kmph is very likely to commence along & off north Andhra Pradesh and Odisha coasts from today afternoon. • It is very likely to increase gradually becoming 140-150 kmph gusting to 165 kmph from today, the 10th October 2018 night onwards along & off south Odisha & adjoining districts of north	

	Andhra Pradesh coasts and 70-80 kmph gusting to 90 kmph along & off north Odisha and remaining districts of north Andhra Pradesh coasts. • Squally winds speed reaching 50-60 kmph gusting 70 kmph is very likely to commence along & off West Bengal coast from today afternoon and gradually increase to 60-70 kmph gusting 80 kmph from today night onwards.	59 kmph at 0530 IST of 12th. • Paradip reported 35 kmph on 10th and 12th and 27 kmph on 11th • Estimated wind speed at the time of landfall : 140-150 kmph gusting to 165 kmph.
11/10/2018 0300 UTC	• Gale wind speed reaching 90-100 kmph gusting to 115 kmph very likely over Gajapati, Ganjam, Nayagarh Kandhamal & Raigada districts of Odisha during next three hours and gradually decrease thereafter becoming squally wind speed of 50-60 kmph gusting to 70 kmph by evening. Gale wind speed reaching 60-70 kmph gusting to 80 kmph very likely along & off south coastal Odisha during next three hours and squally wind speed of 40-50 kmph gusting to 60 kmph likely during subsequent 18 hours. • Squally wind speed of 40-50 kmph gusting 60 kmph very likely along & off north Odisha and West Bengal coasts during next 24 hours. Squally wind speed of 30-40 kmph gusting to 50 kmph is very likely over adjoining districts of north interior Odisha from today afternoon for subsequent 12 hours.	
12/10/2018 0300 UTC	• Squally wind speed of 45-55 kmph gusting to 65 kmph very likely along & off Odisha and West Bengal and 35-45 kmph gusting to 55 kmph likely over adjoining areas of north interior Odisha during next 12 hours.	

Table 4.3.5.6 Verification of Storm Surge Forecast issued by IMD

Date/ Time(UTC)	Storm Surge Forecast	Recorded storm surge
09/10/2018 0600 UTC	Storm surge of height of about 0.5 m above astronomical tide is very likely inundate low lying areas of Srikakulam district of Andhra Pradesh; Ganjam, Khurda & Puri districts of Odisha at the time of landfall.	Gopalpur Port (Odisha) reported tide height of 0.85m and Palasa (Andhra Pradesh) reported tide height of about 1meter on 11th at the time of landfall.
10/10/2018 0300 UTC	Storm surge of height of about 1.0 meter above astronomical tide is very likely to inundate low lying areas of Srikakulam district of Andhra Pradesh; Ganjam, Khurda & Puri districts of Odisha at the time of landfall.	

4.3.6. Very Severe Cyclonic Storm “Gaja” over southeast Bay of Bengal (10-19 November 2018)

4.3.6.1 Genesis Forecast

- ❖ First information about formation of LPA over southeast Bay of Bengal and adjoining Andaman Sea around 9th was issued in the Tropical Weather dated 7th November at 1200 IST (around 48 hours in advance of formation of LPA). LPA from Gulf of Thailand emerged in Andaman Sea in the afternoon of 9th.
- ❖ In the TWO issued at 1200 IST of 8th, it was mentioned that, the LPA will become WML around 9th and will intensify into depression around10th. WML formed in the evening (1730 IST) of 9th and depression formed in the morning of 10th.

4.3.6.2 Landfall Forecast

- ❖ In the first bulletin issued on 10th (issued at 1230 IST), it was mentioned that, the system would move west-northwestwards during next 48 hours and then west-southwestwards towards north Tamil Nadu – south Andhra Pradesh coasts. (about 5 days in advance of actual landfall).
- ❖ The landfall over Tamil Nadu coast during evening hours of 15th (around 1330 IST) was predicted on 11th early morning (0930 IST) more than 4 days in advance. At 1430 IST of 12th November (around 81 hours in advance of actual landfall), it further indicated the landfall of the cyclonic storm over Tamil Nadu coast between Cuddalore and Pamban, around Nagapattinam. Typical observed and forecast track is presented in Fig. 4.3.6.1.
- ❖ The landfall point forecast errors were about 31, 43 and 70 km for 24, 48 and 72 hrs lead period respectively against past five year (2013-17) average errors of 42.3, 94.8 and 122 km respectively. The landfall time forecast errors were about 3.0, 8.5 and 14.5 hours for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 3.6, 5.4 and 3.8 hours respectively. The higher landfall time error for 48 and 72 hrs lead period were mainly due to the fact that the system followed a

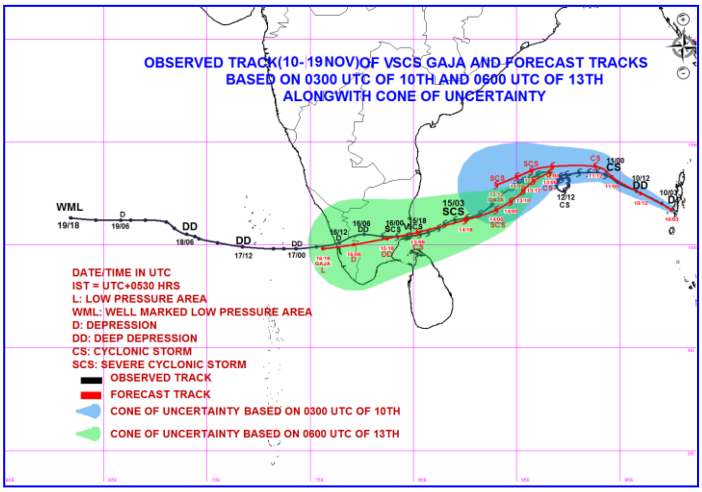
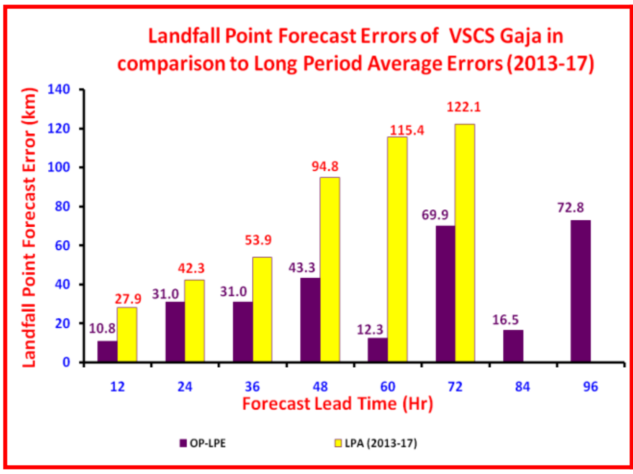


Fig. 4.3.6.1: Typical forecast and observed tracks of VSCS, Gaja demonstrating accurate track and landfall point forecast

looping track during 11th night to 13th morning leading to delay in landfall time. (Fig. 4.3.6.2 and Table 4.3.6.1)



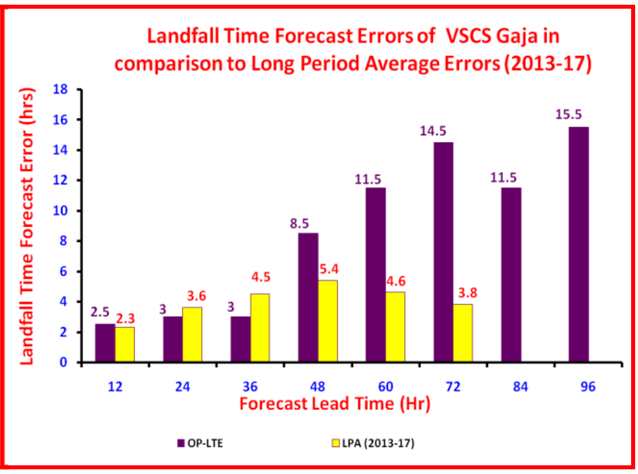


Fig. 4.3.6.2: Landfall Point (km) and Time (hrs) Errors for VSCS Gaja

Table 4.3.6.1: Landfall Point and Time Error in association with VSCS Gaja

Lead Period (hrs)	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	15/12	10.54/79.84	10.45/79.8	15/1800	15/2030	10.8	2.5	27.9	2.3
24	14/18	10.73/79.83	10.45/79.8	15/1730	15/2030	31.0	3	42.3	3.6
36	14/06	10.73/79.83	10.45/79.8	15/1730	15/2030	31.0	3	53.9	4.5
48	13/18	10.84/79.85	10.45/79.8	15/1200	15/2030	43.3	8.5	94.8	5.4
60	13/06	10.55/79.85	10.45/79.8	15/0900	15/2030	12.3	11.5	115.4	4.6
72	12/18	10.15/79.24	10.45/79.8	15/0600	15/2030	69.9	14.5	122.1	3.8
84	12/06	10.30/79.80	10.45/79.8	15/0900	15/2030	16.5	11.5	-	-
96	12/00	11.11/79.86	10.45/79.8	15/0500	15/2030	72.8	15.5	-	-

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point,
LTE= Forecast Landfall Time-Actual Landfall Time

4.3.6.3. Track Forecast

- In the first Bulletin issued a 1230 IST of 10th, it was mentioned that the system would move west-northwestwards for next 48 hours and then west-southwestwards during subsequent 72 hours towards north Tamilnadu-south Andhra Pradesh coasts. The system crossed Tamilnadu & Puducherry coast between Nagapattinam and Vedaranniyam near latitude 10.45˚N and longitude 79.8°E during 0030 to 0230 hours IST of 16th November.
- The track forecast errors were about 121, 185 and 195 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 93, 144 and 201 km respectively. The track forecast skills were about 49, 68 and 82 % for 24, 48 and 72 hrs

lead period against past five year (2013-17) average skills of 55, 68 and 72% respectively. The track error was higher due to recurving and looping nature of the track. However, comparing with long period average error of the recurving tracks, the errors in case of Gaja were less **(**Fig. **4.3.6.3** and Table **4.3.6.2).**

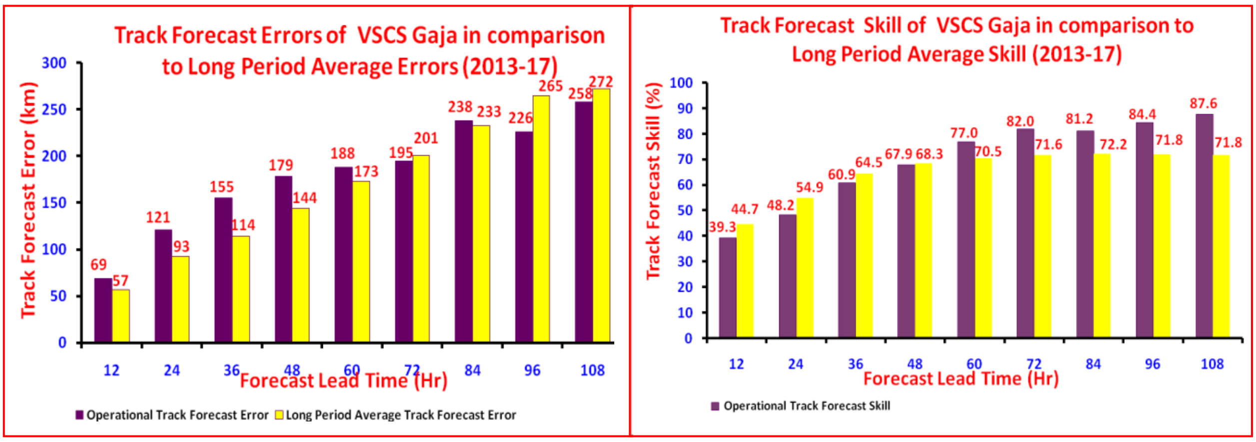


Fig. 4.3.6.3: Track Forecast Errors and Skill for VSCS Gaja

Table 4.3.6.2 Operational & long period average track forecast errors(km) & Skill(%)

Lead Period (hrs)	No. of obs. verified	Operational Track Forecast		Long Period Average (2013-17) Track Forecast	
		Error (km)	Skill (%)	Error (km)	Skill (%)
12	35	69	39.3	57	44.7
24	30	121	48.2	93	54.9
36	25	155	60.9	114	64.5
48	22	179	67.9	144	68.3
60	17	188	77.0	173	70.5
72	13	195	82.0	201	71.6
84	8	238	81.2	233	72.2
96	6	226	84.4	265	71.8
108	2	258	87.6	272	71.8

4.3.6.4. Intensity Forecast

- In the first bulletin issued by IMD at 1230 hrs IST of 10th with the formation of depression, it was indicated that the system would intensify into a deep depression during next 12 hours and into a cyclonic storm during subsequent 24 hours. The depression intensified into a deep depression in the evening (1730 IST) of 10th and into a CS in the early morning (0530 IST) of 11th.
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 9.1, 11.0 and 14.6 knots against the LPA of 10.4, 15.5 and 15.7 knots respectively. The skill in intensity forecast based on AE for 24, 48 and 72 hrs lead period was 22.0, 37.5 and 22.0% respectively (**Fig.** 4.3.6.4 **and Table** 4.3.6.3).
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 10.9, 14.8 and 19.5 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill in intensity (wind) forecast based on RMSE for 24, 48 and 72 hrs lead period was 50.5, 31.7 and 14.5% against the LPA of 40.1, 60.0 and 73.0%

respectively (**Fig.** 4.3.6.5 **and Table** 4.3.6.3). For all lead periods, the errors in intensity forecast were significantly less.

Table 4.3.6.3 Mean Intensity forecast errors (kt) and Skill(%) in association with VSCS Gaja

Lead Period (hrs)	N	Average Intensity Error (kts)		LPA (2013-17) Intensity forecast Error (kts)		Skill (%) in intensity forecast	
		AE	RMSE	AE	RMSE	AE	RMSE
12	33	5.6	7.9	6.3	8.7	16.7	36.2
24	29	9.1	10.9	10.4	14.0	22.0	50.5
36	24	9.1	11.5	13.8	18.4	4.7	5.3
48	21	11.0	14.8	15.5	20.6	37.5	31.7
60	16	10.7	13.6	15.8	20.9	41.8	39.9
72	12	14.6	19.5	15.7	20.6	22.0	14.5
84	8	16.9	22.3	24.6	22.1	46.0	36.9
96	6	20.1	24.3	16.9	20.7	29.1	27.7
108	2	35.3	35.7	14.2	17.1	11.8	20.3

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17).

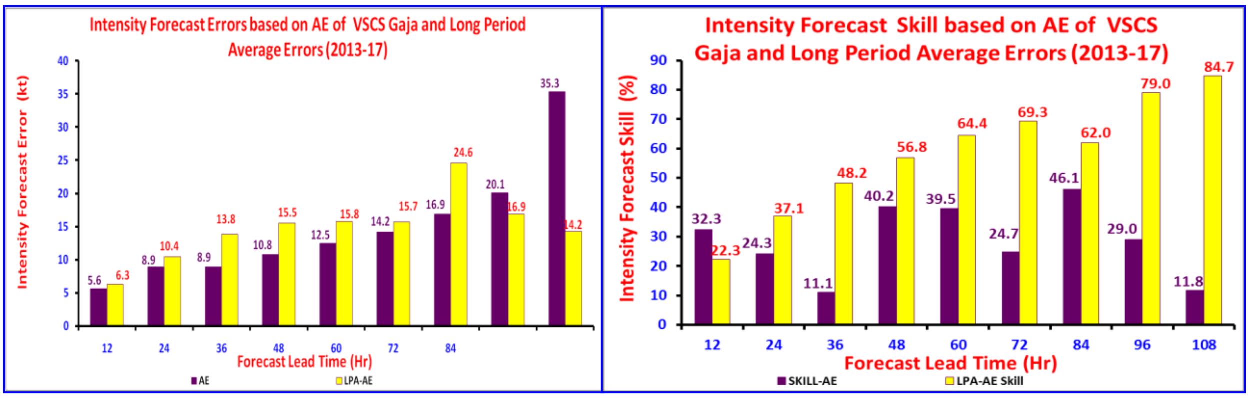


Fig. 4.3.6.4: Absolute errors (AE) of intensity forecast and skill for VSCS Gaja

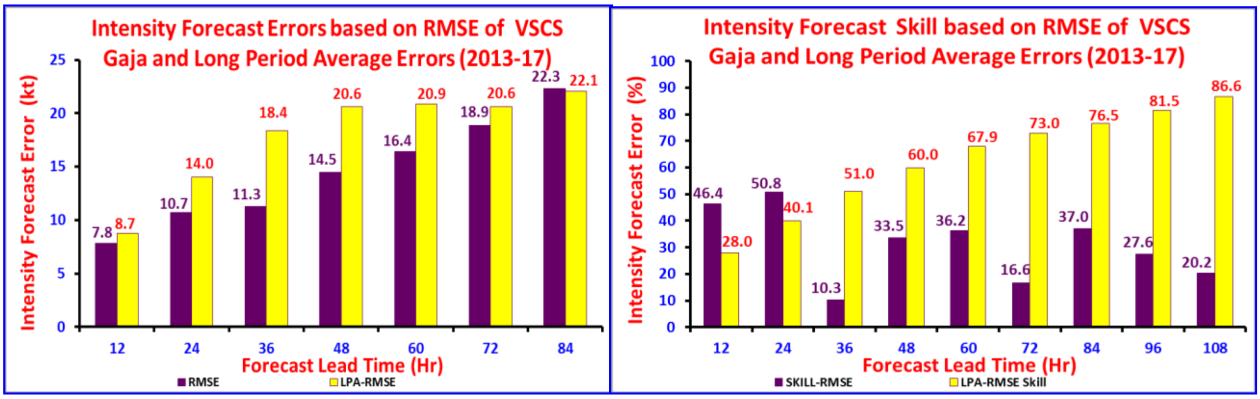


Fig. 4.3.6.5: Root Mean Square Errors (RMSE) of intensity forecast and skill for VSCS Gaja

4.3.6.5 Verification of Adverse Weather associated with the system:

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 4.3.6.4-6. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table – 4.3.6.4: Verification of Heavy Rainfall Forecast

Date/Base Time of observation (UTC)	24 hr Heavy rainfall warning ending at 0830 hrs IST of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
10/11/2018 0300 UTC	• **Heavy falls at isolated places very likely to commence over coastal Tamil Nadu and adjoining south coastal Andhra Pradesh from 14th November.** • **Heavy to very heavy rainfall at isolated places is very likely over Andaman and Nicobar Islands on 10th and isolated heavy rainfall over Andaman Islands on 11th November 2018.**	**10 November 2018** **Andaman & Nicobar Islands:** Long Island-14, Maya Bandar-10, Port Blair-9 **11 November 2018** **Andaman & Nicobar Islands:** Maya Bandar-7, **16 November:** **Tamilnadu & Puducherry:** Thiruthuraipoondi & Muthupet-17 each, Adirampatnam-16, Peravurani, Pattukottai & Neyveli-14 each, Virudachalam-12, Chengalpattu-11, Cuddalore-9, Madukkur, Arantangi & Vandavasi-8 each, and Srimushnam, Valinokkam, Nagercoil, Uthiramerur, Orthanad, Needamangalam, Thuckalay, Sethiathope, Pondicherry & Tozhudur-7 each
11/11/2018 0300 UTC	• **Heavy falls at isolated places very likely to commence over north coastal Tamil Nadu and adjoining south coastal Andhra Pradesh from evening of 14th November. Rainfall intensity is very likely to increase gradually thereafter with rainfall at most places and heavy to very heavy at a few places and** extremely heavy falls (≥ 20 cm) **at isolated places very likely over north Tamil Nadu and at most places with heavy to very heavy falls at isolated places very likely over south Tamil Nadu, south Coastal Andhra Pradesh and Rayalaseema on 15th November.** • **Heavy rainfall at isolated places likely over Andaman Islands on 11th November 2018 and decrease thereafter.**	
12/11/2018 0300 UTC	<u>Tamilnadu</u> 14 November 2018 **Heavy falls at isolated places very likely to commence over north coastal Tamil Nadu from 14th November evening** 15 November 2018 **Heavy to very heavy at a few places and** extremely heavy falls **(≥ 20 cm) at isolated places very likely over north Tamil Nadu and rainfall at most places with heavy to very heavy falls at isolated places very likely over south Tamil Nadu.** 16 November 2018 **Heavy falls at a few places and very heavy at**	

	isolated places very likely over interior Tamil Nadu. South Coastal Andhra Pradesh 14 November 2018 **Heavy falls at isolated places very likely to commence from 14th November evening.** 15 November 2018 **Heavy falls at isolated places** 16 November 2018 **Heavy falls at isolated places.** Rayalaseema 15 November 2018 **Heavy falls at isolated places** Kerala 15 November 2018 **Heavy at isolated places** 16 November 2018 **Heavy to very heavy falls at isolated places**	**17 November:** **Coastal Andhra Pradesh:** Kandukur and Gudivada-7 each, **Telangana:** Aswaraopeta-7, **Tamilnadu & Puducherry:** Sivaganga-17, Kodaikanal-14, Thammampatty-10, Nilakottai, Illuppur, Periyakulam & Bodinaickanur-9 each, Tirupathur-8 and Chinnakalar, Vadipatti-7 each **Kerala:** Kozha-28, Piravam-19, Thodupuzha-15, Cherthala & Munnar Kseb-12 each, Kumarakam-11, Idukki-10, Vaikom, & Myladumpara-9 each, Kottayam-8, Peermade To-7.
13/11/2018 0300 UTC	Tamilnadu 14 November 2018 **Heavy falls at isolated places very likely to commence over north coastal Tamil Nadu & adjoining districts of south coastal Tamil Nadu from 14th Nov. evening** 15 November 2018 **Heavy to very heavy at a few places over Tamilnadu.** Extremely heavy falls **(≥ 20 cm) at isolated places is also likely over Cuddalore, Nagappattinam, Tiruvarur, Thanjavur, Pudukkottai, Tuticorin and Ramanathapuram districts.** 16 November 2018 **Heavy falls at a few places and very heavy at isolated places very likely over interior Tamil Nadu.** South Coastal Andhra Pradesh 14 November 2018 **Heavy falls at isolated places very likely to commence from 14th November evening.** 15 November 2018 **Heavy falls at isolated places** Rayalaseema 15 November 2018 **Heavy falls at isolated places** Kerala 15 November 2018 **Heavy to very heavy falls at isolated places** 16 November 2018 **Heavy to very heavy falls at isolated places.**	

14/11/2018 0300 UTC	**<u>15 November 2018</u>** **Tamilnadu & Puducherry** Heavy to very heavy at a few places over Tamilnadu & Puducherry. **Extremely heavy falls** (≥ 20 cm) at isolated places is also likely over Cuddalore, Nagappattinam, Tiruvarur, Thanjavur, Pudukkottai, Tuticorin and Ramanathapuram districts. **South Coastal Andhra Pradesh** Heavy falls at isolated places **Rayalaseema** Heavy falls at isolated places **Kerala** Heavy falls at isolated places **<u>16 November 2018</u>** **Tamilnadu & Puducherry** Heavy falls at a few places and very heavy at isolated places very likely over interior Tamil Nadu. **South Coastal Andhra Pradesh** Heavy falls at isolated places **Kerala** Heavy to very heavy falls at isolated places	
15/11/2018 0300 UTC	**<u>15 November 2018</u>** **Tamilnadu & Puducherry** Heavy to very heavy at a few places over Tamilnadu & Puducherry. **Extremely heavy falls** (≥ 20 cm) at isolated places is also likely over Cuddalore, Nagappattinam, Karaikal, Tiruvarur, Thanjavur, Pudukkottai, Tuticorin and Ramanathapuram districts. **South Coastal Andhra Pradesh** Heavy falls at isolated places in Nellore and Prakasam districts. **Rayalaseema** Heavy falls at isolated places Chittoor district **Kerala** Heavy falls at isolated places over south Kerala **<u>16 November 2018</u>** **Tamilnadu & Puducherry** Heavy falls at a few places and very heavy at isolated places very likely over south interior Tamil Nadu. Rainfall at most places with heavy falls at isolated places very likely over north interior Tamil Nadu. **Kerala** Heavy to very heavy falls at isolated places	
16/11/2018 0300 UTC	• Heavy falls at a few places and very heavy at isolated places over south interior Tamil Nadu and with heavy falls at isolated places over north interior	

	Tamil Nadu during next 24 hours. Rainfall at most places with heavy to very heavy falls at isolated places very likely over Kerala during next 24 hours. • Heavy falls at isolated places very likely over Lakshadweep on 17th November, 2018.	
17/11/2018 0300 UTC	Heavy to very heavy falls with extremely heavy falls at isolated places very likely over Lakshadweep during next 24 hours and heavy falls at isolated places during subsequent 24 hours.	

Table 4.3.6.5: Verification of Gale/Squally Wind Forecast issued by IMD

Date/ Time of observation (UTC)	Gale/ Squally wind Forecast	Realised wind speed
10/11/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over and around Andaman Islands and north Andaman Sea on 10th and 11th. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over southeast & adjoining eastcentral Bay of Bengal on 10th. The wind speed will gradually increase becoming 50-60 kmph gusting to 70 kmph on 11th, • Gale wind speed reaching 65-75 kmph gusting to 85 kmph is very likely over central parts of south & adjoining west central and eastcentral Bay of Bengal from 11th November 2018 evening. It would gradually increase becoming 90-100 kmph gusting to 110 kmph over west central and adjoining southwest Bay of Bengal from 12th November 2018 evening • Squally wind speed reaching 45-55 kmph gusting 65 kmph likely to commence along and off north Tamil Nadu – south Andhra Pradesh coasts from 13th November evening.	Atiramapattinam reported maximum wind speed of 117 kmph at 0330 hrs IST, Nagapattinam reported 100 kmph during 0230-0330 IST and Karaikal reported 92 kmph at 0130 IST of 16th. Estimated maximum wind speed at the time of landfall was 130 kmph gusting to 145 kmph.
11/11/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over and around Andaman Islands and north Andaman Sea during next 12 hours. • Gale wind speed reaching 65-75 kmph gusting to 85 kmph prevails over Eastcentral and adjoining Westcentral & Southeast Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over west central & adjoining southwest Bay of Bengal from morning of 12th November 2018. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph likely to commence along & off north Tamil Nadu – south Andhra Pradesh coasts from 14th November morning. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off north Tamil Nadu – south	

	Andhra Pradesh coasts over west central & adjoining southwest Bay of Bengal from 14th November mid-night onwards.	
12/11/2018 0300 UTC	• Gale wind speed reaching 70-80 kmph gusting to 85 kmph prevails over Eastcentral and adjoining Westcentral & Southeast Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over southwest & adjoining westcentral and southeast Bay of Bengal from morning of 13th November 2018. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph likely to commence along & off north Tamil Nadu & Puducherry – south Andhra Pradesh coasts from 14th November morning. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off north Tamil Nadu & Puducherry coasts from 14th November night onwards.	
13/11/2018 0300 UTC	• Gale wind speed reaching 70-80 kmph gusting to 90 kmph prevails over Westcentral and adjoining Eastcentral & South Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over southwest & adjoining westcentral and southeast Bay of Bengal from 14th Nov. 2018. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely to commence along & off north Tamil Nadu & Puducherry and adjoining south Andhra Pradesh coasts from 14th November morning. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off Tamil Nadu & Puducherry coasts from 15th November morning onwards. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over interior Tamilnadu, south Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea & along & off Kerala coast on 17th November.	
14/11/2018 0300 UTC	• Gale wind speed reaching 70-80 kmph gusting to 90 kmph prevails over Southwest and adjoining southeast & westcentral Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over these areas from today, the 14th November 2018 evening. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely to commence along & off Tamil Nadu & Puducherry and adjoining south Andhra Pradesh coasts from today, the 14th November 2018 evening. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off central parts of Tamil Nadu & Puducherry coasts from 15th November morning onwards. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph	

	very likely over interior Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th November.	
15/11/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely to prevail along & off Tamil Nadu & Puducherry and adjoining south Andhra Pradesh coasts. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off central parts of Tamil Nadu & Puducherry coasts from today, the 15th November evening onwards. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over interior Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th November.	
15/11/2018 1500 UTC	• Gale wind speed reaching 60-70 kmph gusting to 80 kmph is prevailing along & off Tamil Nadu & Puducherry coasts. It is very likely to increase gradually becoming Gale wind speed 100-110 kmph gusting to 120 kmph along & off central parts of Tamil Nadu & Puducherry coasts during next 09 hours. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over interior Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th November.	
16/11/2018 0300 UTC	• Gale wind speed reaching 65-75 kmph gusting to 85 kmph very likely over central parts of Tamil Nadu during next 03 hours. It would gradually decrease becoming squally wind speed reaching 50-60 kmph gusting to 70 kmph over these areas during subsequent six hours. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over remaining parts of Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th November. • Squally wind speed reaching 40-50 kmph gusting 50 kmph is likely to prevail along and off Tamil Nadu coast during next 6 hours.	

17/11/2018 0300 UTC	• Squally wind speed reaching 55-65 kmph gusting to 75 kmph is prevailing over Southeast Arabian Sea and Lakshadweep Area. It is very likely to gradually increase becoming gale wind speed reaching 70-80 kmph gusting to 90 kmph during next 24 hours. • Squally wind speed reaching 40-50 kmph gusting to 60 kmph very likely along & off Kerala coast during next 24 hours.	
18/11/2018 0300 UTC	• Squally wind speed reaching 40-50 kmph gusting to 60 kmph is very likely to prevail over Lakshadweep Area during next 12 hours and decrease thereafter. • Squally wind speed reaching 55-65 kmph gusting to 75 kmph is likely to prevail over Southeast Arabian Sea to the west of Lakshadweep area on today, the 18th November, 2018. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph is very likely to prevail over central parts of south Arabian Sea on 19th November and southwest Arabian Sea on 20th November, 2018.	
19/11/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph is likely to prevail over Southeast Arabian Sea to the west of Lakshadweep area during next 12 hours and decrease thereafter. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph is very likely to prevail over central parts of south Arabian Sea on today, the 19th November and 40-50 kmph gusting to 60 kmph over southwest Arabian Sea on 20th November, 2018.	

Table 4.3.6.6: Verification of Storm Surge Forecast issued by IMD

Date/ Time(UTC)	Storm Surge Forecast	Recorded storm surge
12/11/2018 0300 UTC	Storm surge of height of about 1.0 meter above astronomical tide is very likely inundate low lying areas of Nagappattinam & Cuddalore districts of Tamil Nadu and Karaikal district of Puducherry at the time of landfall.	Storm surge of about 1 metre above astronomical tide inundated low lying areas upto about 1 km from the coast near the landfall point.
13/11/2018 0300 UTC	Storm surge of height of about 1.0 meter above astronomical tide is very likely to inundate low lying areas of Nagappattinam, Thanjavur, Pudukkottai and Ramanathapuram districts of Tamil Nadu and Karaikal district of Puducherry at the time of landfall.	
14/11/2018 0300 UTC	-DO-	
15/11/2018 0300 UTC	-DO-	
17/11/2018 0300 UTC	Storm surge of height of about 0.5 meter above astronomical tide is very likely to inundate low lying areas of Lakshadweep Islands (Androth, Amini, Agatti, Cherium, Kalpeni, Kavaratti, Bangaram, Suheli Islands) at the time of landfall.	

4.3.7. Severe Cyclonic Storm “PHETHAI” over southeast Bay of Bengal (13-18 December 2018)

4.3.7.1. Genesis Forecast

- First information about formation of low pressure area (LPA) over southeast BoB and neighbourhood around 9th December was issued in the Tropical Weather Outlook (TWO) dated the 5th December at 1230 IST (more than 4 days in advance of formation of LPA). LPA formed at 1730 IST of 9th.
- In the TWO issued at 1300 IST of 7th, it was mentioned that, the LPA will form around 9th and will become more marked thereafter. WML formed at 0830 IST of 11th.
- In the TWO issued at 1300 IST of 10th, it was mentioned that the LPA would become WML during next 48 hours and intensify into a depression around 13th (around 48 hours in advance). WML formed at 0830 IST of 11th. Depression formed at 0530 IST of 13th.

4.3.7.2. Landfall Forecast

- In the bulletin issued at 0830 IST of 14th December when it was a D, it was predicted that the system would cross Andhra Pradesh coast between Ongole and Kakinada during 17h December afternoon as a cyclonic storm.
- The landfall point was further specified to be between Machilipatnam and Kakinada during 17th December afternoon in the bulletin issued at 1430 IST of 16th.

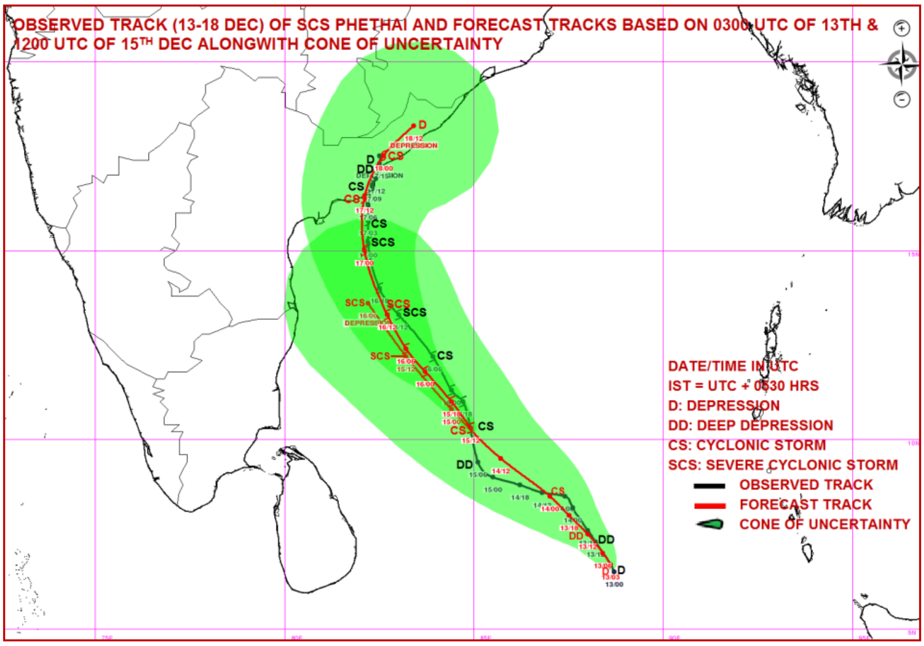


Fig. 4.3.7.1: Observed track of SCS Phethai and forecast based on 0300 UTC of 13th and 1200 UTC of 15th December demonstrating the forecast of movement towards Andhra Pradesh coast since beginning and accurate landfall point forecast.

- The CS Phethai crossed Andhra Pradesh coast close to south of Yanam, about 40 km south of Kakinada during 1330-1430 IST (afternoon) of 17th December with a wind speed of 70-

80 kmph gusting to 90 kmph as a cyclonic storm. Typical observed and forecast track is presented in Fig. 4.3.7.1.

- The landfall point forecast errors (first landfall) were about 15.6, 15.6 and 46.7 km for 24, 48 and 60 hrs lead period against past five year (2013-17) average errors of 42.3, 94.8 and 115.4 km respectively. The landfall time forecast errors were about 2.0, 4.5 and 2.5 hours for 24, 48 and 60 hrs lead period against past five year (2013-17) average errors of 3.6, 5.4 and 4.6 hours respectively. The landfall point and time errors were less than long period average (LPA) of past five years for all lead periods (Fig. 4.3.7.2 and Table 4.3.7.1)

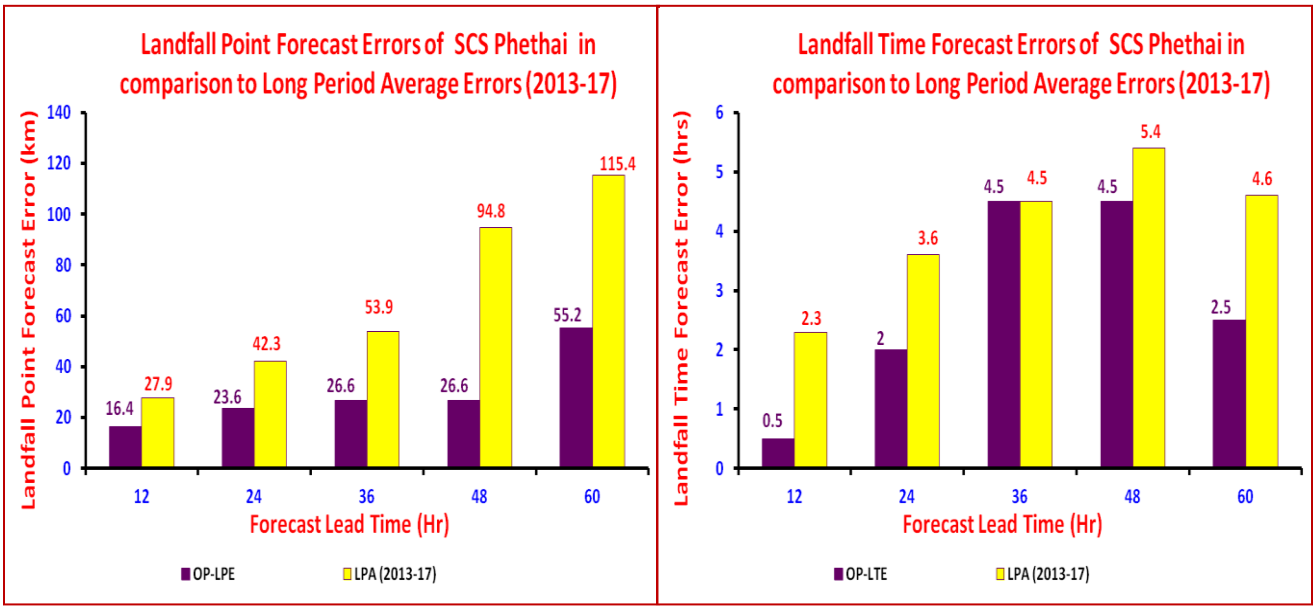


Fig. 4.3.7.2: Landfall Point (km) and Time (hrs) Errors for SCS Phethai for first landfall

Table 4.3.7.1 (a): Operational and long period average landfall point (km) and time (hrs) errors in association with SCS Phethai (first landfall)

Lead Period (hrs)	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	16/18	16.50/82.11	16.55/82.25	17/0900	17/0830	16.4	0.5	27.9	2.3
24	16/06	16.74/82.35	16.55/82.25	17/1030	17/0830	23.6	2.0	42.3	3.6
36	15/18	16.45/82.03	16.55/82.25	17/1300	17/0830	26.6	4.5	53.9	4.5
48	15/06	16.45/82.03	16.55/82.25	17/1300	17/0830	26.6	4.5	94.8	5.4
60	14/18	16.35/81.79	16.55/82.25	17/1100	17/0830	55.2	2.5	115.4	4.6

Table 4.3.7.1 (b): Operational and long period average landfall point (km) and time (hrs) errors in association with SCS Phethai (second landfall)

Lead Period (hrs)	Base Time	Landfall Point (⁰N/⁰E)		Landfall Time (hours)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hrs)	LPE (km)	LTE (hrs)
12	17/00	17.30/82.65	17.20/82.47	17/1430	17/1430	22.7	0.0	27.9	2.3
24	16/12	17.15/82.42	17.20/82.47	17/1400	17/1430	07.8	0.5	42.3	3.6
36	16/06	17.20/82.45	17.20/82.47	17/1330	17/1430	02.2	1.0	53.9	4.5

LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point,
LTE= Forecast Landfall Time-Actual Landfall Time

4.3.7.3. Track Forecast

- In the first Bulletin issued at 0930 IST of 13th, it was mentioned that the system would move northwestwards towards Andhra Pradesh coast during next 72 hours.
- First information about the northeastwards recurvature of system was given in the bulletin issued at 1430 IST of 14th December.

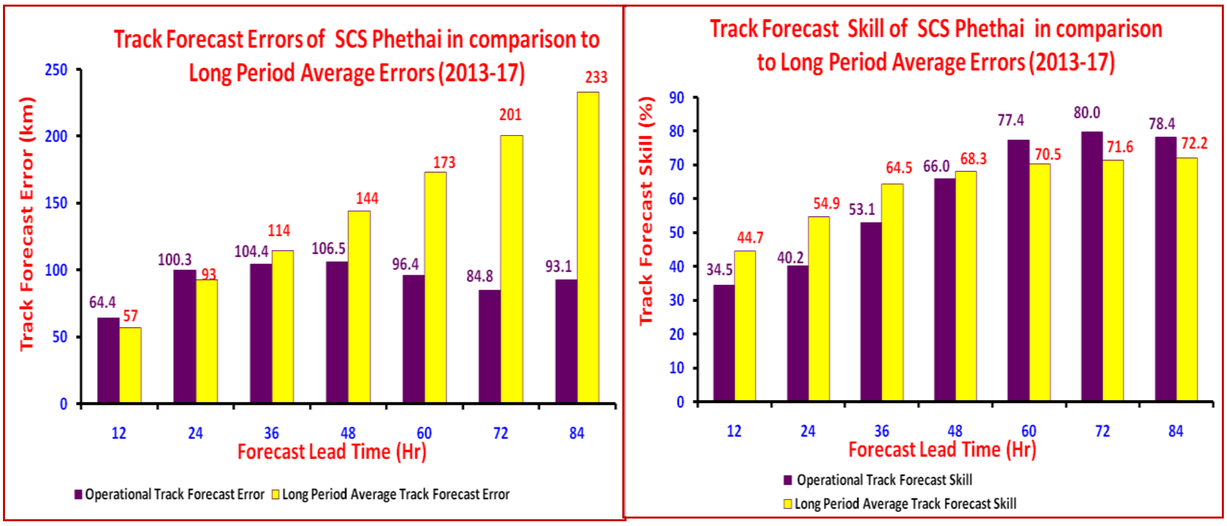


Fig. 4.3.7.3 Track Forecast Errors and Skill for SCS Phethai

- The track forecast errors were about 100.3, 106.5 and 84.8 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 93, 144 and 201 km respectively. For all the lead periods beyond 24 hours, the track forecast errors were significantly less than the past five years average. For 12 & 24 hours lead period, it was comparable to past five years average (Fig. 4.3.7.3 and Table 4.3.7.2).

Table 4.3.7.2 Operational and long period average track forecast errors (km) & Skill (%)

Lead Period (hrs)	No. of obs. verified	Operational Track Forecast		Long Period Average (2013-17) Track Forecast	
		Error (km)	Skill (%)	Error (km)	Skill (%)
12	15	64.4	34.5	57	44.7
24	13	100.3	40.2	93	54.9
36	11	104.4	53.1	114	64.5
48	9	106.5	66.0	144	68.3
60	7	96.4	77.4	173	70.5
72	5	84.8	80.0	201	71.6
84	2	93.1	78.4	233	72.2

4.3.7.4. Intensity Forecast

- In the first bulletin issued by IMD at 0930 hrs IST of 13th with the formation of depression, it was indicated that the system would intensify into a deep depression during next 12 hours and into a cyclonic storm during subsequent 24 hours. The depression intensified into a deep depression at midnight (2330 IST) of 13th and into a CS in the evening (1730 IST) of 15th.
- In the bulletin issued at 0030 IST of 14th with the intensification of system into a DD, it was further predicted that it would intensify into a CS during next 24 hrs and into an SCS during subsequent 24 hrs.
- The weakening of the system from SCS to CS category at the time of landfall was first predicted in the bulletin issued at 1430 IST of 14th Dec.
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 6.7, 7.1 and 4.8 knots against the LPA of 10.4, 15.5 and 15.7 knots respectively. The skill in intensity (wind) forecast based on AE for 24, 48 and 72 hrs lead period was 56.2, 64.4 and 31.7% against the LPA of 37.1, 56.8 and 69.3% respectively (**Fig. 4.3.7.4 and Table 4.3.7.3**). For all lead periods, the errors in intensity forecast were significantly less.
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 7.3, 9.3 and 6.0 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill in intensity (wind) forecast based on RMSE for 24, 48 and 72 hrs lead period was 67.7, 55.3 and 31.2% against the LPA of 40.1, 60.0 and 73.0% respectively (**Fig. 4.3.7.5 and Table 4.3.7.3**). For all lead periods, the errors in intensity forecast were significantly less.

Table 4.3.7.3: Average Intensity forecast errors (kt) and Skill (%) in association with SCS Phethai

Lead Period (hrs)	N	Average Intensity Error (kts)		LPA (2013-17) Intensity forecast Error (kts)		Skill (%) in intensity forecast		LPA (2013-17) Intensity forecast Skill (%)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	15	3.8	4.6	6.3	8.7	43.0	51.9	22.3	28.0
24	13	6.7	7.3	10.4	14.0	56.2	67.7	37.1	40.1
36	11	6.1	7.3	13.8	18.4	64.0	65.9	48.2	51.0
48	9	7.1	9.3	15.5	20.6	64.4	55.3	56.8	60.0
60	7	6.8	8.3	15.8	20.9	36.7	40.8	64.4	67.9
72	5	4.8	6.0	15.7	20.6	31.7	31.2	69.3	73.0
84	2	9.0	9.0	24.6	22.1	55.3	63.9	62.0	76.5

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17).

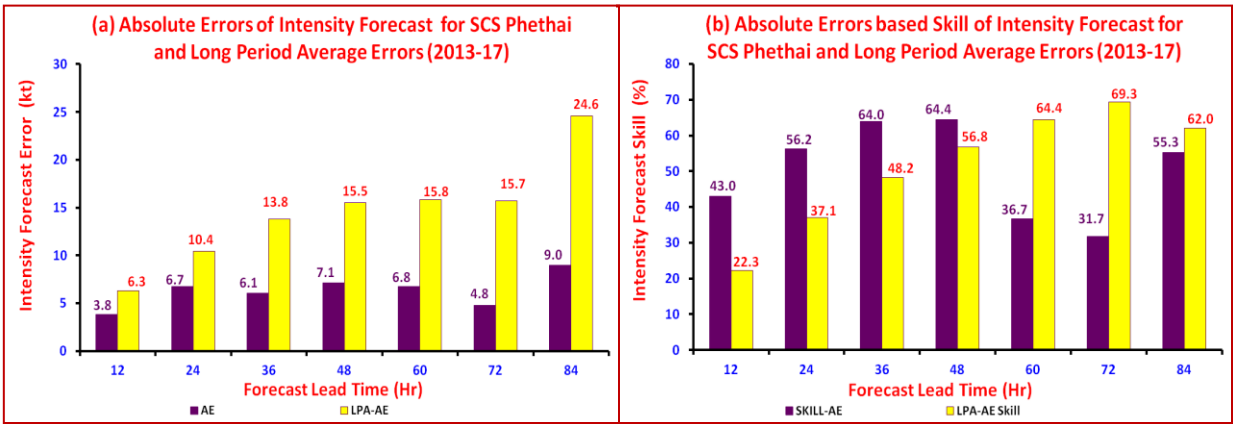


Fig. 4.3.7.4: Absolute errors (AE) of intensity forecast and skill for SCS Phethai

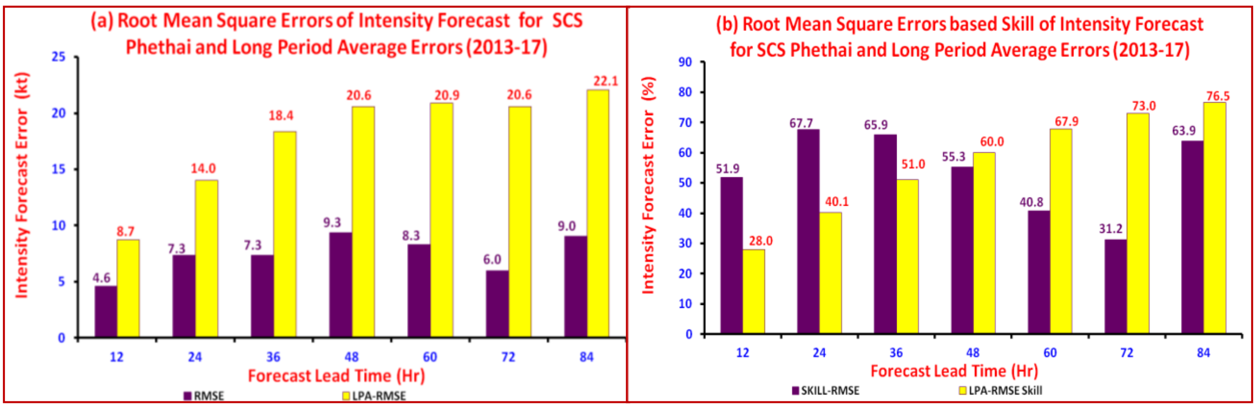


Fig. 4.3.7.5 Root Mean Square Errors (RMSE) of intensity forecast and skill for SCS Phethai

4.4. Performance of cyclone landfall, track and intensity forecast during 2018

4.4.1. Track forecast

The annual average track forecast errors in 2018 had been 88 km, 124 km and 134 km, respectively for 24, 48 and 72 hrs against the past five year average error of 93, 144 and 201 km based on data of 2013-2017. The errors have been significantly lower during this year as compared to long period average (2013-17). The track forecast skills compared to climatology and persistence forecast were 54%, 69% and 78% respectively for the 24, 48 and 72 hrs lead period compared to long period average of 2013-2017 (55%, 68% & 72% respectively). The annual average track forecast errors and skill during 2018 are presented in Fig. 4.4.1 (a-b).

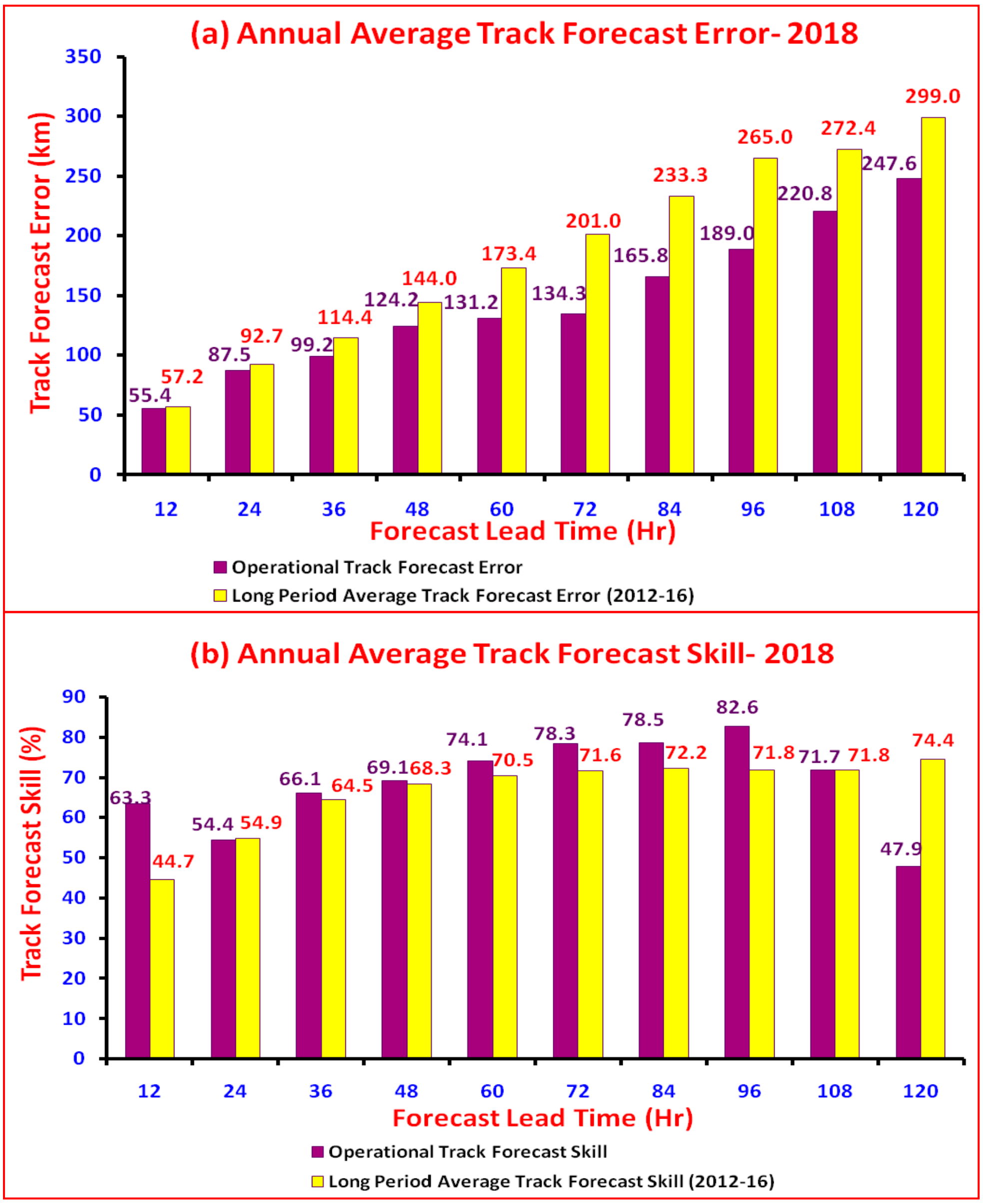


Fig. 4.4.1. Annual average (a) track forecast error (km) and (b) track forecast skill against the climatology and persistence forecast during 2018 as compared to that during 2013-2017

4.4.2. Landfall forecast

The annual average landfall point forecast errors for the year 2018 have been 44 km, 40 km and 68 km for 24, 48 and 72 hrs lead period against the long period average of 42 km, 95 km and 122 km during 2013-2017. The landfall time forecast errors have been 2.8, 5.0 and 7.4 hrs for 24, 48 and 72 hrs lead period during 2018 against the average of past five years of 3.6, 5.4 and 3.8 hrs during 2013-2017. The annual average landfall point and time forecast errors are presented in Fig. 4.4.2 (a-b). The annual landfall point errors during 2018 were significantly less than the long period average errors for all lead periods. The annual landfall time errors during 2018 were also less than the long period average upto 48 hrs lead period.

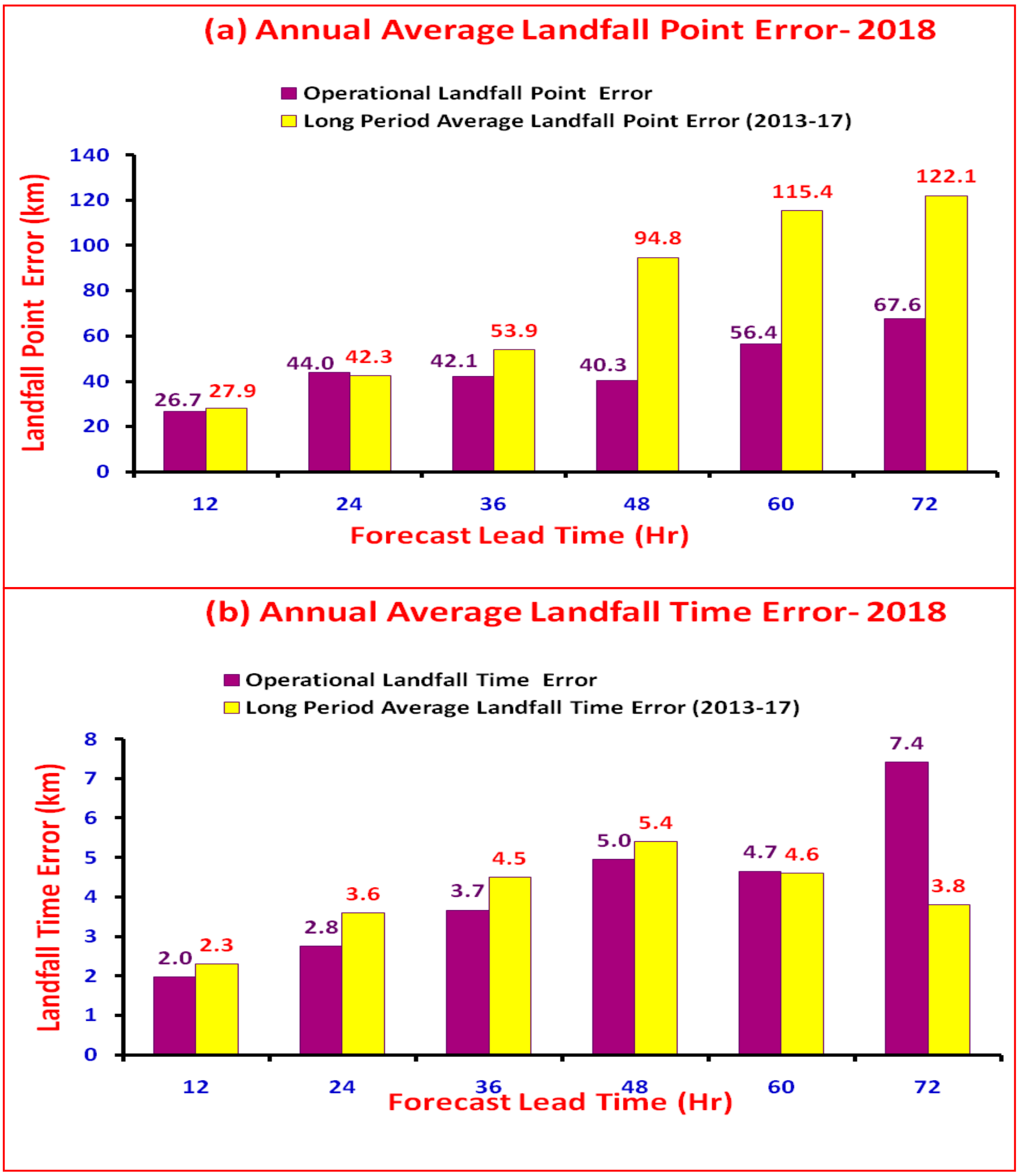


Fig. 4.4.2. Annual average (a) landfall point forecast error (km) and (b) landfall time (hrs) during 2018 as compared to that during 2013-2017

4.4.3. Intensity forecast

The annual average absolute error (AE) and root mean square errors (RMSE) in intensity forecast are presented in Fig. 4.4.3 a-b. The average absolute errors during 2018 have been 8.2 knots, 11.6 knots and 12.9 knots respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 10.4, 15.5 and 15.7 knots. The root mean square errors have been 9.8 knots, 14.4 knots and 15.1 knots respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 14.1, 20.6 and 20.6 knots.

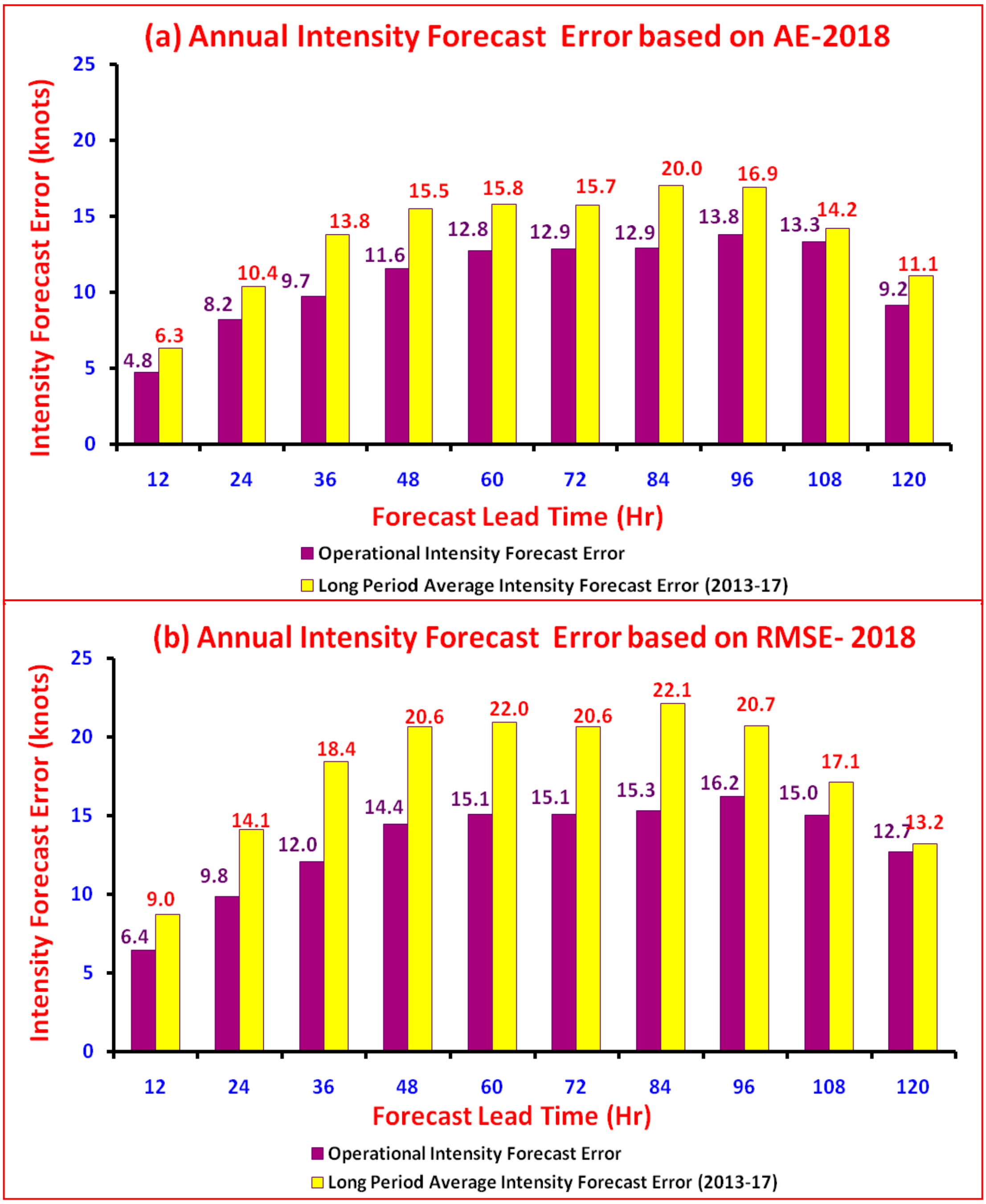
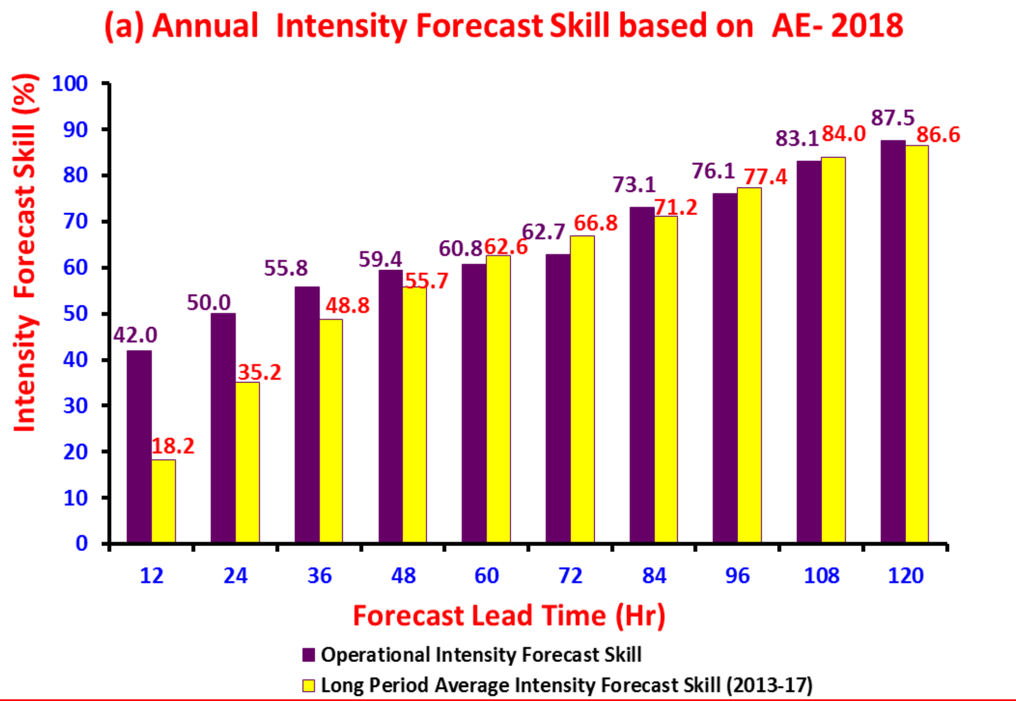


Fig. 4.4.3. Annual average intensity forecast error (knots) based on absolute errors and root mean square errors during 2018 as compared to that during 2013-2017

The annual average skill based on AE and RMSE are presented in Fig. 4.4.4 a-b. The average skill based on AE during 2018 have been 50, 59 & 63 % respectively for 24, 48 and 72 hrs lead period of forecast against the past five year average of 35, 56 & 67%. The average skill based on RMSE during 2018 have been 61, 64 & 70 % respectively for 24, 48 and 70 hrs lead period of forecast against the past five year average of 39, 60 & 72%.



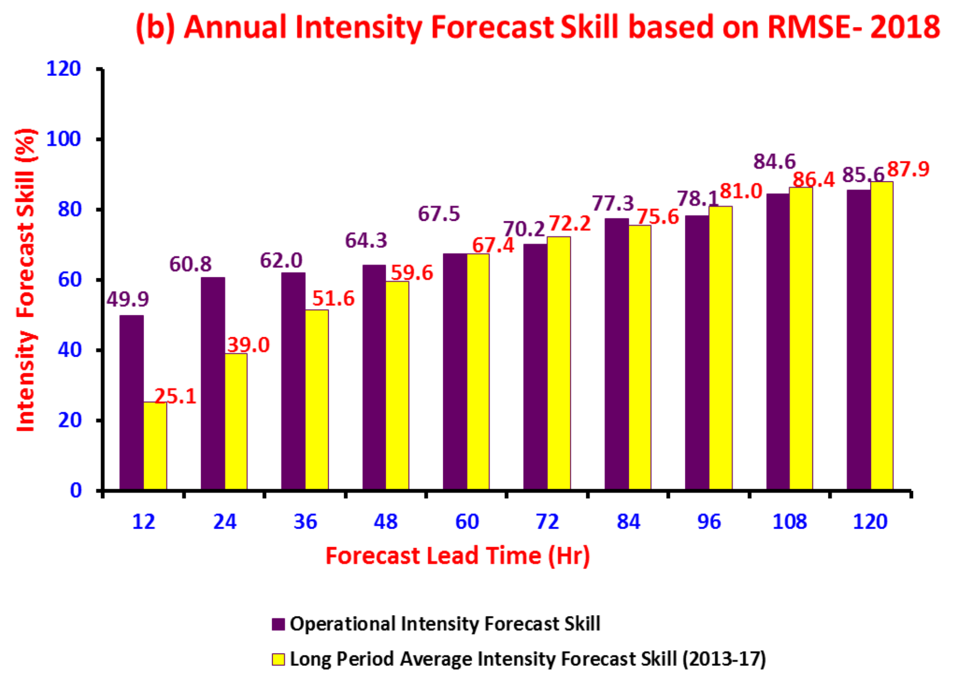


Fig. 4.4.4. Annual average intensity forecast skill (%) based on absolute errors and root mean square errors during 2018 as compared to that during 2013-2017

4.5 Annual average forecast errors

4.5.1. Landfall forecast errors

Annual average landfall point and time errors since 2003 are presented in Fig. 4.5.1 and Table 4.5.1 & 4.5.2. Fig. 4.5.1 indicates a decrease in landfall point error at the rate of 9.2 & 18.9 km/year and decrease in landfall time error at the rate of 0.3 & 0.2 hr/year for 12 and 24 hr lead period respectively.

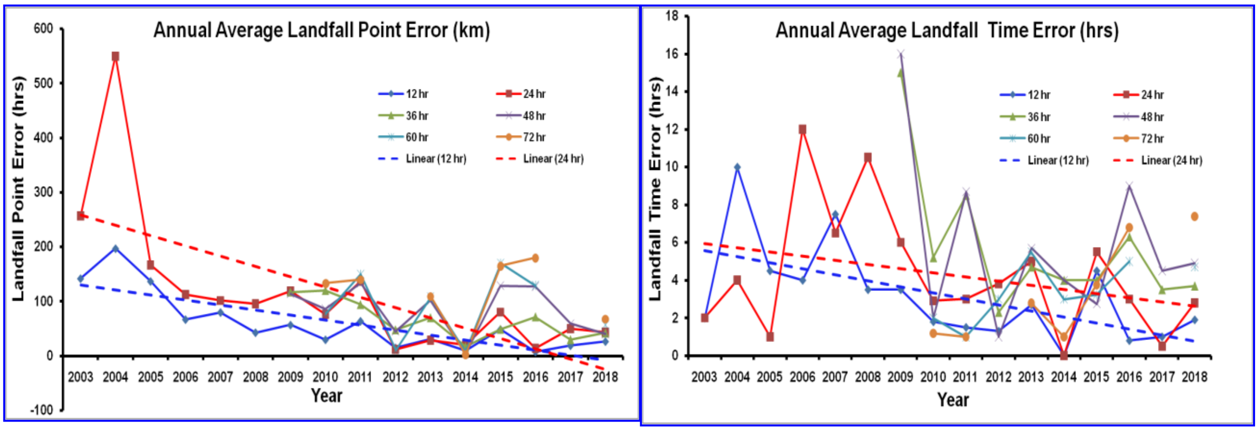


Fig. 4.5.1 Annual average (a)Landfall Point errors (b) Landfall Time errors

Table 4.5.1: Annual average Landfall Point errors (value shown in "()" indicate no. of cases)

Year	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003	142 (2)	257 (1)								
2004	197 (1)	550 (1)								
2005	137 (2)	167 (1)								
2006	67 (2)	113 (2)								
2007	80 (5)	102 (3)								
2008	43 (4)	96 (4)								
2009	57 (4)	119 (4)	117 (4)	114 (3)						
2010	30 (5)	77 (5)	120 (4)	86 (3)	78 (3)	133 (3)				
2011	64 (2)	137 (2)	94 (2)	134 (2)	150 (1)	140 (1)				
2012	15 (2)	12 (2)	48 (2)	45 (2)	11 (2)					
2013	31 (4)	29 (4)	70 (4)	102 (4)	108 (4)	109 (3)				
2014	10 (1)	20 (1)	17 (1)	4 (1)	8 (1)	2 (1)				
2015	48.8 (3)	80.7 (3)	48.8 (3)	129.2 (2)	170.1 (2)	165.2 (1)	284.5 (1)	272.7 (1)	403.8 (1)	435.9 (1)

2016	7.8 (2)	14.1 (2)	71.6 (2)	127.2 (2)	129.2 (2)	180.1 (2)	253.2 (1)	286 (1)	403.4 (1)	
2017	19.1 (2)	50.4 (2)	29.8 (2)	59 (2)						
2018	26.7 (8)	44 (7)	42.1 (7)	40.3 (5)	56.4 (5)	67.6 (3)				

Table 4.5.2: Annual average Landfall Time errors (value shown in "()" indicate no. of cases)

Year	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003	2 (2)	2 (1)								
2004	10 (1)	4 (1)								
2005	4.5 (2)	1 (1)								
2006	4 (2)	12 (2)								
2007	7.5 (5)	6.5 (3)								
2008	3.5 (4)	10.5 (4)								
2009	3.5 (4)	6 (4)	15 (4)	16 (3)						
2010	1.8 (5)	2.9 (5)	5.2 (4)	2 (3)	2 (3)	1.2 (3)				
2011	1.5 (2)	3 (2)	8.5 (2)	8.7 (2)	1 (1)	1 (1)				
2012	1.3 (2)	3.8 (2)	2.3 (2)	1 (2)	3 (2)					
2013	2.7 (4)	5 (4)	4.7 (4)	5.7 (4)	5.5 (4)	2.8 (3)				
2014	0 (1)	0 (1)	4 (1)	4 (1)	3 (1)	1 (1)				
2015	4.5 (3)	5.5 (3)	4 (3)	2.75 (2)	3.25 (2)	3.7 (1)	6.5 (1)	8.5 (1)	7.5 (1)	4.5 (1)
2016	0.8 (2)	3 (2)	6.3 (2)	9 (2)	5 (2)	6.8 (2)	3.5 (1)	2.5 (1)	5 (1)	
2017	1 (2)	0.5 (2)	3.5 (2)	4.5 (2)						
2018	1.9 (8)	2.8 (7)	3.7 (7)	4.9 (5)	4.7 (5)	7.4 (3)	6.4 (3)	15.5 (1)	14.5 (1)	

4.5.2. Track forecast errors and skill

Annual average track forecast errors and skill since 2003 are presented in Fig. 4.5.2 and Tables 4.5.3 & 4.5.4. Fig. 4.5.2 indicates a decrease in track forecast errors at the rate of 4.0 & 6.7 km/year and increase in track forecast skill at the rate of 5.8 & 3.5 % per year for 12 and 24 hr lead period respectively.

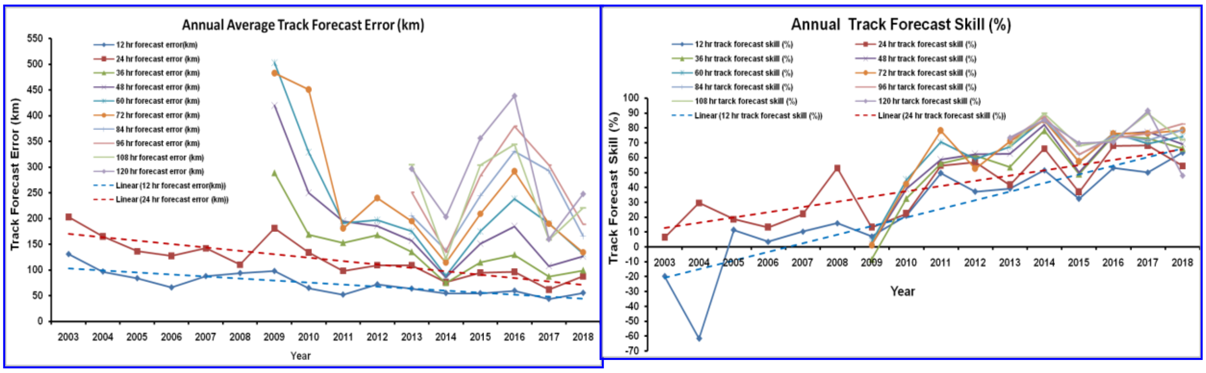


Fig. 4.5.2 Annual average (a) Track forecast errors (b) Track forecast Skill

Table. 4.5.3 Annual average Track forecast errors (value shown in "()" indicate no. of cases)

Year	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003	131 (41)	203 (41)								
2004	97 (3)	165 (3)								
2005	84 (32)	136 (26)								
2006	66 (25)	127 (19)								
2007	88 (29)	142 (24)								
2008	94 (22)	110 (16)								
2009	98 (32)	181 (26)	289 (16)	420 (8)	503 (6)	483 (2)				
2010	65 (56)	134 (48)	169 (38)	250 (29)	329 (23)	451 (19)				
2011	52 (21)	98 (19)	153 (16)	195 (14)	191 (10)	181 (7)				
2012	72 (16)	109 (13)	168 (8)	186 (6)	197 (4)	240 (2)				
2013	63.7 (94)	109 (84)	135.1 (72)	156.9 (65)	175 (55)	194.7 (44)	205.1 (34)	251.3 (26)	304.9 (18)	296.4 (11)
2014	55 (49)	76.1 (44)	74.7 (38)	85.6 (32)	88.5 (25)	114.3 (20)	138.1 (14)	135.1 (10)	121.5 (6)	203 (3)
2015	54.7 (66)	94.4 (60)	114.7 (52)	150.9 (43)	174.9 (37)	209.1 (30)	244.3 (22)	283.3 (17)	303.5 (12)	356 (8)
2016	59.7 (58)	96.1 (50)	129.6 (42)	185.1 (34)	238 (27)	291.7 (21)	330.4 (15)	379.5 (9)	344.1 (4)	438.3 (2)
2017	43.7 (35)	61.4 (29)	87.2 (23)	107.6 (18)	190.1 (14)	189.6 (12)	292.5 (10)	304.2 (8)	158.7 (3)	159.7 (3)
2018	55.4 (127)	87.5 (111)	99.2 (97)	124.2 (80)	131.2 (63)	134.3 (51)	165.8 (34)	189 (24)	220.8 (16)	247.6 (7)

Table. 4.5.4 Annual average Track forecast Skill (value shown in "()" indicate no. of cases)

Skill	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003	-19.8 (41)	6.3 (41)								
2004	-61.7 (3)	29.5 (3)								
2005	11.3 (32)	18.6 (26)								
2006	3.4 (25)	13 (19)								
2007	10.3 (29)	21.9 (24)								
2008	15.9 (22)	53 (16)								
2009	7 (32)	13.1 (26)	-8.4 (16)	1.5 (8)						
2010	20.9 (56)	22.3 (48)	32.5 (38)	39 (29)	45.1 (23)	42.3 (19)				
2011	49.5 (21)	54.5 (19)	56.1 (16)	58.5 (14)	70.4 (10)	78 (7)				
2012	37.1 (16)	56.8 (13)	61.2 (8)	62.3 (6)	58.8 (4)	52.6 (2)				
2013	39.1 (94)	41.6 (84)	53.5 (72)	62.5 (65)	67.3 (55)	70.9 (44)				
2014	51.4 (49)	66 (44)	78.1 (38)	81.9 (32)	85.8 (25)	85.1 (20)				
2015	32.3 (66)	36.8 (60)	48.8 (52)	50 (43)	57 (37)	57.3 (30)	62 (22)	62.3 (17)	67.7 (12)	69.6 (8)
2016	53.1 (58)	67.9 (50)	74.7 (42)	75.6 (34)	76.4 (27)	76 (21)	74.7 (15)	73.2 (9)	72.1 (4)	
2017	50 (35)	68.1 (29)	73 (23)	77.2 (18)						
2018	63.3 (127)	54.4 (111)	66.1 (97)	69.1 (80)	74.1 (63)	78.3 (51)	78.5 (34)	82.6 (24)	71.7 (16)	

4.5.3. Intensity forecast errors and skill

Annual average intensity forecast errors based on AE and RMSE since 2005 are presented in Fig. 4.5.3 & 4.5.4 and Tables 4.5.5 & 4.5.6. Fig. 4.5.3 indicates a decrease in intensity forecast errors based on AE at the rate of 0.3 & 0.5 kt/year and decrease in intensity forecast error based on RMSE at the rate of 0.3 & 0.6 kt/year for 12 and 24 hr lead period respectively.

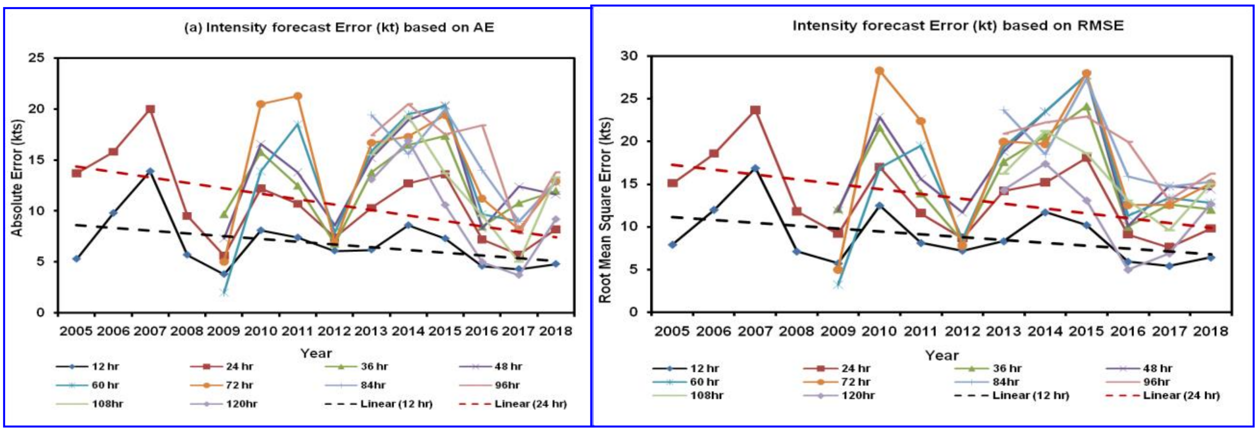


Fig. 4.5.3 Annual average Intensity forecast errors based on (a) AE (b) RMSE

Table. 4.5.5 Annual average Intensity forecast errors based on AE (value shown in "()" indicate no. of cases)

Year	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003	9.7	17.8								
2004	7.5	15.8								
2005	5.3 (31)	13.7 (23)								
2006	9.8 (25)	15.8 (19)								
2007	13.9 (27)	20 (20)								
2008	5.7 (23)	9.5 (18)								
2009	3.8 (33)	5.6 (26)	9.7 (18)	7.3 (11)	2 (5)	5 (1)				
2010	8.1 (55)	12.2 (49)	15.8 (37)	16.6 (29)	13.9 (23)	20.5 (19)				
2011	7.4 (21)	10.7 (19)	12.5 (17)	13.8 (14)	18.5 (10)	21.3 (7)				
2012	6.1 (16)	7.4 (13)	6.8 (10)	8.6 (7)	7.9 (5)	6.9 (3)				
2013	6.2 (94)	10.3 (84)	13.8 (73)	15.2 (63)	15.9 (54)	16.7 (42)	19.4 (34)	17.4 (26)	15.5 (18)	13.1 (11)
2014	8.6 (49)	12.7 (44)	16.5 (38)	18.9 (32)	19.5 (25)	17.3 (20)	15.6 (14)	20.5 (10)	19.3 (6)	16.9 (3)
2015	7.3 (66)	13.6 (60)	17.4 (52)	20.4 (43)	20.3 (37)	19.4 (30)	20 (22)	17.5 (17)	13.7 (12)	10.6 (8)
2016	4.6 (58)	7.2 (50)	8.5 (42)	8.3 (34)	9.7 (27)	11.2 (21)	14 (15)	18.4 (9)	9.5 (4)	5 (2)
2017	4.3 (35)	5.7 (29)	10.8 (23)	12.4 (18)	9 (14)	8.2 (12)	9 (10)	7.8 (8)	5 (3)	3.7 (3)
2018	4.8 (127)	8.2 (112)	12 (98)	11.6 (81)	12.8 (63)	12.9 (51)	12.9 (34)	13.8 (24)	13.3 (16)	9.2 (7)

Table. 4.5.6 Annual average Intensity forecast errors based on RMSE (value shown in "()" indicate no. of cases)

Year	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003	11.4	24.1								
2004	8.5	17								
2005	7.9 (31)	15.1 (23)								
2006	12 (25)	18.6 (19)								
2007	16.9 (27)	23.7 (20)								
2008	7.1 (23)	11.8 (18)								
2009	5.7 (33)	9.2 (26)	12.1 (18)	11.9 (11)	3.2 (5)	5 (1)				
2010	12.5 (55)	17 (49)	21.6 (37)	22.9 (29)	16.9 (23)	28.3 (19)				
2011	8.1 (21)	11.6 (19)	13.9 (17)	15.6 (14)	19.5 (10)	22.4 (7)				
2012	7.2 (16)	8.7 (13)	8.3 (10)	11.7 (7)	8.5 (5)	7.8 (3)				
2013	8.3 (94)	14.2 (84)	17.6 (73)	18.8 (63)	19.3 (54)	20 (42)	23.7 (34)	20.9 (26)	16.2 (18)	14.3 (11)
2014	11.7 (49)	15.2 (44)	20.6 (38)	23.5 (32)	23.5 (25)	19.7 (20)	18.5 (14)	22.2 (10)	21.2 (6)	17.4 (3)
2015	10.2 (66)	18.1 (60)	24.1 (52)	27.8 (43)	27.8 (37)	28 (30)	27.3 (22)	22.9 (17)	18.6 (12)	13.1 (8)
2016	5.9 (58)	9.1 (50)	10 (42)	10.1 (34)	11.3 (27)	12.6 (21)	15.9 (15)	19.9 (9)	13.1 (4)	5 (2)
2017	5.4 (35)	7.6 (29)	12.6 (23)	14.8 (18)	13.4 (14)	12.6 (12)	14.7 (10)	13.1 (8)	9.6 (3)	6.9 (3)
2018	6.4 (127)	9.8 (112)	12 (98)	14.4 (81)	12.8 (63)	15.1 (51)	15.3 (34)	16.2 (24)	15 (16)	12.7 (7)

Fig. 4.5.4 indicates an increase in intensity forecast skill based on AE at the rate of 1.2 & 3.0 % per year and increase in intensity forecast skill based on RMSE at the rate of 2.0 & 3.0 % per year for 12 and 24 hr lead period respectively.

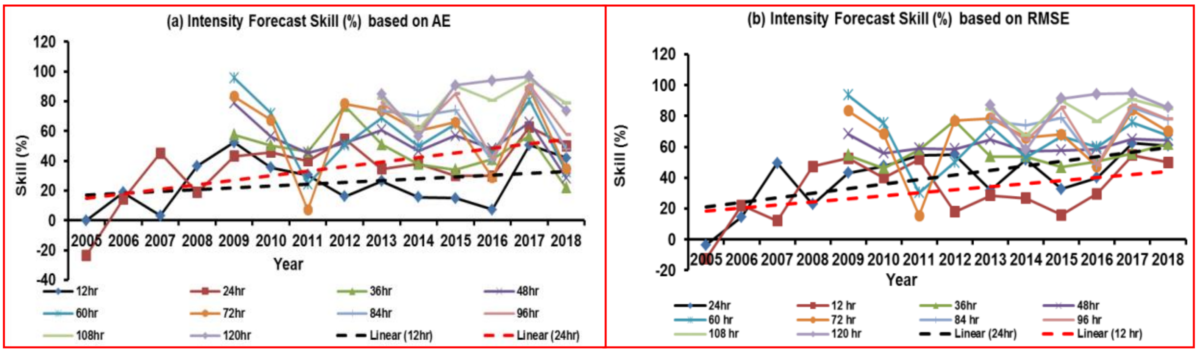


Fig. 4.5.4 Annual average Intensity forecast skill based on (a) AE (b) RMSE

Table. 4.5.7 Annual average Intensity forecast skill based on AE (value shown in "()" indicate no. of cases)

Year	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003										
2004										
2005	0 (31)	-23.5 (23)								
2006	18.7 (25)	14.3 (19)								
2007	3.1 (27)	45.2 (20)								
2008	36.5 (23)	18.7 (18)								
2009	52.4 (33)	43.1 (26)	57.5 (18)	78.8 (11)	95.6 (5)	83.3 (1)				
2010	35.5 (55)	45.9 (49)	50.3 (37)	56.1 (29)	71.8 (23)	67.1 (19)				
2011	30.6 (21)	40 (19)	46.1 (17)	45.4 (14)	24.5 (10)	7 (7)				
2012	16 (16)	54.6 (13)	76.6 (10)	51.9 (7)	50.6 (5)	78.2 (3)				
2013	26.4 (94)	34.6 (84)	51.1 (73)	60.7 (63)	68.8 (54)	73.7 (42)	73.9 (34)	79.2 (26)	82 (18)	84.8 (11)
2014	15.7 (49)	38 (44)	37.7 (38)	46.6 (32)	49.9 (25)	60.3 (20)	69.9 (14)	60 (10)	61.5 (6)	56.1 (3)
2015	14.9 (66)	30.1 (60)	34.2 (52)	56.9 (43)	64.5 (37)	65.9 (30)	74.1 (22)	85 (17)	90.3 (12)	90.8 (8)
2016	7.2 (58)	29.9 (50)	41.2 (42)	48 (34)	45.9 (27)	28.7 (21)	39.9 (15)	41.8 (9)	80.5 (4)	93.9 (2)
2017	50.6 (35)	62.7 (29)	56.8 (23)	66 (18)	80.6 (14)	87.9 (12)	89.5 (10)	91 (8)	94.3 (3)	96.8 (3)
2018	42 (127)	50 (112)	22 (98)	28.5 (81)	32.5 (63)	34.5 (51)	47.9 (34)	57.7 (24)	78.8 (16)	73.6 (7)

Table. 4.5.8 Annual average Intensity forecast skill based on RMSE (value shown in "()" indicate no. of cases)

Year	12-hr	24-hr	36-hr	48-hr	60-hr	72-hr	84-hr	96-hr	108-hr	120-hr
2003										
2004										
2005	-12.4 (31)	-3.5 (23)								
2006	22.2 (25)	14.6 (19)								
2007	12.1 (27)	49.5 (20)								
2008	47.2 (23)	22.7 (18)								

2009	52.7 (33)	43.1 (26)	54.5 (18)	68.3 (11)	93.4 (5)	83.3 (1)				
2010	39.9 (55)	47.6 (49)	46.1 (37)	55.9 (29)	75.5 (23)	68.2 (19)				
2011	51.9 (21)	54.6 (19)	58.2 (17)	59 (14)	30.3 (10)	15.5 (7)				
2012	18 (16)	55 (13)	77.1 (10)	58.6 (7)	50 (5)	76.9 (3)				
2013	28.4 (94)	31.8 (84)	53.7 (73)	64.7 (63)	73.5 (54)	78.4 (42)	76.8 (34)	80.4 (26)	84.2 (18)	86.9 (11)
2014	26.7 (49)	51.8 (44)	53.7 (38)	57.1 (32)	53.2 (25)	65.8 (20)	74.1 (14)	64.4 (10)	67.4 (6)	58.2 (3)
2015	15.8 (66)	32.7 (60)	46.9 (52)	57.8 (43)	66.9 (37)	68.2 (30)	78.8 (22)	85.5 (17)	89.9 (12)	91.4 (8)
2016	29.6 (58)	39.9 (50)	50.3 (42)	58.6 (34)	60 (27)	47.4 (21)	48.5 (15)	48.3 (9)	76.4 (4)	94.3 (2)
2017	54.6 (35)	62.4 (29)	55.8 (23)	65 (18)	75.9 (14)	83.9 (12)	85.4 (10)	87.1 (8)	90.6 (3)	94.7 (3)
2018	49.9 (127)	60.8 (112)	62 (98)	64.3 (81)	67.5 (63)	70.2 (51)	77.3 (34)	78.1 (24)	84.6 (16)	85.6 (7)

4.6. Comparative analysis of forecast accuracy in recent five years (2014-18) as compared to previous five years (2009-13)

4.6.1. Landfall Forecast Error

Significant improvement in landfall forecast errors have been observed during 2014-18 compared to that during 2009-13 due to implementation of modernisation programme in IMD in 2009. The landfall point error during 2014-18 has been 46.6, 69.7 and 104.3 km against 75.0, 97.6 and 123.7 km during 2009-13 (Fig.4.6.1 a) for 24, 48 & 72 hours lead period. Thus, 38%, 28% and 16% improvement in landfall point error was observed during 2014-18 compared to 2009-13 for 24, 48 and 72 hours lead period. Landfall time errors (Fig.4.6.1 b) during 2014-18 has been 2.9, 5.1 and 5.8 hrs against 4.2, 6.9 and 1.9 hrs during 2009-13 for 24 & 48 hrs lead period respectively with an improvement of 32% and 26%. There was improvement in landfall time errors upto a lead period of 48 hrs.

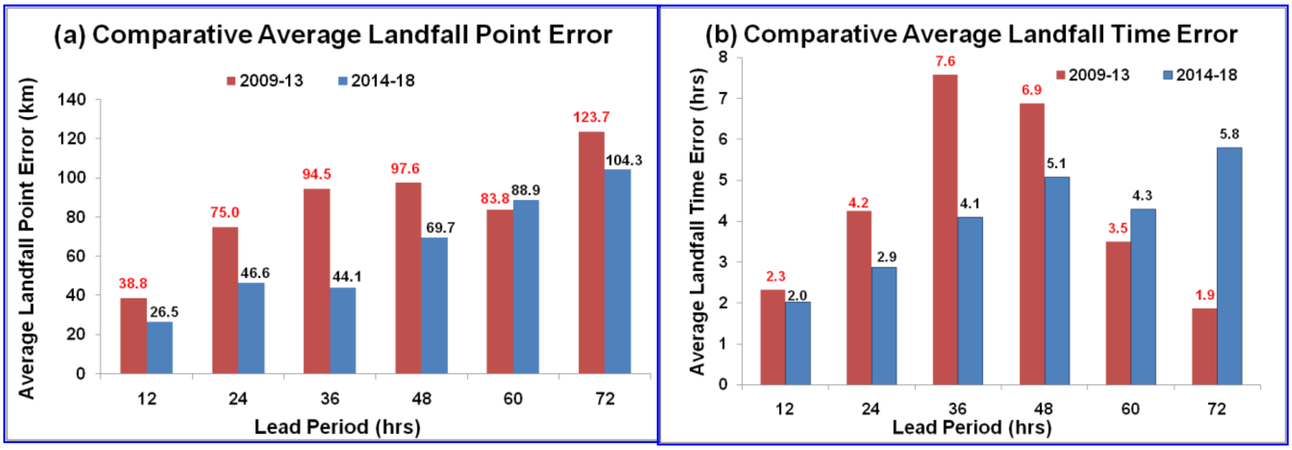


Fig. 4.6.1 Comparative average (a)Landfall Point errors (b) Landfall Time errors

4.6.2. Track forecast error and skill

The track forecast errors during 2014-18 have been 86, 132, 178 km against 124, 202, 268 km during 2009-13 for 24, 48 and 72 hrs lead period respectively (Fig.4.14 a). The period during 2014-18 registered a decrease in track forecast error by 31, 34 & 34% as compared to 2009-13 for 24, 48 and 72 hours lead period respectively. Similarly skill also improved significantly during 2014-18 (Fig.4.14 b) and has been 58, 70 & 74% during 2014-18 against 36, 53 & 22% during 2009-13 for 24, 48 and 72 hrs lead period respectively.

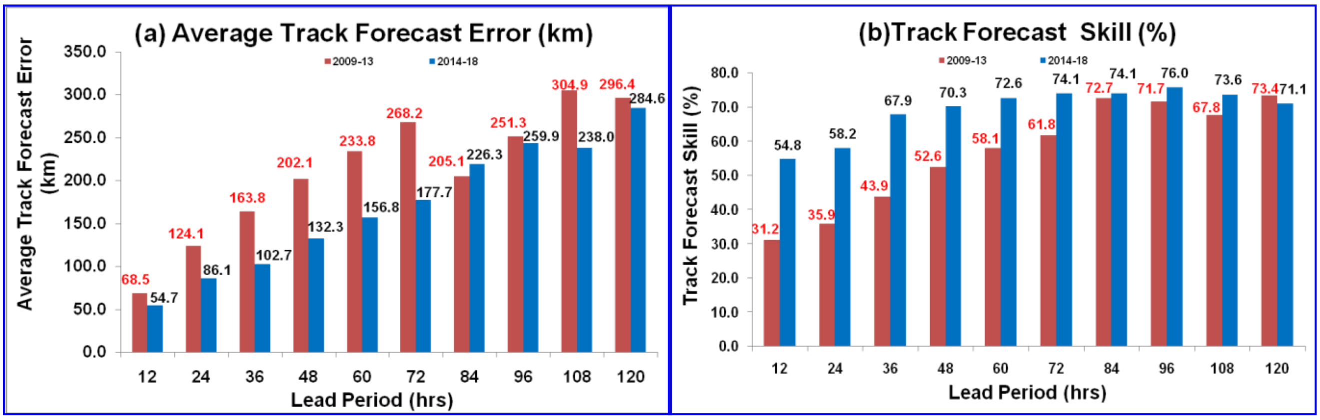


Fig. 4.6.2 Comparative average (a) Track forecast errors (b) Track forecast Skill

4.6.3. 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.4.6.3 (a-b). The intensity forecast errors based on AE during 2014-18 has been 9.6, 14.8 & 14.3 knots against 10, 14.3 & 17.6 knots during 2009-13 for 24, 48 and 72 hrs lead period respectively. The intensity forecast errors based on RMSE during 2014-18 has been 12.5, 19.0 & 19.0 knots against 13.9, 18.7 & 22.3 knots during 2009-13 for 24, 48 and 72 hrs lead period respectively.

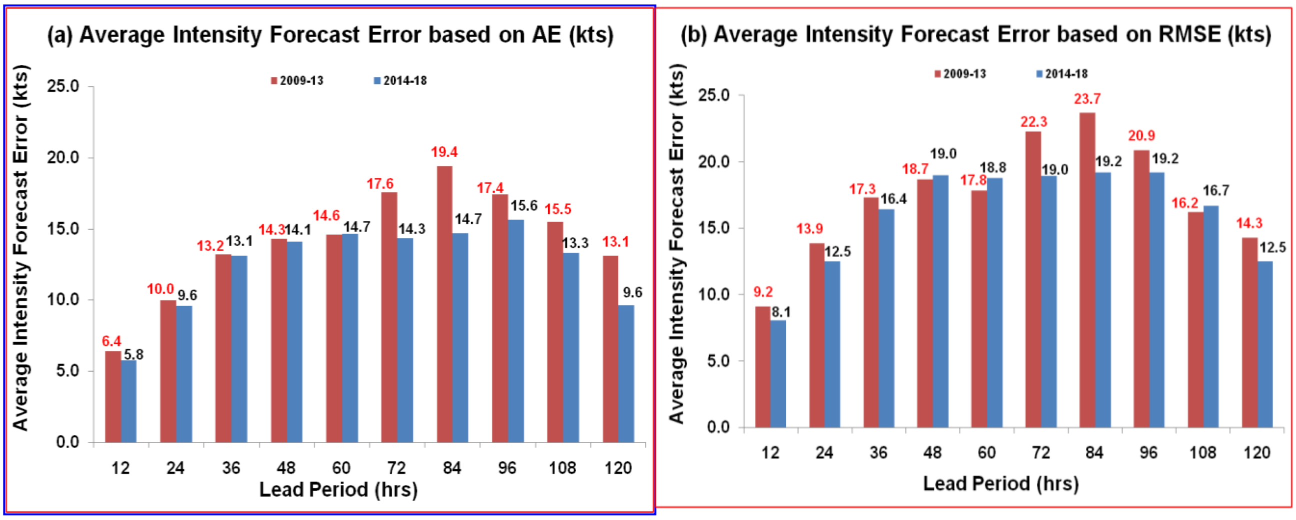


Fig. 4.6.3 Comparative average Intensity forecast errors based on (a) AE (b) RMSE

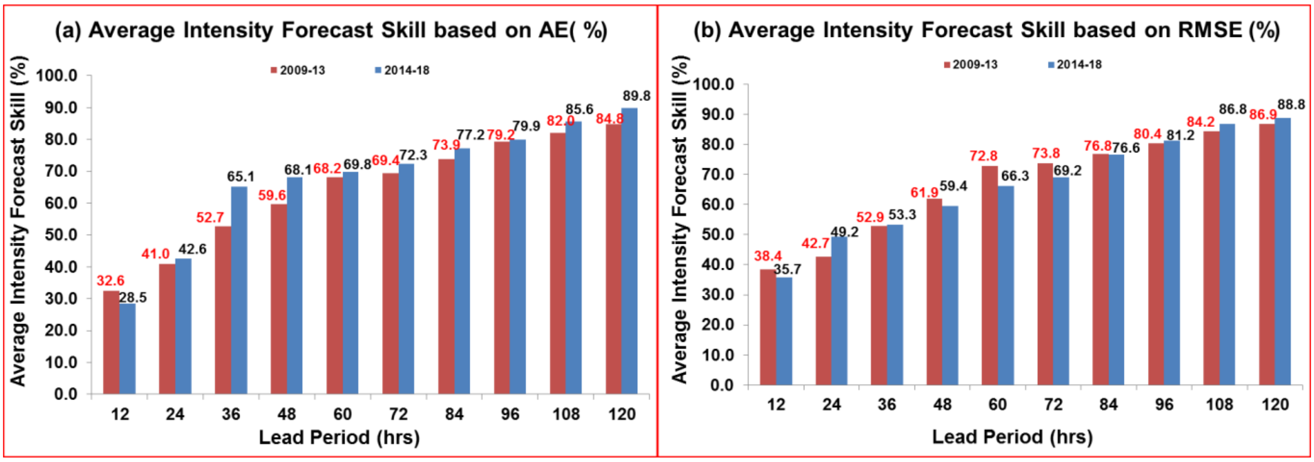


Fig. 4.6.4 Comparative average Intensity forecast skill based on (a) AE (b) RMSE

4.7. Five Year Moving Average of errors and skill

It can be seen from Fig.4.7.1-4.7.3 that there has been continuous improvement in forecast accuracy with decrease in landfall and track forecast errors and increase in skill over the years. Due to modernization programme of IMD and other initiatives of MoES, the improvement has been more significant since 2009. However, the rate of improvement in intensity forecast over the years has been marginal as can be seen from Fig.4.7.3. The 36-

72 hours forecasts commenced from 2009 and it was further extended to 120 hrs from 2013 onwards.

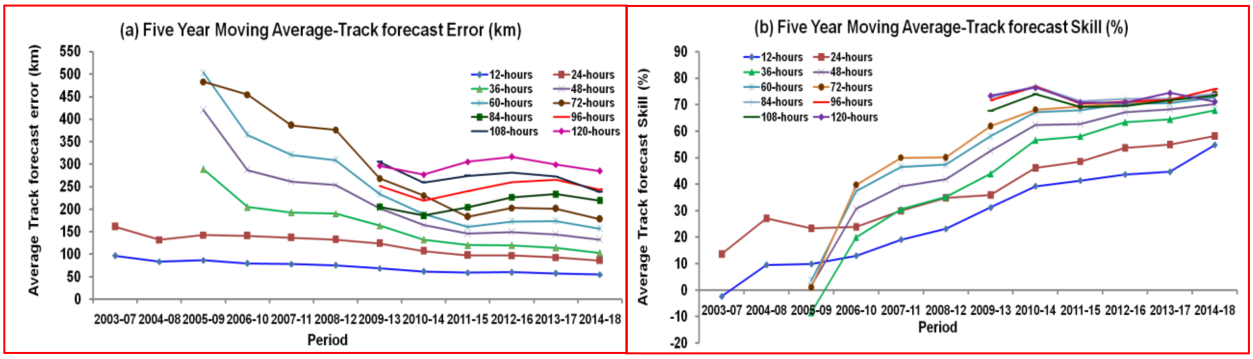


Fig. 4.7.1 Five Year Moving Average (a) Track Forecast Error (km) and (b) Track Forecast Skill (%) of RSMC, New Delhi over North Indian Ocean

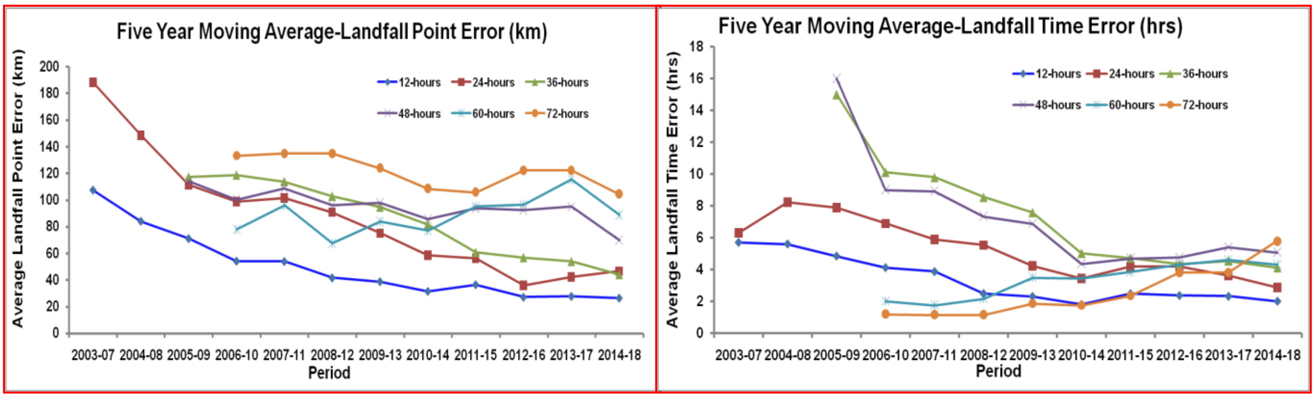


Fig. 4.7.2 Five Year Moving Average (a) Landfall Point Forecast Error (km) and (b) Landfall Time Forecast Error (hrs) of RSMC, New Delhi over North Indian Ocean

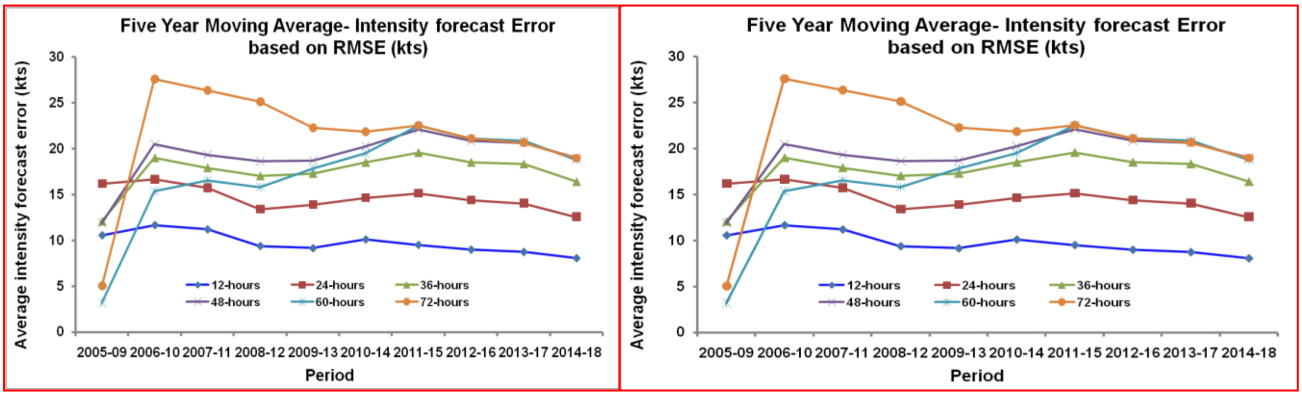


Fig. 4.7.3 Five Year Moving Average Intensity Forecast (a) Absolute Error (kts) and (b) Root Mean Square Error (kts) of RSMC, New Delhi over North Indian Ocean

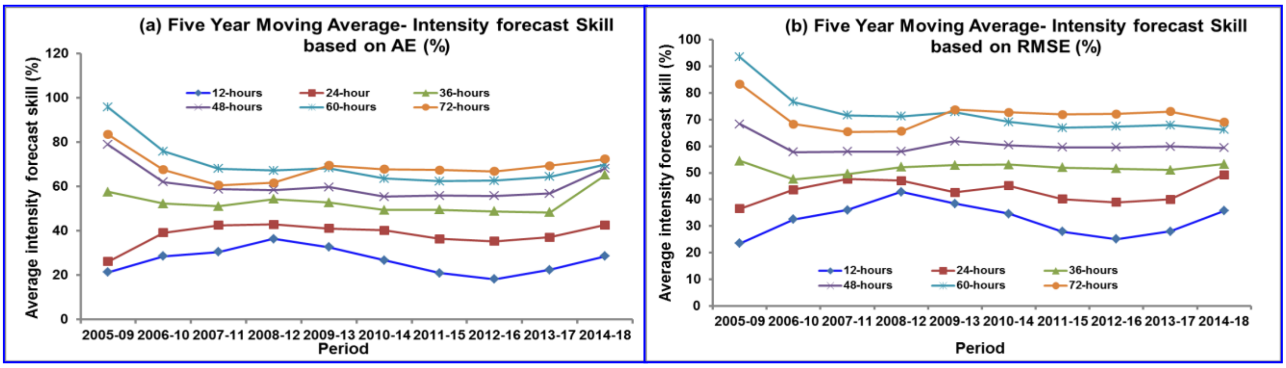


Fig. 4.7.4 Five Year Moving Average Intensity Forecast skill based on (a) Absolute Error (%) and (b) Root Mean Square Error (%) of RSMC, New Delhi over North Indian Ocean

Table 4.7.1 Homogeneous comparison of Official Landfall Forecast Errors over north Indian Ocean in 2018 with Averages for 2013-17 and 2008-17.

Parameter	**Forecast Period (hr)**					
	12	**24**	**36**	**48**	**60**	**72**
2018						
Mean OFCL Landfall Point Error (km)	26.7	44	42.1	40.3	56.4	67.6
Mean OFCL Landfall Time Error (hr)	1.9	2.8	3.7	4.9	4.7	7.4
No. of cases	8	7	7	7	5	3
2013-17						
Mean OFCL Landfall Point Error (km)	27.9	42.3	53.9	94.8	115.4	122.1
Mean OFCL Landfall Time Error (hr)	2.3	3.6	4.5	5.4	4.6	3.8
No. of cases	12	12	12	11	9	7
2008-17						
Mean OFCL Landfall Point Error (km)	35.9	70.7	78.3	95.3	96.3	126.7
Mean OFCL Landfall Time Error (hr)	2.4	4.7	6.5	6.3	3.6	2.9
No. of cases	29	29	24	21	15	11
2018 OFCL Landfall Point Error relative to 2013-17 mean (%)	4.1	-4.1	21.8	57.5	51.1	44.6
2018 OFCL Landfall Time Error relative to 2013-17 mean (%)	18.3	22.8	18.4	9.1	-1.9	-93.6
2018 OFCL Landfall Point Error relative to 2008-17 mean (%)	22.5	40.2	31.2	0.5	-19.8	3.6
2018 OFCL Landfall Time Error relative to 2008-17 mean (%)	4.4	23.6	30.6	14.7	-26.9	-34.1

OFCL: Official. The landfall forecast was issued upto 24 hrs till 2008 and 72 hrs from 2009 onwards, during 2018 forecast upto 72 hrs has been verified

Table 4.7.2 Homogeneous comparison of OFCL & CLIPER Track Forecast Errors over NIO in 2018 with Averages for 2013-17 and 2008-17

Parameter	Forecast Period (hr)									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2018 Mean OFCL Forecast Error (km)	55.4	87.5	99.2	124.2	131.2	134.3	165.8	189.0	220.8	247.6
2018 Mean CLIPER Error (km)	151.1	191.9	292.9	401.5	505.9	619.2	773.1	1084.8	781.5	475.5
2018 Mean OFCL Skill wrt CLIPER (%)	63.3	54.4	66.1	69.1	74.1	78.3	78.6	82.6	71.7	47.9
2018 No. of cases	127	111	97	80	63	51	34	24	16	7
2013-17 Mean OFCL Forecast Error (km)	57.2	92.7	114.4	144.0	173.4	201.0	233.3	265.0	272.4	299.0
2013-17 Mean CLIPER Error (km)	103.4	205.5	322.2	454.4	587.0	707.8	839.7	940.9	964.2	1168.8
2013-17 Mean OFCL Skill wrt CLIPER (%)	44.7	54.9	64.5	68.3	70.5	71.6	72.2	71.8	71.8	74.4
2013-17 No. of cases	302	267	227	192	158	127	95	70	43	27
2008-17 Mean OFCL Forecast Error (km)	63.2	105.2	133.8	169.1	202.4	234.5	233.3	265.0	272.4	299.0
2008-17 Mean CLIPER Error (km)	101.7	204.9	314.8	450.2	587.2	716.5	839.7	940.9	964.2	1168.8
2008-17 Mean OFCL Skill wrt CLIPER (%)	37.9	48.6	57.5	62.4	65.5	67.3	72.2	71.8	71.8	74.4
2008-17 No. of cases	449	389	305	249	201	157	95	70	43	27
2018 relative to 2013-17 mean (%)	-3.2	-5.6	-13.3	-13.8	-24.3	-33.2	-28.9	-28.7	-18.9	-17.2
2018 CLIPER error relative to 2013-17 mean (%)	46.1	-6.6	-9.1	-11.6	-13.8	-12.5	-7.9	15.3	-18.9	-59.3
2018 Skill relative to 2013-17 mean (%)	18.7	-0.5	1.6	0.8	3.6	6.7	6.3	10.7	0.0	-26.5
2018 relative to 2008-17 mean (%)	-12.3	-16.8	-25.9	-26.6	-35.2	-42.7	-28.9	-28.7	-18.9	-17.2
2018 CLIPER error relative to 2008-17 mean (%)	48.6	-6.3	-6.9	-10.8	-13.8	-13.6	-7.9	15.3	-18.9	-59.3
2018 Skill relative to 2008-17 mean (%)	25.5	5.8	8.6	6.6	8.5	11.0	6.3	10.7	0.0	-26.5

The track forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards, OFCL: Official

Table 4.7.3: Homogeneous comparison of OFCL & Persistence Intensity Forecast Errors based on Absolute Error over NIO in 2018 with Averages of 2013-17 and 2008-17

Parameter	Forecast Period (hr)									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2018 Mean OFCL Forecast Error (kts)	4.8	8.2	12	11.6	12.8	12.9	12.9	13.8	13.3	9.2
2018 Mean Persistence Error (kts)	8.2	16.4	55.8	59.4	60.8	62.7	73.1	76.1	83.1	87.5
2018 Mean OFCL Skill wrt Persistence (%)	42	50	22	28.5	32.5	34.5	47.9	57.7	78.8	73.6
2018 No. of cases	127	112	98	81	63	51	34	24	16	7
2013-17 Mean OFCL Forecast Error (kts)	6.3	10.4	13.8	15.5	15.8	15.7	17.0	16.9	14.2	11.1
2013-17 Mean Persistence Error (kts)	8.1	16.5	26.6	35.9	44.4	51.1	64.8	80.7	93.2	92.6
2013-17 Mean OFCL Skill wrt Persistence (%)	22.3	37.1	48.2	56.8	64.4	69.3	73.7	79.0	84.7	88.0
2013-17 No. of cases	302	267	228	190	157	125	95	70	43	27
2008-17 Mean OFCL Forecast Error (kts)	6.4	10.2	13.5	15.0	15.2	16.3	17.0	16.9	14.2	11.1
2008-17 Mean Persistence Error(kts)	8.8	16.6	26.9	34.9	43.3	50.7	64.8	80.7	93.2	92.6
2008-17 Mean OFCL Skill wrt Persistence (%)	27.6	38.9	49.8	57.1	64.9	67.9	73.7	79.0	84.7	88.0
2008-17 No. of cases	450	392	310	251	200	155	95	70	43	27
2018 OFCL error relative to 2013-17 mean (%)	23.8	20.8	13.0	25.2	19.1	17.9	24.3	18.3	6.6	17.4
2018 Persistence error relative to 2013-17 mean (%)	-1.1	0.3	-109.6	-65.7	-36.8	-22.6	-12.9	5.7	10.8	5.5
2018 Relative Skill wrt 2013-2017	-19.7	-12.9	26.2	28.3	31.9	34.8	25.8	21.3	5.9	14.4
2018 OFCL error relative to 2008-17 mean (%)	24.4	19.2	11.1	22.6	15.8	20.9	24.3	18.3	6.6	17.4
2018 Persistence error relative to 2008-17 mean (%)	6.6	1.3	-107.3	-70.1	-40.3	-23.6	-12.9	5.7	10.8	5.5
2018 Relative Skill wrt 2008-2017	-14.4	-11.1	27.8	28.6	32.4	33.4	25.8	21.3	5.9	14.4

The intensity forecast was issued upto 24 hrs till 2008, 72 hrs during 2009-12 and 120 hrs from 2013 onwards, OFCL: Official

Table 4.7.4: Homogeneous comparison of OFCL & Persistence Intensity Forecast Errors based on Root Mean Square Error over NIO in 2018 with Averages of 2013-17 & 2008-17

Parameter	Forecast Period (hr)									
	12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**
2018 Mean OFCL Forecast Error (km)	6.4	9.8	12	14.4	12.8	15.1	15.3	16.2	15	12.7
2018 Mean Persistence Error (km)	12.8	25	31.7	40.4	46.4	50.6	67.4	73.9	97.2	88
2018 Mean OFCL Skill wrt Persistence (%)	49.9	60.8	62	64.3	67.5	70.2	77.3	78.1	84.6	85.6
2018 No. of cases	127	112	98	81	63	51	34	24	16	7
2013-17 Mean OFCL Forecast Error (km)	8.7	14.0	18.4	20.6	20.9	20.7	22.1	20.7	17.1	13.2
2013-17 Mean Persistence Error (km)	12.1	23.4	37.5	51.4	65.2	76.7	94.1	112.0	127.1	115.9
2013-17 Mean OFCL Skill wrt Persistence (%)	28.0	40.1	51.0	60.0	68.0	73.1	76.5	81.5	86.6	88.6
2013-17 No. of cases	302	267	228	190	157	125	95	70	43	27
2008-17 Mean OFCL Forecast Error (km)	577	504	408	332	263	206	129	94	59	14
2008-17 Mean Persistence Error (km)	8.5	13.0	16.8	18.9	18.5	20.2	20.5	19.7	16.5	15.0
2008-17 Mean OFCL Skill wrt Persistence (%)	13.5	24.2	35.8	47.7	59.6	70.6	87.8	103.6	119.8	98.4
2008-17 No. of cases	37.4	46.2	4.7	8.7	15.6	24.5	52.2	89.3	175.0	84.7
2018 OFCL error relative to 2013-17 mean (%)	26.8	30.2	34.6	30.1	38.7	26.9	30.6	21.9	12.2	4.0
2018 Persistence error relative to 2013-17 mean (%)	-5.4	-6.8	15.4	21.4	28.8	34.0	28.3	34.0	23.6	24.1
2018 Relative Skill wrt 2013-2017	-21.9	-20.7	-11.0	-4.3	0.5	2.9	-0.8	3.4	2.0	3.0
2018 OFCL error relative to 2008-17 mean (%)	24.4	24.9	28.5	23.8	30.6	25.2	25.4	17.7	9.3	15.4
2018 Persistence error relative to 2008-17 mean (%)	52.6	-3.1	11.5	15.3	22.1	28.3	23.2	28.7	18.8	10.6
2018 Relative Skill wrt 2008-2017	-12.5	-14.6	-57.3	-55.6	-51.9	-45.7	-25.1	11.2	90.4	-0.9

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 VSCS Titli Uprooted coconut trees in Baruva village, AP

Casuarina Jhau tree twisted and broken by gale wind in Baruva village, AP

Damage due to VSCS Gaja Uprooted Trees in Tamil

Damaged beaches and boats in Tamil due to VSCS Gaja

Damaged Karaikudi Tollways and blocked roads in Tamil due to VSCS Gaja

DAMAGE DUE TO VERY SEVERE CYCLONIC STORM 'TITLI' & "GAJA"